A GIS for spatial and temporal monitoring of microwave remotely sensed soil moisture and estimation of soil properties

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Abstract A Geographical Information System (GIS) has been employed for monitoring and quantifying spatial and temporal changes of surface soil moisture derived from microwave remote sensing over the Little Washita watershed, Oklahoma, USA, for the period between 10 and 18 June 1992. Spatial and temporal variability of moisture content in the surface layers of the soil is of great importance to the hydrological research. Daily microwave measurements were obtained from airborne ESTAR instrument. Surface soil moisture values were derived from brightness temperatures. This data set has been georeferenced in a GIS for spatial analysis to quantify temporal variations of soil moisture during the dry-down period. Analysis of soil moisture changes with digital soils data within a GIS reveals a direct relationship between changes in soil moisture and soil texture. Areas identified by loam/ silt loam soils are characterized by higher changes of total soil moisture and those of sand/ fine sandy loam soils by remarkably lower amounts of change. This reveals an interesting pattern of changes in soil moisture giving an insight into estimation of soil hydraulic properties. A methodology capable of deriving profile soil hydraulic conductivity \( K_{sat} \) from remotely sensed soil moisture has been developed. Results have yielded good correlations between soil moisture change and \( K_{sat} \). The results of the present study have potential applications to obtain quick estimates of spatial distributions of soil properties over large area for input to mesoscale hydrological and global circulation models.

INTRODUCTION

Geographical Information Systems (GIS) provide appropriate tools for the storage, retrieval, analysis, management and display of spatial and temporal data. Remote sensing is an important source of data for input into GIS. Remote sensing platforms,
either airborne or space borne, have capabilities of acquiring data concerning various hydrological parameters on a repetitive basis, and hence generate large volumes of spatial data (Engman & Gurney, 1991). Thus, remote sensing coupled with GIS provide unique opportunities for modelling various aspects of hydrological cycle.

Soil moisture in the surface layers of the soil profile plays a critical role in the hydrological cycle. Specifically, it is important for partitioning rainfall into runoff and infiltration components as well as separating incoming radiation into latent and sensible heat (Engman & Gurney, 1991). Microwave remote sensing holds a great potential for providing areal estimates of soil moisture because of its capability to penetrate clouds, and to a some extent, the vegetation canopy. Passive microwave remote sensing employs measurements of the thermal emission from the soil at the longer microwave wavelengths ($\lambda > 10$ cm) to determine the moisture content in the surface layer of the soil. The relationship between microwave emission of natural surfaces and their inherent moisture content has been studied and well documented in the literature (e.g. Schmugge et al., 1986; Jackson, 1988). Studies involving truck and aircraft measurements not only demonstrated this basic relationship but have also helped to quantify the effects of various surface parameters such as soil texture, roughness and vegetation that distort and confound the basic relationship (e.g. Jackson & Schmugge, 1991). A few studies have made temporal observations to map spatial variation in soil moisture (Engman et al., 1989; Wang et al., 1989).

In this paper, we demonstrate that the temporal measurements of surface soil moisture obtained from microwave remote sensing are useful to estimate soil hydraulic properties. A methodology of employing remotely sensed data to estimate profile $K_{sat}$ has been developed using a hydrological model and a GIS.

STUDY AREA

The Little Washita watershed in the southern part of the Great Plains in southwest Oklahoma has been selected. An airborne campaign (Washita’92) was carried out in the watershed during from 10 to 18 June 1992. The study site, which covers an area of 610 km$^2$, has long term (more than 24 years) hydrological monitoring facility. The climate of Little Washita region is classified as moist and subhumid with an average annual rainfall of about 750 mm (Allen & Naney, 1991). During the experiment, land cover in the watershed was dominated by pasture and senescent or harvested winter wheat (Jackson & Schiebe, 1993). The forest cover within the watershed is very sparse and constitutes a small proportion of the watershed.

DATA DESCRIPTION

During Washita’92, multi-temporal airborne microwave data were collected using the Electronically Steered Thinned Array Radiometer (ESTAR) at spatial resolution of 200 m. The ESTAR is a synthetic aperture, passive microwave radiometer which operates at L band (21 cm wavelength, or 1.4 GHz frequency) (Le Vine et al., 1992). This band has been proved to be the most effective for measuring soil moisture in the top 5 cm soil (Schmugge et al., 1986). Earlier studies have demonstrated that the data
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obtained from ESTAR can be employed to derive soil moisture accurately (e.g., Le Vine et al., 1992; Jackson et al., 1995).

A large number of ground soil moisture measurements (more than 700 gravimetric samples per day) were carried out to support and validate microwave measurements. Profile soil moisture and soil temperature has been measured at thirteen sites using a Resonant Frequency Capacitance (RFC) probe. The study area experienced heavy rainfall (more than 30 mm) on 5 June 1992, and moderate rainfall continued till 9 June 1992. However, there was no rainfall in the watershed for the entire duration of the Washita’92 experiment. Therefore, the hydrological conditions in the watershed were ideal because it was possible to follow a drying period from very wet (about 30%) to dry (about 10%) over a period of 9 days (Fig. 1) (Mattikalli et al., 1995c). A GIS framework was essential in this study to integrate and analyse large volume of spatial data collected from microwave remote sensing and non-spatial data obtained from ground measurements. A raster-based Geographical Resources Analysis Support System (GRASS) has been employed to perform specific tasks of this research.

![Figure 1](image-url)

**Fig. 1** Temporal variations of surface soil moisture during Washita’92 experiment: (a) for various land cover types; (b) for various soil texture types typically found in the Little Washita watershed. The study area experienced a clear dry-down from very wet to dry over a period of 9 days. Different soil types have distinct characteristics of soil moisture contents and the associated temporal changes, which therefore, can be used as indicators of soil texture.

**SPATIAL AND TEMPORAL VARIABILITY OF SOIL MOISTURE**

The ESTAR instrument measures thermal emission from a surface, whose intensity is proportional to the brightness temperature. The brightness temperature data collected during Washita’92 experiment were converted into soil moisture values. Soil moisture data have been corrected, where possible, for vegetation effects (Jackson et al., 1995). The ESTAR derived soil moisture values have been validated by comparing them with the field measured soil moisture values (Jackson et al., 1995; Mattikalli et al., 1995c). Over a large corn field, which represented the densest vegetation cover encountered during the experiment (canopy height of 2.1 m), excellent correlations with an average absolute error of less than 1.5% were obtained between predicted and measured soil moisture (O’Neill et al., 1994).

Figure 2 shows multi-temporal soil moisture information derived from ESTAR brightness temperature. This figure depicts both spatial and temporal variability of
surface soil moisture on a daily time scale for the period 10-18 June 1992. On 10 June 1992, wet and dry soils have a volumetric moisture contents of about 35% and 15%, respectively. The watershed can be partitioned into eastern and western regions characterized by high soil moisture (about 30-35%), and the central region of relatively lower soil moisture contents (about 15-20%). This near saturated status of the soil is expected because of the heavy rainfall recorded on 5 June 1992, which was followed by moderate rainfall till 9 June 1992. The soil experienced a dry-down condition during the experiment because there was no rainfall during that period. Soil moisture available at the start of the experiment was lost by evapotranspiration and subsurface drainage. The dry-down pattern of the soil is captured clearly in the soil moisture maps from 11 to 18 June 1992. During this period, the progressive loss of soil moisture, and the pronounced spatial variability can be observed. At the end of the experiment, the range of soil moisture content varied from about 20% (wet soil) in the eastern and western regions to about 5% (very dry soil) in the central region.

Fig. 2 Temporal maps of surface soil moisture derived from ESTAR brightness temperatures for each day of the experiment: 10-18 June 1992 (15 June was the crew rest day).
RELATIONSHIP BETWEEN CHANGES IN SOIL MOISTURE AND SOIL TEXTURE

The spatial and temporal variations of soil moisture observed during Washita'92 may be attributed to hydro-meteorological parameters (Mattikalli et al., 1995c). Since there was no rainfall during the experiment, the spatial and temporal variations are independent of rainfall effects. Other hydro-meteorological forcing (e.g. evaporation and wind speed, solar radiation etc.) can be considered as spatially and temporally constant because of their small variation across the area during the experiment (Jackson & Schiebe, 1993; Mattikalli et al., 1995a). Therefore, the observed spatial and temporal changes of surface soil moisture may be attributed solely to drainage and redistribution of water content. Drainage is mainly controlled by physical property such as soil texture, and hydrological property such as $K_{sat}$.

Figure 3 shows the map of soil texture for the Little Washita watershed. This figure shows that the watershed is dominated by silt loam and loam on both the eastern and western regions, which are partitioned by an area of fine sandy loam and sand. It is interesting to study the pattern of spatial distribution of soil texture in conjunction with the patterns of spatial and temporal variation of soil moisture (Fig. 2) which suggest a close correspondence between the two. At the start of the experiment on 10 June 1992, silt loam and loamy soils were associated with higher (about 30-35%) moisture contents, while areas identified by sandy loam and sand were characterized by lower soil moisture (about 15-20%). This difference in the moisture contents of the sandy loam and silt loam soils is temporally consistent throughout the experiment.

This observation is more obvious in Fig. 1(b) which shows the temporal variation of soil moisture for five different soil types. It is clear that both sandy and loamy soils have distinct patterns of soil moisture contents and soil moisture drainage. An analysis was carried out within a GIS framework to correlate soil moisture change and soil texture (Mattikalli et al., 1995b). This analysis demonstrated that silt loam and loam
soils are characterized by higher changes of total moisture content, whereas sandy loam and sandy soils are associated with lower changes. These characteristics may be related to hydraulic properties of the soil. Sandy soils with higher hydraulic conductivity drained quickly, whereas loamy soils having lower hydraulic conductivity did not drain before the start of the experiment on 10 June 1992. Therefore, on 10 June 1992, initial moisture contents for sandy soils are lower and that for loamy soils are higher as portrayed in Figs 1(b) and 2. Loamy soils, due to their low hydraulic conductivity, drained steadily during the 9-day period of the experiment, and registered a higher total soil moisture change. This is an important observation in that it suggests that remotely sensed soil moisture information can be employed to identify soil types and to estimate soil hydraulic properties.

ESTIMATION OF SOIL PROPERTIES

Observations made in the previous section have a significant potential to employ remotely sensed soil moisture to derive soil hydraulic properties in a GIS framework. $K_{\text{sat}}$ is an important soil property that is difficult to obtain other than in a laboratory. Therefore, any methods based on remote sensing that have the capability of deriving spatial distribution of $K_{\text{sat}}$ would be an extremely important data source for hydrological applications.

Research has been carried out to establish a relationship between 2-day drainage recorded from passive microwave remote sensing and $K_{\text{sat}}$. The main difficulty encountered in this effort was the absence of data concerning profile soil properties for Little Washita watershed. Therefore, a state-of-the-art, physically-based, hydrological model viz. the Root Zone Water Quality Model (RZWQM) (Ahuja & Hebson, 1992), and a GIS have been employed to carry out soil moisture simulation studies to estimate profile $K_{\text{sat}}$ (Mattikalli et al., 1995b). Soil survey maps were used to extract approximate soil horizon descriptions and rough soil texture information (Mattikalli et al., 1995b).

Model simulations were carried out on a daily time step for one site at a time for all thirteen sites where profile soil moisture data have been measured. Four important hydraulic properties viz. bulk density, 1/3 bar water content, $K_{\text{sat}}$, and pore size distribution index were optimized so as to obtain an acceptable match between modelled and field measured soil profiles, which resulted in a unique set of values for the properties. Figures 4(a)-(c) show the relationships between the 2-day initial surface drainage (0-5 cm depth) and the profile harmonic-mean $K_{\text{sat}}$ for 5 cm, 30 cm, and 60 cm depths, respectively. The least-squares linear regression equations presented in Fig. 4 suggest that profile harmonic-mean $K_{\text{sat}}$ bears strong positive relationships with 2-day changes in surface soil moisture (with correlation coefficients of 0.77, 0.83, and 0.68 for 5 cm, 30 cm, and 60 cm depths, respectively). These results are in close agreement with those reported in literature (Ahuja et al., 1984 and 1993).

CONCLUSIONS

Passive microwave remote sensing was employed to obtain spatial and multi-temporal soil moisture data at a spatial resolution of 200 × 200 m for the Little Washita watershed, Oklahoma. Analysis of multi-temporal soil moisture maps in conjunction
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Fig. 4 Relationships between profile harmonic-mean $K_{sat}$ derived from hydrological model simulations and 2-day initial changes in surface soil moisture obtainable from microwave remote sensing. These relationships are invaluable to obtain quick estimates of spatially distributed profile $K_{sat}$ over large areas from remote sensing.

with a soils map within a GIS framework revealed a direct relationship between soil moisture contents and their changes and soil texture. It was clear that both sandy and loamy soils had distinct patterns of soil moisture contents and soil moisture drainage, which suggested that remotely sensed soil moisture contents and their temporal changes could be employed to identify soil type and to estimate soil hydraulic properties.

A methodology was developed to employ remotely sensed data for estimation of profile $K_{sat}$ using a hydrological model and a GIS. Strong relationships were established between profile harmonic-mean $K_{sat}$ and 2-day soil moisture change. Results clearly demonstrated that temporal changes in surface soil moisture observed from remote sensing can be used to estimate soil hydraulic properties. The results have long term potential applications of space borne remote sensing to obtain quick estimates of spatial distributions of soil properties on a regional and continental scale, which are typically not measured in the field, for input into mesoscale and global circulation models.

Acknowledgement This work was performed while Nandish M. Mattikalli held a National Research Council-NASA GSFC Research Associateship. The support was provided by the Science Division of NASA's Office of Mission to Planet Earth.
REFERENCES


