WATER RESOURCES RESEARCH, VOL. 36, NO. 4, PAGES 1023–1031, APRIL 2000

Analysis and mapping of field-scale soil moisture variability using high-resolution, ground-based data during the Southern Great Plains 1997 (SGP97) Hydrology Experiment

B. P. Mohanty and T. H. Skaggs
U.S. Salinity Laboratory, Riverside, California

J. S. Famiglietti
Department of Geological Sciences, University of Texas at Austin

Abstract. Soil moisture is an important state variable in the hydrologic cycle, and its spatiotemporal distribution depends on many geophysical processes operating at different spatial and temporal scales. To achieve a better accounting of the water and energy budgets at the land-atmosphere boundary, it is necessary to better understand the spatiotemporal variability of soil moisture under different hydrologic and climatic conditions and at different hierarchical space scales and timescales. During the Southern Great Plains 1997 (SGP97) Hydrology Experiment the 0–6 cm soil water content was measured on consecutive afternoons at 400 locations in a small, gently sloping range field (Little Washita field site 07). The soil moisture measurements were made using portable impedance probes. Spatiotemporal data analyses of the two sampling events showed a significant change in the field variance but a constant field mean, suggesting moisture was redistributed by (differential) base flow, evapotranspiration, and condensation. Among the different relative landscape positions (hilltop, slope, valley) the slope was the largest contributor to the temporal variability of the soil moisture content. Using a sequential aggregation scheme, it was observed that the relative position influencing the field mean and variance changed between the two sampling events, indicating time instability in the spatial soil moisture data. Furthermore, high-resolution (impedance probe) sampling and limited (gravimetric) sampling gave different field means and variances.

1. Introduction

The near-surface soil moisture content is critical for addressing issues related to land surface hydrology, subsurface hydrology, and the transfer of mass and energy across the land-atmosphere boundary. In the last 3 decades, several field studies at different scales and geographical locations have been undertaken by NASA and other agencies to understand the influence of soils, topography, vegetation, and climate on soil moisture dynamics. The measurement platforms used in these studies have ranged from spacecraft- and aircraft-mounted passive and active microwave sensors [*Schmugge*, 1998; *Jackson and Le Vine*, 1996; *Ulaby et al*., 1996; *Sellers et al*., 1992; *Wang et al*., 1992] that measure at a scale of thousands of square kilometers (footprint scale) to portable time domain reflectrometry (TDR) sensors and/or gravimetric methods [*Famiglietti et al*., 1999, 1998; *Grayson and Western*, 1998; *Mohanty et al*., 1998; *Ungar et al*., 1992] that measure at a scale of square centimeters (point scale). An important issue related to the ground truthing of remotely sensed measurements is the temporal stability of point-scale data [*Grayson and Western*, 1998; *Kachanoski and de Jong*, 1988; *Vachaud et al*., 1985]. If the areal soil moisture distribution in a complex landscape exhibits temporal stability, it would be possible to reliably estimate the mean moisture content from a limited number of point measurements and thus greatly simplify ground truthing. *Kachanoski and de Jong* [1988] showed that temporal stability may not exist over all scales because soil water storage at a point is the product of hydrologic processes operating at different spatial scales. For example, localized surface runoff may significantly alter the spatial variation of soil water storage on a small scale, but the changes may be insignificant compared to large-scale variations. Other factors such as climatic variation may affect time stability at large scales.

Factors governing the time stability of soil moisture are soil types, topographic features, plant distributions, and/or historical (human-induced, natural) disturbances. *Reynolds* [1970] gave a good discussion of these factors and their static or dynamic nature. *Famiglietti et al*. [1998] gave a good review of studies addressing near-surface soil moisture variability in smaller catchments and field plots. *Hills and Reynolds* [1969] conducted an extensive study and attempted to relate slope and soil moisture. They observed some patterns but could not precisely distinguish the influence of slope from other factors. *Reid* [1973] analyzed soil moisture variability by associating slope orientation (aspect) with accelerated or decelerated rates of evapotranspiration. *Zaslavsky and Sinai* [1981] found topography to be a controlling factor in lateral subsurface flow and in the distribution of soil water in a catchment. *Moore et al*. [1988] also indicated that topographic nonuniformity is a major factor controlling the spatial variability of soil water.

Some research has also indicated that location within a slope is very important in determining soil moisture variation. For example, *Hawley et al*. [1983] discovered that hillslope position

Paper number 1999WR900360.
0043-1397/00/1999WR900360$09.00

(i.e., relative elevation) is the most important factor in explaining the soil moisture clustering phenomenon observed in several watersheds with different soil types and land covers. More recent studies by *Crave and Gascuel-Odoux* [1997] and *Nyberg* [1996] reemphasized the importance of topography on the spatial distribution of surface soil moisture. One important finding of *Crave and Gascuel-Odoux* [1997] was the "altitude threshold" that distinguished two levels of surface soil moisture variability across the hillslope, a distinction that may be useful for strategic sampling. Contrary to the above findings, during the First International Satellite Land Surface Climatology Project (ISLSCP) Field Experiments (FIFE, 1987–1989), *Charpentier and Groffman* [1992] found independence between topography and soil moisture in selected remote-sensing footprints (pixels). However, they concluded that pixels with relatively high topographic heterogeneity encompassed higher variability in soil moisture. On the basis of the Konza prairie catchment microwave remote-sensing experiments, *Ladson and Moore* [1992] concluded that temporally dynamic soil moisture was not well predicted by simple static topographic attributes.

A related controversy in soil moisture studies is in regard to the relationship between the field-scale means and variances of soil moisture across time. Using repeated sampling across time, *Reynolds* [1970] suggested that soil moisture means and variances are positively correlated. One possible reason given for the positive correlation was that following rainfall, spatially variable soil hydraulic properties created differential infiltration, causing maximum variation in soil moisture. During a dry period the soil-related variability becomes minimal, causing lesser variation in soil moisture. *Bell et al*. [1980] conducted a statistical analysis of data from different soil moisture field campaigns that were conducted by NASA during 1974–1978. On the basis of data from 58 forty-acre fields they concluded that soil moisture variations within any given "large field" are inherent and nonunique. Furthermore, no good predictive relationship between soil moisture means and variances was found. In another study, in homogenous areas defined by soil type and land cover, *Hawley et al*. [1983] showed significant differences in mean soil moisture and insignificant differences in variances from one sampling date to the next. *Ladson and Moore* [1992] and *Famiglietti et al*. [1999] showed an exponential relationship between the means and variances of soil moisture content.

Evidently, there is no consensus about the nature and mechanisms of surface soil moisture variability, and additional studies are warranted. Data collected under different hydrologic (topographic, soil, land cover) and climatic conditions, using different spatiotemporal sampling schemes, can be pooled and used later to address some of the critical questions in land surface hydrology, including (1) How can watersheds be optimally subdivided into homogenous areas of hydrologic response? (2) For remote-sensing platforms, what pixel size maximizes temporal stability and minimizes within-pixel error? (3) What is the optimal sampling design for ground truthing, and how many samples are needed to achieve a specified level of accuracy under complex terrain? (4) In addition, what is the relative contribution of different factors to soil moisture variation under different hydrologic and climatic conditions?

2. Southern Great Plains 1997 Hydrology Experiment

The Southern Great Plains 1997 (SGP97) Hydrology Experiment was a coordinated, collaborative effort by an interdisciplinary science team sponsored by NASA, the U.S. Department of Agriculture Agricultural Research Service (USDA-ARS), the National Oceanic and Atmospheric Administration, the Department of Energy, the National Science Foundation, and other agencies. A detailed description of the experimental plan, including the different scientific objectives of the mission, can be found elsewhere (http://hydrolab.arsusda.gov/sgp97/). The southern Great Plains region in Oklahoma was selected for this experiment because it is one of the best instrumented sites in the world for surface soil moisture, hydrology, and meteorology. A key objective of the SGP97 soil moisture team is to develop a good understanding of the spatiotemporal variability of soil moisture at hierarchical scales. During the SGP97 hydrology experiment (June 18 through July 17, 1997) the soil moisture content was measured over an area >10,000 km^2 at different resolutions using different platforms, including an aircraft-based push broom type *L* band Electronically Scanned Thinned Array Radiometer (ESTAR) measuring at a resolution of 800 m × 800 m, a truck-mounted microwave remote sensor measuring at a scale of 2.5 m × 2.5 m, and others. Concurrent to remote sensing, point-scale soil moisture measurements were made using (ground-based) gravimetric or electromagnetic techniques. Most of the ground measurement activities were centered around three key facilities, namely, the ARS facilities in the Little Washita (LW) watershed southwest of Chickasha, the ARS facility at El Reno, and the Atmospheric Radiation Measurement Cloud and Radiation Test beds central facility near Lamont. A total of 9–14 gravimetric soil moisture measurements were made daily at 49 different quarter sections (800 m × 800 m).

Recent advances in portable TDR and impedance probe technologies are making it possible to rapidly monitor surface soil moisture at a large number of locations within a field [e.g., *Grayson and Western*, 1998; *Nyberg*, 1996; *Robinson and Dean*, 1993]. As posed by *Grayson and Western* [1998], these techniques could be useful in developing relatively simple and rapid sampling protocols for identifying catchment average soil moisture monitoring locations, as well as defining terrain and soil features that could be used to determine such locations a priori. Such a sampling scheme would provide an efficient framework for ground-truthing soil moisture measurements made using remote-sensing platforms. Proceeding along these lines, *Famiglietti et al*. [1999] studied during SGP97 the spatiotemporal variability of soil moisture at six selected quarter sections (800 m × 800 m) by measuring daily soil moisture contents at 49 locations on a 7 × 7 regular grid using impedance probes (Theta probe soil moisture sensor, type ML1, Delta-T Devices, Cambridge, England). To complement the effort of *Famiglietti et al*. [1999], we took the next step in the hierarchical scale by limiting the soil moisture measurement area to approximately an eighth of a quarter section and increased the density of observations. We conducted the study at the (SGP97) Little Washita field site 07 (LW07). The primary objective is to quantify short-range (space and time) variations in the first and second moments of soil moisture content during a drying phase. Secondary objectives are to identify the relative contribution of different relative landscape positions (hilltop, slope, valley) to the field-scale variability of soil moisture content and to investigate the time stable behavior of the different positions.

3. Experimental Design

The Little Washita watershed was a critical study area of SGP97. The watershed has been the focus of hydrologic research for over 35 years. The climate is classified as subhumid, with an average annual rainfall of 75 cm. The topography of the region is moderately rolling with a maximum relief of ~200 m. Soils include a wide range of textures with large regions of both coarse and fine textures. Rangeland and pasture with significant areas of winter wheat and other crops dominate land use. Additional background information on the watershed can be found in the works of *Allen and Naney* [1991] and *Jackson and Schiebe* [1993].

The LW07 field is located near the western edge of the Little Washita watershed. The field is predominantly loamy sand as per the county soil survey map. Table 1 gives pertinent soil physical properties for the field (P. J. Shouse et al., unpublished U.S. Salinity Laboratory report, 1999; also http://daac.gsfc.nasa.gov/CAMPAIGN_DOCS/SGP97/sgp97.html). During the SGP97 experiment the field was categorized as rangeland with 30–35 cm long Bermuda grass cover. It has gentle positive slopes of 3–4% in the east to west direction and 1–2% in the south to north direction. In general, the western part of the field can be viewed as the hilltop, and the eastern part can be viewed as the valley with an east-west slope. On the basis of a reconnaissance survey of the landscape we designed a grid of forty 40 m × 40 m squares, as shown in Figure 1. The dimensions of the field (160 m × 400 m) resulted in a grid that had 10 rows in the east-west direction and 4 columns in the north-south direction. Junction points were identified and flagged using a Differential Global Positioning System (DGPS). The DGPS was operated by using the correction signal transmitted by radio beacon from a reference station in Sallisaw, Oklahoma, which is part of a network maintained by the U.S. Coast Guard. For this study we defined the grid blocks 1–10 as the hilltop, 11–30 as the slope, and 31–40 as the valley (Figure 1), and we considered soil type, vegetation, and precipitation to be uniform across the field. Note, however, each relative landscape position defines the integrated influence of associated topography, soil, and vegetation factors on soil moisture content. In other words, general data interpretation corresponds to these relative landscape positions without distinguishing the relative contributions of individual components. During the SGP97 campaign, using available resources at hand, 800 soil moisture measurements were made in this grid within a narrow window of time (27 hours), with the objective of observing the short-term temporal variability of soil moisture in the field. Using portable Theta probes, 2 sets of 400 soil moisture measurements were made at the field site between 1400 LT on June 19, 1997, and 1700 LT on June 20, 1997. Each set of measurements was made within 2–3 hours in the afternoons of June 19 and 20. Measurements were made at 10 random sites within each 40 m × 40 m grid block (Figure 1). The most recent rain at the field site occurred on June 18, 1997 (3.03 mm), meaning the sampling was done during a drying cycle.

Table 1. Soil Properties at Little Washita Field Site 07 (LW07)

Property	Value/Characteristic
Saturated hydraulic conductivity, cm/s	0.00062
Texture	loamy sand
Percent sand	83.89
Percent silt	8.605
Percent clay	7.5
Bulk density, g/cm^3	1.493
Organic carbon, %	0.41

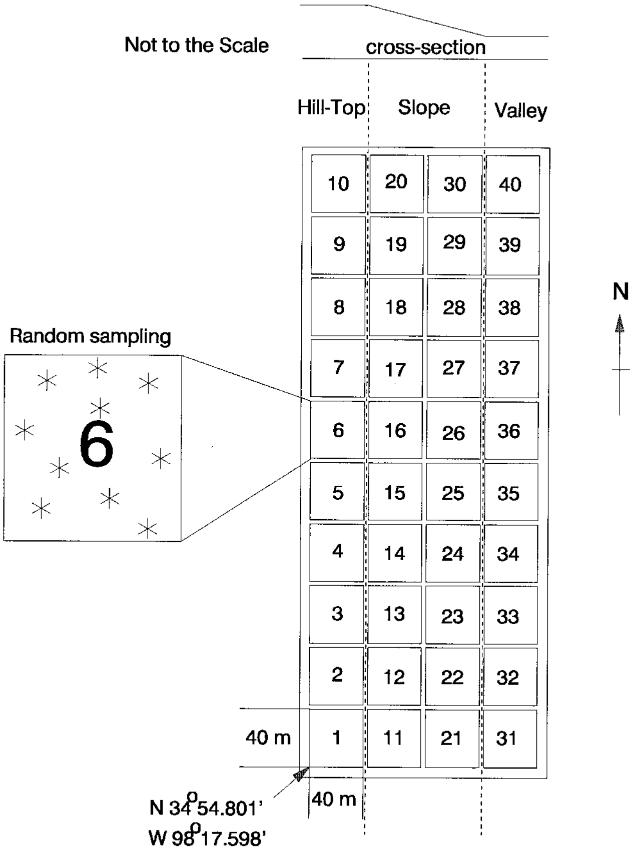

Figure 1. Soil moisture sampling grid in Little Washita field site 07 (LW07).

Soil moisture was measured using a commercially available impedance probe (Theta probe soil moisture sensor, type ML1, Delta-T Devices, Cambridge, England). This device was chosen because it is robust, portable, rapid, and accurate. Furthermore, this probe measures soil moisture in the 0–6 cm soil layer, which closely matches other gravimetric and remote sensing measurements (0–5 cm) made during SGP97. The probe uses a simplified voltage standing wave method to determine the relative impedance of its sensing head (which consists of four sharpened, 6 cm long stainless steel wire rods) and thus the dielectric constant of the soil matrix, which is related to the volumetric water content of soil. Further details of the design and application of this technique is shown by *Gaskin and Miller* [1996]. Calibration of this method around the SGP97 region by our collaborators indicated close agreement with the calibration curve of *Gaskin and Miller* [1996]. Thus we used the same curve without any site-specific reevaluation. Two probes were used for our 800 measurements at the LW07 field. In situ evaluation showed no significant difference between the two probes. The analyses in the following sections are based on pooled data from both probes.

4. Data Analysis and Discussion

Univariate statistical analysis of the soil moisture content for June 19 and 20 is summarized in Table 2. No statistically

Table 2. Summary Statistics of Volumetric Soil Moisture Content at LW07

	Impedance Probe Sampling		Gravimetric Sampling*	
Statistics	June 19, 1997	June 20, 1997	June 19, 1997	June 20, 1997
Number of observations	400	400	9	9
Mean†	0.262(a)	0.266(a)	0.358(b)	0.209(c)
Mode	0.302	0.268	···	···
Maximum	0.420	0.411	0.486	0.315
Minimum	0.108	0.166	0.180	0.079
Variance	0.004	0.001	0.011	0.006
Skewness	−0.077	0.372	−0.608	−0.188
Kurtosis	−0.910	−0.172	−0.572	−0.622
Shapiro-Wilk W statistics (probability level)	0.975 (<0.0001)	0.988 (<0.0042)	0.932 (<0.574)	0.967 (<0.872)

Ellipsis indicates no mode is found for limited sampling.

*Volumetric soil moisture content was calculated as gravimetric soil moisture content multiplied by measured bulk density at the field site.

†Means with same letter are not significantly different at $\alpha = 0.05$. Mean comparisons are made within a sampling method.

significant difference was found between the field mean values for June 19 (0.262 cm^3/cm^3) and June 20 (0.266 cm^3/cm^3). However, the soil moisture coefficient of variation reduced from 25 to 16% within the 24-hour period. The most significant change occurred in the third moment (skewness), which increased from −0.077 to 0.372. Furthermore, the sample histogram showed some bimodality and a significantly different mean and mode on June 19, as opposed to a unimodal distribution and good matching mean and mode on June 20.

To show the significance of our result in the context of one of the primary objectives of the SGP97 hydrology experiment, statistics of the data collected using gravimetric sampling techniques at LW07 during the same dates are also presented in Table 2 (T. J. Jackson, personal communication, 1999). Using the Tukey algorithm (SAS Institute, Inc., 1998), comparison of the (high-resolution) data from impedance probe sampling versus (limited) data from gravimetric sampling reflects two important findings: (1) High-resolution impedance probe data show no statistically significant difference between the mean soil moisture contents for the two dates, while limited gravimetric sampling indicates otherwise, and (2) on both dates, variance of the daily soil moisture content reduced while normality of the data improved with increasing number of samples.

Figures 2 and 3 present all of the soil moisture content data collected on the two dates across the 40 grid blocks. The soil moisture content ranged from 0.108 to 0.420. On June 19, soil moisture contents on the hilltop and valley were generally higher than those on the slope. Careful inspection of the slope data showed that the soil moisture content was more variable at higher elevations (block 11–20) than at lower elevations (block 21–30). Interestingly, the transition between the hilltop and the slope soil moisture was smoother than the transition between the slope and the valley. A possible reason for this behavior is that once surface overland flow and/or subsurface base flow from the slope reached the valley, horizontal flow was retarded resulting in a sharp increase in soil moisture content. Furthermore, a drying trend in the north-south direction was apparent on the hilltop and lower slope positions. In contrast to these findings for June 19, no clear soil moisture trend was observed on June 20, except for a north-south drying trend on the hilltop position. By plotting the mean soil moisture content for different grid blocks across the field (Figure 4) we found that within the 24-hour period the soil moisture

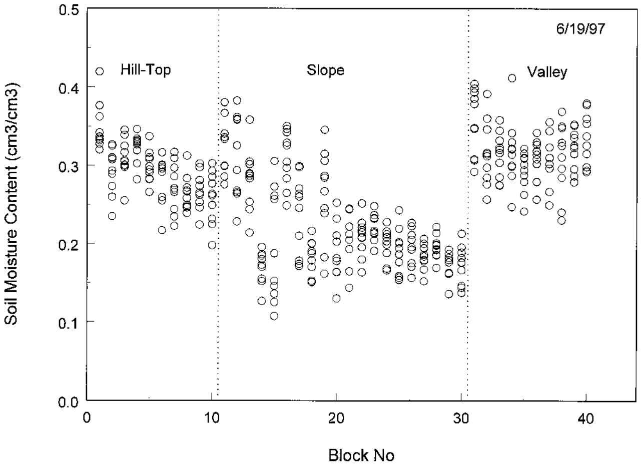

Figure 2. Raw soil moisture content data across the field on June 19, 1997.

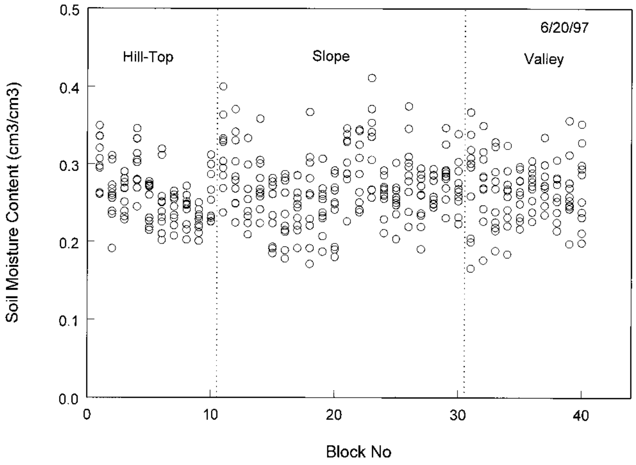

Figure 3. Raw soil moisture content data across the field on June 20, 1997.

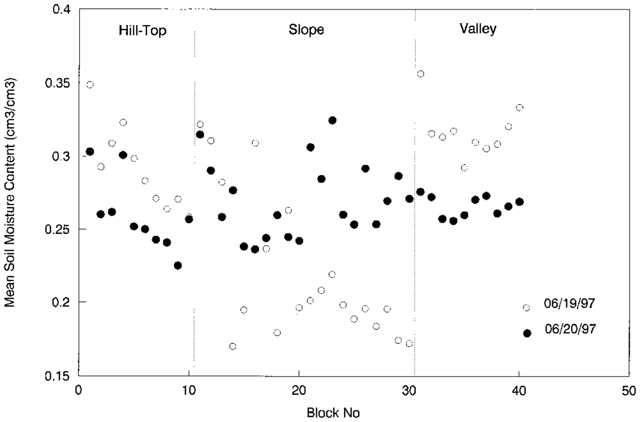

Figure 4. Block mean soil moisture contents across the field for two sampling events on June 19 and 20, 1997.

content generally deceased by 5–15% in the hilltop and the valley positions. On the contrary, the blocks on the upper slope position (11–20) showed no increasing or decreasing trend, whereas the lower slope position (blocks 21–30) showed a 50–60% increase in soil moisture content during the same period. Statistical comparison of soil moisture content among the three landscape positions showed significant differences on June 19 but not on June 20 (Table 3). We suggest that interactive soil moisture redistribution smeared out the effect of landscape position over time.

We conducted an exploratory data analysis to study the relative contributions of the three landscape positions to field mean and variance of soil moisture for the two sampling events. Running means and variances were calculated for each grid block by sequentially including all observations (i.e., increasing the support size) up to the designated block number. For example, the running mean and variance for block "*n*" are based on all soil moisture content observations between the blocks 1 and *n*. Block means and variances and running means and variances (starting from the SW corner of the field) are plotted in Figures 5 (June 19) and 6 (June 20). On June 19 the running mean and field mean soil moisture content are approximately equal at block 23, indicating that at least observations between blocks 1 and 22 (on the hilltop and the slope positions) are needed for estimating the field average. Correspondingly, the running variance indicates that at least observations between blocks 1 and 32 (on the hilltop, slope, and valley positions) are needed to calculate the field variance.

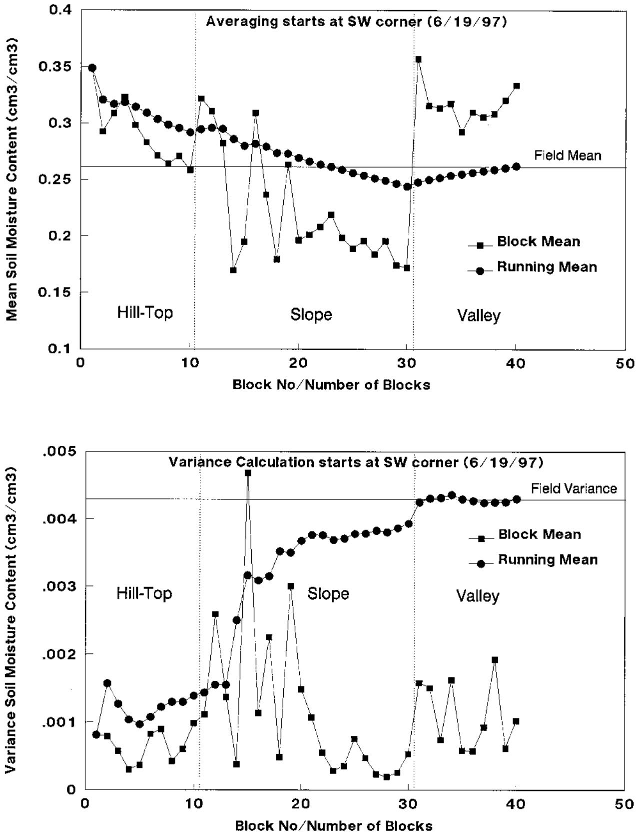

Figure 5. Comparison of block means/variances with running means/variances on June 19, 1997.

Running means and variances for June 20 showed significantly different behavior than for June 19. A smaller support size (blocks 1–10, hilltop position only) gives a good estimate of the field average and variance on June 20. The differences between the two sampling events indicate that the east-west slope positions were the largest contributors to the temporal variability of the surface soil moisture. Redistribution occurred through this zone as subsurface base flow and aspect-driven accelerated or decelerated evapotranspiration and condensation. For comparison purposes we plotted running means and variances for the two sampling events starting from (1) the SW corner (hilltop, Figure 7) and (2) the SE corner (valley, Figure 8). The trends in these plots are similar to those in Figures 5 and 6,

Table 3. Summary Statistics of Volumetric Soil Moisture Content at LW07 Under Different Relative Landscape Positions

	June 19, 1997			June 20, 1997		
Statistics	Hilltop	Slope	Valley	Hilltop	Slope	Valley
Number of observations	100	200	100	100	200	100
Mean*	0.292(b)	0.220(a)	0.317(c)	0.259(a)	0.270(a)	0.266(a)
Mode	0.297	0.176	0.256	0.230	0.286	0.231
Maximum	0.419	0.383	0.412	0.350	0.411	0.367
Minimum	0.197	0.107	0.229	0.191	0.171	0.165
Variance	0.001	0.003	0.001	0.001	0.002	0.001
Skewness	0.117	0.828	0.210	0.551	0.376	0.026
Kurtosis	0.524	−0.005	0.109	−0.243	0.236	−0.083
Shapiro-Wilk *W* statistics (probability level)	0.986 (<0.396)	0.933 (<0.0001)	0.987 (<0.489)	0.966 (<0.013)	0.983 (<0.020)	0.995 (<0.988)

*Means with same letter are not significantly different at $\alpha = 0.05$. Mean comparisons are made within a sampling method.

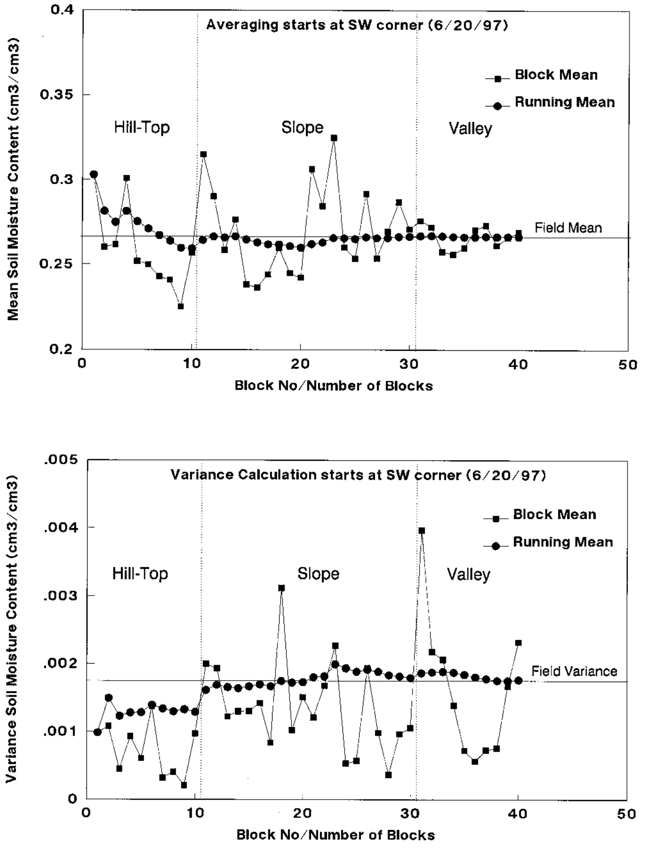

Figure 6. Comparison of block means/variances with running means/variances on June 20, 1997.

reemphasizing that redistribution occurs from hilltop to slope positions and that a significant amount of variance is coming from changes in the slope, the most dynamic portion of the field. More importantly, we again observe that the field means did not change significantly over this short time period (24 hours), but the field variances did change because of a redistribution of soil moisture across the landscape. This finding, along with visual inspection of Figure 4, indicates that the 40 m × 40 m block mean water contents do not exhibit time stability over the short timescale considered here.

As discussed earlier, field means and variances can be reliably estimated from limited, strategic sampling when patterns of soil moisture variability exhibit time stability. The observed time instability in LW07, a field that is representative of many of the lands studied in SGP97, is therefore somewhat discouraging. However, a couple of factors should be considered before ruling out the use of time stable concepts in analyzing SGP97 ground truth data. First, our data and analysis are limited to a short time, thus any time instability at this scale may turn out to be insignificant for a longer-term (e.g., seasonal, annual) perspective. Second, time instability observed in this small field may smear out in the context of a larger spatial scale (e.g., quarter section, basin, watershed) [*Kachanoski and de Jong*, 1988]. However, on the basis of our results a caveat should be in place for future space-time soil moisture monitoring and analysis studies, and thus better estimates of field mean, variance, and patterns will help the interpretation of remote-sensing data. This work supports earlier work of *Famiglietti et al.* [1999] to the fact that the number of required samples changes, but the connection to the slope position is new. In the future it may be possible to incorporate the dy-

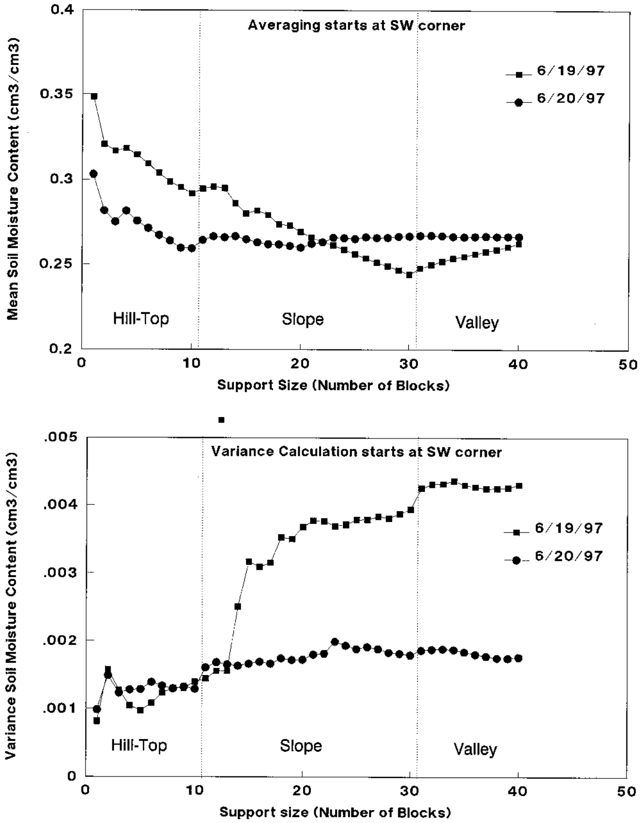

Figure 7. Comparison of running means and variances between June 19 and 20, 1997, starting from the SW corner (hilltop position).

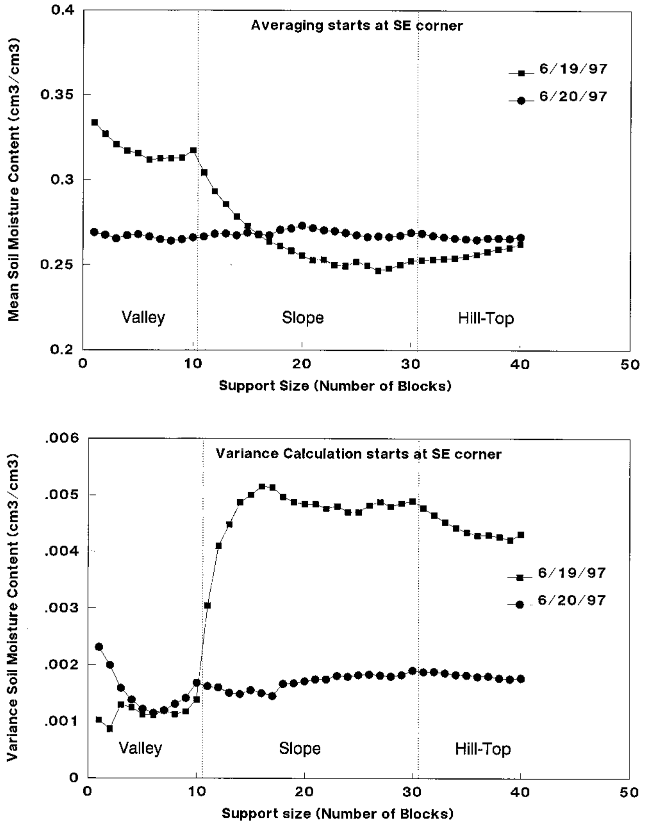

Figure 8. Comparison of running means and variances between June 19 and 20, 1997, starting from the SE corner (valley position).

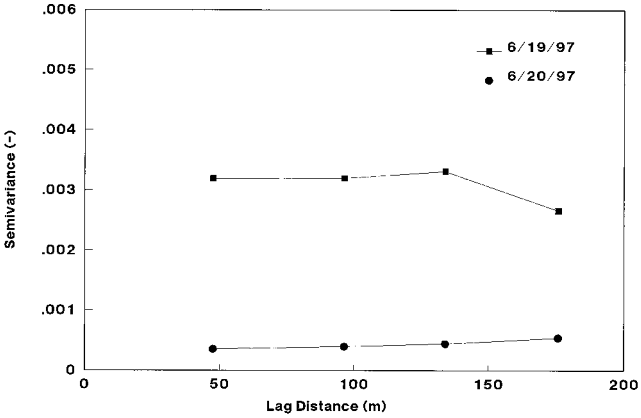

Figure 9. Isotropic semivariograms of soil moisture content for two sampling events.

namic nature of the slope position into sampling design. We note that we are looking at the time stability of block-averaged data rather than the usual case of point data [e.g., *Kachanoski and de Jong*, 1988].

To identify any spatial structure in the soil moisture data at the LW07 field site, we calculated (isotropic) semivariograms [*Journel and Huijbregts*, 1978, p. 12] for both sampling events using the (40) block means (Figure 9). No apparent spatial structure was found on either date. On the basis of this finding we created contour maps of surface soil moisture using the block mean values for two sampling events (Figures 10 and 11) and their difference (Figure 12). These maps show the intrinsic features of spatiotemporal variability at the field site. Figure 10 shows a clear relationship between soil moisture pattern and landscape positions that disappeared in 24 hours (Figure 11), indicating "time instability" of areal data. More notably, the contour plot for the difference in surface soil moisture between the two sampling events (Figure 12) indicating local outflow (plus) or inflow (minus) followed the relative landscape positions, reconfirming our suggestion of redistribution of moisture due to slope-driven subsurface base flow and aspect-driven accelerated or decelerated evapotranspiration and condensation.

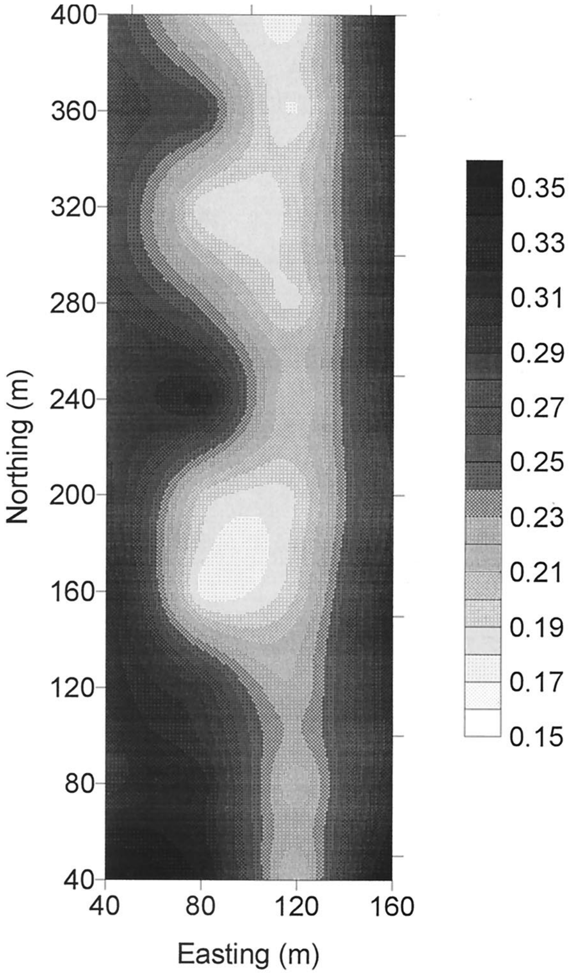

Figure 10. Contour maps of surface soil moisture on June 19, 1997.

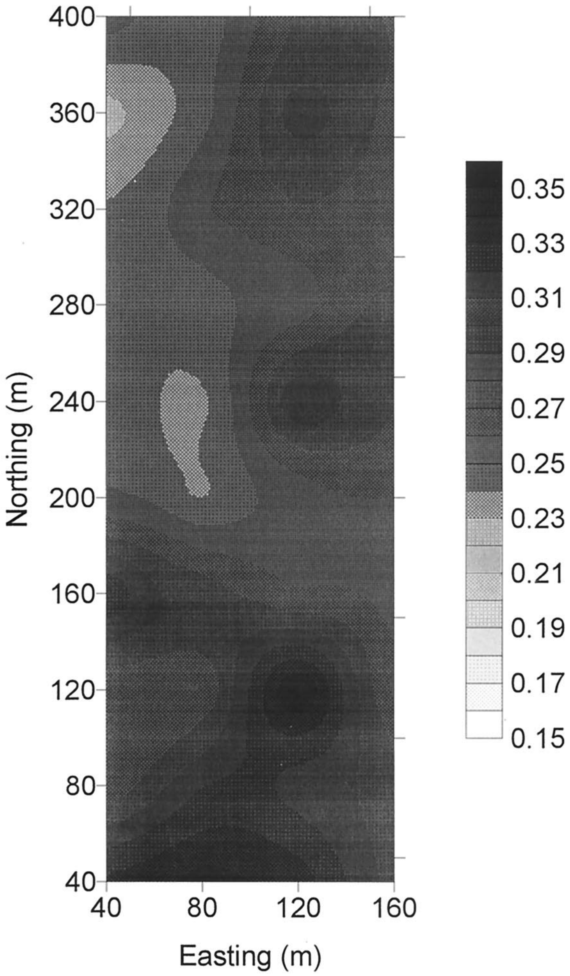

Figure 11. Contour maps of surface soil moisture on June 20, 1997.

5. Conclusions

During the SGP97 hydrology experiment in Oklahoma, near-surface (0–6 cm) soil moisture was measured with a portable impedance probe in a small, gently sloping grass field (LW07). Measurements were made on consecutive afternoons with 400 measurements taken on each day. On the basis of spatiotemporal analyses of the soil moisture content we derived the following conclusions:

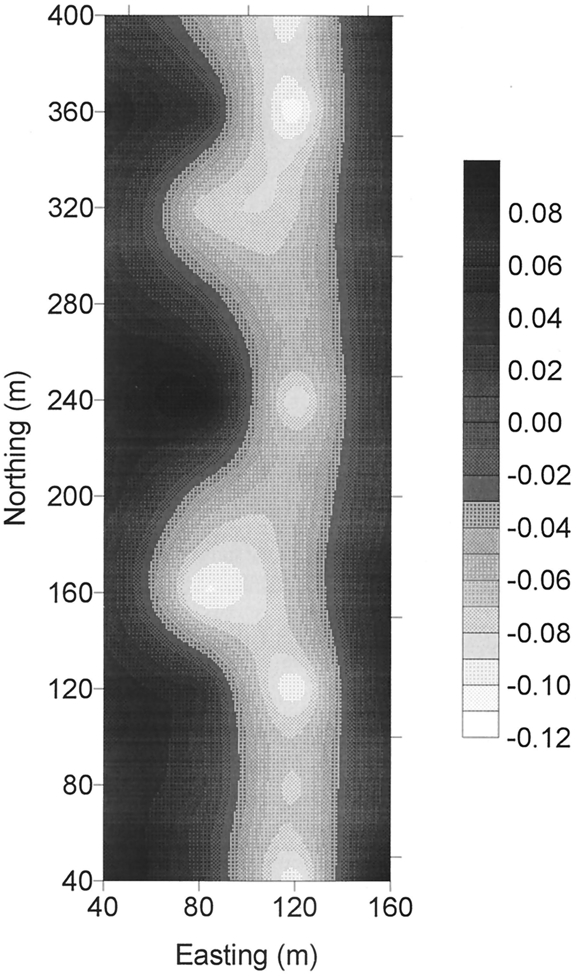

Figure 12. Contour maps of difference in surface soil moisture between June 19 and 20, 1997.

1. The field mean soil moisture content was approximately equal for both sampling events, although the spatial distribution of the moisture changed within the field, with the redistribution being affected by the relative position (hilltop, slope, valley) in the field.
2. The field variances changed significantly between the two sampling events.
3. Slope positions were the biggest contributors to the temporal variability of the surface soil moisture. Possible mechanisms of moisture redistribution in this zone during our study include lateral base flow and aspect-driven accelerated or decelerated evapotranspiration and condensation.
4. The minimum support (relative landscape position of observations) required for estimating the field mean and variance changed with the time, indicating time instability in the diurnal data.
5. No field-scale spatial structure was found in the 40 m × 40 m block-averaged data from either sampling event. Spatial distributions of soil moisture were dominated by landscape positions.
6. High-resolution (impedance probe) sampling and limited (gravimetric) sampling gave different field means and variances.

Acknowledgments. This study was partly funded by NASA-MTPE program. Walter Russell, Steven Graham, Rajat Bindlish, Karen Mohr, and Gwangseob Kim participated in the data collection effort. Comments of two anonymous reviewers helped improve the clarity of the paper.

References

Allen, P. B., and J. W. Naney, Hydrology of the Little Washita river watershed, Oklahoma: Data and analyses, *Rep. ARS-90*, 74 pp., U. S. Dep. of Agric., Agric. Res. Serv., Washington, D. C., 1991.

Bell, K. R., B. J. Blanchard, T. J. Schmugge, and M. W. Witczak, Analysis of surface moisture variations within large field sites, *Water Resour. Res.*, *16*, 796–810, 1980.

Charpentier, M. A., and P. M. Groffman, Soil moisture variability within remote sensing pixels, *J. Geophys. Res.*, *97*, 18,987–18,995, 1992.

Crave, A., and C. Gascuel-Odoux, The influence of topography on time and space distribution of soil surface water content, *Hydrol. Processes*, *11*, 203–210, 1997.

Famiglietti, J. S., J. W. Rudnicki, and M. Rodell, Variability in surface moisture content along a hillslope transect: Rattlesnake hill, Texas, *J. Hydrol.*, *210*, 259–281, 1998.

Famiglietti, J. S., J. A. Devereaux, C. A. Laymon, T. Tsegaye, P. R. Houser, T. J. Jackson, S. T. Graham, M. Rodell, and P. van Oevelen, Ground-based investigation of soil moisture variability within remote sensing footprints during the Southern Great Plains (1997) Hydrology Experiment, *Water Resour. Res.*, *35*, 1839–1851, 1999.

Gaskin, G. J., and J. D. Miller, Measurement of soil water content using a simplified impedance measuring technique, *J. Agric. Eng. Res.*, *63*, 153–160, 1996.

Grayson, R. B., and A. W. Western, Towards areal estimation of soil water content from point measurements: Time and space stability of mean response, *J. Hydrol.*, *207*, 68–82, 1998.

Hawley, M. E., T. J. Jackson, and R. H. McCuen, Surface soil moisture variation on small agricultural watersheds, *J. Hydrol.*, *62*, 179–200, 1983.

Hills, T. C., and S. G. Reynolds, Illustrations of soil moisture variability in selected areas and plots of different sizes, *J. Hydrol.*, *8*, 27–47, 1969.

Jackson, T. J., and D. E. Le Vine, Mapping surface soil moisture using an aircraft-based passive microwave instrument: Algorithm and example, *J. Hydrol.*, *184*, 85–99, 1996.

Jackson, T. J., and F. R. Schiebe (Eds.), Washita '92 Data Report, *NAWQL Rep. 101*, U.S. Dep. of Agric. Natl. Agric. Water Qual. Lab., Durant, Okla., 1993.

Journel, A. G., and C. J. Huijbregts, *Mining Geostatistics*, 600 pp., Academic, San Diego, Calif., 1978.

Kachanoski, R. G., and E. de Jong, Scale dependence and the temporal persistence of spatial patterns of soil water storage, *Water Resour. Res.*, *24*, 85–91, 1988.

Ladson, A. R., and I. D. Moore, Soil water prediction on the Konza Prairie by microwave remote sensing and topographic attributes, *J. Hydrol.*, *138*, 385–407, 1992.

Mohanty, B. P., P. J. Shouse, and M. T. van Genuchten, Spatio-temporal dynamics of water and heat in a field soil, *Soil Tillage Res.*, *47*, 133–143, 1998.

Moore, I. D., G. J. Burch, and D. H. Mackenzie, Topographic effects on the distribution of surface water and the location of ephemeral gullies, *Trans. ASAE*, *31*, 1098–1107, 1988.

Nyberg, L., Spatial variability of water content in the covered catchment at Gardsjon, Sweden, *Hydrol. Processes*, *10*, 89–103, 1996.

Reid, I., The influence of slope orientation upon the soil moisture regime and its hydromorphological significance, *J. Hydrol.*, *19*, 309–321, 1973.

Reynolds, S. G., The gravimetric method of soil moisture determination, part III, An examination of factors influencing soil moisture variability, *J. Hydrol.*, *11*, 288–300, 1970.

Robinson, M., and T. J. Dean, Measurement of near surface soil water content using a capacitance probe, *Hydrol. Processes*, *7*, 77–86, 1993.

Schmugge, T. J., Applications of passive microwave observations of surface soil Moisture, *J. Hydrol.*, *212–213*, 188–197, 1998.

Sellers, P. J., F. G. Hall, G. Asrar, D. E. Strebel, and R. E. Murphy, An overview of the first international satellite land surface climatology project (ISLSCP) field experiment (FIFE), *J. Geophys. Res.*, *97*, 18,345–18,371, 1992.

Ulaby, F. T., P. C. Dubois, and J. van Zyl, Radar mapping of surface soil moisture, *J. Hydrol.*, *184*, 57–84, 1996.

Ungar, S. G., R. Layman, J. E. Campbell, J. Walsh, and H. J. McKim, Determination of soil moisture distribution from impedance and gravimetric measurements, *J. Geophys. Res.*, *97*, 18,969–18,977, 1992.

Vachaud, G., A. P. De Silans, P. Balabanis, and M. Vauclin, Temporal stability of spatially measured soil water probability density function, *Soil Sci. Soc. Am. J.*, *49*, 822–828, 1985.

Wang, J. R., S. P. Gogineni, and J. Ampe, Active and passive microwave measurements of soil moisture in FIFE, *J. Geophys. Res.*, *97*, 18,979–18,985, 1992.

Zaslavsky, D., and G. Sinai, Surface hydrology, I, Explanation of phenomena, *J. Am. Soc. Civ. Eng. Hydrol. Div.*, *1*, 1–18, 1981.

J. S. Famiglietti, Department of Geological Sciences, University of Texas at Austin, Austin, TX 78712. (jfamiglt@maestro.geo.utexas.edu)

B. P. Mohanty and T. H. Skaggs, U. S. Salinity Laboratory, 450 W. Big Springs Road, Riverside, CA 92507. (bmohanty@ussl.ars.usda.gov)

(Received August 26, 1999; revised December 20, 1999;
accepted December 23, 1999.)