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Use of limited soil property data and modeling to estimate root zone soil water content

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Abstract

Estimation of soil water content in the root zone with time in different parts of a watershed is important for both strategic and tactical management of water resources, as well as of agricultural production, water quality, and soil resources. This estimation requires detailed knowledge of rainfall intensities and meteorological variables over space and time, as well as the physical and hydraulic properties of the soil horizons and plant growth information. However, all this detailed spatial information is extremely expensive and time consuming to obtain. New technologies are helping to increase the spatial sampling of rainfall and other meteorological variables, but spatially detailed measurement of soil properties is still not practical. The best we can obtain from the existing soil survey database is the spatial distribution of soil textural class. We investigated the use of a hierarchy of limited soil input data, ranging from soil textural class of soil horizons alone, to measured soil texture and bulk densities of horizons, additional lab or field measurement of − 33 kPa soil water content, to additional field measurement of average saturated hydraulic conductivity. These five modeling scenarios, along with meteorological and plant information, were input to the Root Zone Water Quality Model (RZWQM) to estimate 0–60 cm soil water content over a 30-day period in 1997 at the Little Washita River Experimental Watershed in Oklahoma. The estimated water contents were compared with time-domain reflectometry (TDR) profile measurements and gravimetric samplings of soil surface moisture. In addition to the five scenarios using limited input data, a more detailed set of data based on laboratory measured soil water retention curves and field measured saturated conductivity was supplied to the model for all Brooks–Corey function parameters (full description mode). Estimates of root zone soil water content using detailed input were compared to estimates obtained using minimum input data. Adjustments in specific hydraulic parameters were also made in an effort to calibrate the model to the soils in this region. Overall, reasonable agreement was found between TDR-measured and RZWQM-predicted average water contents for 0–60 cm depths. Surprisingly, the smallest errors in the predicted water contents were achieved using either the textural class only or the hydraulic properties determined in situ, with root mean square errors ranging from 0.012 to 0.018 $m^3\ m^{-3}$. Hence, the model provided adequate estimates of average profile soil water content based on textural class-name only which was considered the most limited input data condition.
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Keywords: Soil moisture profile; Soil water modeling; Soil properties

1. Introduction

Estimation of soil water content in the root zone in different parts of a watershed is important for both strategic (long-term) and tactical (year to year and within a year) management of agricultural production, soil resources (e.g. erosion, fertility), and water quality, as well as efficient management of water resources in streams and reservoirs. Knowledge of the general soil water status in a watershed during the growing season and its

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variance from year to year is required to determine the optimal long-term land use and management options within that land use, that maximize the use of water with minimum impact on the soil resources. Knowledge of detailed spatial soil water status at the time of planting helps to decide which crop/s and management practice to chose within the possible options. For example, a low soil water content of certain fields at planting may call for choosing sorghum over corn, and/or to choose a lower seeding rate, a lower amount fertilizer at planting, and an appropriate herbicide application (the intensity and type of weeds may vary with such conditions). Estimates of soil water during the growing season will help decide if any additional fertilizer should be applied as a top-dressing. These seeding, fertilizer, and weed control decisions will apply to managed pastures as well. For rangelands, the spatial soil water status during late Spring will determine early season forage availability, and hence help make adjustments in the grazing versus lot feeding plans. Knowledge of the spatial soil water status in a watershed at any time during a year will help determine the potential for runoff and erosion, and the consequential impact on streams and reservoirs used for irrigation or other purposes.

The soil water status in different parts of a watershed can be estimated through the use of modern theory/processed-based models (e.g. Ahuja et al., 2000). This estimation requires the knowledge of rainfall intensities and other meteorological variables over space and time, as well as the physical and hydraulic properties of the soil horizons and plant growth information. All this detailed spatial information is extremely expensive and time consuming to obtain. Fortunately, the advent of new technology in portable and electronic-recording weather stations is helping to enable spatial sampling of rainfall and other important meteorological variables. However, the detailed measurement of the required soil properties is still not practical. At present, the best we can obtain from soil survey information is a crude spatial distribution of soil textural classes.

The soil properties required to describe or model infiltration, soil water movement, soil water storage, and plant water uptake are: (1) the soil water characteristic or soil water retention curve (SWRC), i.e. the relationship between the volumetric soil water (θ) and matric pressure head (h) or matric suction, $\tau(\tau = -h)$; and (2) soil hydraulic conductivity (K) as a function of θ, h, or τ. Several laboratory and field methods are available for direct measurement of these hydraulic properties on soil cores or in situ, respectively (Klute, 1986), though they are generally tedious and time consuming. For these reasons, and for more general field applications, a number of investigators have developed simpler estimation techniques to obtain these relationships from soil properties that are more easily measured, such as soil texture, bulk density, and 33 kPa soil water content (e.g. Rawls et al., 1982, 1983; Wösten and van Genuchten, 1988; Ahuja et al., 1985; Williams and Ahuja, 1993; Vereecken, 1995). Ahuja et al. (1999) summarizes these simpler estimation techniques. Ahuja and Ma (2002) classified the available techniques into a hierarchy ranging from simplest to more complex and assumed more accurate. For $\theta(h)$ the hierarchy is: (1) estimation from soil textural class only; (2) estimation from soil composition (soil texture, organic matter content, and bulk density); (3) estimation from soil composition and one measured value of θ (h); and (4) measurement of the entire hydraulic function. The estimation of $K(\theta)$ or $K(h)$ follows two steps: (1) estimation of saturated hydraulic conductivity, K_s, from: (i) textural class, (ii) effective porosity (equal to the saturated θ minus θ at 33 kPa suction); (iii) other simpler techniques (Ahuja and Ma, 2002), or (iv) actual measurement; and (2) the estimation of $K(\theta)$ or $K(h)$ from $\theta(h)$ obtained from one of the four methods in hierarchy given above, using K_s obtained from one of the above four approaches. The ARS Root Zone Water Quality Model (RZWQM) provides for the main hierarchy of options discussed above for estimating soil hydraulic properties based on the amount of input data available.

The use of estimation techniques requiring only a limited set of soil data is appealing since it is seldom that a full description of soil physical and hydraulic properties is readily available for watershed soils. A particular advantage in using the RZWQM is that the model offers a choice in ‘soil hydraulic input options' where the user may chose either from a hierarchy of limited data or the 'full description' mode. The limited input mode employs the use of certain estimation techniques based on limited soil information, as described above, while detailed soil profile information must be provided for the full description input mode. The question to investigate is how well the limited data set simulates the hydrologic system and, in particular, gives satisfactory estimates for profile soil water content. Modeled output for the hierarchy of limited data cases could be compared to measured data which would provide information about a threshold level of input data required to obtain soil water profile estimates within an acceptable range of measured values.

Another consideration in modeling the dynamics of soil water flow is that often laboratory and field measurements of a given soil property do not necessarily correspond. This lack of correspondence may be due to differences in sample size, measurement and sampling procedures, differences between measurements on so-called undisturbed soil cores (that may be disturbed to an extent) compared to those made in situ, or the differences may reflect spatial variability of the soil which may not be adequately captured by a point sample. Laboratory and field measured hydraulic properties may also indicate differences between layer-specific point measurements and data that are more representative of 'average' profile conditions, respectively, such as the case for hydraulic conductivity values. Thus, considering the time required for certain laboratory analyses, it would be of practical significance to determine the effect on soil water profile estimates using soil hydraulic input data derived from standard laboratory analyses versus those obtained by relatively simple in situ techniques.

The objectives of this study were: (1) to evaluate RZWQM estimates of profile soil water content obtained using a hierarchy of limited soils information to a nearly complete set of input data against measured profile data, and (2) to assess the performance of the model for the data sets where input data were derived from either laboratory or in situ analyses.

2. Material and methods

2.1. Model overview

The RZWQM is a comprehensive, one-dimensional model that integrates physical, biological, and chemical processes to simulate plant growth and predict the effects of agricultural management practices on the movement of water and chemicals through the root zone. Detailed documentation of it's process components is given in Ahuja et al. (2000), whereas up-to-date applications and evaluations of the model can be found in Ma et al. (2000). Of main importance here is the physical process component that includes a number of interrelated hydrologic processes. The present research focuses on this component since it controls the simulation of infiltration, redistribution, and plant uptake of water in the soil matrix and thus, predicts the profile soil water content.

The physically-based nature of RZWQM requires that the user provide a somewhat extensive amount of data to adequately parameterize and initialize the model. At a minimum, the RZWQM requires the usual driving variables of meteorological data (daily minimum and maximum air temperature, solar radiation, relative humidity, wind speed, and break-point rainfall or irrigation), coupled with specific site and soil profile descriptions (soil horizons, physical and hydraulic properties, surface residue cover, and crop specifications). To facilitate use of the model, RZWQM allows for input options where certain parameters are estimated or obtained from default table values when measured values are not available (described below). The model features of interest in the present study are the 'soil hydraulics data input options' where the user may chose either the 'limited data' or 'full description' mode. For this work we have chosen the limited input mode using different levels and combinations of soil physical/hydraulic input data for a given scenario, as well as a nearly full description mode based on measured hydraulic properties and some common approximations.

Infiltration of water into the soil is simulated in RZWQM by a modified Green–Ampt approach (Green and Ampt, 1911; Ahuja et al., 1993, 1995), whereas redistribution of water in the soil matrix is simulated by a mass-conservative numerical solution of the Richard's equation (Ahuja et al., 2000).

The Green–Ampt equation for infiltration is:

$$V = K_s \frac{\tau_c + H_0 + Z_{wf}}{Z_{wf}} \tag{1}$$

where V, infiltration rate at any given time (cm h^{-1}), K_s, effective average saturated hydraulic conductivity of the wetting zone (cm h^{-1}), τ_c, capillary drive or suction head at the wetting front (cm), H_0, depth of surface ponding (cm), and Z_{wf}, depth of the wetting front (cm). The Richard's equation for soil water redistribution between rainfall events is:

$$\frac{\partial \theta}{\partial z} = \frac{\partial}{\partial z}\left[K(h,z)\frac{\partial h}{\partial z} - K(h,z)\right] - S(z,t) \tag{2}$$

where θ, volumetric soil water content (cm^3 cm^{-3}), t, time (h), z, soil depth (cm), h, soil water pressure head (cm), K, unsaturated hydraulic conductivity (cm h^{-1}), and $S(z,t)$, sink term for root water uptake (h^{-1}). The Green–Ampt and Richards equations require hydraulic properties (saturated and unsaturated hydraulic conductivity, respectively) of the soil, but often these hydraulic properties are not known and must be estimated.

The $\theta(h)$ and $K(h)$ relationships are described by the Brooks and Corey (1964) functional forms, with a slight modification introduced for $\theta(h)$:

$$\theta(h) = \theta_s - A_1^*|h| \tag{3a}$$

$$\theta(h) = \theta_r + B|h|^{-\lambda} \tag{3b}$$

$$K(h) = K_s|h|^{-N_1} \tag{4a}$$

$$K(h) = K_2|h|^{-N_2} \tag{4b}$$

where A_1, B, λ, N_1, N_2, and K_2 are constants and θ_s, saturated soil water content (cm^3 cm^{-3}), θ_r, residual water content (cm^3 cm^{-3}), and K_s, field-saturated hydraulic conductivity (cm h^{-1}). With A_1 and N_1 set equal to zero (which is equivalent to assuming a fully saturated sample at all matric suction values below the bubbling pressure), Eqs. (3a) and (4a) reduces to the Brooks–Corey models.

The hydraulic description of the soil in the RZWQM forms the cornerstone of the model's ability to interact with all the other components of the system. The primary focus of our work was to examine how different soil hydraulic descriptions may affect model estimates of profile soil water content. In order to simulate the hydrologic responses of the model, the soil profile is divided into individual soil horizons or layers. The model requires an adequate description of the physical and hydraulic soil properties for each of these horizons. Physical soil properties include the textural class, fraction of sand, silt, and clay, bulk density and porosity. Levels of hydraulic soil properties accepted by the RZWQM may range from the volumetric water content at 1/3 or 1/10 bar (−33 and −10 kPa, respectively) and saturated hydraulic conductivity, to a 'full description' of all the necessary parameters to characterize the Brooks and Corey soil water relationships (Brooks and Corey, 1964). If only limited input data are available, RZWQM has a subroutine that estimates all other necessary Brooks–Corey parameters.

The RZWQM approaches for estimating unknown soil hydraulic parameters are described below as Method 1 when only soil physical properties are known, and Method 2 when some hydraulic data are also known. The two methods of hydraulic parameter estimation described below should not be confused with the different modeling scenarios that are described later in this section. Modeling scenarios represent different levels of input data.

2.1.1. Method 1

(i) When only the soil textural class (e.g. sandy loam, silt loam, clay loam) of soil horizons is known, the model uses the average values for $\theta(h)$ and K_s Brooks–Corey parameters as compiled by Rawls et al. (1982). These default parameters are average values obtained from a large experimental $\theta(h)$ and K_s data set. The parameter A_1 in Eq. (3a) is set equal to zero. The parameters for $K(h)$ are obtained from those of $\theta(h)$ and given K_s using the approach of Campbell (1974).

(ii) When measurements of soil texture are provided as percent sand, silt, and clay, the model calculates a more accurate textural class. The rest of the procedure is the same as in (i), however, if a measured value of soil bulk density is also provided, the model uses the extended similar-media scaling approach (Warrick et al., 1977; Ahuja et al., 1985) to adjust the θ_s (based on porosity) and air-entry or bubbling pressure head parameters.

2.1.2. Method 2

When, in addition to soil texture and bulk density, one measured value of $\theta(h)$ at $h = -33$ or -10 kPa is also provided, the model uses the extended similar-media approach to derive the Brooks–Corey parameters for $\theta(h)$ (Warrick et al., 1977; Ahuja et al., 1985). The experimental textural class mean of parameters (Rawls et al., 1982) employed under Method 1 are used to represent the reference curve from which the new scaled curve parameters are obtained. Ahuja et al. (1985) found this scaling method to produce better estimates of $\theta(h)$ than those obtained from soil texture and bulk density based regression equations.

The saturated hydraulic conductivity (K_s) is estimated using an empirical equation (a modified form of the Kozeny–Carmen equation) describing K_s as a power function of effective porosity (φ_e). The method is based on the experimental studies of Ahuja et al. (1984, 1989), in which effective porosity is defined as saturation water content (θ_s) minus the -33 kPa water content. The equation is written as,

$$K_s = 764.5\ \varphi_e^{3.29} \tag{5}$$

where K_s is in cm h^{-1}, and φ_e is given in cm^3 of pores per cm^3 of bulk soil. The unsaturated conductivity–suction relationship, $K(h)$, is then estimated by utilizing the approximate capillary-bundle approach of Campbell (1974), given K_s and $\theta(h)$ functions.

When the laboratory or field measured $\theta(h)$ data are available, the Brooks–Corey parameters for $\theta(h)$ are obtained by fitting the function to these data. When K_s is also available, this K_s is used with the fitted $\theta(h)$ parameters to obtain all the parameters for the $K(h)$ function according to Campbell (1974). The case of measured $\theta(h)$ and K_s input is called 'full description' of parameters in the following test.

In this study, Methods 1 or 2 above were used in five limited-data scenarios to obtain the hydraulic parameters for each soil layer in the RZWQM. Five study sites (described later) were used to evaluate these scenarios. A sixth scenario was modeled at two of the five sites using the full description mode (as described above) for hydraulic input data. The full description mode allows the user to input all data for the Brooks–Corey equations for each soil layer which are used to represent the $\theta(h)$ and $K(h)$ relations for solving the Richards equation. These scenarios were selected to investigate the influence of soil type, soil layering, levels of input data, and soil properties obtained from the field versus those measured in the laboratory on model estimates of profile soil water content. Soil properties measured in the field, in situ, were considered to be more representative of average profile values, whereas laboratory measurements provided more detailed layer descriptions, especially in the case of conductivity values. To maintain consistency in the calculation of effective porosity throughout the scenarios, all input data for texture and bulk density were taken from lab soil-core analysis. However, such data could also be obtained from different types of survey information for a given soil type, i.e. Natural Resource and Conservation Service county soil surveys or STATSGO. Also, soil samples collected in the field during infiltration and drainage experiments to measure soil water content could be used to determine texture class and bulk density.

In Scenario 1 (RZS1), the model is supplied only the soil textural-class name. According to the texture class, the model uses the class mean soil physical and hydraulic default values as input for all parameters (Method 1 estimation technique). In Scenario 2 (RZS2), the model is supplied site-specific, lab-measured particle size fraction and bulk density values for each layer, from which the model then derives soil texture and assigns the default values for $\theta(h)$ parameters and calculates the corresponding -33 kPa θ values. K_s is estimated according to Method 2 described above. Porosity is calculated from measured bulk density and assumes a value of 2.65 g cm^{-3} for particle density. Scenario 3 (RZS3) is the same as Scenario 2 with the exception that -33 kPa θ is explicitly specified and was measured in the laboratory on soil cores. Again, hydraulic conductivity functions are calculated according to Method 2. Scenario 4 (RZS4) is the same as RZS3 but θ at -33 kPa was measured in situ based on 2-day drainage data (described later) taken at each site during infiltration experiments. In scenarios RZS1 through RZS4, the soil properties mentioned above were specifically described for each soil layer utilized by the model. Table 1 shows the different levels of soil property input data for all modeling scenarios.

Table 1
Soil property input data for each of the modeling scenarios

Scenario	Soil texture	Bulk density	θ at -33 kPa	K_s	Brooks–Corey
RZS1	✓				
RZS2	✓	✓			
RSZ3	✓	✓	✓[a]		
RZS4	✓	✓	✓[b]		
RZS5	✓	✓	✓	✓	
RZS6	✓	✓	✓	✓	✓
RZS7, 7a, 7b	✓[c]				

[a] θ at -33 kPa was measured in the laboratory on soil cores.

[b] θ at -33 kPa was measured in situ based on 2-day drainage data taken at each site during infiltration experiments.

[c] The scenario is a sensitivity analysis in response to changes in the values of θ at -33 kPa and K_s for the most limited data set.

In Scenario 5 (RZS5) the model is supplied texture class name and field measured values of θ at -33 kPa and K_s. The value for θ at -33 kPa for different soil layers was assumed to be the water content sampled 2 days after saturated conditions. Matric potential was measured using tensiometers placed at different depths in the soil profile and served as a check for -33 kPa conditions at the time of sampling. The value obtained for K_s was considered an average for the soil profile and thus, assumed constant for all soil layers. Scenario RZS5 was included in this study since it seeks to mimic soil properties (θ at -33 kPa and K_s) that might be derived from remotely sensed data (Mattikalli et al., 1996, 1998). Scenario RZS5 also provides an alternative to using soil hydraulic data obtained from more intensive laboratory methods. In all scenarios, the model was supplied the minimum required soil, vegetation and meteorological data and was run without benefit of prior calibration.

Of the five study sites, two sites were selected to model Scenario 6 (RZS6) using the RZWQM full description mode for hydraulic input, as described above. These sites were chosen due to their difference

Table 2
Soil physical properties and vegetative cover type for the study sites

Site ID	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Texture name[a]	Bulk density ($\mathrm{g\ cm^{-3}}$)[b]		Vegetative cover
						Measured	Estimated	
LW06-133	0–15	70.8	19.6	9.6	SL	1.41	1.45	Bermudagrass
	15–30	72.8	17.6	9.6	SL	1.43	1.45	
	30–45	70.8	17.6	11.6	SL	1.45	1.45	
	45–60	68.8	19.6	11.6	SL	1.38	1.45	
LW11-136	0–15	50.8	35.6	13.6	L	1.37	1.42	Bermudagrass
	15–30	54.8	25.6	19.6	SL	1.42	1.45	
	30–45	52.8	26.6	21.2	SCL	1.41	1.60	
	45–60	48.8	25.6	25.6	SCL	1.44	1.60	
LW07-151	0–15	74.4	17.2	8.4	SL	1.37	1.45	Bermudagrass
	15–30	80.4	11.2	8.4	LS	1.47	1.49	
	30–60	86.4	7.2	6.4	LS	1.32	1.49	
	60–90	86.4	9.2	6.4	LS	1.46	1.49	
LW18-154	0–15	36.8	37.6	25.6	L	1.43	1.43	No cover
	15–30	46.8	25.6	27.6	SCL	1.42	1.60	
	30–45	48.8	21.6	29.2	SCL	1.44	1.60	
	45–60	50.8	21.6	27.6	SCL	1.39	1.60	
LW02	0–15	28.4	45.2	26.4	L	1.53	1.42	No cover
	15–30	24.4	47.2	28.4	CL	1.49	1.42	
	30–45	26.4	47.2	26.4	L	1.54	1.42	
	45–60	26.4	53.2	20.4	SiL	1.54	1.32	

[a] Symbols used in the texture name category are as follows: S: sand(y), L: loam(y), Si: silt, C: clay.

[b] Measured values of bulk density are used in scenarios RZS2, 3, and 4, and used in the model to determine K_s. Bulk density values for scenarios RSZ1 and 5 are default estimated values determined by the model from the soil texture name.

in texture with site LW06-133 being a uniform sandy loam and site LW18-154 being predominately a sandy clay loam (Table 2). These sites were also used to evaluate how sensitive the model was to changes in the θ at -33 kPa and K_s hydraulic parameters (Scenario RZS7). For each site, the previous model input for RZS3, based on lab soil-core analysis, was expanded to meet the full description input requirements. The field-measured steady infiltration rate was taken as the harmonic mean K_s for the 0–60 cm profile. This K_s was apportioned to each 15 cm soil layer in proportion to K_s calculated from Eq. (5) from the effective porosities.

Four soil layers were specified in the model at four sites and five layers at the remaining site to correspond with TDR profile soil water content measurements (described below). Initial soil water contents required by the model were taken from TDR measurements at each study site on day one of simulation. Daily profile soil water averages of θ from RZWQM output were calculated and compared to measured values.

Plant water uptake is accounted for in the RZWQM according to plant species utilizing a generic plant growth and crop production submodel. Although a number of agricultural crops are available to choose from in the model, options for rangeland vegetative species, at this time, are limited. The ‘quick turf’ management option was chosen in this study where grass growth parameters (leaf area index development over time, rooting depth, etc.) were selected which closely approximated the vegetative conditions at the study sites. Where applicable, the species of grass chosen was bermudagrass. Some sites had so little vegetative cover that no plant type was specified.

2.2. Study area

The 610 km^2 Little Washita River Experimental Watershed (LWREW), located in south central Oklahoma (Fig. 1), was selected as the study site due to availability of meteorologic and soil data sets and diversity of soil types and land cover. Land use on the LWREW is approximately 60% rangeland, 20% cropland, and 20% miscellaneous (forests, riparian areas, water bodies, urban areas and oil waste land). The topography is gently to moderately rolling with maximum relief of about 183 m. The climate is classified as subhumid with total annual precipitation of about 75 cm, which largely comes during the spring and fall months. There are 64 defined soil series in the LWREW, with fine sand, loamy fine sand, fine sandy loam, loam and silty loams being the predominant textures of the soil surface (Allen and Naney, 1991).

A meteorological network (*Micronet*) of 45 stations is distributed across the watershed on a 5 km spacing (Fig. 1). Forty-two of these stations continuously measure a basic suite of meteorological data: rainfall, incoming solar radiation, air temperature, relative humidity, and soil temperature at three depths. At three stations, windspeed and wind direction at two heights and barometric pressure are also recorded in addition to the basic suite of data. The meteorological data are measured every 5 min and reported every 15 min to a central archiving facility via radio telemetry. The data are quality controlled and final output is written in both 5 min and daily summary files. Meteorological data from selected sites were used to determine break point precipitation required by the model, and to supply the required model inputs to calculate evapotranspiration.

Five Micronet sites were selected (Fig. 1) for use in this study based on availability of measured soil properties and soil water content at the site, and differences in soil texture and vegetative cover. The five study sites are identified as LW06-133, LW11-136, LW07-151, LW18-154 and LW02. Where applicable each site name serves as two types of identification. Hyphenation separates the Southern Great Plains 1997 (SGP97) Hydrology Experiment site name, given first, from the permanent USDA-ARS Micronet station number. Both are provided here as a cross-reference to accommodate the reader and their association with different projects on the watershed. Three of the five study sites had a relatively dense vegetative cover of bermudagrass (*Cynodon dactylon* spp.). Vegetative cover at the other study sites consisted of a mix of big bluestem (*Andropogon gerardii* Vitman), little bluestem (*Schizachyrium scoparium* (Michx.) Nash), switchgrass (*Panicum virgatum* L.) and indiangrass (*Sorghastrum nutans* (L.) Nash) and ranged from sparse to moderate cover. Vegetative and soil characteristics of each site are listed in Table 2.

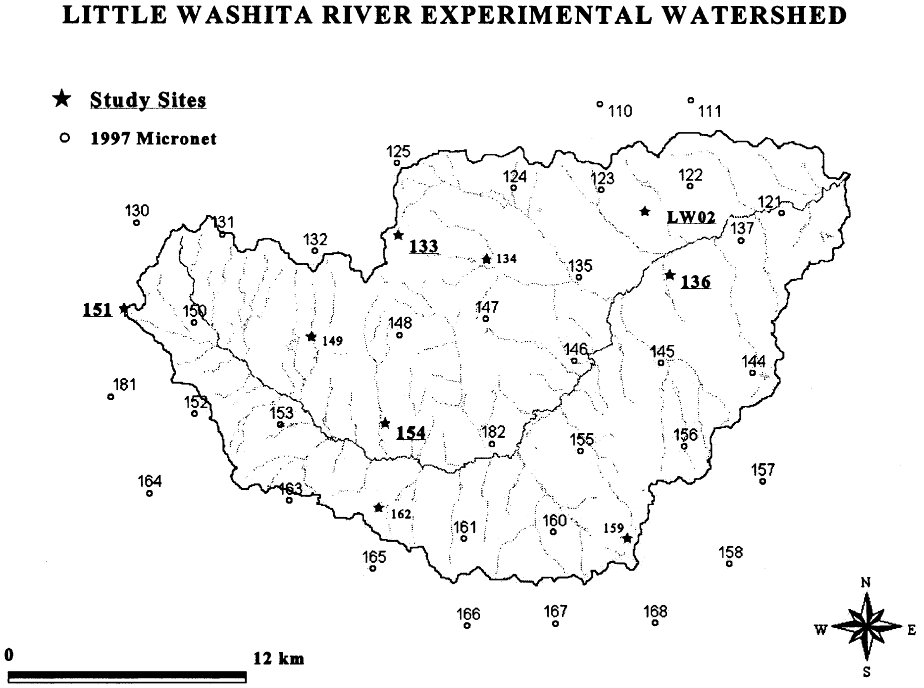

Fig. 1. Location of Micronet stations and five experimental study sites in the LWREW.

2.3. Soil properties and water content measurements

The ability of the soil in the vadose zone to conduct or retain water is a function of its hydraulic properties. As described earlier, the basic soil hydraulic properties and characteristic functions that govern the flow of water in soils are soil hydraulic conductivity as a function of soil water content $K(\theta)$ or matric suction $K(h)$ and soil water content as a function of matric suction $\theta(h)$, commonly referred to as the soil water characteristics curve (Hillel, 1980; Ahuja and Nielsen, 1990). These hydraulic properties depend on the pore size distribution, which is, in turn, affected by soil texture and structure (Ahuja et al., 1976; Paige and Hillel, 1993). The techniques used in this study to measure the soil physical and hydraulic properties in the laboratory and field are described below.

2.3.1. Laboratory-derived soil physical and hydraulic properties

Selected soil physical and hydraulic properties were determined at each site to a depth of at least 60 cm in 15 cm intervals. Soil cores were extracted from the site using a soil-core sampling tool having a 15 cm long barrel with a 5 cm inside diameter. Care was taken to minimize compaction during sampling. Each soil core was divided into 7.5 cm long subsamples. One subsample was used to determine soil texture using the hydrometer method (Day, 1965). The remaining subsample was used to determine the soil water characteristics using the procedure given in Ahuja et al. (1985). Bulk density and θ at saturation and at 1, 5, 10, 20, 33, 100, 500, 1000, and 1500 kPa were determined for each 15 cm interval in the profile.

2.3.2. Soil hydraulic properties determined in situ

Soil hydraulic properties at each of the five field sites were measured in situ using the instantaneous profile method (Hillel, 1980). According to a comparative study by Paige and Hillel (1993), the instantaneous profile method is the most effective method for determining soil hydraulic properties in situ. The method involved gravimetric soil sample analysis, double-ring infiltrometry, and tensiometric data analysis. The soil water content-matric pressure relationship can be obtained by periodic measurement of soil water content during the drainage phase by gravimetric, neutron thermalization, TDR, or gamma-ray attenuation techniques (Richards et al., 1956; van Bavel et al., 1968).

The instantaneous profile method involves measuring the rate of water entering the soil surface and the changes in soil water potential with depth and over time using tensiometers. A double-ring infiltrometer with two concentric metal rings having diameters of approximately 90 and 50 cm, respectively, were co-located with tensiometers placed at depths of 15, 30 and 60 cm in the soil profile located just outside the inner ring. The rings were completely filled with water the day before measurements began to pre-wet the soil. By pre-wetting the soil, sufficient wetting to at least a depth of 1 m is more easily and readily obtained on the day measurements begin. On the day of measurement, water was carefully ponded in the rings with the change in water level over time observed. Once the rate of change became constant, the vertical flux of water in the profile was assumed to be at steady state. At this time the hydraulic conductivity in the zone of constant matric potential is said to be numerically equal to the flux density of water and thus a value of saturated conductivity was obtained (Table 3). Tensiometric readings were taken at this time as a check on unit gradient conditions and saturated water content. The rings were then covered to minimize evaporation and protect the area from rainfall. In this data set, tensiometric data and gravimetric soil samples were obtained from each site to determine matric potential and soil water content, respectively, for 4 to 6 days during the drainage phase.

2.3.3. Soil water content measurements

During the spring of 1997,[1]MoisturePoint (Environmental Sensors, Inc., British Columbia, Canada) profiling TDR probes were installed at selected Micronet locations, in support of research objectives for the Southern Great Plains 1997 Hydrology Field Experiment (Jackson et al., 1999). Each probe consisted of four 15 cm long segments, enabling measurements of θ_v down to 60 cm. At site LW07-151 a 5-segment TDR probe was used reaching to a depth of 120 cm, in segments of 0–15, 15–30, 30–60, 60–90, and 90–120 cm. To coincide with available soil property data, readings from only the first four segments were used in this work. The TDR probes were calibrated in situ against site-specific gravimetric and bulk density data (Heathman, 2001; Heathman et al., 2002). The TDR probes were usually read once each day, depending on weather conditions and available personnel, between 08:00 and 10:00 h local time, during the June 18–July 16, 1997 study period.

2.4. Statistical methods

To evaluate the overall correspondence of model output to measured values, we use the standard statistical measures of the correlation coefficient (r), coefficient of variation (r^2), root mean square error (RMSE), mean bias error (MBE) and mean relative error (MRE). As an aid to evaluate model performance we also employ the D-index of model agreement proposed by Willmott (1982). Willmott and Wicks (1980) and Willmott (1981, 1982) raised concerns about the exclusive use of r and r^2 in the context of measuring model performance. They observed that at times very dissimilar values of estimates and measurements can produce an r very near 1, while small differences between measured and estimated quantities can produce a low or even negative r. The D-index (D) varies between 0 and 1, with $D = 1$ indicating complete agreement between modeled and measured values, while $D = 0$ indicates complete disagreement. The statistics of RMSE, MBE, MRE, and D are defined as

$$\mathrm{RMSE} = \sqrt{\frac{\sum(P-O)^2}{n}} \tag{6}$$

$$\mathrm{MBE} = \frac{\sum(P-O)}{n} \tag{7}$$

$$\mathrm{MRE} = \frac{\sum(P-O)100}{n} \tag{8}$$

$$D = 1 - \left[\sum(P-O)^2 \Big/ \sum(|P-\bar{O}| + |O-\bar{O}|)^2\right] \tag{9}$$

where P, O, and $\bar{O}$ are predicted, observed, and the average of n observations, respectively.

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[1] Use of company or trade names is for informational purposes only and does not constitute endorsement by the United States Department of Agriculture to the exclusion of any other product that may be suitable.

Table 3
Measured and estimated soil hydraulic properties for each study site

Site ID	Depth (cm)	Measured			Estimated by RZWQM				
		θ at -33 kPa ($\mathrm{m^3\,m^{-3}}$)		K_s[a] (In situ,cm $\mathrm{h^{-1}}$)	θ at -33 kPa[b] ($\mathrm{m^3\,m^{-3}}$)	K_s (scenario, cm $\mathrm{h^{-1}}$)			
		Lab[c]	In situ[d]			1	2	3	4
LW06-133	0–15	0.127	0.176	29.3	0.192	2.59	11.1	22.2	13.3
	15–30	0.110	0.214	29.3	0.192	2.59	10.1	24.2	7.61
	30–45	0.086	0.149	29.3	0.192	2.59	9.24	28.3	15.1
	45–60	0.126	0.271	29.3	0.192	2.59	12.6	24.9	4.35
LW11-136	0–15	0.207	0.125	3.4	0.234	1.32	1.32	11.1	26.0
	15–30	0.197	0.181	3.4	0.192	2.59	2.59	9.92	12.0
	30–45	0.219	0.151	3.4	0.246	0.43	0.43	7.89	17.5
	45–60	0.236	0.176	3.4	0.246	0.43	0.43	5.33	11.7
LW07-151	0–15	0.093	0.199	4.8	0.192	2.59	13.2	2.6	12.2
	15–30	0.098	0.133	4.8	0.106	6.11	21.7	6.1	16.6
	30–60	0.138	0.127	4.8	0.106	6.11	36.3	6.1	30.5
	60–90	0.162	0.127	4.8	0.106	6.11	22.9	6.1	18.8
LW18-154	0–15	0.239	0.246	0.4	0.234	1.32	5.77	5.33	4.79
	15–30	0.242	0.315	0.4	0.246	0.43	5.11	5.41	1.46
	30–45	0.295	0.305	0.4	0.246	0.43	4.59	1.92	1.55
	45–60	0.332	0.347	0.4	0.246	0.43	6.00	1.27	0.88
LW02	0–15	0.263	0.314	0.15	0.234	1.32	1.84	1.84	1.84
	15–30	0.208	0.244	0.15	0.312	0.23	6.07	6.07	6.07
	30–45	0.212	0.250	0.15	0.234	1.32	4.29	4.29	4.29
	45–60	0.212	0.243	0.15	0.286	0.68	4.27	4.27	4.27

[a] Values used in Scenario RZS5.

[b] Value used in scenarios RZS1 and 2.

[c] Values used in Scenario RZS3.

[d] Values used in scenarios RZS4 and 5. However, in Scenario RZS5 an average of all values is used to represent whole soil profile.

The correlation coefficient (r) represents a measure of the strength of the relationship between predicted θ_v and observed measurements, whereas the MBE and RMSE are indicative of mean bias and overall error in the estimation procedure, respectively.

3. Results and discussion

Fig. 2(a)–(e) are graphical comparisons of the daily time series of average root zone θ at each site as measured by the TDR and as estimated using the five limited data hierarchy scenarios. Scenarios tested at site LW06-133 consistently underestimated measured values over the course of the study period, except for day of year (DOY) 169 and 192 where modeled and measured values agreed (Fig. 2(a)). This underestimation was largely due to faster soil drying rates exhibited by the scenarios than was indicated by the TDR measurements. Modeled θ reached a minimum value of about 0.10 $\mathrm{m^3\,m^{-3}}$ on DOY 182, 8 days before that shown by the measured data. The average underestimation (MBE, Table 4) is 0.01 $\mathrm{m^3\,m^{-3}}$ for Scenario RZS1, and 0.02 $\mathrm{m^3\,m^{-3}}$ for scenarios RZS2, 3 and 4. Scenario RZS5 showed the largest MBE at this site with a value of 0.03 $\mathrm{m^3\,m^{-3}}$. Although the model simulations underestimated measured θ, the D, r and r^2 statistics (Table 4) indicate that all model simulations agreed well with measured values.

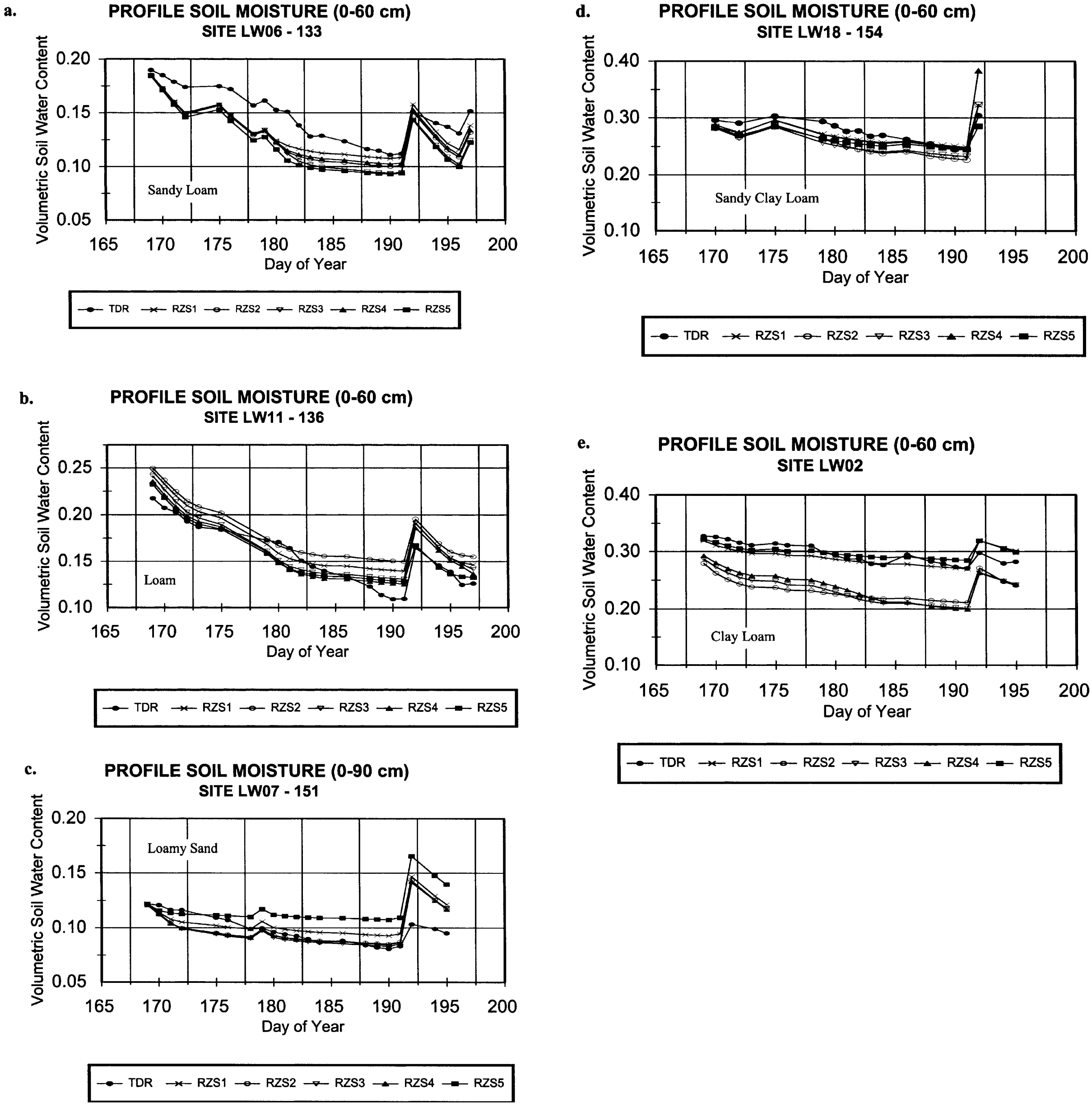

Fig. 2. Measured (TDR) and modeled average profile soil water content (0–60 cm) for five scenarios (see Table 1) at sites; (a) LW06-133, (b) LW11-136, (c) LW07-151, (d) LW18-154, and (e) LW02.

Model estimates of θ at site LW11-136 (Fig. 2(b)) closely agreed among the scenarios, but tended to overestimate measured values at the beginning and end of the modeling period. Scenarios RZS1 and RZS2 consistently overestimated θ relative to scenarios RZS3 through RZS5. Similar to site LW06-133, the modeling results show faster soil drying rates than that indicated by measurements. Additionally, the measured data show a minimum θ of about 0.10 $m^3\ m^{-3}$ occurring around DOY 190, but modeled θ was at least 0.02–0.06 $m^3\ m^{-3}$ higher for all scenarios. The MBE indicates overestimates of

Table 4
Results from statistical analysis of the five scenarios implemented at the five study sites

Site ID	Scenario	D	r^2	r	± s.d.	RMSE ($m^3\ m^{-3}$)	MBE ($m^3\ m^{-3}$)	MRE (%)
LW06-133	1	0.99	0.84	0.92	0.02	0.02	−0.01	−9.97
	2	0.99	0.88	0.94	0.03	0.02	−0.02	−13.54
	3	0.99	0.92	0.96	0.03	0.02	−0.02	−16.80
	4	0.99	0.87	0.93	0.03	0.02	−0.02	−12.28
	5	0.99	0.88	0.94	0.03	0.03	−0.03	−18.03
LW11-136	1	0.99	0.85	0.92	0.03	0.02	0.01	10.32
	2	0.99	0.85	0.92	0.03	0.03	0.02	15.69
	3	0.99	0.83	0.91	0.03	0.02	0.01	6.13
	4	0.99	0.84	0.92	0.03	0.01	0.00	3.27
	5	0.99	0.88	0.94	0.03	0.01	0.00	1.37
LW07-151	1	0.97	0.26	0.51	0.01	0.01	0.01	7.87
	2	0.98	0.30	0.55	0.01	0.01	0.00	1.38
	3	0.98	0.34	0.58	0.01	0.01	0.00	0.13
	4	0.98	0.32	0.57	0.01	0.01	0.00	1.08
	5	0.96	0.05	0.23	0.02	0.03	0.02	20.43
LW18-154	1	0.99	0.72	0.85	0.02	0.01	−0.01	−2.23
	2	0.98	0.79	0.89	0.03	0.02	−0.02	−7.56
	3	0.98	0.69	0.83	0.02	0.02	−0.02	−7.15
	4	0.98	0.49	0.70	0.03	0.02	0.00	−1.26
	5	0.98	0.82	0.90	0.02	0.02	−0.01	−5.00
LW02	1	0.99	0.51	0.71	0.02	0.01	0.00	−1.54
	2	0.97	0.51	0.71	0.04	0.06	−0.06	−21.11
	3	0.97	0.71	0.84	0.04	0.06	−0.06	−20.97
	4	0.97	0.77	0.88	0.04	0.06	−0.06	−19.29
	5	0.99	0.63	0.80	0.01	0.01	0.00	1.16

measured θ for all scenarios. Scenarios RZS1 and RZS2 had the largest MRE at this sites (≥10%). Scenario RZS5 performed best overall, having the highest r and r^2, the lowest MRE and one of the lowest RMSEs and MBEs.

LW07-151 was the most sandy textured site in the study. The high fraction of sand and limited rainfall contributed to the small range (0.04 $m^3\ m^{-3}$) of measured θ at this site (Fig. 2(c)), which largely explains the rather low r and r^2 values. Observation of Fig. 2(c) coupled with the statistical data indicates that model estimates of θ from scenarios RZS1 through RZS4 closely approximated measured values over most of the study period. Scenario RZS5 exhibited the largest overestimation of θ (MBE = 0.02 $m^3\ m^{-3}$) compared to all other scenarios. The RMSE of Scenario RZS5 at this site was 0.03 $m^3\ m^{-3}$, and the MRE was approximately 20%.

The modeling scenarios employed at site LW18-154 produced similar estimates of θ over most of the study period (Fig. 2(d)). The measured values of θ were underestimated by ≤0.02 $m^3\ m^{-3}$, on average, with MREs and RMSEs <10% and ≤0.02 $m^3\ m^{-3}$, respectively, for all scenarios. Scenario RZS4 overestimated measured θ on DOY 192 by about 0.08 $m^3\ m^{-3}$. The other scenarios produced estimates of θ within ±0.02 $m^3\ m^{-3}$ of the measured value on this day.

At site LW02, scenarios RZS1 and RZS5 produced estimates of θ closely corresponding to each other, and agreeing well with measured values (Fig. 2(e)). The MREs for these two scenarios were <2%, with RMSEs of 0.01 $m^3\ m^{-3}$. Scenarios RZS2, 3 and 4 also produced estimates of θ similar to each other, but these estimates were lower than measured values by 0.06 $m^3\ m^{-3}$, on average, leading to MREs of about

20% and RMSEs of 0.06 $m^3\ m^{-3}$. This site represents one of the most complex relative to soil layering (Table 2), but it is interesting to note that the K_s values used in Scenario RZS1 are much lower, in general, than those in scenarios RZS2 through RZS4 (Table 3), and are much closer in value to those used in Scenario RZS5.

The results of modeling average profile soil water content using the full description hydraulic input mode (RZS6) are presented in Fig. 3(a) and (b) for sites LW06-133 and LW18-154, respectively. In addition to plotting TDR measured data, the results from Scenario RZS1 are also shown to allow comparisons between not only the measured values, but with the most limited level of data input as well. Though the soil properties are quite different between the sites, the results are similar in that, compared to measured values, Scenario RZS6 underestimates the average profile soil water content at both sites. Furthermore, RZS6 estimates are also lower than those plotted for RZS1. Since it was apparent from the graphs in Fig. 3(a) and (b) that using the full description of hydraulic parameters in RZS6 did not improve profile estimates, no statistical tests were made. The results were somewhat surprising, but indicate that the use of mean values based on textural class or in situ measurements seem sufficient considering the range in values for some properties (i.e. total porosity and conductivity) and their spatial variation which may not be well represented by traditional lab soil-core analyses. Furthermore, the model appears less sensitive to using the full description of hydraulic properties for estimating average soil water content in the entire 0–60 cm profile rather than at 15 cm depth intervals. This may be due to either over or underestimating the water content in different layers. A more detailed analysis for different depth intervals or soil horizons is the subject of further study. However, the focus of the work presented here was the estimation of average profile water content using limited soils data.

In Fig. 4(a)–(d), the results of the hydraulic parameter sensitivity analysis for θ at -33 kPa (RZS7, 7b) and K_s (RZS7a) are presented for the surface layers at sites LW06-133 and LW18-154. Gravimetric sample data and TDR measured data at 0–5 and 0–15 cm, respectively, are compared with predicted values of soil water content. The results for deeper layers were essentially the same as those for near-surface layers. Scenario RZS1 was chosen for the analysis since it was a simple case of replacing the model default values with new values for either -33 kPa water content or K_s. Otherwise, RZS7 has the same input as RZS1 (Table 1). The method is similar to parameter optimization in that the hydraulic parameters for θ at -33 kPa and K_s are adjusted in an effort to match model estimates to measured values of profile soil water content. Several combinations of input were applied, taking into consideration the range of values representative of the texture class as given in Rawls et al. (1982), i.e. θ at -33 kPa values of 0.126–0.288 $m^3\ m^{-3}$ for the sandy loam at site LW06-133. We only present the results using the extreme values for θ at -33 kPa (RZS7-low and RZS7b-high) and the higher K_s values (RZS7a).

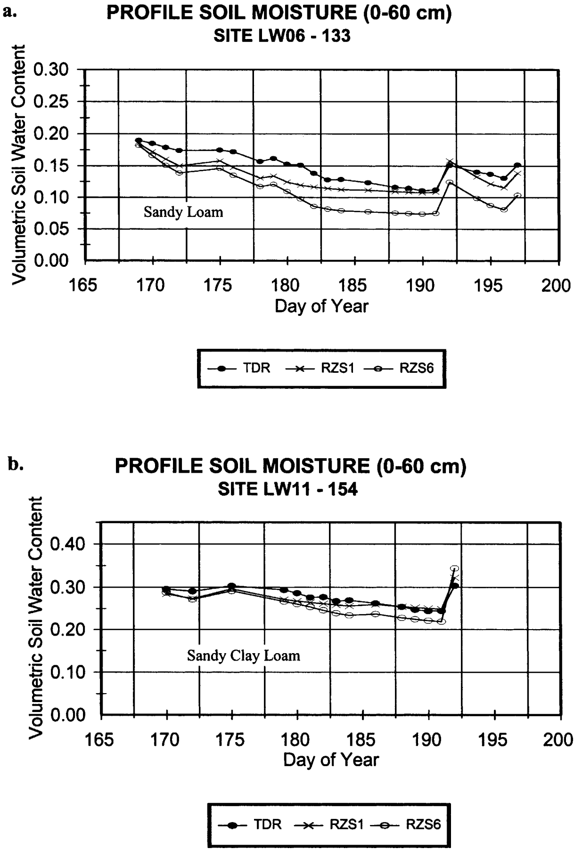

Fig. 3. Comparisons between TDR measured water content and modeled estimates for scenarios RZS1 and RZS6 (full description input—Table 1) at sites; (a) LW06-133 and (b) LW18-154.

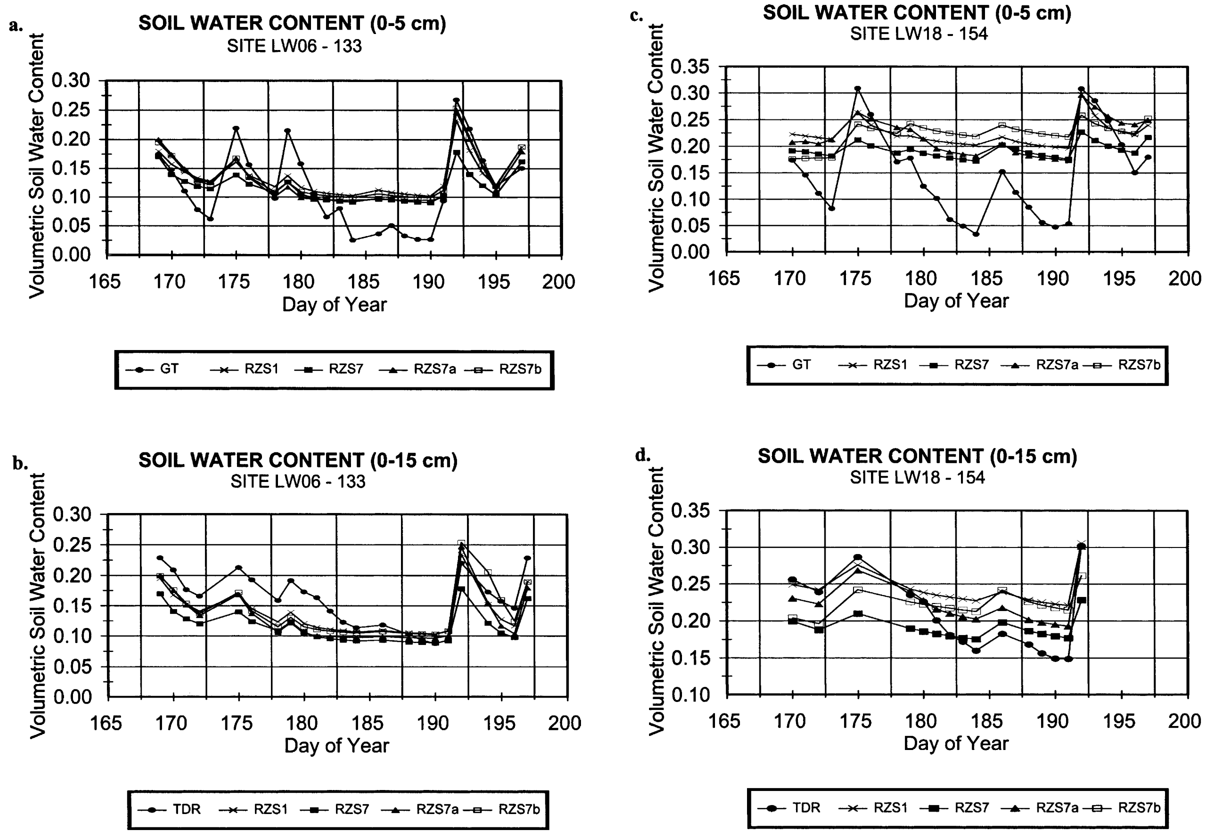

Fig. 4. Comparisons between model results for hydraulic parameter adjustment and measured gravimetric (GT) or TDR data at sites; (a) LW06-133, 0–5 cm, (b) LW06-133, 0–15 cm, (c) LW18-154, 0–5 cm, and (d) LW18-154, 0–15 cm.

Although we do not consider this a rigorous analysis, the results do provide certain insight. The overall effect of adjusting the hydraulic parameters was a general shift in the model estimates above or below the measured values. The shape of the graphed data basically remained the same. Thus, the results for our data set indicate that while the difference between predicted and measured values may be reduced by these adjustments, it is difficult to capture the absolute dynamic structure of the measured time series of soil water content.

At sites LW06-133, LW11-136 and LW07-151 we found that model estimates of profile soil moisture were influenced by plant water uptake in the root zone. In our first attempts at modeling these sites, the model consistently overestimated the 0–60 cm average soil water content. Once the crop growth component of the model was initialized at these sites to account for plant water uptake by the bermudagrass, model estimates of soil water content compared well with measured values. Although the model does not provide specific plant growth options for different types of rangeland vegetation, the 'quick turf' component gave good results at these sites where bermudagrass was the predominant cover. An extension of the model's crop growth component to account for various rangeland conditions is the subject of future work.

4. Conclusions

Comparisons between RZWQM simulated and measured TDR soil water content values demonstrates that the model provided reasonable estimates of average soil water content at five sites within the LWREW. Experiments were conducted on several different soil types and modeled for a one-month period. Variable levels of physical and hydraulic input data were applied in the model, as well as the use of field or laboratory measurements of soil hydraulic properties.

This study illustrates how soil type, different levels of input data, and differences in soil hydraulic parameter estimation or measurement influence the capability of the RZWQM in simulating average profile soil water content under rangeland conditions. Interestingly, Spaeth et al. (1996) stated that rangelands comprise over 60% of the land area of the 48 contiguous states, and that agricultural, industrial, recreational and municipal water supplies in many areas of the US are linked directly to rangeland watershed management. Taking into consideration the increased competition for available water supplies, a model such as RZWQM could be modified in terms of a spatially distributed format and used to quantify soil water resources over large land areas, such as rangelands, to further aid in the efficient management of our nations water resources and watersheds.

Generally, the model provided satisfactory results, especially considering that no soil hydraulic properties were calibrated or optimized (except Scenario RZS7), though measured (site-specific) hydraulic properties were used in some cases. In addition, the environmental and site conditions for our experimental study were quite different from those reported in previous RZWQM evaluation and calibration studies (Hanson et al., 1999; Ma et al., 1998; Wu et al., 1996). The experimental time-scale for this work was also considerably shorter than what is normally applied to the model, in order to coincide with other studies during the SGP97 Hydrology Experiment. It does not appear that the shorter time-scale had any appreciable effect on model results, though some studies have suggested that soil moisture predictability may be related to modeled time-scale (Schlosser and Milly, 2000).

We found, as did Martin and Watts (1999), that correct simulation of plant water uptake is essential for soil water prediction. From our work at three sites, it became apparent that not only is the choice of plant species important, but that the manner in which the model calculates the root distribution can be a significant factor as well. We suggest that further research in this area should be considered for representing various species of rangeland vegetation in the model. This would be of particular interest in areas of watershed management where rangeland production systems are more predominant than agronomic systems.

The results from Scenario RZS1, using hydraulic properties estimated from soil texture, show good agreement between predicted and measured soil water content. In most cases, the results are better than those where detailed laboratory measured values were used as input. These results are consistent with those of Landa et al. (1999) where they used hydraulic properties estimated from soil texture and obtained close agreement between predicted and measured soil water content. This implies that the default values used in RZWQM are acceptable input for model applications when using a very limited input data set. An advantage of using this particular approach might be in large scale studies where remotely sensed surface soil moisture data are used to model profile soil water content.

In all cases, scenarios RZS4 or RZS5 (field input data) showed good agreement between predicted and measured values indicating that the use of field measured $-33\,\mathrm{kPa}$ water content and/or K_s as hydraulic input data, may be preferable to those obtained by more detailed laboratory measurements (Scenario RZS3). This, in part, could be due to the large spatial variation in soil properties and the fact that for a given texture class, the corresponding range of property values can be quite broad, thus, the use of average profile values obtained in the field is quite adequate. Besides improving model estimates of soil water content, the input data obtained from field measurements requires much less time than laboratory analysis, is less expensive, and may be considered more representative of actual field conditions. As mentioned earlier, the data may also typify hydraulic properties obtained through the use of remotely sensed data.

Results presented here are consistent with previous studies that evaluated the capability of the RZWQM to predict soil water content, but also show that use of a limited input data set or soil hydraulic properties obtained in the field using relatively simple techniques provided the best estimates of average profile soil water content. These findings illustrate the potential application for modeling profile soil water content based on very limited soil data information and support the use of soil hydraulic properties obtained from remotely sensed surface soil moisture data as model input.

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