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Simulating sensitivity of soil moisture and evapotranspiration under heterogeneous soils and land uses

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Abstract

Soil moisture (SM) plays an important role in land surface and atmospheric interactions. It modifies energy balance at the surface and the rate of water cycling between the land and atmosphere. In this paper we provide a sensitivity assessment of SM and ET for heterogeneous soil physical properties and for three land uses including irrigated maize, rainfed maize, and grass at a climatological time-scale by using a water balance model. Not surprisingly, the study finds increased soil water content in the root zone throughout the year under irrigated farming. Soil water depletes to its lowest level under rainfed maize cultivation. We find a 'land use' effect as high as 36 percent of annual total evapotranspiration, under irrigated maize compared to rainfed maize and grass, respectively. Sensitivity analyses consisting of comparative simulations using the model show that soil characteristics, like water holding capacity, influence SM in the root zone and affect seasonal total ET estimates at the climatological time-scale. This 'soils' effect is smaller than the 'land use' effect associated with irrigation but, it is a source of consistent bias for both SM and ET estimates. The 'climate' effect basically masks the 'soils' effect under wet conditions. These results lead us to conclude that appropriate representation of land use, soils, and climate are necessary to accurately represent the water and energy balance in real landscapes.

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Keywords: Soil moisture; Land use; Sensitivity; Modeling

1. Introduction

Accurate estimation of soil moisture (SM) plays a critical role in water balance calculation by hydrologic, land-surface, and the General Circulation Models (GCMs) (Robock et al., 2000; Srinivasan et al., 2000). The reliability of estimates is largely dependent upon model formulation, assumptions

related to model parameterization, quality of input data, and characterization of land surface heterogeneity (Mahmood, 1996). It has been suggested that soil characteristics and associated land use can notably modify soil water calculation and eventually water balance estimates (Qiu et al., 2001; Mahmood and Hubbard, 2002a,d; Mahmood et al., 2002c). Soils act as a filter to convert a white noise process (precipitation) to a red noise process (SM) in the time domain (Delworth and Manabe, 1988; Vinnikov and Yeserkepova, 1991). Thus, high frequency quasi-random events and processes become low frequency

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non-random and continuous processes. In addition, SM modifies radiative properties of the soil and vegetation and therefore, energy partitioning and land atmosphere feedback processes.

In recent years, due to the absence of long-term measured data, a series of international efforts have been undertaken to estimate global SM with temporal resolution extending from daily to annual (e.g. Dirmeyer, 1999, 2000; Dirmeyer et al., 1999). The estimates of SM are model-based, collectively known as Land Surface Schemes (LSSs). The LSS applications are not specifically focused on determining sensitivity of these schemes to soil characteristics and land use variations. In this paper we investigate sensitivity of a SM process model to soil physical properties. Particularly, we are interested in identifying on a climatological time-scale the extent of the soils effect on root zone SM and ET. A SM moisture model developed by Robinson and Hubbard (1990) is applied to multiple locations in Nebraska, USA for this purpose (Fig. 1).

This study is part of our ongoing effort to build and analyze a SM data set for the Northern Great

Plains (NGP). The SM model was developed and successfully validated by Robinson and Hubbard (1990) (R&H hereafter) and is currently offered as a tool for irrigation scheduling in the NGPs (Mahmood et al., 2001). For validation, measured SM data from several sites in Nebraska under a number of land uses including maize, wheat, sorghum, soybean, and grass was collected and subsequently model estimates were compared to measured SM to determine the performance of the R&H soil model. The model performed satisfactorily (Robinson and Hubbard, 1990). A detailed model description and performance evaluation is provided in Section 3. Further assessment of the R&H model performance was given by Robinson and Hubbard (1990); Camargo (1993), and Camargo et al. (1994). This model is successfully applied to determine impacts of land use on energy partitioning (Mahmood et al., 2001), on land surface hydrology (Mahmood and Hubbard, 2002a), on near surface temperature records (Mahmood et al., 2002c) and to develop SM climatology of the Great Plains (Mahmood and Hubbard, 2002d).

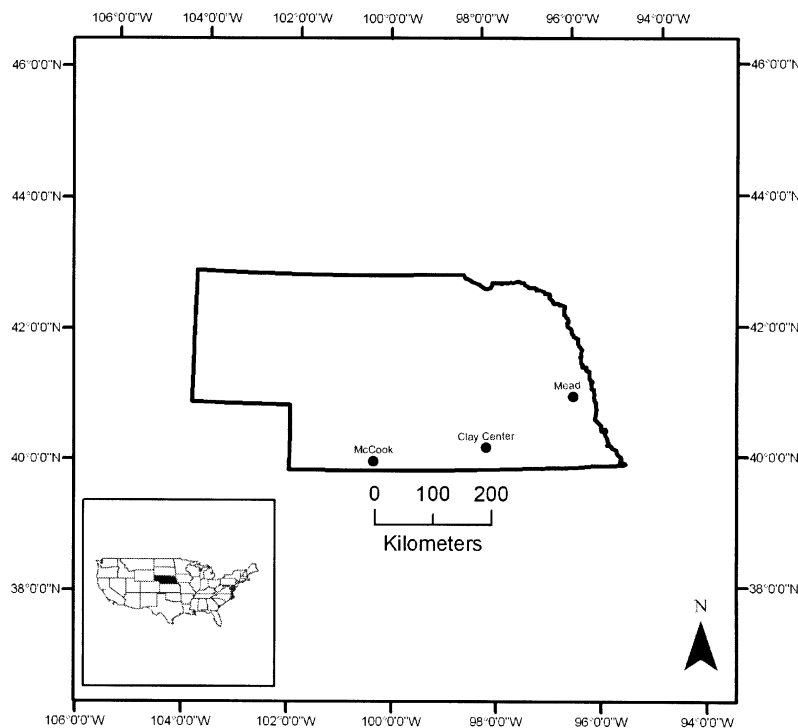


Fig. 1. Location of the study sites in Nebraska.

Literature review suggests that there is a lack of detailed quantitative assessment of the LSSs. Most of the studies only employed qualitative assessment by providing graphics on observed vs. modeled SM. [Chen and Mitchell \(1999\)](#) present a plot of observed and NCEP-LSM simulated SM, for example. Unfortunately, any quantitative assessment on reliability of the model estimates is absent. In addition, some of the major SM modeling efforts under the umbrella of GSWP, AMIP and PILPS (e.g. [Matsuyama et al., 1999](#); [Zhang et al., 1999](#)) provided alike qualitative assessment of LSS validation. Graphical presentation (without any accompanying quantitative assessment) of observed and modeled data indicates notable disagreement. Moreover, application of Japan Meteorological Agency SiB shows its consistent underestimation of SM compared to observed SM ([Matsuyama et al., 1999](#)). [Entin et al. \(1999\)](#) concluded that none of the models under GSWP did a satisfactory job in estimating SM while [Dirmeyer et al. \(1999\)](#) agreed with this observation. In comparison, accuracy of the R&H model estimated SM at the root zone is quantitatively evaluated in detail by comparing model estimated and measured data from multiple land uses, years, and hydroclimatic regimes.

2. Background and rationale

Due to its (SM) important role in modulating climate, over last couple of decades, a significant importance has been placed on the research activities focusing on the relationship between SM and climate. [Shukla and Mintz \(1982\)](#) demonstrated that dry (no ET) and wet (ET at the potential rate) soil conditions significantly influence seasonal rainfall. In a subsequent study, [Delworth and Manabe \(1989\)](#) showed that soil wetness influences near surface relative humidity and temperature by modifying energy partitioning. From their study, it can be concluded that SM, ET, and precipitation are closely tied within the hydrological cycle and are able to significantly affect each other over time and space.

Hong and Pan identified a strong positive feedback between initial SM and simulated seasonal precipitation (2000). They used the National Centers for Environmental Prediction Regional Spectral Model

(NCEP RSM) for their simulations. These simulations suggest that soil water storage effects moisture distribution within the boundary layer atmosphere and its structure ([Hong and Pan, 2000](#)). Recently, it is suggested that inter-annual variations of SM may play a role in seasonal predictability of surface climate anomalies ([Wang and Kumar, 1998](#)). They have noted a strong correlation between SM and surface temperature anomalies. In addition, [Huang et al. \(1996\)](#) noted that SM is a better predictor of temperature over large areas during the summer season than precipitation. [Dirmeyer \(1999, 2000\)](#) suggested that incorrect SM inputs reduced the accuracy of simulated precipitation anomalies. [Milly and Dunne \(1994\)](#) addressed the influence of water holding capacity of soil on the global water cycle. Their models indicate that each doubling of storage capacity (from <1 to 60 cm) results in 7 cm increase of global evaporation from the land surface. Earlier, [Milly \(1992\)](#) showed that inaccurate assumptions related to evaporation calculation by GCMs resulted in biased estimates of continental SM.

In the recent past, the Global Soil Wetness Project (GSWP) and the Intercomparison of Land-Surface Parameterization Schemes (PILPS) provided an umbrella for a series of sensitivity studies for several LSSs (e.g. [Qu et al., 1998](#); [Morrill et al., 1999](#); [Pitman et al., 1999](#); and [Dirmeyer, 1999](#)). [Morrill et al. \(1999\)](#) noted that sensitivity of SM and latent heat flux to the diurnal distribution of downward longwave radiation is small for the Biosphere-Atmosphere Transfer Scheme (BATS) when used for simulating large-scale monthly averages. However, [Schlosser et al. \(2000\)](#) found that most of the LSSs are sensitive to longwave forcing for the snowpack simulations. The PILPS compared and suggested improvements in estimates of water and energy flux by the LSSs ([Chen et al., 1997](#); [Wood et al., 1998](#); [Liang et al., 1998](#); and [Lohmann et al., 1998](#)). It was reported that there was a qualitative agreement in changes in modeled mean seasonal cycles of SM storage and observations ([Lohmann et al., 1998](#)).

A new project, Land Data Assimilation System (LDAS) was undertaken ([Mitchell et al., 2000](#)) to overcome some of the uncertainties in LSS design and the inaccuracy of estimates of energy and water flux and storage. A key objective of the project is to produce global SM data. Results from this project are

not yet available. It is reported that none of the models within the domain of the Atmospheric Model Inter-comparison Project (AMIP) captured interannual variations in SM (Robock et al., 1998). In addition, no improvement in capturing seasonal variations in SM is recorded by the revised AMIP models (Srinivasan et al., 2000). The GSWP produced global SM data by using ten LSSs and it is noted that none of the models provided satisfactory estimates of SM for any regions (Entin et al., 1999). Robock et al. (2000) made a similar observation. Moreover, Entin et al. (1999) found that model biases vary from region to region. Thus, it is suggested that we need to devise a more robust approach and future research projects should consider experiments with longer time scale (Entin et al., 1999).

A few issues become clear from the above discussion. (1) The role of spatial variability of soils and the physical properties within a hydroclimatic domain during calculation of SM and ET was not explicitly addressed; (2) there is an absence of long-term SM data for climatic interpretations; and (3) there is a lack of assessment of SM variations under a number of prevalent soils and vegetation types. In the present study, we have applied the R&H SM model to estimate daily SM and ET for three typical root zone soils and three associated land uses at three sites in the NGP from 1982–1999. This study identifies SM and ET variations due to changes in soil characteristics and associated land uses. Simultaneous estimates of SM for three different types of soil in the root zone and three land uses for each of the three locations provide a quantitative assessment of response over what represents a broad range of landscapes. One of the advantages of using the R&H model is related to the fact that it is tuned to local (the NGP) land use and hydroclimatic condition. Moreover, it is critical that we investigate SM of croplands along with grasslands. Large-scale modification of natural grasslands to agricultural land use in the Great Plains made it imperative. Note that several authors emphasized that the relationship between land use and SM needs to be investigated under a variety of conditions (cf. Qiu et al., 2001). Thus, it can be said that the current study addresses this issue.

Development of a long-term SM dataset for climatological studies and understanding of the land memory process and its relationships with

predictability was identified by Global Energy and Water Cycle Experiment (GEWEX)/GEWEX Americas Prediction Project (GAPP) as a high priority for future research (Leese, 2000; Leese et al., 2001). In addition, during an international workshop on SM, it was strongly recommended that the development of a global system to produce model-derived estimates of SM should be started immediately (Leese et al., 2001, pp. 1423). The importance of understanding variations in water cycle at climatological scale is identified as a key research issue by the United States Global Change Research Program (USGCRP) (USGCRP, 2001). The long-term objective of the authors of this paper is to address this research theme. The investigation of sensitivity of the R&H SM model for soil physical properties is an important step towards fulfilling these goals. The setting for this study is within a GAPP area (Mississippi watershed).

3. R&H SM model and data

The framework for the R&H SM model can be expressed as follows:

$$\partial S/\partial t = P + I - ET - R_0 - D_r \quad (1)$$

where S (mm) is soil water in the root zone, t is time, P (mm) is precipitation, I (mm) is irrigation, ET (mm) is actual evapotranspiration, R_0 is runoff, and D_r is drainage below the root zone. A 24-h time step is used with daily precipitation, and irrigation (if applied) as inputs to the model. Runoff is estimated from total precipitation, relative fraction of soil water present, and soil water retention factor (McCuen, 1982). Campbell's equation is used in this model to calculate drainage (Campbell, 1985).

The model calculates actual evaporation and transpiration separately and the summation of the two is ET . A modified version of Penman (1948) combination method of potential ET estimation is applied to derive actual evaporation (E) and transpiration (T). The modification of the Penman method is conducted by including Kincaid and Heerman (1974) wind function. Actual evaporation is a function of potential ET and the number of days (ND) since the last precipitation occurred. The relationship between E and potential ET is

presented as follows:

$$E = ET_p(1/ND)^{1/2} \quad (2)$$

where ET_p is potential evapotranspiration based on modified Penman method. A function of crop and phenology specific crop-coefficient (K_c), ET_p , and a soil water reduction factor (f) provides actual transpiration. The model assumes, when SM content approaches wilting point, a soil water reduction factor restricts crop-water use. The f is a function of available soil water and water holding capacity of the soil and changes in response to the ratio of available water to potential available water. Actual transpiration can be expressed as follows:

$$T = (f)(K_c)(ET_p - E) \quad (3)$$

The model was validated and its performance was evaluated for various crops, sites (representing varied soil conditions), and for six layers up to 1.8 m depth in Nebraska (cf. Robinson and Hubbard, 1990; Camargo, 1993; and Camargo et al., 1994). In addition, the SM model simulates water in each layer, current water stress, runoff, drainage, phenology, actual and potential evapotranspiration, sensible heat flux, and net radiation.

Tables 1–3 and Fig. 2 present detail of the model validation from Robinson and Hubbard (1990). SM data were collected from nine locations in NGPs, at six depths for each location, and for multiple land uses at each of these locations during two growing seasons of 1986 and 1987 (Table 1). These sites are located in Nebraska (5), South Dakota (2), and Wyoming (2) (Table 1). The six depths were 150, 450, 750, 1050, 1350, and 1650 mm. It was assumed that the data from each of these points represent a soil layer of 300 mm. Thus, these points are mid-point for each of 300 mm soil layer. Each of the nine locations represent varying root zone soil characteristics, for example, clay soil to sandy soil. Combination of location and land use suggest that SM data were collected from 20 different land surface conditions (Table 1). The R&H model evaluation statistics is presented in Table 2. A model evaluation statistic, index of agreement and known as d index (Legates and McCabe, 1999; Willmott, 1981), can be expressed as follows:

$$d = 1.0 - \left(\frac{\sum_{i=1}^N (O_i - P_i)^2}{\sum_{i=1}^N (|P_i - \bar{O}| + |O_i - \bar{O}|)^2} \right) \quad (4)$$

Table 1
Location and land use for soil water measurements. Source: Robinson and Hubbard, 1990

Site	Year	Land use	# of days with measured water	Dates
North Platte, NE	1986	Maize	13	June: 4, 11, 18, 25; July: 2, 9, 16, 23, 30; August: 13, 20, 27; Sept: 3
		Wheat	12	April: 23, 30; May: 7, 14, 21, 28; June 4, 11, 18, 25; July: 2, 9
North Platte, NE	1987	Maize	12	June: 2, 11, 17; July: 7, 14, 21, 27; August: 4, 11, 18; Sept: 1, 8
		Wheat	4	May: 26, June: 2, 11, 17
		Sorghum	12	June: 2, 10, 17; July: 7, 14, 21, 27; August: 4, 11, 18; Sept: 1, 8
		Soybean	12	June: 2, 10, 17; July: 7, 14, 21, 28; August: 4, 11, 18; Sept: 1, 8
Clay Center, NE	1987	Maize	8	June: 30; July: 7, 21, 30; August: 6, 21, 27; Sept.: 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; Sept.: 30
		Soybean	8	June: 30; July: 7, 22, 30; August: 6, 21, 27; Sept.: 30
Concord, NE	1987	Maize	11	June: 11, 25; July: 1, 9, 16, 23, 30; August: 5, 14; Sept.: 11, 28
		Sorghum	9	July: 1, 8, 16, 23, 30; August: 5, 14; Sept.: 11, 28
		Soybean	11	June: 11, 25; July: 1, 9, 16, 23, 30; August: 5, 14; Sept.: 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	Maize	4	June: 29; July: 13; August: 6, 26
Chamberlin, SD	1987	Maize	5	July: 1, 14, 30; August: 20; Sept.: 14
Wheatland, WY	1986	Wheat	8	May: 30; June: 15, 30; July: 14, 28; August: 11, 26; Sept.: 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

Table 2

Model evaluation results for the R&H soil water balance model. Source: Robinson and Hubbard, 1990

Site	Year	Land use	d index	r^2	MAE (mm)	P (mm)	σ_p mm	O (mm)	σ_o mm	E_s (mm)	E_u (mm)	RMSE (mm)
North Platte, NE	1986	Maize	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	Maize	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	Maize	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	Maize	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	Maize	0.95	0.93	11	244	33	251	43	12	7	14
Chamberlin, SD	1987	Maize	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	Wheat	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

MAE = Mean absolute error, P = Predicted soil moisture, O = Observed soil moisture, σ_p = Variance of predicted soil moisture, σ_o = Variance of observed soil moisture, RMSE = Root Mean Square Error, E_s = Systematic component of RMSE, E_u = Unsystematic component of RMSE.

where O and P are observed and predicted values, respectively. This index includes differences in the observed and model-simulated means and variances and thus provides an improvement over correlation based model evaluation measures (Legates and McCabe, 1999). This index varies from 0.0 to 1.0 with higher values indicating better agreement between modeled and measured values. Table 2 shows that for most of the land uses d index is greater than 0.90. The range of the d is from 0.70 to

1.0 (Table 2). For most (13 out of 20 cases) of the land uses, r^2 estimates also reported greater than 0.90 values (Table 2). Evaluation shows that the highest and the lowest r^2 estimates are 0.99 and 0.67, respectively. It is reported that the ranges of observed and predicted SM values are between 234–645 and 226–625 mm, respectively (Table 2). Variances for observed SM range between 17–108 mm and predicted SM between 15–102 mm. High d index values, high r^2 estimates, and high

Table 3

Model evaluation results for various depths of the root zone under maize land use: statistics for North Platte, NE. Source: Robinson and Hubbard, 1990

Soil layer (mm)	d index	r^2	MAE (mm)	P (mm)	σ_p (mm ²)	O (mm)	σ_o (mm ²)	E_s (mm)	E_u (mm)	RMSE (mm)
0–300	0.97	0.94	5	56	18	60	18	4	4	6
300–600	0.95	0.97	7	56	21	62	17	7	4	8
600–900	0.99	0.98	4	56	21	56	17	3	3	4
900–1200	0.98	0.96	4	61	18	57	20	4	4	6
1200–1500	0.92	0.92	9	62	15	55	19	8	4	9
1500–1800	0.88	0.95	8	62	11	56	17	9	3	9

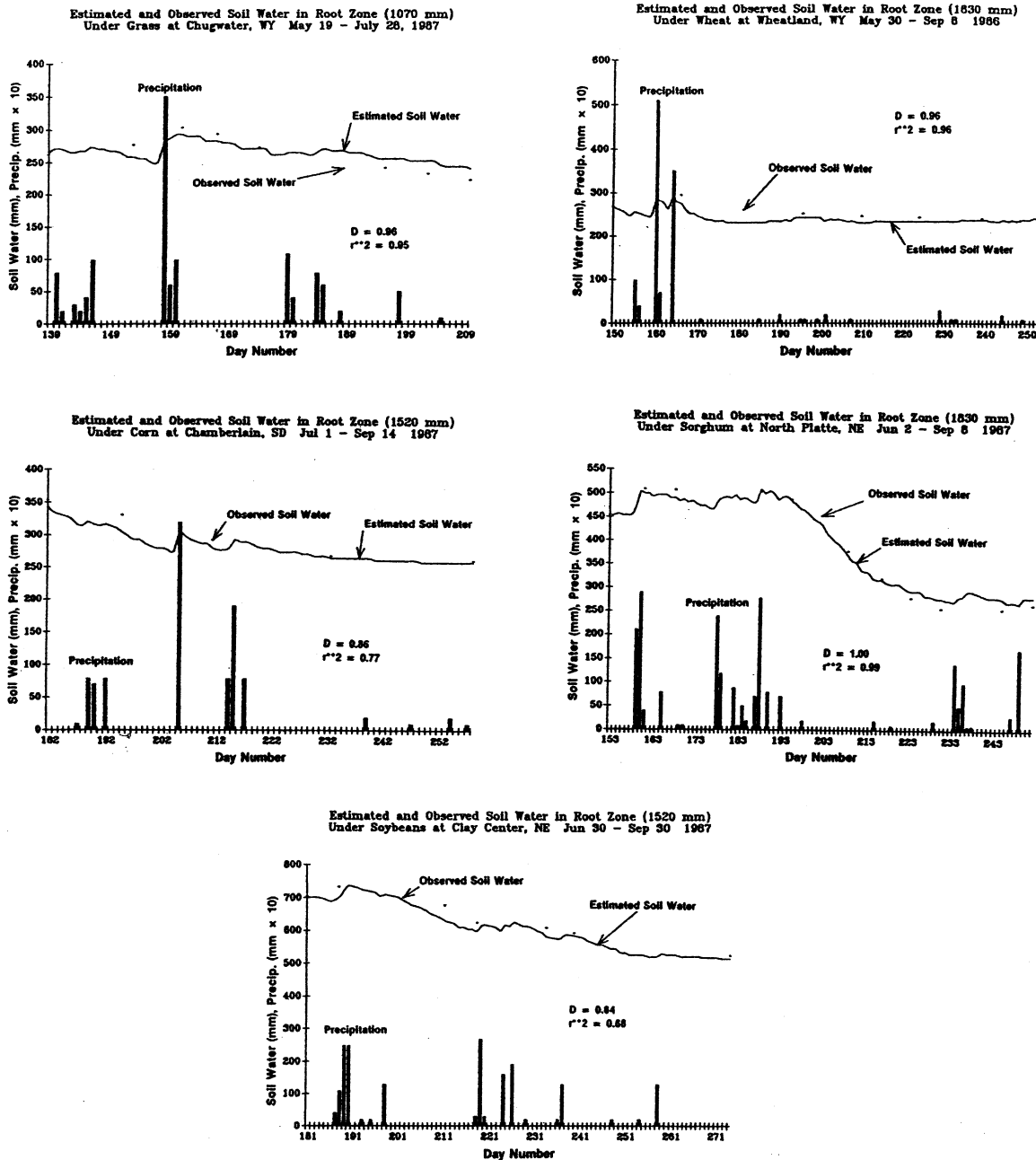


Fig. 2. Observed (dots) and modeled (line) root zone total SM for five land uses. Source: Robinson and Hubbard, 1990.

degree of agreement in distribution of observed and predicted SM values and their variances clearly ascertain that the model performance is satisfactory for various land uses with varying soil physical

properties. Fig. 2 shows Distribution of measured and observed SM and precipitation for five land uses at five locations is presented in Fig. 2. In this figure, small dots indicate measured SM and thin line shows

modeled SM. Satisfactory estimate of SM by the R&H model, again, is quite apparent. Responses of measured and modeled SM to precipitation events are also in close agreement. In other words, phase and amplitude of modeled and measured SM are also in agreement.

The R&H model's performance was also assessed for its accuracy in estimation of SM at various depths of root zone soil layers. The model evaluation results at various depths of root zone for maize land use at North Platte, NE is presented in Table 3. It is reported that d and r^2 estimates for observed and modeled SM for 6 layers ranged between 0.88 to 0.98 and 0.92 to 0.98, respectively (Table 3). Observed SM for these six layers of root zone ranged between 55 to 62 mm and predicted SM between 56 to 62 mm (Table 3). Moreover, variance of observed and predicted SM for these layers ranged between 17 to 20 and 11 and 21 mm, respectively. Hence, results from quantitative evaluation suggest that the R&H model is estimating SM satisfactorily for various soil layers of the root zone.

Additional R&H model assessment activities were undertaken during subsequent years by Camargo (1993); Camargo et al. (1994). They have evaluated the model for sorghum land use at Mead, NE in 1990 and 1991. Eight irrigation treatment designs were developed and applied. The treatment designs were formulated based on plant phenological development. Depletion of plant available SM to 50% of its capacity in the 0–90 cm layer initiated irrigation water application. The field experiments and SM data collection were completed for 1990 and 1991 growing season. Results from the model estimated and observed SM is presented in Fig. 3. Satisfactory estimates of SM by the R&H model are quite evident from this figure. An evaluation of modeled to observed SM shows that the d -index and r^2 values range from 0.78 to 0.96 and 0.64 to 0.93, respectively. In addition, it is to be noted that most of the d -index and r^2 values for model evaluation are above 0.90 and 0.80, respectively. For total of 16 treatment designs (8 + 8 treatment design over two years), nine times d -index reached greater than 0.90 and 14 times greater than 0.80. It is also found that, for the same number of treatments over two years, on 12 occasions r^2 reached over 0.80. For each treatment design model evaluation was conducted

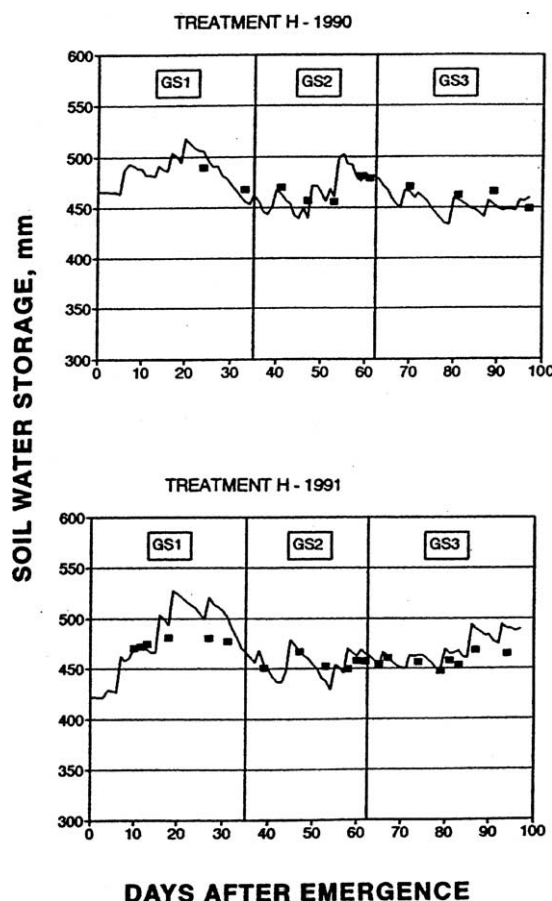


Fig. 3. Observed (small boxes) and modeled (line) root zone (1500 mm) total SM for sorghum land use under treatment-H. This treatment is characterized by application of irrigation water during all three growth stages. GS1: Vegetative stage (planting to panicle initiation); GS2: Inflorescence stage (panicle initiation to anthesis (bloom)); GS3: Grain filling stage (bloom to physiological maturity). Source: Camargo et al., 1994.

for its estimates of SM for top 5 soil layers (as assigned by Robinson and Hubbard, 1990) during 1990 and 1991. Performance evaluation results demonstrate that d -index and r^2 estimate reaching 0.95 and 0.96, indicating satisfactory model performance. Recent applications by Mahmood and Hubbard (2002a); Mahmood et al. (2001) show that the model is simulating soil water satisfactorily.

In short, quantitative validation for the R&H SM model was conducted for five land uses and at nine locations with varied soil physical properties and under significantly different hydroclimatic forcings.

Validation is also completed for six depths from the surface to root zone. Four SM data collection campaigns were under taken for this purpose. Therefore, based on results from quantitative assessment and accuracy of calculated SM values, we conclude that the R&H model will provide satisfactory estimates of SM for the study area.

For this study, the R&H model is applied for three predominant land uses and associated soils characteristics in Nebraska, namely, irrigated and rainfed maize and rainfed grass. Three sites in Nebraska were selected to simulate SM climate under varying land use and moisture regimes. The Mead, Clay Center, and McCook sites (Fig. 1) follow an east to west gradient from moist (Mead) to very dry (McCook) conditions (Fig. 4). There were nine applications per site (three types of land use \times three soil characteristics). For each site we have individually simulated soil water with soil input data from all three sites to determine the effect of soil properties. This setting allows us to estimate and understand potential responses of SM in more than one moisture regime. Daily weather data for the R&H model simulations were provided by the automated weather stations at these locations. Soil input data for these sites for the model application are available from a soils database maintained by the High Plains Regional Climate Center (HPRCC). These data include bulk density, soil texture, wilting point, field capacity, and saturation point for each soil layer. Weather inputs were not switched between sites. The model estimated soil water for the total root zone and for a period from 1982 to 1999.

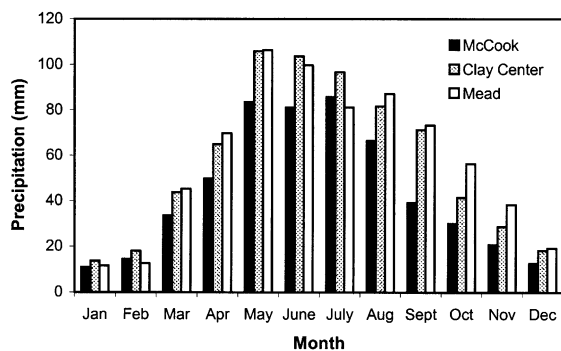


Fig. 4. Mean monthly precipitation at Mead, Clay Center, and McCook, Nebraska.

4. Applications of SM model at the climatological scale

For the R&H model estimations, May 5 was set as the beginning of the growing season. The model completes each run on May 4 of the subsequent year. The modeled soil water balance from the previous year is carried over to the next year. Three separate accumulated growing degree-days were included during the model simulations to reflect phenological development of grass, rainfed and irrigated maize. The selection of growing degree-days is necessary because phenological development influences the growing season consumption and utilization of water by plants. In due course this affects soil water status, evapotranspiration rates, and energy balance. The irrigated maize requires a higher number of days to mature (\cong 20–24 weeks) while grass requires the least (\cong 14–16 weeks). Time required to mature rainfed maize is somewhat similar to grass. However, seasonal distribution of root zone SM and ET from rainfed maize is quite different from grass. These effects account for some of the differences discussed below. Note that the use of climate and soils input data from respective locations for the R&H model simulation provided a baseline SM and ET estimate. Simulations that where the soils input data are switched show the sensitivity of the model to soil properties and their effect on SM and ET.

4.1. The model applications to McCook, Nebraska: Role of Land use and soil physical properties:

4.1.1. ET and SM:

The R&H soil water model to the McCook, NE indicates the amount of plant available soil water throughout the growing season is relatively higher for irrigated maize compared to rainfed maize and rainfed grass (Fig. 5a–c). Supply of water by irrigation to sustain growth led to higher plant available SM under irrigated case land use. Long-term data from the model application suggests quick depletion of SM due to vigorous consumption of water by rainfed maize (Fig. 5b). This study finds that the lowest amount of average plant available soil water during a growing season is 9, 4, and 6 cm for irrigated and rainfed maize, and grass, respectively (Fig. 5a–c).

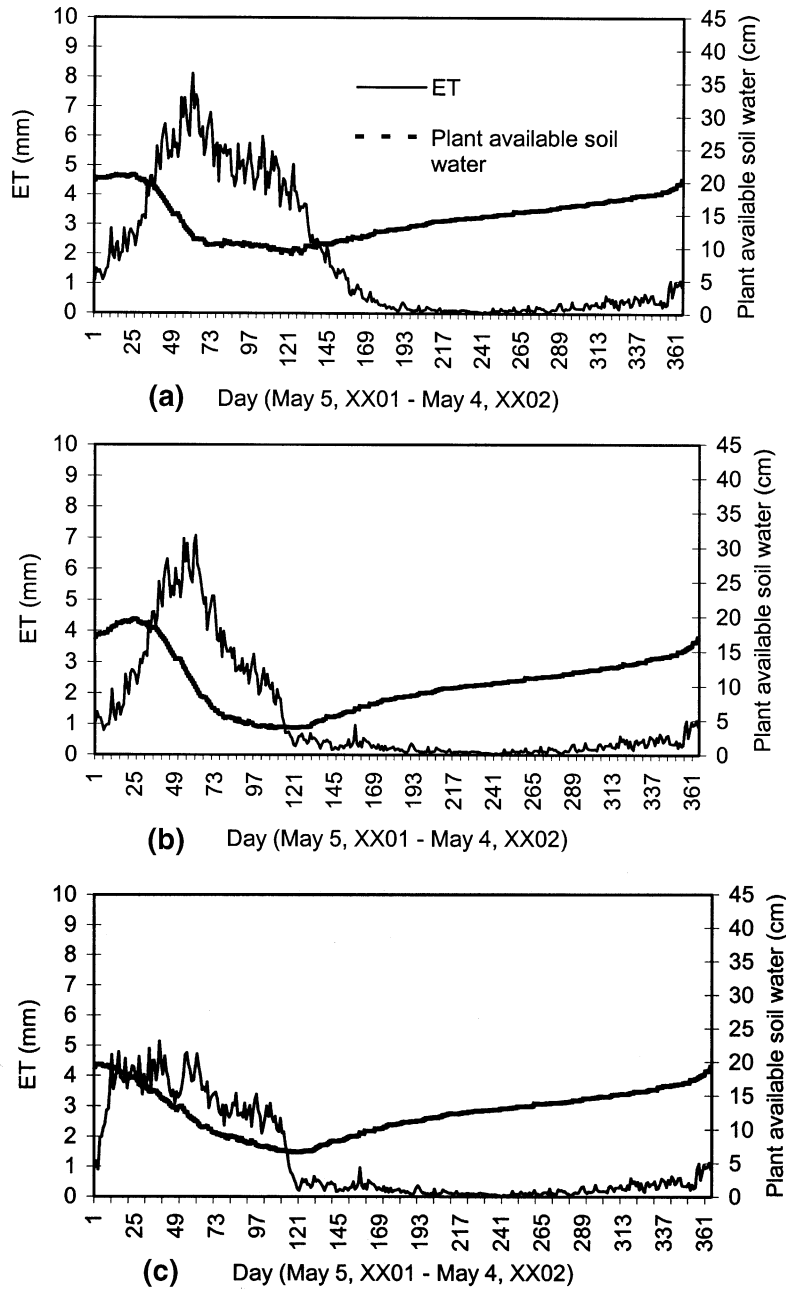


Fig. 5. Mean (1982–1999) daily ET and plant available soil water at McCook, Nebraska: (a) irrigated maize; (b) rainfed maize; and (c) grass. (Source: Mahmood and Hubbard, 2002a)

Atmospheric demand (energy availability), soil water availability, crop water requirements, and plant response to the surrounding environment are the notable controlling factors of ET. The results from

McCook indicate that irrigated maize and grass produce the highest and the lowest daily rates of ET, respectively (Fig. 5a–c). We found that the daily ET during the growing season for rainfed grass

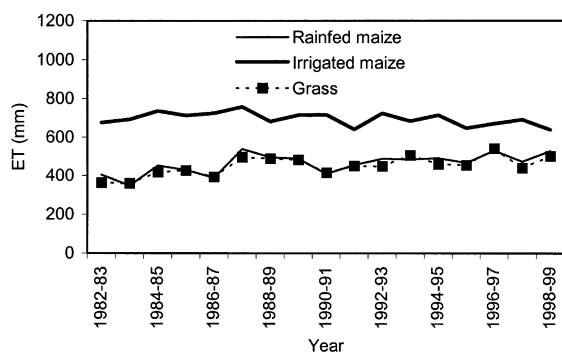


Fig. 6. Seasonal ET from three land uses at McCook, NE. (Source: Mahmood and Hubbard, 2002a)

increases and decreases more rapidly than either rainfed or irrigated maize (Fig. 5c). Mean estimates suggest that the increase and decrease of ET for irrigated and rainfed maize is relatively gradual. Results suggest that ET reduces significantly by 121st day, on the average, for rainfed maize and grass (Fig. 5a,b). Shorter growing season produces this type of response in ET. Furthermore, compared to rainfed maize and grass, relatively higher daily rates of ET under irrigated maize produces notably larger annual totals (Fig. 6). The model estimates that the annual total ET for irrigated and rainfed maize, and grass, on the average, is 694, 462, and 449 mm, respectively. Hence, compared to irrigated maize, average annual total ET for rainfed maize and grass is 34 and 36% less, respectively.

4.1.2. ET and SM under three different soils

The model applications to McCook show that seasonal total ET for irrigated maize is the highest for McCook soil followed by Clay Center and Mead soil (Fig. 7a). The crop and weather factors are held constant here so the factors causing these differences are soils related. Runoff and drainage are two factors that will be affected by soil characteristics. Likewise, Table 4 shows that the Mead soils have higher clay content and thus higher water holding capacity (Table 5) compared to McCook and Clay Center soils. These properties will cause the irrigation frequency to be lower with the Mead soil and with less surface wetting there is less direct evaporation. More of the ET will be due to transpiration as compared to the case for either the Clay Center or

McCook soil. This results in a lower irrigation water requirement and lower seasonal total ET for the Mead soil.

Maturity groups were selected according to producer strategy to reach maturity before the driest part of the season. Thus, the length of time required to reach maturity for rainfed maize and grass in this study was less compared to irrigated maize. In addition rainfed maize and grass is totally dependent on naturally occurring rain. These features result in lower ET from rainfed land uses (compare Fig 7b to a). We find that under rainfed maize, the simulation using Mead soil at McCook is similar to that using Clay Center soil at McCook. Under grass, McCook soil results in the lowest annual total ET (Fig. 7b). Again, soil physical properties and their influence on runoff and drainage are responsible for the differences in rainfed results at McCook.

Under McCook and Clay Center soil and irrigated maize land cover, SM depletion occurs at a high rate between 1st and 11th week after planting. However, overall, SM depletion is allowed to be higher under Mead soil because of its relatively higher water holding capacity compared to McCook and Clay Center soil. The ET continues, for the higher water holding capacity Mead-soil, to avoid water stress condition with less evaporation and proportionately more transpiration than is the case with the McCook and Clay Center soil.

SM depletion is higher under rainfed maize land use for all three soils. However, unlike for Mead soil under irrigated maize, rainfed maize on Mead soil experiences lower SM depletion compared to McCook and Clay Center soil (Fig. 7c). For rainfed condition, plants depend only naturally available SM. Thus, a soil with higher water holding capacity loses less water compared to the soils with lower water holding capacity.

4.2. The model applications to Clay Center, Nebraska: Role of Land use and soil physical properties:

4.2.1. ET and SM

Mean daily ET and plant available SM in Clay Center contains a temporal pattern that shows resemblance to that observed for McCook. It is

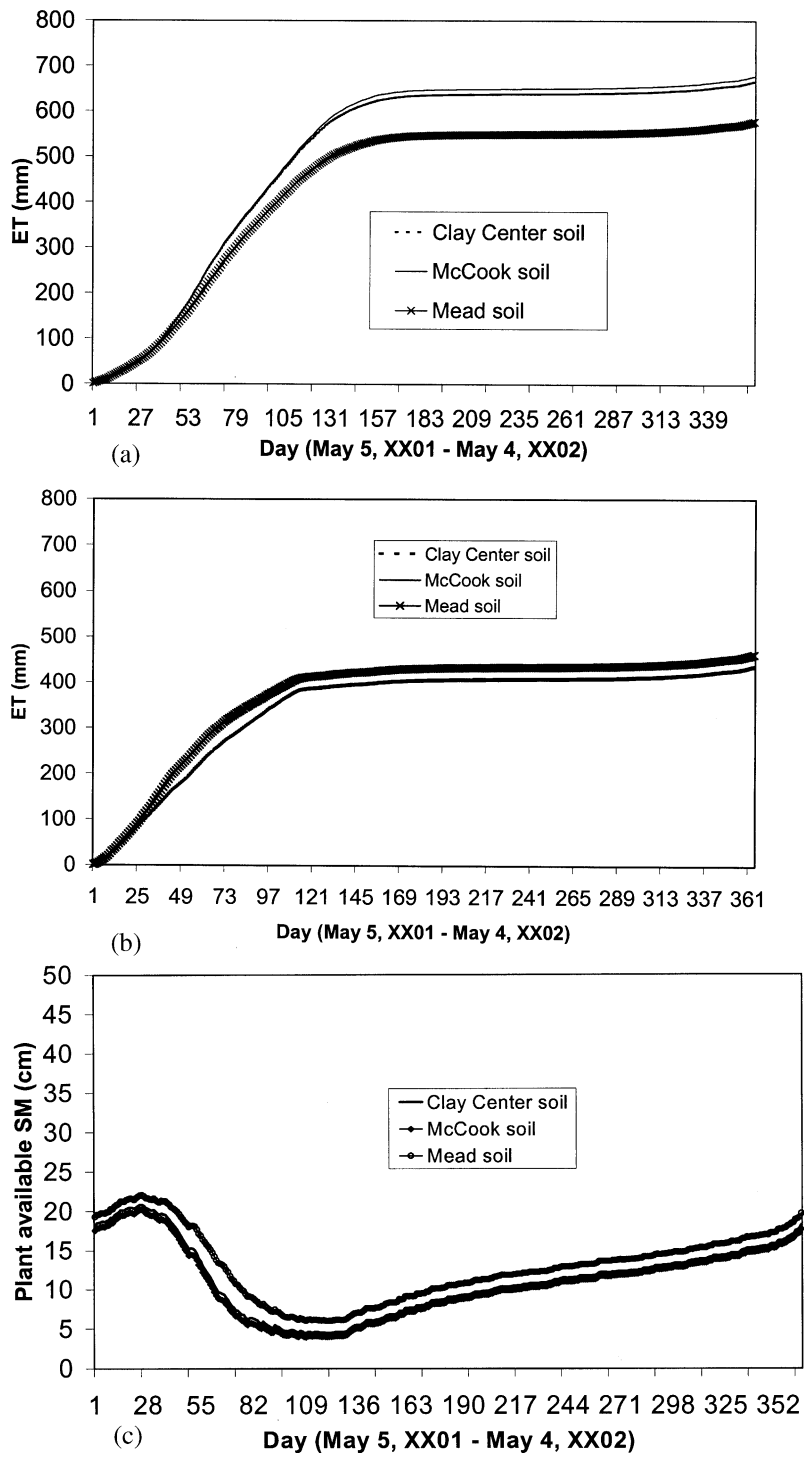


Fig. 7. McCook, NE: (a) cumulative ET under irrigated maize for three different soils; (b) cumulative ET under grass for three different soils; and (c) plant available SM under grass for three different soils.

Table 4
Clay, sand, and silt distribution at three locations in NE

Location	Clay (%)	Sand (%)	Silt (%)
McCook	15	20	65
Clay center	30	10	60
Mead	65	5	30

found that the mean daily plant available SM is the highest for irrigated maize and the lowest for rainfed maize. Clay Center stores more plant available SM, compared to McCook, for all three types of land uses. This is exemplified by the fact that the lowest mean daily plant available SM at Clay Center during growing season for irrigated and rainfed maize and grass is approximately 11, 9, and 11 cm, respectively. At this location, the R&H model estimated average annual total ET for irrigated and rainfed maize and grass is 683, 521, and 503 mm, respectively. Thus, compared to irrigated maize, ET from grass and rainfed maize is 27% and 24% lower, respectively. Relatively dry conditions and high atmospheric demand resulted in slightly higher average annual total ET for irrigated maize at McCook. On the other hand, relatively higher precipitation and resultant greater availability of moisture at Clay Center permitted

rainfed maize and grass to evapotranspire at higher rates to fulfill atmospheric demand and attain higher annual total ET.

4.2.2. ET and SM under three different soils

The R&H model application with Clay Center climate data, irrigated maize and three soil types (Clay Center, McCook, and Mead) resulted in higher average annual total ET for the McCook soil compared to Clay Center and Mead soil. As above, lower water holding capacity required higher amount of irrigation water application, thus more frequent irrigation, and resulted in higher average annual total ET. It is to be noted that the difference between annual total ET from Mead soil and McCook and Clay Center soil has decreased. The primary reason for this is higher annual total precipitation at Clay Center. Higher precipitation reduces the effect of changing soil types.

At Clay Center average annual total ET from rainfed maize and Mead soil is higher than McCook and Clay Center soil. Higher water holding capacity played a critical role in this case. Average annual total ET from grass is higher for the Mead soil (Fig. 8a). Again, higher water holding capacity of Mead soil allowed higher amount of water to be available for plants to transpire. Annual daily average plant available SM under Mead soil is also higher for all

Table 5
Selected hydrologic properties (in volumetric water content) of soils at three sites in NE

Location	Depth (cm)	Saturation point	Field Capacity	Wilting point
McCook	0–2.5	0.46	0.36	0.22
	2.5–30.5	0.52	0.36	0.22
	30.5–61	0.48	0.36	0.22
	61–91.5	0.42	0.36	0.22
	91.5–122	0.46	0.36	0.22
Clay center	0–2.5	0.46	0.32	0.12
	2.5–30.5	0.52	0.32	0.16
	30.5–61	0.48	0.33	0.17
	61–91.5	0.42	0.33	0.14
	91.5–122	0.46	0.34	0.14
Mead	0–2.5	0.46	0.36	0.18
	2.5–30.5	0.55	0.36	0.18
	30.5–61	0.65	0.40	0.20
	61–91.5	0.65	0.40	0.20
	91.5–122	0.59	0.42	0.20

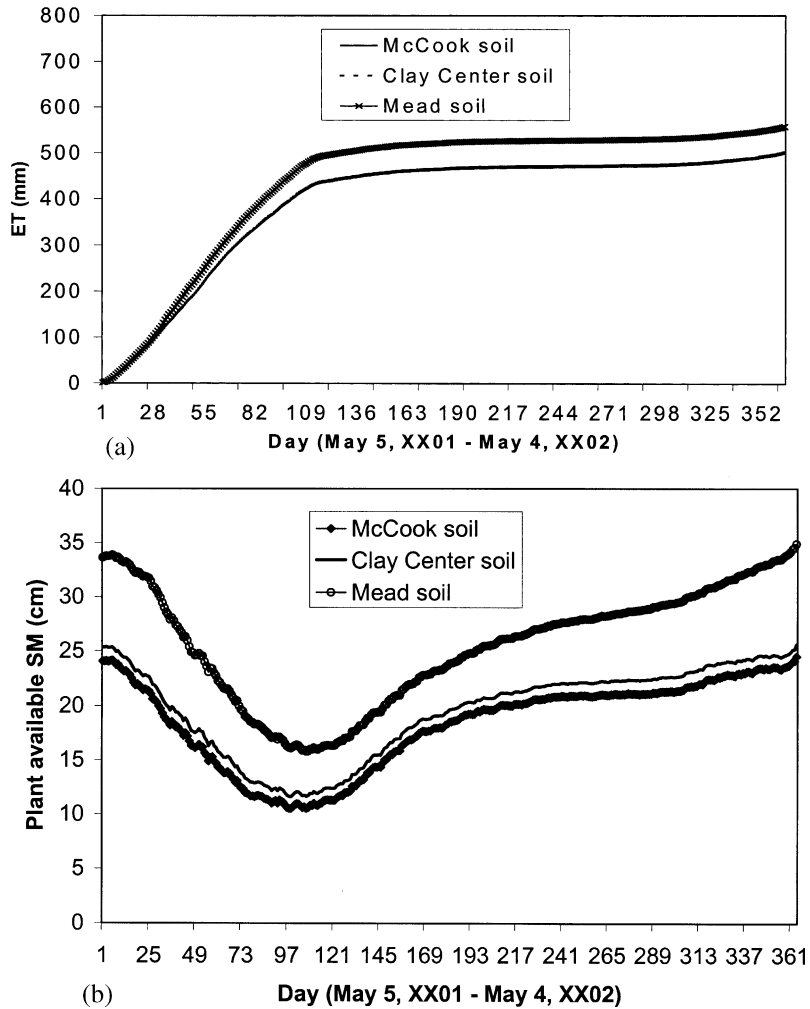


Fig. 8. Clay Center, NE: (a) cumulative ET under grass for three different soils; and (b) plant available SM under grass for three different soils.

three land uses (Fig. 8b). Higher water holding capacity and higher annual precipitation resulted in higher plant available SM at Clay Center under Mead soil.

4.3. The model applications to Mead, Nebraska: Role of Land use and soil physical properties:

4.3.1. ET and SM

Mean daily distribution of SM and ET at Mead demonstrates a comparable temporal pattern to that of McCook and Clay Center. Nonetheless, the R&H model finds that, compared to McCook and Clay Center, the daily mean plant available soil water is

higher for all three-land uses at Mead. This study reports that the lowest mean daily plant available SM for irrigated and rainfed maize and grass is 12, 14, and 17 cm, respectively. Interestingly, irrigated maize, as opposed to rainfed, land use reports the lowest mean daily plant available SM. This results from the fact that the growing season for irrigated maize is longer, natural plant available SM quantity is higher due to moist sub-humid environment, and water holding capacity of the soil is higher at this location. The latter helped plants to use available soil water in the root zone for a longer period before requiring application of irrigation water. In addition, a shorter growing season for rainfed maize did not use as much water as

irrigated maize due to shorter growing season. The model simulations demonstrate that annual total ET from irrigated maize is higher compared to rainfed maize and grass and for any given year. It is estimated that the average annual total ET for irrigated and rainfed maize and grass is 625, 544, and 531 mm, respectively. In other words, on the average, compared to irrigated maize, ET for rainfed maize and grass is 13 and 16% lower, respectively. The results of this study suggest that, as the model simulations progressed from relatively drier McCook to relatively moist Mead, there is a decreasing trend in ET for irrigated maize and increasing ET for rainfed maize and grass. We suggest that higher atmospheric demand in western Nebraska resulted in higher annual total ET from irrigated maize land use at McCook. However, relatively restricted supply of moisture for rainfed maize and grass resulted in lower annual total ET at McCook. Unavailability of soil water failed to meet similar atmospheric demand.

4.3.2. ET and SM under three different soils

Average annual total ET from irrigated maize for all three soils conditions at Mead shows nearly identical response. Climatic records show that Mead is the wettest site among the three. Higher annual total precipitation along with irrigation significantly reduced any effects due to soil physical properties. Similar to Clay Center, the annual total ET under Mead soil for rainfed maize and grass is higher than that of McCook and Clay Center soil. It is found that SM depletion at Mead under Mead soil, compared to McCook and Clay Center soil, is the lowest for all three crops. As in the cases of previous applications, soil water holding capacity is the primary factor producing this result.

5. Applications of SM model for extreme hydroclimatic conditions

To determine the response of SM and ET, the R&H model is further applied at the three sites under the three soils and three and land uses for extremely wet and dry conditions. The extremely wet and dry conditions are determined by the highest and the lowest annual total precipitation, respectively, during the study period (1982–1998).

Annual total precipitation data shows 1982–83 and 1998–99 are the driest and wettest year at McCook, NE, respectively. The annual total ET response of irrigated maize during dry 1982–83 shows a pattern that is generally similar to the climatological-scale response. In other words, ET from the Mead soil would be less compared to McCook and Clay Center. However, the differences in total ET among all crops, as the growing season progresses, appears at a much later date compared to average conditions. Extremely dry condition restricted ET during the first part of the growing season. It is also found that the seasonal total ET for rainfed maize and Mead soil is slightly higher than McCook and Clay Center soil. Higher water holding capacity of the Mead soil resulted in this difference under extremely dry condition. SM distribution for rainfed maize and grass during dry 1982–83 is different from the long-term average. Under dry condition SM recharge during non-growing season leads SM recharge to a higher level for Mead soil compared to McCook soil. Under dry condition SM depletion is highest for McCook soil at McCook. Lower soil water holding capacity for McCook soil resulted in this outcome.

During wet 1998–99, at McCook, the difference between seasonal total ET from the Mead soil and the McCook and Clay Center soil for rainfed maize and grass has increased. Increased rainfall has changed the soil-plant-water dynamics and resulted in these larger ET differences. Plant available root zone SM distribution during a wet year is similar to long-term average for all three soil types and crops.

At Clay Center, model applications for 1995–96 (a dry year) shows an increasing difference in total ET from Mead, McCook, and Clay Center soils for all three crops. Distribution of daily SM in dry 1995–96 under three types of soil and land cover shows a pattern that is similar to long-term SM distribution. During the wet year 1993–94, the difference among annual total ET for three crops under three soils is much less. A sufficient supply of moisture has reduced the forcing of soil physical properties on ET. Plant available daily SM distribution for all crops and all soils shows a distribution pattern similar to that of long-term average. However, as expected, the actual amount of plant available SM is much higher than the average.

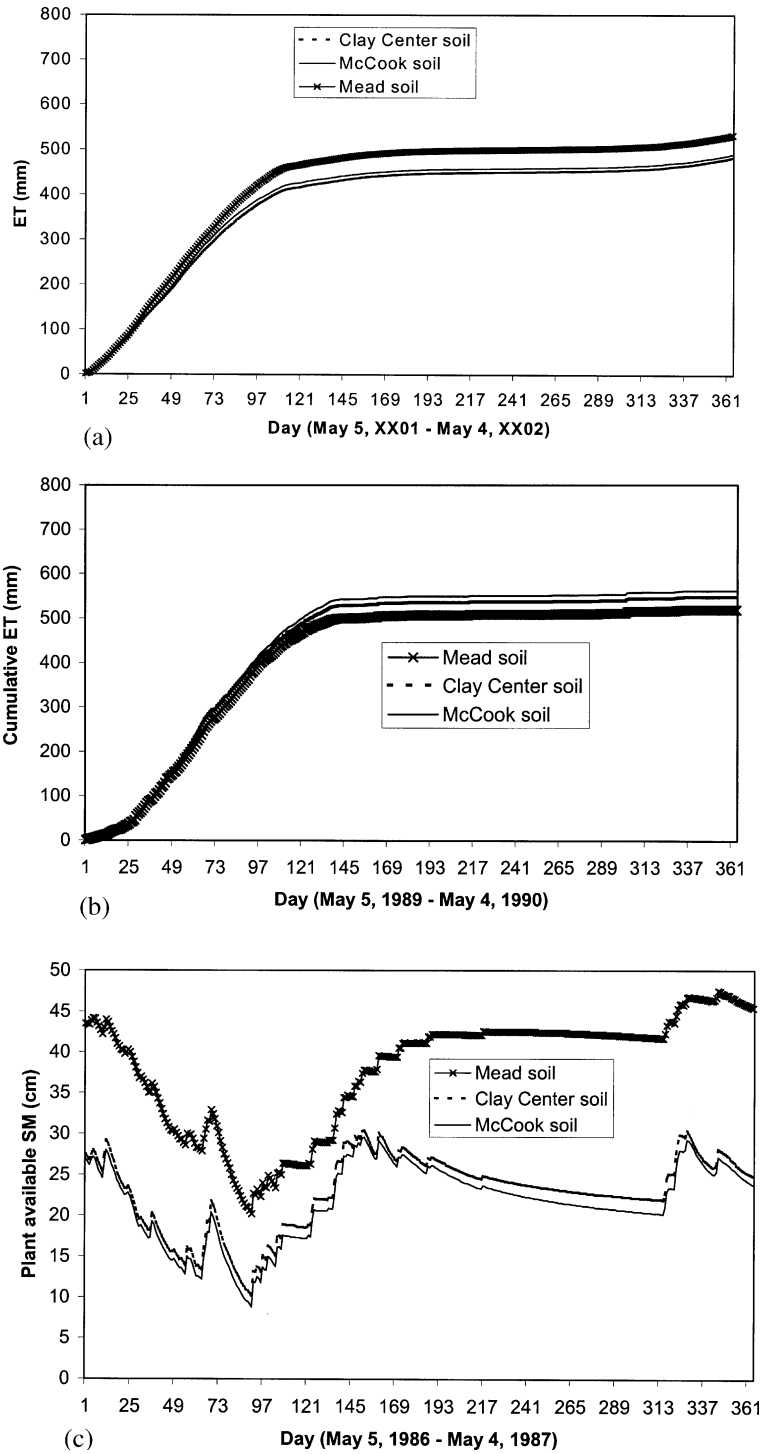


Fig. 9. Mead, NE: (a) cumulative ET under grass for three different soils; (b) cumulative ET from grass during a dry year for three different soils; and (c) plant available SM under grass during a wet year for three different soils.

R&H model application to Mead shows that differences among annual average seasonal total ET under three soil types are greater under grass and rainfed maize. In addition, plant available SM is higher under Mead soil compared to Clay Center and McCook soil. During dry 1989–90 differences among annual total ET under three different soils at Mead have increased because differences in water holding capacity are more important during dry years (Fig. 9a,b). Daily plant available SM distribution follows a similar pattern to that of the long-term temporal distribution. Annual total ET during wet 1986–87 for all crops under three soils, again, closely resembles the long-term average. In addition, the model applications to Mead show increased (decreased) effect of soils during a dry (wet) year that resulted in higher differences in ET under grass. Daily plant available SM distribution for all three crops under three different soils show a similar distribution to that of the long-term average. However, recharge of Mead soil at Mead is more spectacular than the McCook and Clay Center soil (Fig. 9c).

6. Summary and final remarks:

The present study investigated the effect of soils and land use on SM and ET estimates using the R&H SM model (Robinson and Hubbard, 1990). The three sites in Nebraska represent a dynamic range from dry to relatively moist hydroclimatic conditions. Rainfed maize evapotranspires at a higher rate compared to grass. Compared to grass lands, irrigated and rainfed maize farming elevated and lowered plant available SM through adding and mining water from the soil profile, respectively. It is found that the general pattern in SM depletion and recharge estimated by this model is comparable to Georgakakos et al. (1995); Georgakakos and Bae (1994). Failure to include irrigation in the simulation of landscape water balance resulted in a 'land use' ET error as large as 36 percent in semi-arid environments.

In general soils with lower water holding capacity required a higher amount (and frequency) of irrigation water applications that resulted in the highest ET. This is due to the increased surface evaporation associated with more frequent irrigations and the changes in

the runoff and drainage components of the model under different soil types. As expected the soil with higher water holding capacity was better able to buffer the crops against stress by maintaining higher SM in the different land use climate scenarios. These 'soils' effects were somewhat smaller than the 'land use' effects but, are a source of consistent bias if the soil is not characterized correctly.

Additional analyses were conducted to determine model sensitivity to changes in soils during hydrologically extreme years. The affect of soils on ET becomes less prominent during a wet year. In other words, differences of seasonal total ET under three soils become less during an extremely wet condition. Applications of the model to Mead show increased (decreased) soil effects during a dry (wet) year that resulted in higher differences in ET under grass. We also found that Mead soil experiences a more spectacular recharge of SM, compared to Clay Center and McCook soil during a wet year at Mead. Simply stated the 'climate' effect masks the 'soils' effect in wet years.

We believe the results presented in this paper have important significance in understanding how soils across a landscape can affect SM and ET and subsequent interpretation of results from model simulated estimates. It is clear from the R&H SM model simulations that variations of soils affect ET and SM. The extent of the affect varies due to land use and local hydroclimatology. The affects are evident at both long-term and annual climatological scale. The unusually dry and wet years enhanced and muted, respectively, the affect of soils on local ET and SM. Certainly, these are encouraging findings in the context of proposed extensive applications of the R&H model for development of SM climatology of the NGP.

The relationships between SM and temperature and precipitation have been shown by a number of studies (cf. Hong and Pan, 2000; Wang and Kumar, 1998). However, variations of SM and ET due to a variable 'soils' effect under changing hydroclimatic conditions at the inter-annual time-scale is not well documented. This study has demonstrated quantitatively that variations in soils can force the resulting SM and ET estimates within stated limits. In addition, we found that the extent of the soils affect on SM and ET will change according to the prevailing precipitation.

Unanswered questions include: what are the impacts of the ‘soils’ effect on temperature and precipitation via changes in SM and ET? To what extent do heterogeneous soils and associated SM and ET during abnormal hydroclimatic conditions affect temperature and temperature predictability? Can we quantify the extent of these ‘soils’ effect on temperature predictability? At this point we cannot completely answer these questions. Nonetheless, we hope that the results of this study will encourage further investigation into these issues.

The R&H soil water balance model and its potential future use for estimating SM of the past under complex soils and vegetation landscapes is adequately ascertained in this study. The authors have completed a soils database for 150 locations corresponding to automated weather data measurements sites. Predominant soil types of the local county are represented by these locations. Currently, preparation of soils database for cooperative weather recording locations is also underway. To fulfill our overall goal, the authors developed methods for estimating solar radiation and relative humidity of the NGP (Mahmood and Hubbard, 2002b; Hubbard et al., 2003). We suggest that, in the near future, soils and weather data with reliably estimated solar and relative humidity will allow us to estimate SM of the past for a large number of locations in this region. The design of the study is such that it is inclusive of both automated and cooperative weather observing sites and thus expected that it will provide higher spatial density for SM model applications. Therefore, we suggest that the future research activities in hydrology and land-atmosphere interactions in the NGP and the Mississippi basin will have critical use of these SM data. The sensitivity analyses herein provides us with useful information regarding the relative ‘soils’ and ‘climate’ effect on SM and ET.

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