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Soil Water Assessment Model for Several Crops in the High Plains

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ABSTRACT

Soil properties, soil water content and precipitation vary widely within the High Plains of the USA. Reliable estimates of crop water status have been hampered by a general sparsity of soil water monitoring. This study examined the feasibility of determining soil water status using a soil water balance model. Soil water content was measured under corn (*Zea mays* L.), wheat (*Triticum aestivum* L.), sorghum (*Sorghum vulgare* L.) and soybean (*Glycine max* L.) at different sites in the High Plains during 1986 and 1987. Surface weather data collected from the High Plains Automated Weather Data Network (AWDN) served as Input to a model that estimates evapotranspiration (ET) and soil water content on a daily time step. Atmospheric demand was represented by potential evapotranspiration (ET_p) calculated from the Penman method. Model estimates of total water in the root zone were compared to measured values using statistical measures Including the *D* index of agreement. Comparison at one site between measured and estimated soil water by individual soil layers beneath a corn Indicated that water content was slightly underestimated in the upper layers and overestimated in the lower layers. The performance of the model in estimating total soil water over a range of soil types, crops and weather was satisfactory, with the majority of *D* index values exceeding 0.75. Based on the results of this study, we conclude that it is now possible to accurately estimate soil water conditions In a timely fashion under reasonably flat terrain, provided near-real time weather data are available.

AGRICULTURAL PRODUCTIVITY is greatly influenced by the uncontrollable forces of weather and climate. For instance, prolonged periods of dry weather are recognized as a characteristic feature of North American climate, particularly in the High Plains (Rosenberg, 1987). A crisis in world food supply can occur as a result of drought in the High Plains, because of the large North American contribution to world food production. Technological advances in electronics and communications have made it possible to monitor weather at remote agricultural sites (Hubbard, 1987). This near-real time weather data can be used as input to models that estimate factors related to crop production.

Soil water content is the most variable of all the resources in High Plains cropping systems from one growing season to the next. Models have not been used to estimate the water in the root zone on a wide area basis, although a suitable estimate seems inherently more useful in assessing weather impacts on agriculture than current climatic drought indices. Intuitively, soil water estimates throughout a region seem valuable yet prior to presenting the estimation technique used in this study we consider some of the problems and consider why estimates on a wide area basis have not been available previously.

The root zone water content may vary considerably in response to variations in precipitation and irrigation, evaporation, transpiration, runoff, and drainage from the root zone. In turn, the spatial variability of *ET* from a crop-covered field is caused by field variability in microclimatic conditions, soil physical properties, and pertinent crop properties (Hansen and Jensen, 1986). Soil physical proper-ties that may vary include porosity, permeability and hydraulic conductivity, whereas pertinent crop properties that influence water use patterns include leaf area index, phenological developmental rate, aerodynamic roughness of the crop canopy and the ability of the roots to extract soil water. Variations in topography, vegetative cover and soil properties can result in large within-field variations of soil water content (Hawley et al., 1983). Vertical variations in soil properties can result from the formation of a claypan beneath the soil surface, crusting of the soil surface, and soil compression resulting in altered infiltration and drainage patterns. Vertical variability of soil properties can, in turn, vary markedly in the horizontal (Wetzel and Chang, 1987). Models can be used to explain the majority of the variance in a set of observations only if the above mentioned sources of variation are dealt with by the models. Perhaps the lack of a suitable regional or national source of real time weather data for calculating evaporation and transpiration has previously prevented the development of a crop and soil water status system.

Kincaid and Heermann (1974) used the Penman equation to calculate potential evapotranspiration (Penman, 1948). They derived new coefficients for the wind function with data collected over alfalfa (*Medicago saliva* L.) in western Nebraska. The ET_p was defined as the rate of water use by a well-watered alfalfa crop with 300 to 460 mm of growth. Alfalfa was suggested as the reference crop for use in and and semiarid climates for activities such as irrigation scheduling (Jensen et al., 1971), and Wright (1982) suggested that alfalfa is preferable in and regions because it is capable of near-maximum *ET* under conditions of considerable sensible heat advection. Crop coefficients (K_c) have been employed with ET_p to estimate values of crop water use for well watered crops other than the reference crop (Jensen, 1973). When crops are not well watered, the actual rate of *ET* falls below the potential rate when water in the root zone has been depleted below about one-half of the potentially available water (Dyer and Baier, 1979).

Although the Penman equation includes many of the climatic variables that affect *ET*, it has rarely been used on a regional scale due to lack of appropriate input data. The objective of th I s study was to assess the performance of a model that estimates soil water. This was accomplished by comparing estimated to measured soil water values at widely separated locations in the High Plains region.

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Table 1. Frequency of soil water measurements by location and crop.

Site	Year	Crop	Days with measured water	Dates
			no.	
North Platte, NE	1986	Corn	13	June: 4,11,18,25; July: 2.9.16,23,30; August: 13,20,27; September 3
		Wheat	12	April: 23,30; May: 7,14,21,28; June: 4,11,18,25; July. 2,9
North Platte, NE	1987	Corn	12	June: 2,11,17; July. 7,14,21,27; August: 4,11.18; September 1,8
		Wheat	4	Mar. 26; June: 2,11,17
		Sorghum	12	June: 2,10,17; July: 7,14,21,27; August: 4,11,18; September. 1,8
		Soybean	12	June: 2,10,17; July. 7,14,21,28; August: 4,11,18; September. 1,8
Clay Center, NE	1987	Corn	8	June: 30; July 7,21,30; August: 6,21,27; September 30
		Wheat	9	April: 23,29; May: 7,15,29; June: 9,18,30; July. 7
		Sorghum	8	June: 30; July. 7,21,30; August: 6,21,27; September. 30
		Soybean	8	June: 30; July. 7,22,30; August: 6,21,27; September. 30
Concord, NE	1987	Corn	11	June: 11,25; July. 1,9,16,23-1& August: 5,14; September. 11,28
		Sorghum	9	July. 1,8,16,23,30; August: 5,14; September. 11,28
		Soybean	It	June: 11,25; July. 1,9,16,23,30; August: 5,14; September 11,28
Mead, NE	1986	Wheat	5	May: 14,30; June: 13; July: 2,16
		Soybean	5	June: 6,13; July: 2,17,29
Brookings, SD	1987	Corn	4	June: 29; July- 13; August: 6,26
Chamberlain, SD	1987	Corn	5	July: 1,14,30; August: 20; September. 14
Wheatland, WY	1986	Wheat	8	May: 30; June: 15,30; July: 14,28; August: 11,26; September 8
Sidney, NE	1987	Wheat	8	May: 27, June: 3,11,18,26; July: 2,9,16
Chugwater, WY	1987	Grass	10	May: 19; June: 2.10.16,23,30; July: 7,14,21,28

MATERIALS AND METHODS

Weather data were collected by an AWDN. The AWDN (Hubbard et al., 1982) collected hourly values of air temperature and humidity, solar radiation, wind speed and direction, soil temperature and precipitation. The hourly data were summarized into daily values for use in this study.

Soil water measurements were taken on 1- and 2-wk intervals during the growing seasons of 1986 and 1987 for corn, wheat, sorghum and soybean at widely separated sites in the High Plains, and under a pasture, primarily buffalo grass (*Buchloe dactyloides* L.) at Chugwater, WY (Table 1). Measuring sites were restricted to flat or gently sloping terrain. Most of the soil water data were obtained using neutron probes, although some soil water data were determined gravimetrically. The soil water measurements were recorded at sites that also had stations, except at Chugwater. Because there is not an AWDN station at that site, the meteorological data were taken 36 km away at Wheatland, WY. For most of the sites, the soil water data were taken by University of Nebraska Extension Soil Specialists for as many as six layers (300 mm in depth) if necessary to represent the rooting zone of field crops. To obtain readings representative of these layers, measurements were taken at the midpoint depths of 150, 450, 750, 1050, 1350, and 1650 mm when a neutron probe was used. Data taken using neutron probes were converted to volumetric soil water content using calibration curves specific to the neutron probe used, whereas data taken by gravimetric measurement were converted to volumetric soil water content by considering the bulk density of the soil from which the samples were taken.

$$\theta_v = (W_w/W_s) \times (\rho_s/\rho_w) \qquad [1]$$

Where θ_v, is the volumetric water content. The W_s and W_w are the mass of the soil and the water respectively from each sample; ρ_w and ρ_s are the density of water and the bulk density of the soil. Information concerning crop phenology was included with the soil water data for most sites.

The soil water model (Hanks, 1974; Hubbard and Hanks, 1983) used in this study was modified so that the model root depth at any one time was divided into four layers of equal thickness (Sagar et al., 1988). The model estimates root extraction as: 40% of the transpired water from the top root layer, 30% from the second layer, 20% from the third layer, and the remaining 10% from the bottom layer. Root growth was estimated as a linear function of the time elapsed between the crop planting date and maturity date. The model used the soil water balance equation to calculate the soil water in the rootzone (S) from the value 24 h ago (S_o) Precipitation (p), irrigation (I), ET, runoff (R_o) and drainage below the rootzone (D_r) are input to the equation with a daily time step

$$S = S_O + p + I - ET - R_o - D_r. \qquad [2]$$

Phenological growth stages were calculated from growing degree days accumulated since planting. Potential evapotranspiration (ET_p) was calculated using the Penman combination equation with the wind function derived by Kincaid and Heermann (1974)

$$ET_p = [\Delta(R_n\text{-}G) + \gamma f(U_2)(e_s - e_a)]/(\Delta+\gamma) \qquad [3]$$

where R_n, G, $f(U_2)$, e_s, e_a are the net radiation, soil heat flux, wind function (at 2 m). saturated vapor pressure, and vapor pressure of air respectively. Other terms in the equation are the psychrometric constant (γ), and the slope of the saturation vapor pressure curve (Δ). The soil heat flux term (G) was set to zero in this study because it is not commonly measured in networks and its estimation in a previous study did not increase the accuracy of the ET_p, estimate (Norman and Nielsen, 1983). Meteorological inputs for the equation were derived from hourly values of air temperature and humidity, wind speed, and global solar radiation. Net radiation, R_n, was estimated using the coefficients and equations of Kincaid and Heermann (1974) which employ global radiation, expected clear day global radiation, saturated vapor pressure at the mean dew point, and the maximum and minimum air temperature.

Evapotranspiration in the model is made up of crop transpiration (T_a) and surface evaporation (E) components ($ET = T_a + E$). Evaporation is calculated as a function of the days (d) since the last wetting by either precipitation or irrigation (p or I)

$$E = E_p(d_p / d)^{1/2}.$$

The day (d_p) when E was assumed equal to E_p was taken as one (i.e., the day of the wetting) and E_p was assumed equal to ET_p, on Day d.

Actual transpiration (T_a) was treated in the model as a function of the transpiration from a crop with adequate soil water (T_p)

$$T_a = f \times T_p. \qquad [4]$$

Potential transpiration was estimated by employing crop coefficients (K_c) adapted from the literature (Wright, 1982; Hinkle et al., 1984; Innis, 1978) for use with the phenological growth stages employed in the model (Vanderlip, 1972; Waldren and Flowerday, 1979; Ritchie et al., 1982; Hanway, 1971)

$$T_p = K_c \times ET_p. \qquad [5]$$

The reduction factor (f) in Eq. [4] was employed to limit the crop water use as the soil water approached wilting point

$$f = 1.0 \;\; if \;\; S/AW_p > F \;\; or$$
$$f = S/(F \times AW_p) \;\; if \; S/AW_p \le F.$$

The potential available water for crop use in each layer (AW_p) was estimated as the difference between the volumetric percentage of water at wilting point and at field capacity. The threshold value (F) given in Table 2 was determined by trial and error where a modest range of F values was tested in the model to determine a reasonable fit between measured and observed soil water values. Estimated maximum rooting depth was input to the model. The model was further modified so that estimation of the soil bulk density and mass fractions of sand, silt and clay (Table 2) were used in the model to calculate the exponent of the hydraulic conductivity function and the saturated hydraulic conductivity (Campbell, 1985), which determine the modeled rate of water movement through the soil. Other specified crop parameters include maximum crop height, maximum rooting depth, the month and day on which senescence or dormancy begins, and the respective accumulated growing degree days (GDD) at which these values are attained. Other specified parameters are the upper and lower temperature limits for crop growth (used to calculate daily GDD values), the accumulated GDD (from planting) and Kc values at the beginning and end of each growth stage.

The model estimated the water content of each specified soil layer on a daily basis. and these soil water estimates were compared to the measured soil water. Although historically r^2 has been widely used as an index of agreement. the relationship between r^2 and performance of a model is not always instructive and it should not be used alone in model performance analysis. Willmott and Wicks (1980) cautioned that "high" or statistically significant values of Pearson's product-moment correlation coefficient (r) and coefficient of simple determination (r^2) may be misleading because such measures are often unrelated to the size of the differences between observed and model-predicted variates. Willmott (1981) devised the D index of agreement

$$D = 1 - [\Sigma(P_i - O_i)^2 / \Sigma(|P_i - O| + |O_i - O|)^2] \qquad [6]$$

for assessing model performance. Where P_i and O_i are the predicted and observed quantities of interest and P and O are the respective means of these quantities. The D index is more sensitive to systematic model error than are r and r^2, and reflects systematic model bias when coupled with the *1-1* statistic. Values of D range from 0.0 for complete disagreement between observed and predicted values, to 1.0 for perfect agreement The systematic (E_s) and unsystematic (E_u) components of the root mean square error (*RMSE*) were calculated, and E_s and E_u values were compared to indicate the systematic error relative to random error. The mean absolute error (*MAE*) is less sensitive to extreme values than is *RMSE* (Fox, 1981), and avoids the physically artificial exponentiation that is an artifact of the statistical-mathematical

Table 2. Soil parameters influencing soil water status.

Soil type	Sites, Crops	Reduction factor†	Threshold‡	Clay	Sand	Silt	Bulk density
			mm		%		Mg m^{-3}
Cozad silt loam	All North Platte crops	0.35	28	20	30	50	1.40
Hastings silt loam	Clay Center corn, sorghum, and soybean	0.45	25	33	10	57	1.30
Crete silt loam	Clay Center wheat	0.50	23	35	6	59	1.27
Kennebec silt loam	Concord, corn and soybean	0.45	28	25	7	68	1.20
Nora silt loam	Concord, sorghum	0.45	28	25	7	68	1.25
Sharpsburg silt	Mead, wheat and soybean	0.35	28	35	10	55	1.30
Estelline silt loam	Brookings, corn	0.50	33	25	10	65	1.25
Uly silt loam	Chamberlain, corn	0.50	33	25	10	65	1.25
Keith silt loam	Sidney, wheat	0.50	30	20	33	47	1.27
--	Wheatland, wheat	0.40	30	10	43	47	1.32
--	Chugwater, grass	0.50	36	10	43	47	1.32

† Reduction factor (F); ET rate falls below the potential rate when (available water/potential available water) < F.

Table 3. Statistics and measures of model performance are shown for crops included in this study at various locations in the High Plains (1986-1987).

Site	Year	Crop	D	r^2	*MAE*	*P*	σ_p†	*O*	σ_o†	E_s	E_u	*RMSE*
					(mm)	(mm)	(mm')	(mm)	(mm)	(mm)	(mm)	(mm)
North Platte, NE	**1986**	**Corn**	**0.99**	**0.98**	**12**	**354**	**102**	**346**	**103**	**8**	**13**	**15**
		Wheat	**0.78**	**0.94**	**44**	**321**	**38**	**277**	**59**	**48**	**9**	**49**
North Platte, NE	**1987**	**Corn**	**0.98**	**0.98**	**17**	**310**	**88**	**327**	**95**	**18**	**13**	**22**
		Wheat	**0.79**	**0.91**	**16**	**306**	**18**	**290**	**20**	**16**	**5**	**17**
		Sorghum	**1.00**	**0.99**	**11**	**391**	**97**	**389**	**108**	**11**	**8**	**14**
		Soybean	**0.96**	**0.99**	**31**	**367**	**78**	**336**	**90**	**34**	**7**	**34**
Clay Center, NE	**1987**	**Corn**	**0.91**	**0.91**	**41**	**544**	**84**	**585**	**82**	**41**	**23**	**47**
		Wheat	**0.78**	**0.40**	**38**	**612**	**46**	**595**	**56**	**31**	**34**	**46**
		Sorghum	**0.98**	**0.98**	**17**	**610**	**83**	**596**	**95**	**18**	**10**	**20**
		Soybean	**0.96**	**0.96**	**20**	**625**	**67**	**645**	**70**	**21**	**13**	**24**
Concord, NE	**1987**	**Corn**	**0.92**	**0.74**	**20**	**295**	**54**	**298**	**46**	**3**	**27**	**27**
		Sorghum	**0.75**	**0.67**	**46**	**288**	**65**	**242**	**54**	**46**	**35**	**58**
		Soybean	**0.70**	**0.78**	**79**	**406**	**67**	**327**	**75**	**80**	**30**	**86**
Mead, NE	**1986**	**Wheat**	**0.79**	**0.98**	**29**	**454**	**31**	**425**	**62**	**40**	**4**	**40**
		Soybean	**0.79**	**0.71**	**27**	**580**	**36**	**553**	**43**	**30**	**17**	**34**
Brookings, SD	**1987**	**Corn**	**0.95**	**0.93**	**11**	**244**	**33**	**251**	**43**	**12**	**7**	**14**
Chamberlain, SD	**1987**	**Corn**	**0.96**	**0.95**	**10**	**291**	**35**	**301**	**40**	**12**	**7**	**14**
Wheatland, WY	**1986**	**Wheat**	**0.84**	**0.68**	**10**	**226**	**15**	**234**	**17**	**10**	**8**	**13**
Sidney, NE	**1987**	**Wbeat**	**0.86**	**0.99**	**33**	**284**	**54**	**317**	**41**	**35**	**6**	**36**
Chugwater WY	**1987**	**Grass**	**0.86**	**0.77**	**12**	**265**	**15**	**261**	**26**	**13**	**7**	**15**

† σ_p and σ_o are the variance (square of the standard deviation) for the predicted and observed data sets, respectively.

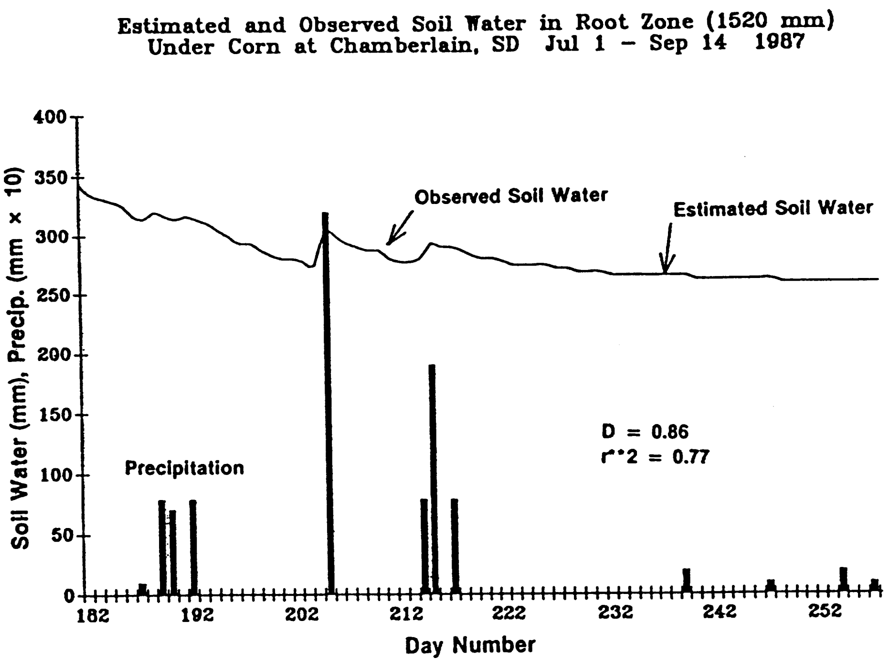

Fig. 1. Daily precipitation totals and total observed and estimated soil water in the root zone for a corn crop at Chamberlain, SC, 1987 growing season.

reasoning from which *RMSE* comes

$$E_s = [N^{-1}\Sigma(P_{ri} - O_i)^2]^{0.5} \quad [7]$$

$$E_u = [N^{-1}\Sigma(P_{ri} - P_i)^2]^{0.5} \quad [8]$$

$$RMSE = MSE^{0.5} = (E_s^2 + E_u^2)^{0.5} \quad [9]$$

$$MAE = N^{-1}\Sigma|P_i - O_i|. \quad [10]$$

Model performance was examined by layer underneath the 1986 corn crop at North Platte, NE. Where P_{ri} is calculated from the slope and intercept, $P_{ri} = a + b \times O_i$. Model estimates of water content for six 300-mm-soil layers were compared to the measured values.

RESULTS AND DISCUSSION

Soil water model performance over a range of soil types, crops and weather was considered satisfactory, with the majority of D index values exceeding 0.75. The *D* indices and other statistical measures are presented in Table 3. The model used in this study gave the best performance for corn. Differences in performance on crops could be attributable to several causes, most notably differences in crop water use and root water extraction characteristics from crop to crop. We speculate that the empirical nature of the sensible heat advection term in the Penman equation and the lack of explicit resistance terms prevents realization of crop to crop difference at a location. Of course, sensible heat advection,

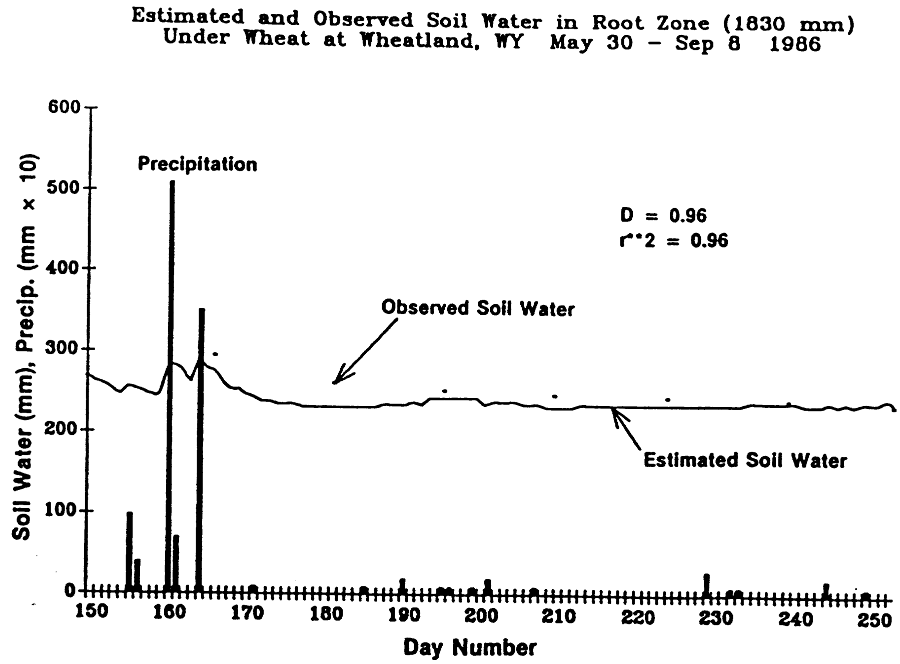

Fig. 2. Daily precipitation totals and total observed and estimated soil water in the root zone for a wheat crop at Wheatland, WY, for the 1986 growing season.

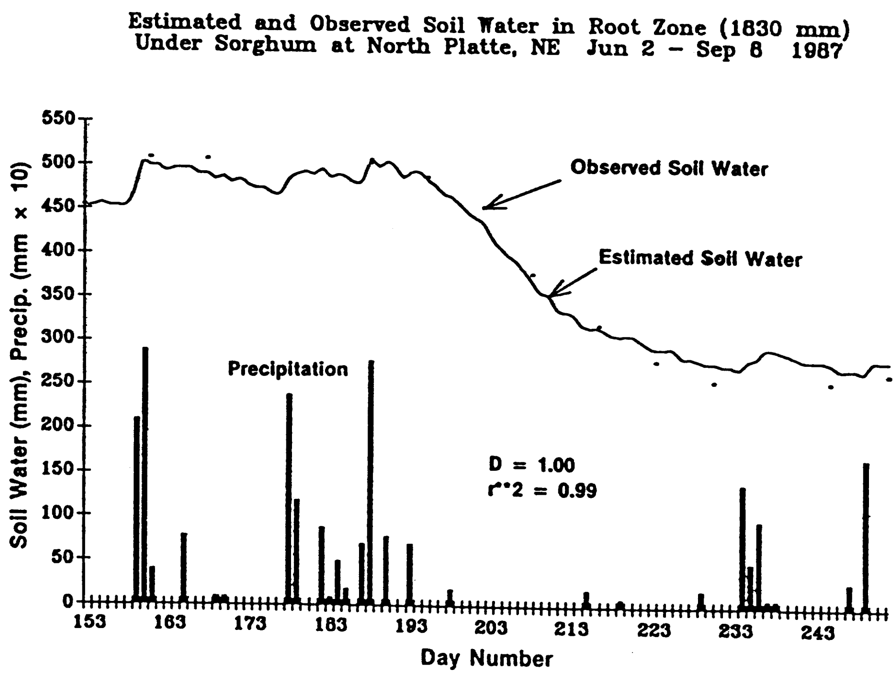

Fig. 3. Daily precipitation totals and total observed and estimated soil water in the root zone for a sorghum crop at North Platte, NE, for the 1987 growing season.

may vary considerably from semiarid to subhumid portions of the High Plains as well.

Figures 1 through 5 are typical of the daily estimates of root zone water content determined by the model for each crop, at various sites. The observed water content is also plotted on these figures. Figure 1 shows the soil water pattern under the corn grown at Chamberlain in 1987. Soil water content was underestimated during the first part of the growing season, with agreement between the predicted and observed values improving as the season progressed. The estimated water content can be seen to increase with major precipitation events and decrease in response to evaporative demand.

Figure 2 illustrates that neither the predicted nor the measured water content of the soil changed appreciably under the wheat grown at Wheatland in 1986. Although the r^2 value was 0.68, the *D* index value was 0.85. Figure 3 depicts the soil water pattern under the

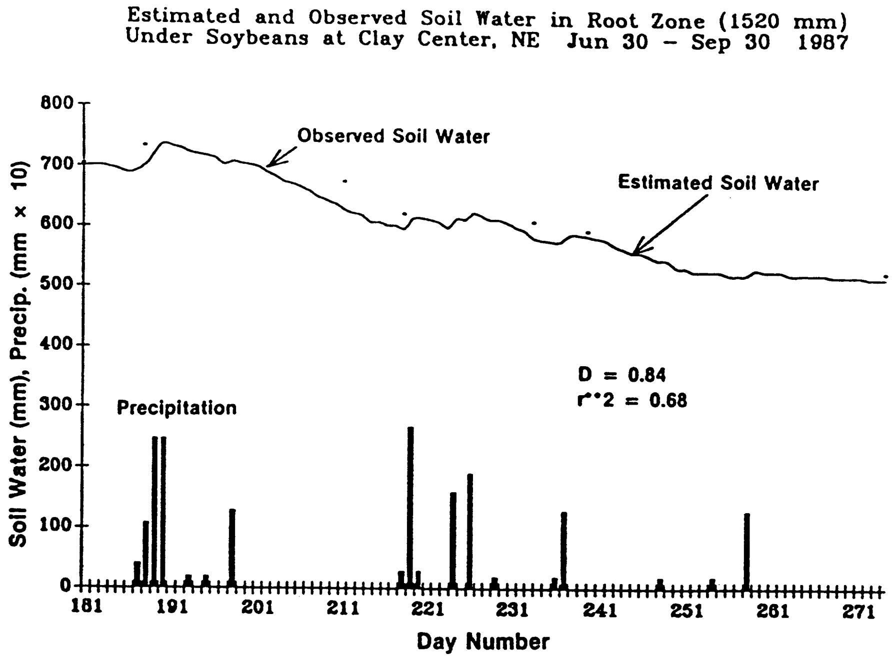

Fig. 4. Daily precipitation totals and total observed and estimated soil water in the root zone for a soybean crop at Clay Center, NE, for the 1987 growing season.

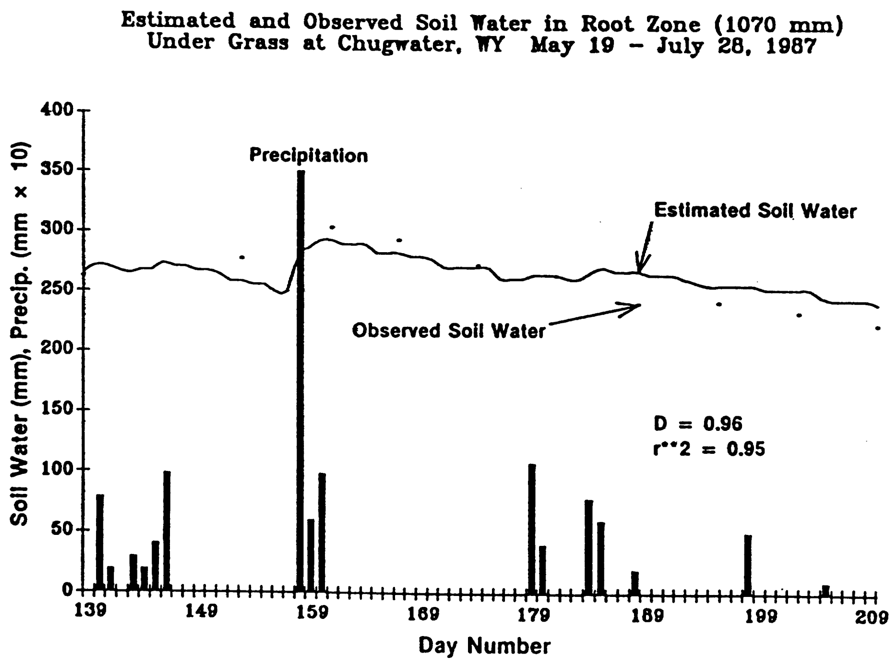

Fig. 5. Daily precipitation totals and total observed and estimated soil water in the root zone for grass at Chugwater, WY, for the 1987 growing season.

sorghum grown at North Platte in 1987, and the good agreement between predicted and observed values is evidenced by the high values of *D* and r^2.

The model estimated rapid decline of total soil water after Day 193, when rainfall became less frequent, and water content was slightly overestimated later in the season. This in conjunction with the slight underestimation of water content earlier in the season indicated that the water content of the rooting zone decreased at a faster rate than was modeled. Figure 4 shows slight underestimation of water content under the soybeans grown at Clay Center in 1987, but the values of *D* and r^2 indicate generally good agreement between the predicted and observed values. Figure 5 illustrates the pattern of soil water content under the pasture at Chugwater in 1987. The model underestimated water content for approximately 1 wk, predicted accurately for 2 wk, then overestimated the water content over the last several weeks of the modeled period. Although the modeled and measured values peaked at the same time, the rooting zone lost water at a more rapid rate than was modeled.

Table 4. Statistics on model performance, by layer. Data is for six 305-mm-soil layers for 1986 North Platte corn.

Soil layer	*D*	*r^2*	*MAE*	*P*	σ_p	0	σ_o	E_s	E_u	*RMSE*
			(mm)	(mm)	(mm^2)	(mm)	(mm^2)	(mm)	(mm)	(mm)
0-305 mm	*0.97*	*0.94*	*5*	*56*	*18*	*60*	*18*	*4*	*4*	*6*
305-610 mm	*0.95*	*0.97*	*7*	*56*	*21*	*62*	*17*	*7*	*4*	*8*
610-915 mm	*0.99*	*0.98*	*4*	*56*	*21*	*56*	*17*	*3*	*3*	*4*
915-1220 mm	*0.98*	*0.96*	*4*	*61*	*18*	*57*	*20*	*4*	*4*	*6*
1220-1525 mm	*0.92*	*0.92*	*9*	*62*	*15*	*55*	*19*	*8*	*4*	*9*
1525-1830 mm	*0.88*	*0.95*	*8*	*62*	*11*	*56*	*17*	*9*	*2*	*9*

Table 4 gives the model performance statistics for each of the six 300-mm-soil layers under the corn grown at North Platte in 1986. Water content was underestimated in the upper layers of soil and overestimated in the lower soil layers; consequently the closest agreement between simulated and measured values occurred for the middle soil layers.

Such models may be useful in determining the status of agricultural crops over wide regions, so it is essential to discuss model representativeness, model limitations and other factors affecting the results of the current study. The current soil water model was tested in flat terrain immediately surrounding the sites at which meteorological inputs to ET_p, were measured. In variable terrain the slope of the surface results in altered runoff and altered infiltration patterns. Spatial variability of precipitation amounts and soil properties limit the area for which the modeled soil water contents are valid; however, further study is required to quantify this effect.

Although most of the soil water measurements were taken within several hundred meters of AWDN stations, spatial variability of precipitation is such that it is possible to have a difference of recorded precipitation of several centimeters (and often much greater) between sites only a few hundred meters apart. This is particularly the case during a high-intensity, shortduration-precipitation thunderstorm event, a characteristic of summer precipitation events in the study area. In this study, the precipitation received at the soil water measurement site was equated to that recorded at the nearby AWDN station. Other inputs to the model (solar radiation, temperature, etc.) are not as variable as precipitation or soil characteristics so it may be possible to interpolate the weather measurements to sites between AWDN stations where the soil characteristics and precipitation are known.

The estimated rate of water movement through the root zone is governed by the model values of the hydraulic conductivity and saturated hydraulic conductivity. The mass fractions of sand, silt and clay present in the soil and the bulk density of the soil are inputs to the rate of soil water movement in the model. The bulk density and particle composition inputs represent average values throughout the rooting zone, although wide vertical and horizontal variability of these properties exists in many soils.

The threshold value above which daily precipitation is assumed to runoff was selected with the permeability and infiltration rate of the soil surface in mind. Infiltration is decreased by zones of low soil permeability such as surface crusts, surface compaction caused by farm implements and human and animal traffic, and chemically dispersed clays. The thickness of each soil layer represented in the model was varied to parallel the thicknesses and depths used in soil water sampling schemes, and the modeled layers do not necessarily simulate the vertical variations of soil properties actually present in the soil. The maximum rooting depth is also an approximate parameter, and differences between the modeled and actual rooting depth can lead to disparities between the modeled and measured values of soil water content, particularly in lower soil layers.

Table 5. Dates of selected crop phenological stages for the crops included in this study at various locations in the High Plains (1986-1987).

Corn			Maturity	
Site	Year	Silking date	Date	GDD†
North Platte, NE	1986	14 July	12 September	2500
North Platte, NE	1987	9 July	1 September	2500
Clay Center, NE	1987	16 July	13 September	2750
Concord, NE	1987	11 July	8 September	2580
Brookings, SD	1987	14 July	13 September	2400
Chamberlain, SD	1987	16 July	10 September	2750
Wheat			**Maturity**	
Site	Year	Flowering date	Date	GDD
North Platte, NE	1996	27 May	29 June	1600
North Platte, NE	1987	2 June	3 July	1600
Clay Center, NE	1987	18 May	21 June	1840
Mead, NE	1986	5 June	7 July	1840
Wheatland, WY	1986	11 June	13 July	1600
Sidney, NE	1987	3 June	6 July	1600
Sorghum			**Maturity**	
Site	Year	Half-bloom date	Date	GDD
North Platte, NE	1987	5 August	21 September	2369
Clay Center, NE	1987	7 August	12 September	2125
Concord, NE	1997	12 August	27 September	2200
Soybean			**Maturity**	
Site	Year	Bloom date	Date	GDD
North Platte, NE	1987	6 July	15 August	1950
Clay Center, NE	1987	28 July	27 September	2360
Concord, NE	1987	23 July	28 September	2400
Mead, NE	1986	17 July	16 September	2450
Pasture			**Dormancy**	
Site	Year	Flowering date	Date	GDD
Chugwater, WY	1987	22 May	4 August	2800

† Growing degree day (GDD) accumulations for cool season crops were calculated with a base of 4 °C and an upper limit of 25 °C (10 and 25 °C for warm season crops).

The Penman equation used in this study was calibrated for alfalfa 300 to 460 mm tall, and its empirical nature presumably leads to errors in field crop ET_p estimation. A constant crop canopy albedo of 0.23 was used to calculate ET_p, when in fact the canopy albedo changes as a function of crop phenology and canopy development (Table 5). Such differences between reference and actual crop were accounted for in this study by introducing K_c. Under certain situations the Penman approach underestimates sensible heat advection; ET_p is often underestimated under conditions of sensible heat advection (Rosenberg, 1969). Under extreme conditions of wind, temperature, and humidity the Penman approach overestimates ET_p.

The precipitation and solar radiation represent totals over a 24-h period; therefore the modeled values of soil water represent the soil water status at midnight. The measured values represent the soil water status at a time earlier in the day, typically late morning to afternoon.

In this study these time differences were ignored. The occurrence of *ET* and sometimes precipitation during the 1st d of the modeled period lead to disparities between the modeled and measured soil water values at some sites.

Crop parameters used in the model vary among different hybrids of the same crop. Parameters such as the maximum rooting depth and the accumulated GDD associated with the maximum root depth and crop height can vary not only among crops, but among different hybrids or varieties of the same crop. Discrepancies between the modeled and actual values of the maximum root depth and crop height, and between the accumulated GDD associated with those parameters, may lead to errors in the modeled amount of crop water use as well as the depth of soil from which water was extracted by roots. Generally, hybrids grown in the northern and western regions of the High Plains require fewer accumulated GDD to reach physiological maturity.

Based on the fact that model simulations were in close agreement with observations, we conclude that it is now possible to accurately estimate soil water conditions in a timely fashion under reasonably flat terrain, provided near-real time automated weather station data are available.

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