Inferring Root Zone Soil Water Content by Assimilating Remotely Sensed Data Into A Soil Water Model

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Abstract

Increased demand for available water supplies necessitates that tools and techniques be developed to quantify soil water reserves over large land areas as an aid in management of water resources and watersheds. Microwave remote sensing can provide measurements of volumetric water content of the soil surface up to about 10 cm deep. The objective of this study was to examine the feasibility of inferring the volumetric water content of the root zone by combining remotely sensed estimates of surface soil water content and modeling techniques. A simple soil water budget model was modified to estimate root zone soil water content from remotely sensed estimates of surface soil water content. Two modeling scenarios were evaluated at four tallgrass prairie sites located in central and south central Oklahoma: 1) model simulation without assimilation of remotely sensed estimates of soil water content, and 2) model simulations with assimilation of soil surface water content estimated from remote sensing. The unmodified model (scenario 1) underestimated measurements with root mean square errors (RMSE) between 0.03 and 0.06 m^3m^{-3} and mean errors (ME) between 0.02 and 0.04 m^3m^{-3}. Simulations from scenario 2 agreed well with measured data at two study sites (0.00 $m^3m^{-3} \geq$ ME $\leq$ 0.02m^3m^{-3}, RMSE $\leq$ 0.03 m^3m^{-3}) but underestimated measurements at the remaining sites, in one case by as much as 0.15 m^3m^{-3}. The underestimation was due largely to inaccurate remotely sensed soil surface water content values. These preliminary results suggest that it is feasible to infer root zone soil water content in tallgrass prairies by assimilating remotely sensed estimates of surface soil water into soil water models, provided that the remotely sensed data correctly estimates surface conditions.

Keywords: water budget, microwave, soil profile

Introduction

Soil water accounts for only about 0.0001% of the total water on earth, but its status in the root zone is a key parameter in many aspects of agricultural, hydrological, and meteorological applications. In agriculture, accurate knowledge of soil water content is essential for proper water resource management, irrigation scheduling, crop production, and chemical monitoring. Meteorologically, soil water content plays a significant role in the partitioning of available energy at the earth's surface into heating the air and that used in evapotranspiration. In hydrology, soil water partitions rainfall into infiltration or runoff.

Increased demand for available water supplies coupled with the vagaries and variabilities of climate, necessitate that tools and techniques be developed to quantify soil water resources over large, and often spatially variable, land areas as an aid in management of water resources and watersheds. Point-based, direct measurement methods are either impractical or too expensive for large land area applications. Microwave remote sensing is a technique that offers potential for providing frequent measurements of soil water content over large land areas in a timely and cost-effective manner. However, these measurements only represent the soil surface down to about 10 cm deep, depending upon sensor type and wavelength used (Engman and Chauhan 1995).

In this paper, microwave surface measurements of soil water content are assimilated (input) into a simple soil water budget model to determine the feasibility of estimating soil water content down to about 60 cm. Study sites from the USDA-ARS' Little Washita River Experimental Watershed (LWREW), located in

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southwestern Oklahoma, are used to demonstrate the potential of using remotely sensed data to estimate soil water reserves over large land areas.

Methods

Site description

The LWREW (Fig. 1) is about 610 km^2 (236 mi^2) in size and is climatologically described as subhumid to semi-arid with total annual precipitation of about 75 cm (30 in). The topography is gently rolling and the land use is about 60% pastureland, 20% cropland, and 20% miscellaneous (forests, riparian areas, water and urban areas).

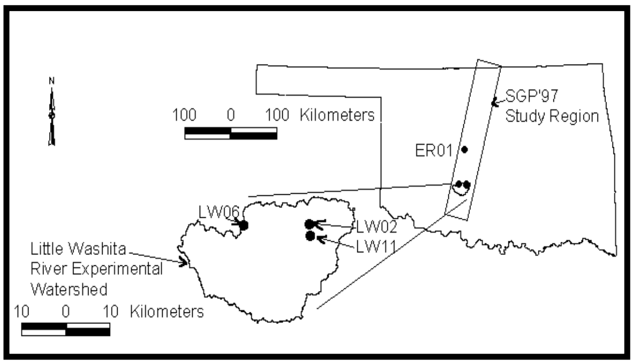

Figure 1. Location of the LWREW and study sites.

There are 64 defined soil series, with fine sand, loamy fine sand, loam and silty loam being the predominant textures of the soil surface (Allen and Naney 1991). The LWREW has a network of 45 meteorological measurement stations, collectively called the Micronet, distributed on a 5 km (3 mi) grid spacing. Each Micronet station measures rainfall, relative humidity, air temperature, incoming solar radiation, and soil temperature at four depths. These data are measured every 5 min and reported every 15 min to a central archiving facility. Co-located at 13 of these sites is a Soil Heat and Water Measurement Station (SHAWMS). Each SHAWMS measures soil water matric potential at 5, 10, 15, 20, 25 and 60 cm, as well as soil temperature at 2.5, 5, 10, 15, 20, 25, 60 and 100 cm, and soil heat flux at 5, 25, and 60 cm. A profiling time domain reflectometer (TDR) waveguide is also located at each SHAWMS.
Three Micronet/SHAWMS sites (LW02, LW06 and LW11) were selected for this study. An additional site (ER01), located on the grounds of the USDA ARS Grazinglands Research Laboratory, El Reno, Oklahoma, was also selected for study to provide vegetation and soil conditions not represented by the other sites (Tables 1 and 2).

Remotely sensed data

Because of its historical data bases and the presence of the Micronet, the LWREW became a primary study site for a large, multi-agency hydrology experiment known as the Southern Great Plains Hydrology Experiment 1997 (SGP97). The SGP97 experiment is described further in Jackson et al. (1998). The experiment was conducted from June 18 to July 17, during which time the electronically scanned thinned array radiometer (ESTAR) was flown to provide microwave-based estimates of surface soil moisture at a spatial resolution of about 1 km (0.6 mi.). Due to weather, instrument, and logistic constraints, the ESTAR was only flown on 10 days out of the 30 day experimental period.

Model

The model chosen for this study was developed by Ragab (1995). This model is a simple two-layer soil water budget that simulates the one-dimensional vertical movement of water in the surface (0-5 cm) and the root zone (in this study, the 0-60 cm) layers. The model operates on a daily time step and the required meteorological data are daily values of rainfall and potential evapotranspiration (ET_P). Rainfall was obtained from the Micronet stations and ET_P was calculated using the Penman-Monteith equation (Rosenberg et al. 1983). Initial water contents needed by the model were based upon measured data and empirical relationships derived
between the surface layer and the root zone. Other required soil parameters required by the model are given in Starks and Jackson (2002).

The model was modified to run as originally written until a remotely sensed value of surface soil water content becomes available. At this point, the model replaces the original calculated surface value with the remotely sensed value and then proceeds as normal. Thus, the surface layer is “updated” with remotely sensed data at the frequency of availability, and the root zone calculations are based upon the new surface information.

Table 1. Leaf area index (LAI) and biomass measurements for the study sites. Data taken from Hollinger and Daughtry (1999).

Site	LAI	Green Standing Biomass			Brown Standing Biomass			Surface Residue		
		Wet	Dry	Water Content	Wet	Dry	Water Content	Wet	Dry	Water Content
		---(gm^{-2})---		%	---(gm^{-2})---		%	---(gm^{-2})---		%
ER01	4.7	1403	460	67	133	97	26	967	510	47
LW02	2.2	350	161	53	184	158	19	160	141	14
LW06	0.9	112	41	62	22	18	17	18	12	10
LW11	3.6	940	246	73	67	44	43	494	319	35

Table 2. Soil particle fractions and texture of the profile for each site.

Site	Sand	Silt	Clay	Texture
	---------------%---------------			
ER01	22	60	18	Silt loam
LW02	26	48	26	Loam
LW06	73	17	10	Sandy loam
LW11	54	24	22	Sandy clay loam

The model was run for two scenarios. The first scenario examines the model's ability to simulate the root zone soil water content for the meteorologic, soil, and vegetation conditions at each study site. In the second scenario, ESTAR surface (0-5cm) soil water content estimates are assimilated into the model, at the frequency of availability, to determine if model output is improved over that of the original simulations. Model output is compared to soil water content values acquired from the SHAWMS and/or TDR at the study sites.

Statistical analysis

Wilmott's (1982) d-index, root mean square error (RMSE), the coefficient of determination (r^2), and mean error (ME) are used to evaluate the model simulations. The d-index is a measure of correspondence between model output and measured data. A d = 1 means complete agreement between measured and modeled values, while a d = 0 means complete disagreement.

Results

Scenario 1 - Original model

The range of measured root zone soil water content over the course of the study period was about 0.04 m^3m^{-3} at sites ER01 and LW02, 0.08 m^3m^{-3} at LW06, and 0.14 m^3m^{-3} at LW11. These ranges represent 50, 20, 93, and 61% of the total plant available water (defined as the difference in water content at field capacity and wilting point) at these sites, respectively. Time series simulations from the original model exhibit the general patterns portrayed by the measured data, but the model consistently underestimated measured values at all sites (Figs. 2a-2d). The differences between measured and modeled root zone soil water content generally increase with time at sites ER01 and LW02, while at sites LW06 and LW11 there appears to be a constant offset or bias in the model simulations (Figs. 2a-2d).

The r^2 values indicate that the variation in the modeled values is strongly associated with the variation in the measurements at all sites (Table 3). The d-index (Table 3), however, indicates weak agreement between measured and modeled values at ER01, moderate agreement at sites LW02 and LW06, and stronger agreement at LW11. The ME reveals that the model underestimated measured values from 0.02 m^3m^{-3} at site LW02 to 0.05 m^3m^{-3} at site ER01. Only site LW02 had a RMSE <0.05 m^3m^{-3}.

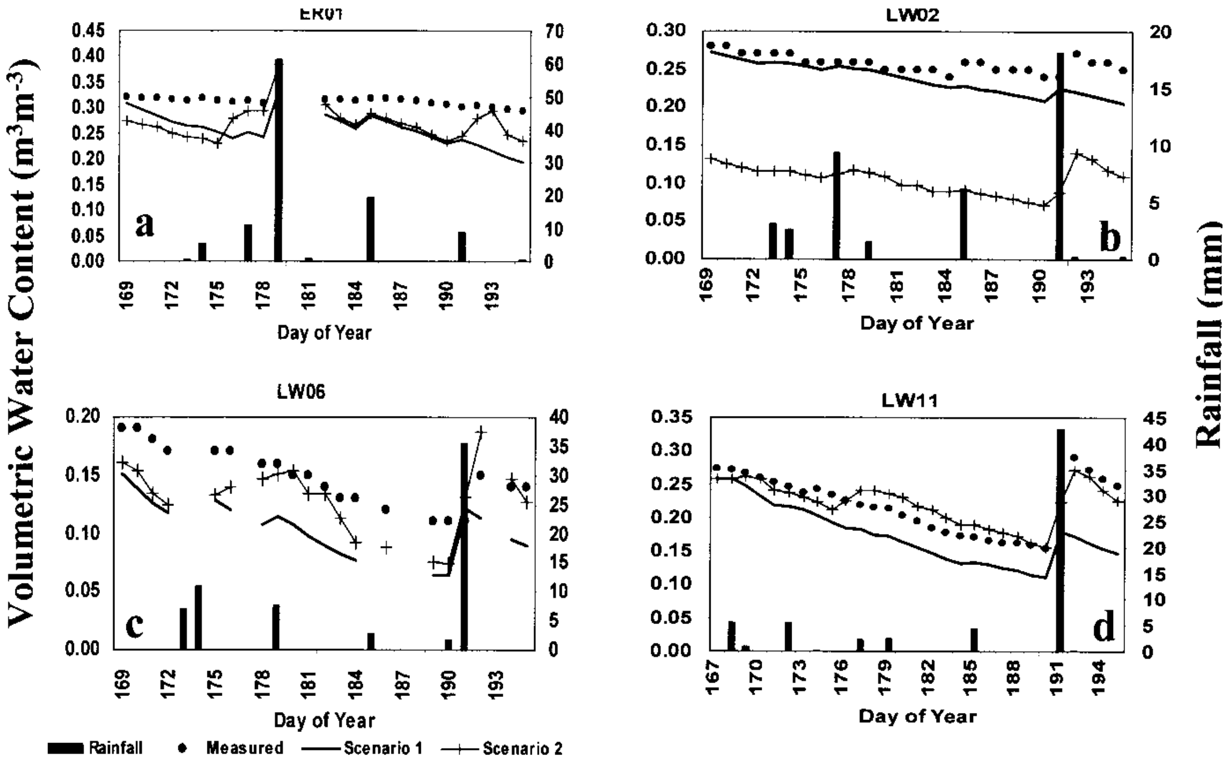

Figure 2a-2d. Time series plots of modeled root zone soil water content for study sites ER01 (a), LW02 (b), LW06 (c), and LW11 (d). Gaps in the time series reflect days when measured values were unavailable.

Scenario 2 – Assimilation of remotely sensed data

Model output at sites ER01 and LW02 did not agree well with measured data (d-index ≤ 0.23) (Figures 2a-d, Table 3), although at site ER01, both the ME and RMSE decreased by 0.01 m^3m^{-3} over that observed in scenario 1. At site LW02, assimilation of remotely sensed surface values into the model produced ME and RMSE values larger than any others encountered in the study. In contrast, the d-index, ME and RMSE values at sites LW06 and LW11 indicated good agreement with measured values.

Table 3. Results from statistical analysis of the comparison of modeled and measured root zone soil water content for the two scenarios.

Site	d	ME	RMSE	r^2
		Scenario 1		
ER01	0.25	0.05	0.06	0.990
LW02	0.52	0.02	0.03	0.996
LW06	0.56	0.04	0.05	0.985
LW11	0.69	0.05	0.06	0.973
		Scenario 2		
ER01	0.23	0.04	0.05	0.989
LW02	0.12	0.15	0.15	0.982
LW06	0.73	0.02	0.03	0.986
LW11	0.91	0.00	0.02	0.991

Conclusions

The objective of this paper was to examine the feasibility of inferring root zone soil water content by combining remotely sensed estimates of surface water content and modeling techniques. The model of Ragab (1995) was selected for this study because of its simplicity and because it does not require detailed soil physical, hydraulic, and vegetation properties to parameterize the model–properties that are not generally available or easily measured over large and/or spatially variable watersheds. This is particularly advantageous for applications where little is known about an area's soil physical properties, since the required model inputs may be estimated from general soil texture information (e.g., Rawls et al. 1982).

The original model was able to reproduce the time series patterns of root zone soil water content, but consistently underestimated measured values from0.02 to 0.05 m^3m^{-3}, on average. When remotely sensed data were assimilated into the model at sites ER01 and LW02, the model output underestimated measurements throughout the study period. At site ER01, the modeling results were similar to those observed in scenario 1, but the simulation at site LW02 underestimated measured values by about 0.15 m^3m^{-3} throughout the study period. Underestimation of the root zone water content at these 2 sites was probably a result of vegetational effects on the ESTAR data. Jackson et al. (1999) noted that tall grasses and heavy litter deposits will cause the ESTAR to underestimate the surface soil water content. Site ER01 was the most densely vegetated of the study sites and possessed the heaviest litter layer. Although site LW02 was classified as a rangeland site, there are a number of trees in the area which have the same effect on the ESTAR surface estimates. Thus, assimilated remotely sensed values from these sites probably led to underestimated root zone values. Jackson et al. (1999) indicated that adjustments to vegetational aspects of the ESTAR soil moisture retrieval algorithm can be made to better account for litter and trees. These adjustments will be necessary if microwave-based remote sensing techniques are to be widely used to assess soil water content. The results from scenario 2 suggest that it is feasible to infer root zone soil water content in tallgrass prairies by combining remotely sensed surface observations into a soil water budget model, provided that the remotely sensed data has not been corrupted by vegetational effects.

A remote sensing/modeling approach such as that described above could be integrated with weather forecasts and/or climate outlooks to project future soil water supplies, as well as assessing the current status of soil water content. Such assessments and predictions could be used by agricultural producers and others to schedule irrigation and predict crop or forage production rates, and by water resources managers to better manage watersheds and surface, soil, and groundwater water resources.

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References

Allen, P.B., and J.W. Naney. 1991. Hydrology of the Little Washita River Watershed, Oklahoma: Data and Analysis. U.S. Department of Agriculture, Agricultural Research Service, ARS-90.

Engman, E.T., and N. Chauhan. 1995. Status of microwave soil moisture measurement with remote sensing. Remote Sensing of Environment 51:189-198.

Hollinger, S.E., and C.S.T. Daughtry. 1999. Southern Great Plains 1997 hydrological experiment: Vegetation sampling and data documentation. http://daac.gsfc.nasa.gov/CAMPAIGN_DOCS/SGP97/sgpvegdatrptvv3b.html

Jackson, T.J., D.M. LeVine, A.Y. Hsu, A. Oldak, P.J. Starks, C.T. Swift, J.D. Isham, and M. Haken. 1999. Soil moisture mapping at regional scales using microwave radiometry: the Southern Great Plains hydrology experiment. IEEE Transactions on Geoscience and Remote Sensing 37(5):2136-2151.

Ragab, R. 1995. Towards a continuous operational system to estimate the root-zone soil moisture from intermittent remotely sensed surface moisture. Journal of Hydrology 173:1-25.

Rawls, W.J., D.L. Brakensiek, and K.E. Saxton. 1982. Estimation of soil water properties. Transactions of the American Society of Agricultural Engineers 25(5):1316-1320, 1328.

Rosenberg, N.J., B.L. Blad, and S.B. Verma. 1983. Microclimate: The Biological Environment. John Wiley and Sons, New York.

Starks, P.J., and T.J. Jackson. 2002. Estimating soil water content in tallgrass prairie using remote sensing. Journal of Range Management 55:474-481.

Wilmott, C.J. 1982. Some comments on the evaluation of model performance. Bulletin of the American Meteorological Society 63:1309-1313.