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Variability in surface moisture content along a hillslope transect: Rattlesnake Hill, Texas

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Abstract

Surface soil moisture content exhibits a high degree of spatial and temporal variability. The purpose of this study was (a) to characterize variations in moisture content in the 0–5 cm surface soil layer along a hillslope transect by means of intensive sampling in both space and time; and (b) to make inferences regarding the environmental factors that influence this variability. Over a period of seven months, soil moisture content was measured (gravimetric method) on a near-daily basis at 10 m intervals along a 200 m downslope transect at the Rattlesnake Hill field site in Austin, Texas. Results indicate that significant variability in soil moisture content exists along the length of the transect; that variability decreases with decreasing transect-mean moisture content as the hillslope dries down following rain events; and that the dominant influences on moisture content variability are dependent upon the moisture conditions on the hillslope. While topographic and soil attributes operate jointly to redistribute soil water following storm events, under wet conditions, variability in surface moisture content is most strongly influenced by porosity and hydraulic conductivity, and under dry conditions, correlations are strongest to relative elevation, aspect and clay content. Consequently, the dominant influence on soil moisture variability gradually changes from soil heterogeneity to joint control by topographic and soil properties as the transect dries following significant rain events. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: Hydrology; Soil moisture; Field studies; Statistical analysis; Correlation coefficient

1. Introduction

Soil moisture stored near the land surface affects a wide variety of earth system interactions over a range of spatial and temporal scales. The moisture content of surface soils exerts a major control on the partitioning of net radiation into latent and sensible heat and of rainfall into runoff and infiltration. Through the process of evapotranspiration, soil moisture provides a significant source of moisture for the formation of

clouds and precipitation over land. Like the world oceans, soil moisture provides thermal inertia to the climate system (though to lesser degree), storing and later releasing heat, dampening out diurnal and seasonal variations in surface temperatures (Wei, 1995).

Given the importance of surface soil moisture to earth system processes, quantification of its spatial–temporal behavior is receiving increased attention from the hydrologic community (e.g. from the scale of hillslopes and small watersheds (Western et al., 1997) to the global scale (IGPO, 1995)). This task is not trivial however, since surface soil moisture

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exhibits a high degree of variability in both space and time. Consequently, high resolution ground-based monitoring is required to accurately characterize these variations, at least until remote sensing (e.g. passive and active microwave) progresses to the point of providing routine, reliable, high resolution observations of surface soil moisture. Unfortunately, ground-based methods (e.g. gravimetric, neutron thermalization, gamma attenuation, time domain reflectometry) are far too labor or equipment intensive to remain feasible with increasing spatial scale and space/time sampling frequencies. As a result, a consistent picture regarding spatial/temporal soil moisture variability and the processes that control it has yet to emerge.

In view of the intensive labor demands of ground-based monitoring, this study was initiated at the hillslope scale in order to ensure the high sampling frequencies required for a detailed study of soil moisture variability. From 20 September 1995 to 25 April 1996, soil moisture content was measured on a near daily basis at 10 m intervals (0–5 cm, 5–10 cm, and 10–15 cm depths) along a 200 m downslope transect at the Rattlesnake Hill field site in Austin, TX. A total of 4440 samples were collected during this seven month period. Since it was not always possible to retrieve samples from the lower two depths at each transect location on each day that samples were collected, only the 0–5 cm samples (totaling 1848) are analyzed in this paper. The purpose of the study was (a) to quantify surface soil moisture variability along the hillslope transect by means of intensive monitoring in space and time; and (b) to make inferences regarding the environmental factors that influence this variability. Specific objectives of this paper are (a) to characterize the transect mean and variance of the moisture content in the 0–5 cm surface soil layer, the downslope moisture content profile in this surface layer, and the temporal dynamics of these quantities; and (b) to understand the relative roles of topographic attributes and soil properties in controlling the observed variability. Variations in vegetation, meteorological factors and other significant influences on soil moisture variability, were observed to be negligible at the hillslope scale.

Although the spatial scale of the study is small, this research has implications for a range of issues in hydrology. First, a thorough knowledge of

hillslope-scale soil moisture variability will provide a foundation for better understanding hillslope hydrological, ecological and biogeochemical processes, many of which are nonlinearly related to soil moisture content. Second, since hillslopes are fundamental landscape units, this work will provide a basis for characterizing soil moisture variations at larger scales. Consequently, this work will provide insight into the parameterization of soil moisture dynamics in larger scale hydrological models, and into the design of larger-scale soil moisture monitoring networks. Finally, this study will contribute towards an improved understanding of the representativeness of point soil moisture measurements as indicators of larger-scale average moisture conditions, and of the variability of soil moisture within larger-scale remote sensing footprints.

2. Background

Soil moisture variability is influenced by a number of factors. These include variations in topography, soil properties, vegetation type and density, mean moisture content, depth to water table, precipitation depth, solar radiation and other meteorological factors. This section reviews previous studies in which the influence of several of these variables, either independently or in combination, has been investigated. The emphasis of this review is on field investigations of near-surface (0–15 cm) soil moisture variability at small spatial scales (plot to small watershed scale). Table 1 lists the basic attributes of the studies included in this review.

2.1. Topography

Variations in slope, aspect, curvature, upslope contributing area and relative elevation all affect the distribution of soil moisture near the land surface. Slope angle influences infiltration, drainage and runoff; steeper slopes are likely to be drier than flat areas owing to lower infiltration rates, rapid subsurface drainage, and higher surface runoff. Hills and Reynolds (1969), Moore et al. (1988) and Nyberg (1996) all found that slope angle influences soil moisture variability. Aspect, or slope orientation, influences solar irradiance and thus evapotranspiration and soil

moisture. Reid (1973) found a significant correlation between aspect and soil moisture content.

Curvature is a measure of convexity or concavity of the landscape, and thus influences the convergence of lateral flow. For example, depressions, or areas of high curvature, tend to be wetter than planar areas, where curvature is low. Curvature can be further characterized as planform (perpendicular to the slope direction), profile (in the same direction as the slope), or mean (the average of curvature in all directions). Moore et al. (1988) found a significant correlation between profile curvature and moisture content, though the variance accounted for by their regressions was low.

Specific contributing area, or the upslope surface area that drains through a unit length of contour on a hillslope, influences the distribution of soil moisture by controlling the potential volume of subsurface moisture flowing past a particular point on the landscape; hillslope locations with larger contributing areas are likely to be wetter than those with smaller contributing areas. Moore et al. (1988) and Nyberg (1996) found moderate, positive correlation between specific contributing area and soil moisture content.

A number of researchers have demonstrated the influence of slope location, or relative elevation, on the distribution of soil moisture. Relative elevation is often correlated with various soil and topographic attributes that may influence soil water redistribution (e.g. specific contributing area, clay content). Krumbach (1959), Henninger et al. (1976), Hawley et al. (1983), Robinson and Dean (1993) and Nyberg (1996) all found that moisture content is inversely proportional to relative elevation. Crave and Gascuel-Oudou (1997) found that a threshold value of relative elevation distinguished between drier and slowly varying moisture conditions upslope, and wetter, more variable conditions downslope.

2.2. Soil properties

Soil heterogeneity affects the distribution of soil moisture through variations in texture, organic matter content, structure and the existence of macroporosity, all of which affect the fluid transmission and retention properties of the soil column. Additionally, soil color influences its albedo and thus the rate of evaporative drying. Reynolds (1970a,b), Henninger et al. (1976)

and Crave and Gascuel-Oudou (1997) all found that variations in soil moisture were related to variations in soil texture. Hawley et al. (1983) noted that differences in soil moisture content due to differences in soil texture were more pronounced under wet conditions rather than dry. Niemann and Edgell (1993) found that macroporosity exerted a controlling influence on moisture movement and thus soil moisture variability.

2.3. Vegetation

Vegetation influences soil moisture variability by the pattern of throughfall imposed by the canopy; by shading the land surface and affecting the rate of evaporative drying; by generating turbulence and enhancing evapotranspiration rates; by affecting soil hydraulic conductivity through root activity and the addition of organic matter to the soil surface layer; and by extracting moisture for transpiration from the soil profile. The degree to which these factors affect the soil moisture distribution varies with vegetation type, density and season. Lull and Reinhart (1955) found that the amount of vegetative cover was one of the major factors influencing soil moisture variability. They found further that variability increased with decreasing, or partial canopy coverage. Similar findings were made by Reynolds (1970b); Reynolds (1970c). Hawley et al. (1983) and Francis et al. (1986) found significant differences in moisture content due to differences in vegetative cover, and Hawley et al. (1983) noted further that these differences were often greater on wetter days than dry days.

2.4. Mean moisture content

Several investigations have noted that the variance of soil moisture decreases with decreasing mean moisture content (Hills and Reynolds, 1969; Reynolds, 1970c; Henninger et al., 1976; Bell et al., 1980; Hawley et al., 1982 and Robinson and Dean, 1993). Speculating on temporal dynamics of the variance, Reynolds (1970c) proposed that variability might be largest following a rainfall event since the effects of soil heterogeneity would be at a maximum; and similarly, that the variance would be lowest after an extended dry period, when the effects of soil heterogeneity would be minimized. Hawley et al.

(1983) extended this proposed scenario by suggesting that the variance might increase with increasing precipitation depth and under extremely dry conditions. Hills and Reynolds (1969) envisioned an alternative scenario in which the variance peaks in the mid-range of mean moisture content, when small areas of rapid drying might co-exist with wet areas, resulting in more heterogeneous wetness conditions.

Several studies have also observed that near-surface soil moisture is normally distributed (Hills and Reynolds, 1969; Bell et al., 1980; Hawley et al., 1983; Francis et al., 1986; Loague, 1992 (transect data; see Table 1) and Nyberg, 1996). Hills and Reynolds (1969), Reynolds (1970c) and Bell et al. (1980) all pointed to the need for long-term studies to fully characterize the time dynamics of soil moisture variability.

2.5. Combined influences

A number of previous studies have explored the influence of multiple environmental factors on the distribution of soil moisture (Reynolds, 1970c; Henninger et al., 1976; Hawley et al., 1983; Moore et al., 1988; Nyberg, 1996; and Crave and Gascuel-Oudou, 1997). Reynolds (1970c) examined the relationship between soil moisture variability, the amount of rainfall and insolation received in the week preceding the sampling, and the moisture content and vegetation cover at the time of sampling. Although no attempt was made to infer the relative influence of each of these factors, trends were identified that were consistent with the notion that soil moisture variability increases with increasing mean moisture content. Specifically, it was noted that low variance was associated with dry periods (low mean moisture content, high insolation and low precipitation depth) and that high variance was associated with wet periods (high mean moisture content, low insolation and high precipitation depth). Marked seasonal changes in vegetative cover were also thought partially to explain differences in soil moisture variability observed on different sampling dates.

Henninger et al. (1976) found that both relative elevation along a downslope transect and the internal drainage properties of soils were important factors influencing soil moisture variability. However, no

effort was made to distinguish between the relative importance of each of these factors.

Hawley et al. (1983) examined the influence of variations in vegetation, soil properties and topography on the distribution of soil moisture. Their results indicated that relative elevation was the dominant control on soil moisture variability; that the presence of vegetative cover tended to diminish the variations explained by topography; and that minor variations in soil type had minimal impact on the observed soil moisture variability. They also cautioned that larger differences in soil type may exert a more pronounced influence on the soil moisture distribution, but that because these differences are often related to slope location, determining the relative importance of each is often not possible.

Moore et al. (1988) explored the relationship between surface moisture content and aspect, slope, curvature and specific contributing area. Correlation between each of these topographic variables and surface moisture content was low, but significant. However, they found that the most statistically-significant regression equation contained both the compound variable $\ln(a/b)$ (where a is the specific contributing area and b is the surface slope angle) and aspect.

More recently, Nyberg (1996) explored the relative importance of the lateral distribution of roots, the thickness of the soil humus layer, relative elevation, slope, $\ln(A)$ (where A was defined as the upslope area draining through a 5 m grid cell) and the wetness index (Beven and Kirkby, 1979) $\ln(a/\tan b)$, in influencing soil moisture variations. No significant correlation between the moisture content and either the root distribution or the soil thickness was observed. Slope and elevation were significantly (and negatively) correlated with soil moisture. The highest correlations observed were between moisture content and both $\ln(A)$ and $\ln(a/\tan b)$. The similarity in correlation coefficients between $\ln(A)$ and $\ln(a/\tan b)$ versus moisture content, and the lower correlation between slope and moisture content, led Nyberg (1996) to conclude that upslope contributing area (either A or a) was a more important factor than slope in controlling the spatial distribution of soil moisture.

2.6. Contradictions

Although the above summary attempts to provide a

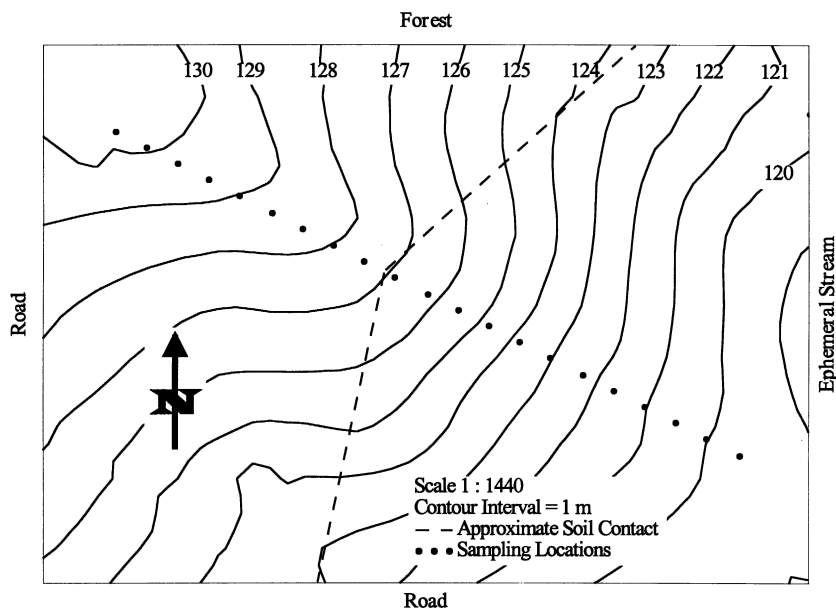


Fig. 1. Map view of the Rattlesnake Hill hillslope field site. Sampling locations are located at 10 m intervals along the transect and are shown as black dots. North is at the top of the page. Map dimensions are 220 m east–west and 155 m north–south. Contour interval is 1 m. The approximate location of the contact between the two distinct soil types located on the hillslope is shown as a dashed line.

consensus view of the factors that influence surface soil moisture variability, enough contradictory findings appear in the literature so that our basic understanding of these processes must be called into question. For example, several of the studies cited above noted the influence of topography on soil moisture variability, yet Charpentier and Groffman (1992), Whitaker (1993) and Niemann and Edgell (1993) found no correspondence between relative elevation and moisture content; Niemann and Edgell (1993) found no relationship between curvature and surface moisture content; and Crave and Gascuel-Odoux (1997) found no correlation between moisture content and $\ln(a/\tan b)$. Ladson and Moore (1992) investigated the relationship between soil moisture and several topographic attributes (including relative elevation, slope, aspect, curvature and $\ln(a/\tan b)$ among others) and found, with minor exceptions, that no significant correlations existed.

Although in numerous previous investigations the variance of soil moisture content has been observed to decrease with decreasing mean moisture content, Hawley et al. (1983) and Charpentier and Groffman (1992) found no systematic relationship between the

variance and the mean moisture content, and Owe et al. (1982) observed that soil moisture variability peaked in the mid-range of mean moisture content. While several previous studies noted that the distribution of surface moisture content is often normal, Charpentier and Groffman (1992) reported that the daily distributions observed in their study had low probabilities of representing normal distributions. Loague (1992) found that surface moisture contents measured along transects were normally distributed, while those measured on a square grid were not.

Some of the differing findings can be explained by differences in climate, soils, vegetation, topography and time and depth of sampling between the various field studies. However, close inspection of the literature reveals that a common feature in each of the studies listed in Table 1 is a low sampling frequency in space, time, or both. An underlying premise of this work is that previous studies have undersampled near-surface soil moisture content in either space or time (or both), so that no consistent picture of soil moisture variability, its behavior through time, and the processes that control it, currently exists at the small spatial scales that are the focus of this research.

Table 1
 Characteristics of previous small-scale studies of near-surface soil moisture variability

Study	Location	Area	Number of samples	Temporal frequency	Sampling depth
Krumbach, 1959	Mississippi, USA	270 m ²	120	twice	15–30 cm
Hills and Reynolds, 1969	Chew Stoke, UK	2.4 m ² to 6 km ²	60 per field/watershed	once	0–8 cm
Reynolds, 1970a; Reynolds, 1970b; Reynolds, 1970c	Somerset, UK	715 5.9 m ² plots	10 per plot	monthly for 8 months	0–8 cm
Reid, 1973	Caydell, UK	2 10 000 m ² fields	12 per field	weekly for 1 year	0–32.5 cm
Henninger et al., 1976	Pennsylvania, USA	560 m transect	57	weekly for 6 months	0–15 cm
Bell et al., 1980	Arizona, Kansas and South Dakota, USA	62 160 000 m ² fields	9–36 per field	1–5 times per field	0–15 cm
Hawley et al., 1982	Maryland, USA	2 m ² plot	80	3 dates	0–10 cm
Owe et al., 1982	South Dakota, USA	160 000 m ² to 2.6 km ² fields	42–69 per field	9 dates in 3 years	0–10 cm
Hawley et al., 1983	Oklahoma, USA	8 51 000 m ² to 179 000 m ² watersheds	16–92 per watershed	4 dates in 1 month	0–15 cm
Francis et al., 1986	Murcia, Spain	5 transects in 3000 m ² plot	23–113 per transect	3 dates in 13 months	0–7.5 cm
Moore et al., 1988	New South Wales, Australia	6 190–200 m transects in 7.5 ha watershed	20–21 per transect	twice	0–10 cm
Charpentier and Groffman, 1992	Kansas, USA	2 4356 m ² plots	49 per plot	twice	0–5 cm
Ladson and Moore, 1992	Kansas, USA	377 000 m ² watershed	20	9 consecutive days	0–5 cm
Loague, 1992	Oklahoma, USA	100 000 m ² watershed	4	90 dates in 4 years	0–15 cm
		100 000 m ² watershed	34	84 dates in 4 years	0–15 cm
		100 000 m ² watershed	157	once	0–10 cm
		100/250 m transects in 100 000 m ² watershed	50 per transect	once	0–10 cm
Niemann and Edgell, 1993	British Columbia, Canada	10 000 m ²	31	5 dates in 4 months	0–100 cm
Robinson and Dean, 1993	Oxford, UK	150 m transect	151	4 dates in 15 months	0–10 cm
Whitaker, 1993	Arizona, USA	44 000 m ²	134	4 dates in 2 weeks	0–15 cm
Nyberg, 1996	Gardsjon, Sweden	6300 m ²	57–73	monthly for two months	0–30 cm
Crave and Gascuel-Oudou, 1997	Brittany, France	10 500 m transects in 1.3 km ² watershed	20 per transect	4 dates in 18 months	0–5 cm; 5–10 cm

Listed studies in which sampling depths exceeded 15 cm included sampling intervals in the 0–15 cm range

3. Site description

The experiment was conducted on a 56 000 m² hillslope of Rattlesnake Hill (30° 17'N, 97° 37'W), located approximately seven miles east of Austin on the western edge of the Black Prairie, a large agricultural region in Texas characterized by gently undulating terrain and silt and clay soils. A contour map of the site (Fig. 1) shows that the hillslope has an east–southeasterly aspect and approximately 12 m of relief. It is bounded to the north and east by trees, and to the west and south by roadways. An ephemeral (most often dry) stream runs parallel to the eastern tree line, just east of the site. Native prairie grass uniformly covers the hillslope.

Two distinct soil types are found on the hillslope (Soil Survey of Travis County, Texas, 1974). Their contact is shown in Fig. 1. The Houston Black gravelly clay is located on the upper portion of the hillslope. It is characteristically 30–75% chert gravel, dark gray in appearance, has a surface layer over 0.6 m thick, and a total depth of almost 2 m. The Heiden clay occupies the lower portion of the hillslope. It is a dark grayish-brown clay with a surface layer approximately 0.4 m deep and a typical depth of 1 m.

Climate at the site is humid–subtropical, and is typical of the Austin area. This region of central Texas receives an average of 80 cm of precipitation each year, most of which falls in the late spring (May–June) and early fall (September–October). Pan evaporation averages 185 cm per year, with monthly average depths ranging from 6 to 8 cm in the winter months to 22 to 25 cm in the summer months. Average mid-day relative humidity varies from a winter high near 60% to a summer low near 50%. Average daily maximum temperatures range from 16.4°C in winter to 34.4°C in summer.

A 200 m transect was established in the maximum downslope direction along the hillslope (see Fig. 1). Elevations at the top and bottom of the transect are 130.1 m and 119.5 m respectively, yielding a total of 10.6 m of relief.

4. Methods

4.1. Soil moisture sampling transect

Survey stakes were located at 10 m intervals along

the transect (see Fig. 1) resulting in a total of 21 locations for moisture content sampling. While a larger number of sampling locations may have been desirable for statistical purposes, the 10 m spatial resolution was chosen so that sampling time would be minimized, in order that the results would not be significantly affected by diurnal variations in soil moisture content. Elevation at each of the sampling locations was determined to within 1 cm using differential, kinematic GPS (Global Positioning System). Non-recording raingages were secured to the survey stakes and were monitored daily to determine the occurrence and variability of precipitation. Elevation at several additional hillslope points was measured to construct a digital elevation model (DEM) from which Fig. 1 and several terrain-based attributes (described later) were derived.

4.2. Moisture content sampling

Soil samples were collected almost daily at each sampling location and at three depth horizons (0–5 cm, 5–10 cm and 10–15 cm) using a 3 cm diameter hand auger. It was not always possible to collect samples at the lower two depths at each location on each day, particularly under dry conditions in the gravelly clay on the upper portion of the hillslope. Consequently, the 0–5 cm data represent the most complete data set resulting from the sampling campaign, and are the subject of the analyses presented in this paper.

Owing to the destructive nature of the gravimetric method, soil samples were collected within a 1 m radius of the survey stakes. Each sample had a volume of approximately 15 cm³. Once extracted from the ground, samples were placed in three-ounce metal cans with tight-fitting lids. Shortly thereafter, samples were weighed before and after oven-drying for 24 h at 105°C. The gravimetric moisture content (in percent) of each sample was then computed as the ratio of the mass of the water contained in the soil (g) to the mass of the dry soil (g), multiplied by one hundred. Note that all moisture contents in this study are reported as gravimetric rather than volumetric owing to the inaccuracies associated with the volumetric method applied to soils with significant clay fractions.

Samples were collected for several consecutive days following precipitation events to monitor the rapidly changing moisture conditions on the hillslope.

As the rate of change of hillslope surface moisture content decreased with time during an interstorm period, samples were collected every other or every third day. Over the 217 day period of the experiment this resulted in 88 days on which samples were collected.

4.3. Soil properties

Particle size distribution, dry bulk density, particle density and porosity were determined at each of the 21 sampling locations along the transect. Particle size distributions were measured using traditional sieving methods to quantify the coarser grains (gravel and sand) and pipette analyses to determine the silt and clay fractions (see Rudnicki, 1996, for more details on the methodology). Dry bulk density (g/cm^3), ρ_b , was computed as the ratio of the mass of dry soil (g) to the volume of the sample (cm^3). Particle density (g/cm^3), ρ_s , was determined as the ratio of the mass of dry soil (g) to the volume of the dry soil (cm^3) with the aid of gas pycnometry (see Klute, 1986, for details on the gas pycnometer method). Porosity, ϕ , was computed as $(1 - \rho_b/\rho_s)$. Particle size distributions and porosity measurements are discussed in Section 5. Hillslope-average dry bulk measured $1.1 \text{ g}/\text{cm}^3$.

5. Results and discussion

5.1. Mean and variance of transect moisture content

The daily transect-mean moisture content and its variance are shown versus time in Fig. 2. Also shown are the daily precipitation depths. The time series is characterized by at least nine distinct 'dry down' sequences (beginning on 22 September, 1, 6 and 18 November 1995; and 1, 19 and 28 March and 8 and 23 April 1996) in which the mean moisture content peaks following significant precipitation events and decays rapidly thereafter. While several smaller and trace (unrecorded) rain events occurred between these dates (e.g. on 30 October 1995 and 6 February, 26 and 30 March, and 13 April 1996), they served only to temporarily interrupt more pronounced drying trends, unless they immediately followed, and were effectively part of, larger events on the previous day (e.g. 22 September 1995). The longest of the dry downs include the six-week period between 22

September and 31 October 1995, and the 15-week period between 18 November 1995 and 1 March 1996.

In general, the magnitude of the moisture content peaks corresponds to the depth of precipitation, with higher mean moisture contents occurring after heavier rains. Other factors influencing the magnitude of the peaks include antecedent mean-moisture conditions (wetter pre-existing conditions yield higher mean moisture contents for storm events with similar characteristics), rainfall intensity (higher intensity rainfall may yield more surface runoff and thus lower mean moisture contents than storms of lower intensity), and the timing of precipitation relative to moisture content sampling (sampling was routinely conducted in the early afternoon, so that infiltrated storm water would have ample time to drain following rain events that significantly preceded data collection). Since the rain-gauges employed in the study were non-recording, no attempt was made to determine the influence of these variables on the transect-mean moisture content other than the qualitative description given above.

Important seasonal trends in the mean moisture content are also apparent in Fig. 2. First, peaks in the mean moisture content time series are greater following storm events in the fall and spring months than in the winter, owing to the greater precipitation depths resulting from those storms. Second, the time required to reach a comparatively minimum value of moisture content at the end of a dry down is far greater during the winter than in the fall or spring. This is likely the result of lower evapotranspiration rates during the winter months. Third, the spring months experienced more frequent storm events so that more temporal variability is evident in the time series in March and April relative to the previous months. Consequently, the spring dry down sequences are brief with generally higher minimum mean moisture contents than the minima observed during the fall and winter months.

The temporal dynamics of the variance are more difficult to characterize. It is likely that a larger sample size, fixed, rather than random sampling at each transect location, and an increased temporal monitoring frequency would have resulted in better constrained estimates of the variance and its behavior through time. However, some general observations can be made. Fig. 2 shows that the behavior of the variance loosely mimics that of the mean, peaking after storm and trace events and decreasing rapidly

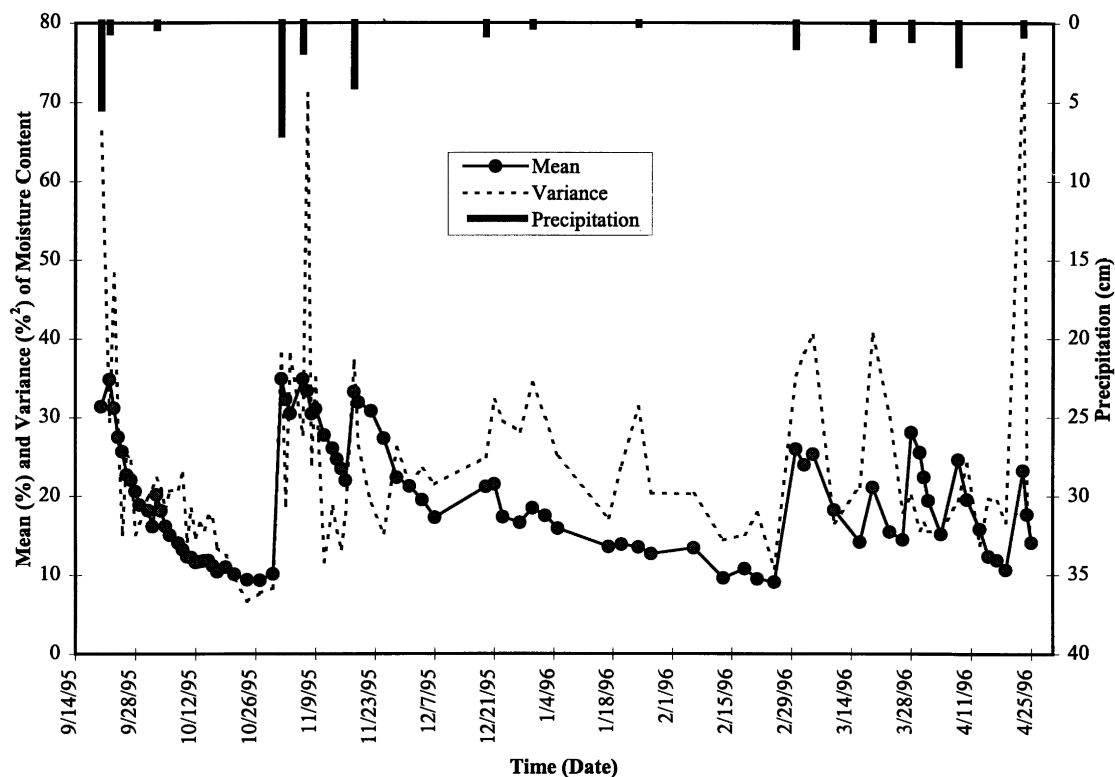


Fig. 2. Daily transect-mean moisture content (%) in the 0–5 cm soil layer versus time. Also shown are the variance ($\%^2$) and daily precipitation depth (cm).

during the ensuing days. This is shown most clearly in the first dry down sequence that follows the storm event of 21–22 September 1995. Thus, heavier rains and higher mean moisture contents are often associated with higher variability, and vice versa. Fig. 3 shows that the variance generally decreases with decreasing mean moisture content (consistent with previous findings by Hills and Reynolds, 1969; Reynolds, 1970c; Henninger et al., 1976; Bell et al., 1980; Hawley et al., 1982; and Robinson and Dean, 1993), but that scatter in the relationship increases with increasing wetness. This scatter can be attributed to the above-mentioned factors.

Given the above relationships, seasonal trends in the variance may be best understood in the context of seasonal trends in the mean moisture content. For example, of the highest peaks in the variance time series, several occurred during the fall months (e.g. 20, 23 September and 7 November 1995), when transect-mean moisture contents were at their highest for

the study period. Similarly, lower peaks occurred during the winter (e.g. 21 and 30 December 1995 and 24 January 1996), and intermediate magnitude peaks are evident in the spring (e.g. 5 and 19 March 1996). The fall dry down sequences show the greatest range in soil moisture variability, as the highest and lowest mean moisture contents were observed during this period. Because, owing to the lower evapotranspiration rates, transect mean moisture content decreases more slowly during the winter dry down (beginning on 18 November 1995) than the fall (beginning on 22 September 1995), so too does the variance. Just as the frequency of spring storms prevents the transect mean moisture content from decreasing to the minimum values observed during the fall and winter months, the variance is prevented from similar decreases.

5.2. Downslope moisture content profiles

Fig. 4 shows along-transect profiles of soil moisture

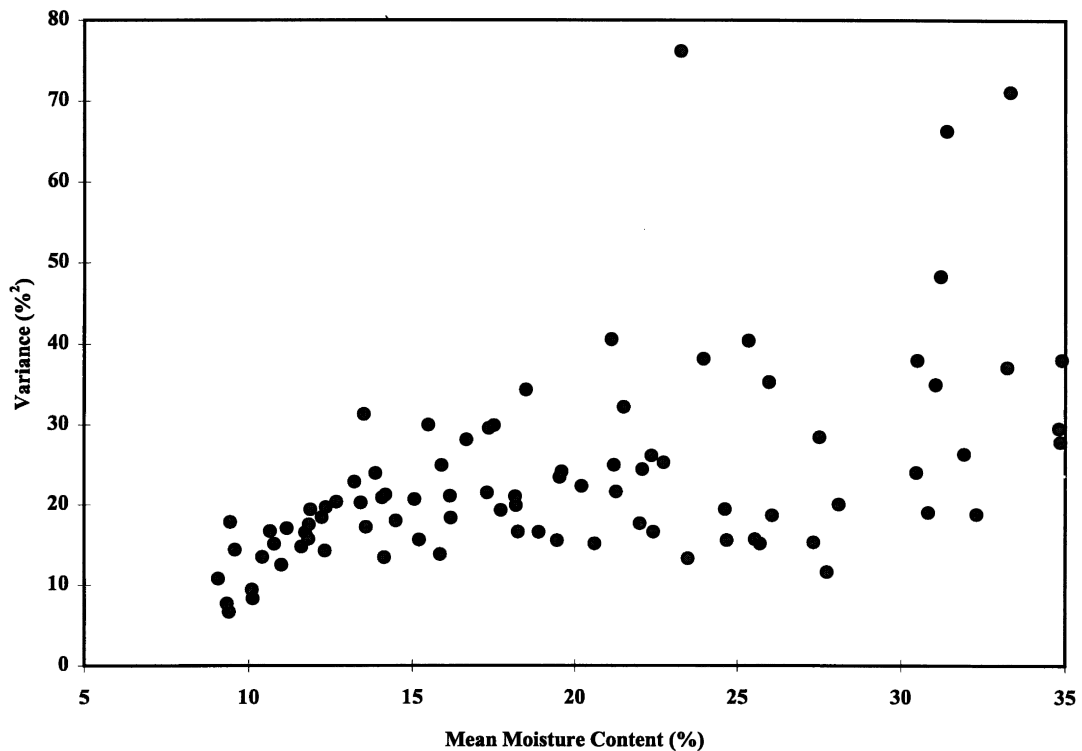


Fig. 3. Variance of moisture content ($\%^2$) in the 0–5 cm soil layer versus mean moisture content (%).

content in the 0–5 cm layer for three representative dry down sequences (fall, winter and spring). Also shown is the elevation profile for the transect. Several aspects of the variance and its temporal dynamics are apparent when examining these moisture content profiles. For example: significant spatial variability in moisture content exists along the length of the transect regardless of season or wetness conditions; spatial variability is greatest immediately following a storm event and decreases with time into the interstorm period; and the degree of variability apparent in the early phase of hillslope drying is directly related to the depth of precipitation falling on the hillslope (see Fig. 2).

The profiles also share the following characteristics which have implications for the environmental factors that influence moisture content variability along the transect. Immediately following a precipitation event, variability is greatest on the upper portion of the hillslope, and decreases towards levels observed on the lower portion of the hillslope with time into a dry down. Also, early in the interstorm period, soil

moisture content appears uncorrelated with relative elevation, but increasing negative correlation is evident with time into the dry down. Negative correlation is consistent with previous findings by Krumbach (1959), Henninger et al. (1976), Hawley et al. (1983), Robinson and Dean (1993) and Nyberg (1996), all of whom noted an inverse relationship between relative elevation and surface moisture content.

Fig. 5 shows the frequency distributions corresponding to each of the dates for which downslope moisture content transects appear in Fig. 4. In each case, the progressive hillslope drying with time into a dry down sequence is reflected by a translation of the distribution to the left along the x-axis, towards lower values of the moisture content. Larger decreases in variance, such as those associated with the first fall dry down, are also apparent in the histograms.

5.3. Correlation analyses

In this section we explore the relative roles of

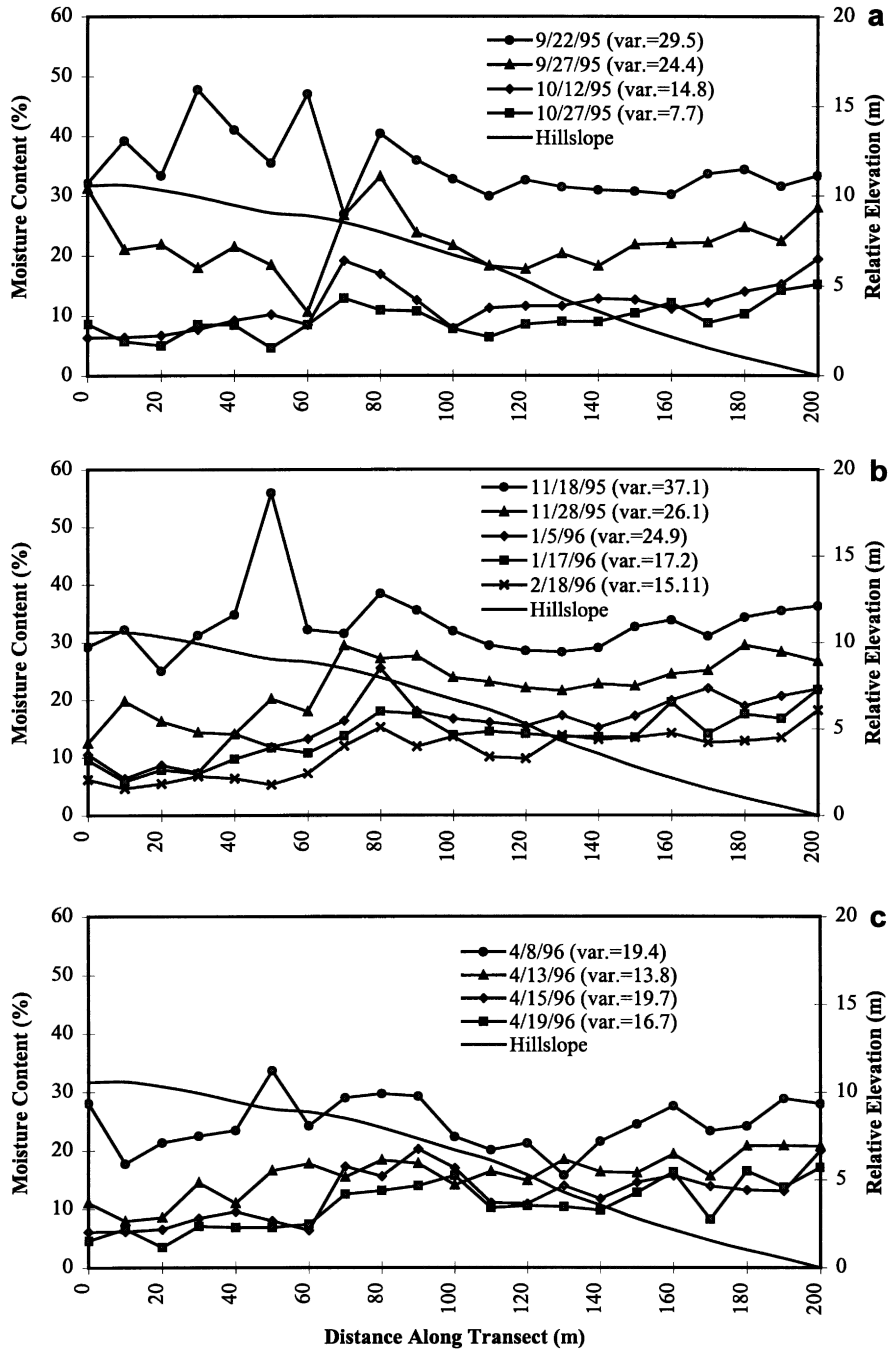


Fig. 4. Moisture content (%) at each sampling location versus distance of sampling location along transect (m), for several dates during the sampling period. Also shown is the vertically-exaggerated relative elevation profile (m) for the transect. Panels a, b and c show progressive drying along the transect during three separate dry down sequences (fall, winter, spring).

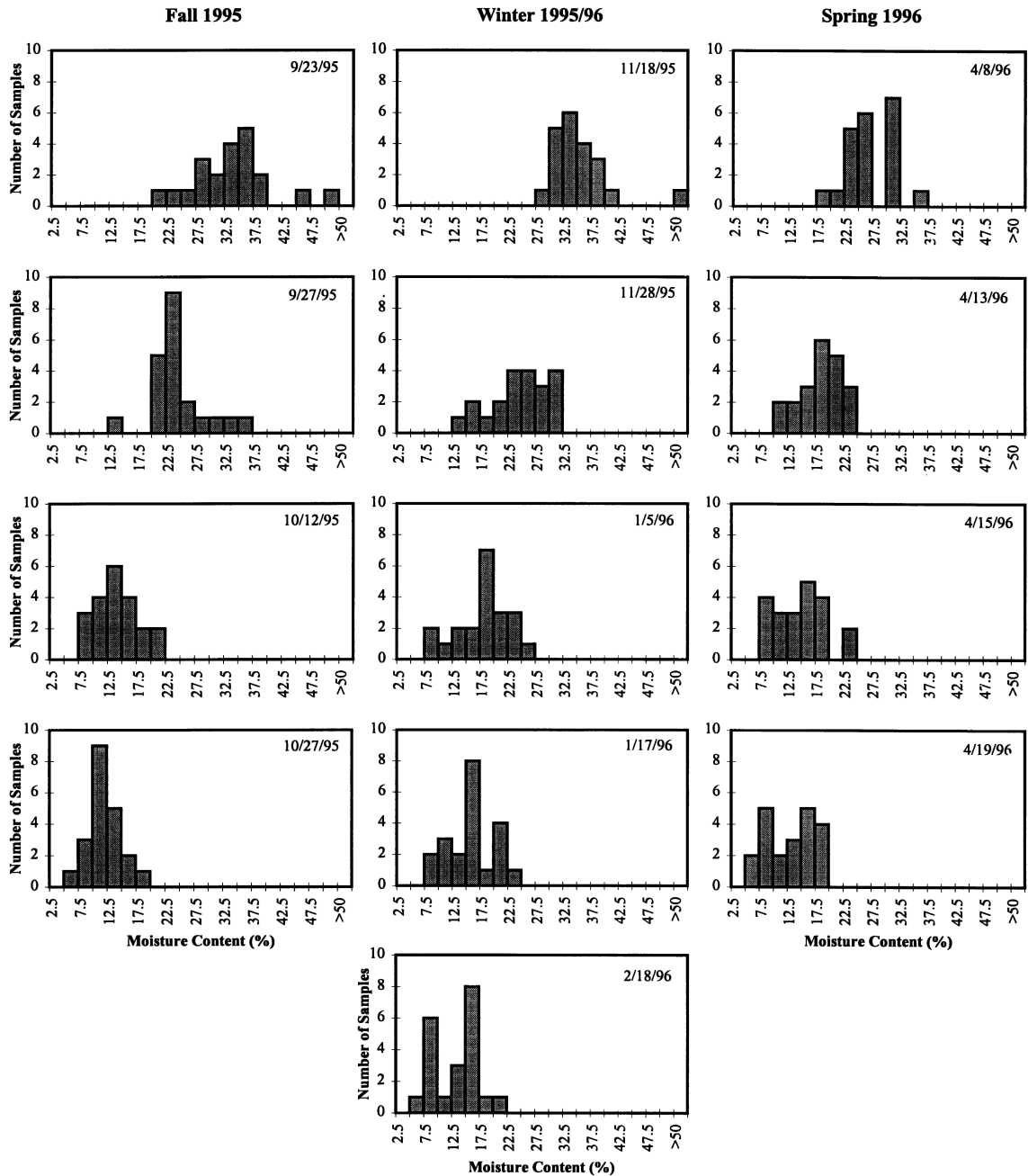


Fig. 5. Frequency (number of samples) of moisture content (%) for each of the dates shown in Fig. 4.

topography and soils in controlling the variability in surface moisture content observed at Rattlesnake Hill. We first present the results of a number of correlation analyses, in which the time series of correlation

coefficients between surface soil moisture and several topographic attributes (relative elevation, specific contributing area, slope, $\ln(a/\tan b)$, mean curvature, profile curvature, planform curvature, and aspect) are

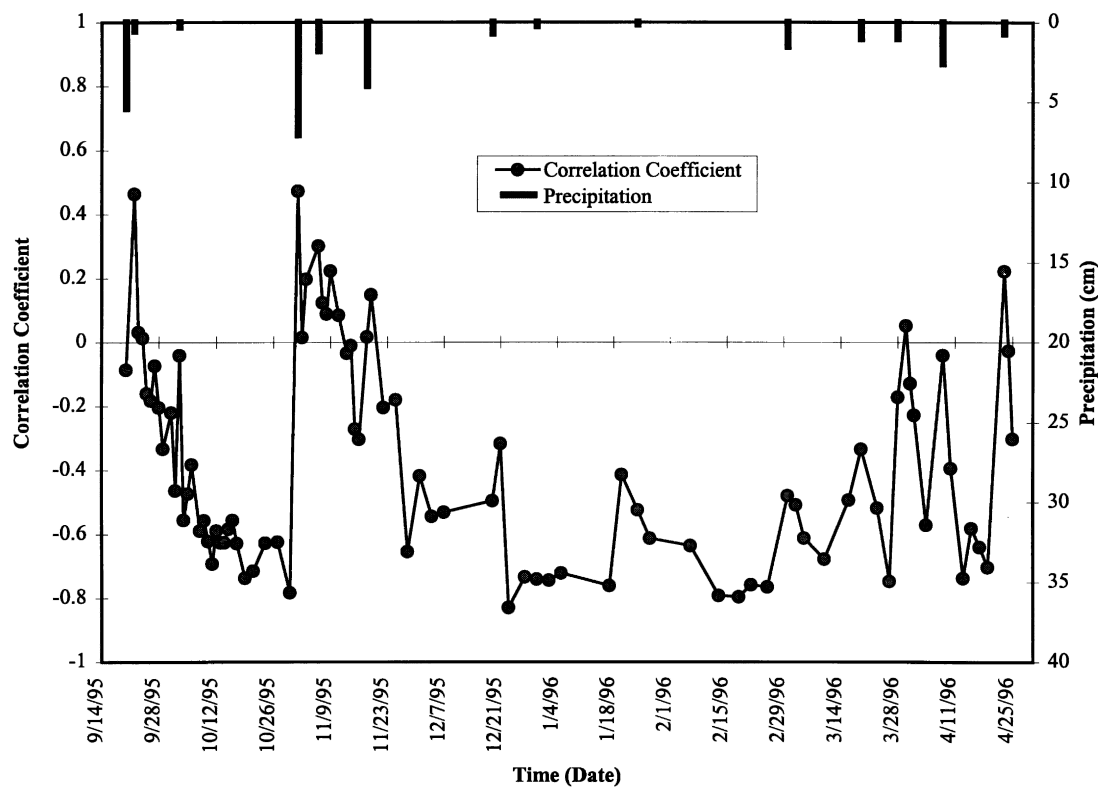


Fig. 6. Daily correlation coefficient between relative elevation and moisture content versus date. Also shown is daily precipitation depth (cm).

interpreted in the context of the vertical and lateral moisture redistribution processes occurring during and after storm events.

It is important to note that the presentation of such time series is only possible because of the high temporal sampling frequency in this work. In fact, none of the previous studies cited in Section 2 presented their results in this fashion. The benefit of the time series approach is that it elucidates the evolution of correlation through time, which enhances our ability to understand the factors which influence variations in surface moisture content, and how they change through time.

Following the analysis of the role of topographic attributes, we next discuss the results of the particle size analysis and present additional correlation coefficient time series between moisture content and porosity and clay content. Based on these findings, in the next section we summarize the mechanisms by which we believe the along-transect moisture content profiles shown in Fig. 4 evolve through dry down

sequences, with implications for the factors responsible for the observed variability.

The relationship between surface soil moisture and topography is first explored via the time history of the correlation coefficient between moisture content and relative elevation (Fig. 6). Relative elevation is an easily and accurately measured surrogate for a number of topographic and soil attributes which influence lateral redistribution of soil water, and with which it varies jointly (e.g. specific contributing area, $\ln(a/\tan b)$, aspect, water table elevation, clay content, etc. (see Table 2)). In general, positive correlation increases with the occurrence of precipitation events, and is followed by a rapid increase in negative correlation, towards high values of the correlation coefficient (near -0.8 at the 95% significance level; note that for the purpose of this discussion, we refer to positive and negative correlation levels between 0 and 0.5 as weak, between 0.5 and 0.8 as moderate, and between 0.8 and 1.0 as strong). The magnitude of the increase in positive correlation generally corresponds

Table 2
Cross correlation matrix

	Relative elevation	Specific contributing area (<i>a</i>)	Slope ($\tan b$)	$\ln(a/\tan b)$	Mean curvature	Profile curvature	Planform curvature	cos (aspect)	Porosity	Clay content
Relative elevation	1	– 0.81	0.05	– 0.67	0.46	0.52	0.38	– 0.98	0.77	– 0.86
Specific contributing area (<i>a</i>)		1	– 0.56	0.93	– 0.68	– 0.61	– 0.69	0.82	– 0.51	0.48
Slope ($\tan b$)			1	– 0.70	0.59	0.40	0.71	– 0.09	– 0.16	0.33
$\ln(a/\tan b)$				1	– 0.84	– 0.71	– 0.87	0.69	– 0.41	0.34
Mean curvature					1	0.95	0.97	– 0.49	0.28	– 0.24
Profile curvature						1	0.84	– 0.52	0.36	– 0.37
Planform curvature							1	– 0.43	0.18	– 0.11
cos(aspect)								1	– 0.75	0.85
Porosity									1	– 0.82
Clay content										1

to the depth of rainfall, with the larger fall rain events resulting in the largest increases and smaller winter rain events yielding the smallest increases. Table 3 further characterizes the moisture content–relative elevation correlation coefficient time series (as well as those of the additional topographic and soil attributes considered in this work) by presenting its maximum positive and negative daily values, and an average value of the correlation coefficient for the entire study period.

Although the correlation between relative elevation and surface moisture content grows increasingly strong during dry down sequences, on its own, relative elevation may not act as a significant driving force for moisture redistribution. It may simply reflect the degree to which the topographic and soil

characteristics shown in Table 2 influence soil water movement and hence moisture content variability at the land surface. In order to understand better the roles of the various topographic and soil attributes listed in Table 2, the time series of their correlation coefficients with moisture content were computed.

Fig. 7 shows these time series for specific contributing area, *a*, the tangent of the slope angle, $\tan b$, and the wetness index, $\ln(a/\tan b)$. The time series of the specific contributing area–moisture content correlation coefficient (Fig. 7a) behaves similarly to that of relative elevation, though it is opposite in sign, and maximum correlation levels are somewhat less. Positive correlation decreases with the occurrence of storm events and increases towards moderate levels (correlation coefficients between 0.6 and 0.7) with

Table 3

Maximum positive, negative and time series-average correlation coefficients (95% significance level) between surface moisture content and topographic and soil characteristics (20 September 1995–25 April 1996)

Attribute	Maximum negative correlation coefficient	Maximum positive correlation coefficient	Average correlation coefficient
Relative elevation	– 0.83	0.48	– 0.37
Specific contributing area (<i>a</i>)	– 0.34	0.70	0.36
Slope ($\tan b$)	– 0.64	0.23	– 0.12
$\ln(a/\tan b)$	– 0.36	0.62	0.29
Mean curvature	– 0.66	0.33	– 0.34
Profile curvature	– 0.70	0.35	– 0.40
Planform curvature	– 0.63	0.28	– 0.27
cos(aspect)	– 0.49	0.83	0.39
Porosity	– 0.73	0.62	– 0.19
Clay content	– 0.56	0.86	0.36

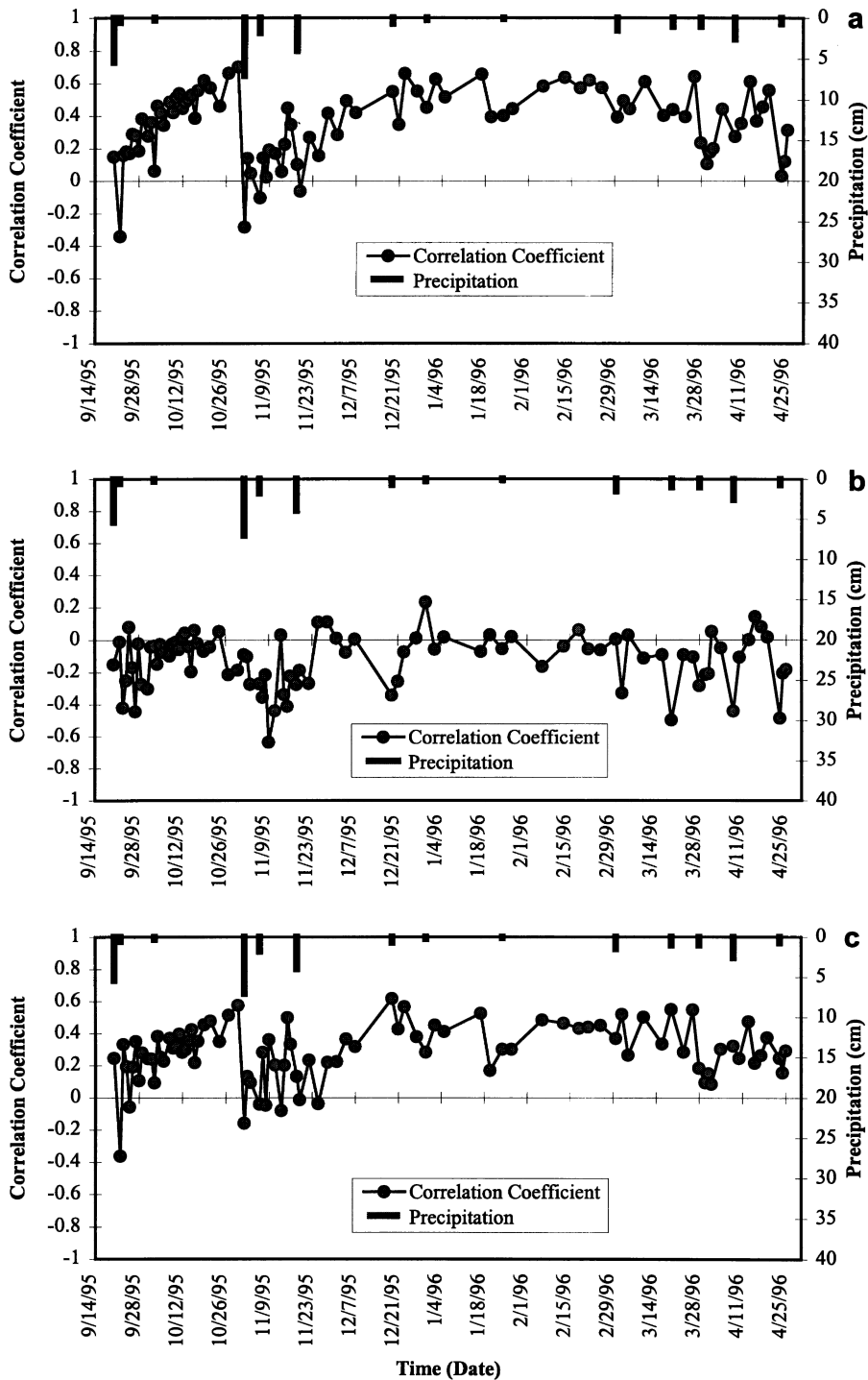


Fig. 7. Daily correlation coefficient between moisture content and (a) specific contributing area; (b) $\tan b$; and (c) $\ln(a/\tan b)$. All versus date. Also shown is daily precipitation depth (cm).

time into a dry down sequence. Note that positive correlation between specific contributing area and surface moisture content is in agreement with previous findings by Moore et al. (1988) and Nyberg (1996).

Decorrelation with specific contributing area during storms is explained by the fact that the 0–5 cm soil layer is relatively thin. During a significant precipitation event, the storage capacity of the thin surface layer is quickly satisfied, in particular along the lower porosity, lower half of the transect (described later), so that no correlation with topography is evident. However, owing to the wetness of the soil, lateral and vertical hydraulic conductivities are high, resulting in active moisture redistribution down slope and to greater depths in the soil profile. As drying of the surface soil layer progresses, the correlation between moisture content and specific contributing area increases, as downslope transect locations, with greater specific contributing areas and thus a greater influx of moisture from upslope sources, remain wetter than upslope locations, in part due to the redistribution of soil water from upslope to downslope locations. These mechanisms will be discussed further in the next section.

As shown in Fig. 7b, moisture content and slope exhibit weak negative correlation during and immediately following storm events (maximum negative correlation between -0.3 and -0.6). With increasing time into a dry down sequence, the correlation coefficient tends to zero. The concentration of correlation around precipitation events is indicative of a mechanism that only operates during storms. One possible explanation is that during precipitation events, locations with higher slopes yield more infiltration excess runoff, and thus less infiltrated water and lower moisture contents than those with lesser slopes. An alternative explanation is that greater slopes foster rapid drainage, and hence relatively lower moisture contents under the wet conditions following storm events. However, if this were the case, correlation would be expected to persist, if not increase with time, as in the case of specific contributing area. Weak correlation between surface moisture content and slope has also been noted by Moore et al. (1988) and Nyberg (1996).

Fig. 7c shows the wetness index–moisture content correlation coefficient time series. It behaves similarly to that between moisture content and specific contributing area, approaching moderate levels of

correlation (between 0.5 and 0.6) with increasing time into a dry down sequence. However, overall correlation levels are somewhat less than those shown in Fig. 7a, owing to the combined impact of incorporating slope, with which moisture content is only weakly correlated, and taking the natural logarithm of the combined quantity $a/\tan b$. The moderate level of correlation reported on here is consistent with previous findings by both Moore et al. (1988) and Nyberg (1996).

The correlation coefficient time series of moisture content with mean curvature, planform curvature and profile curvature is shown in Fig. 8. All three time series behave similarly. As in the case of relative elevation, negative correlation tends to decrease with storm events and increase with time into interstorm periods. The strength of the correlation for all three curvature measures hovers in the weak to moderate range, with profile curvature displaying the strongest relationship to moisture content (approaching maximum correlation levels between -0.4 and -0.7). Moore et al. (1988) have previously reported a weak correlation between surface moisture content and profile curvature.

As in the case of specific contributing area, the decorrelation of curvature with moisture content during storm events is likely due to the fact that the thin, near-surface soil layer wets up quickly, and therefore shows little relationship to topography. Only after the thin layer begins to dry, and soil water has had sufficient time to travel laterally, does the impact of curvature on moisture redistribution become evident.

While our results indicate that moisture content is more strongly correlated to profile curvature than planform or mean curvature, it is important to note that in this study, profile curvature was better resolved than planform curvature, owing to the manner in which elevation measurements were collected. Hence, correlation of moisture content with planform and mean curvature may in reality be stronger than our results indicate. It should be noted further that the transect is located along primarily divergent terrain, so that in general, variations in curvature are under-sampled with respect to this experiment.

The time series of the correlation coefficient between the cosine of aspect and moisture content is shown in Fig. 9. It is nearly identical to that between relative elevation and moisture content, though opposite

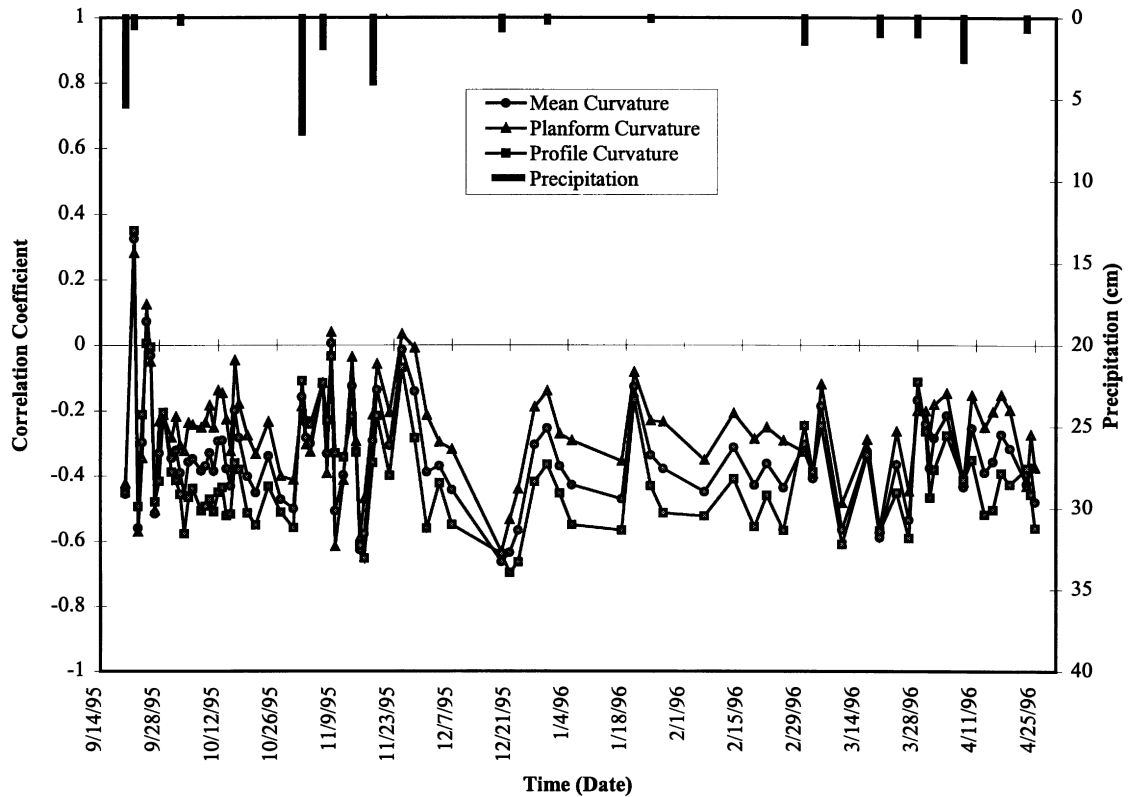


Fig. 8. Daily correlation coefficient between moisture content and planform curvature, profile curvature and mean curvature. All versus date. Also shown is daily precipitation depth (cm).

in sign. In fact, Table 2 indicates that $\cos(\text{aspect})$ and relative elevation are highly correlated, with a correlation coefficient of -0.98 . Consequently, the behavior of the time series shown in Fig. 9 mimics that of the relative elevation–moisture content correlation coefficient: positive correlation decreases during storm events; the strength of the decorrelation of moisture content with $\cos(\text{aspect})$ generally corresponds to the depth of rainfall; and positive correlation increases following storm events, often approaching strong levels (maximum values of the correlation coefficient near 0.8) late into dry down sequences. Positive correlation between surface moisture content and aspect is consistent with previous findings by Reid (1973).

The progressively increasing correlation of $\cos(\text{aspect})$ with moisture content during dry downs most likely reflects the influence of topographic variability on evapotranspiration, and thus surface soil

moisture. As seen in Fig. 1, aspect varies systematically moving upslope, from east–southeast at the foot of the transect, to south at the transect head. Consequently, downslope locations receive less daily solar radiation than upslope. This variation in solar radiation input along the transect implies lower rates of evaporative drying downslope and greater rates upslope. This effect would become more pronounced with time into a dry down sequence, as the difference in cumulative evapotranspiration losses increases between upslope and downslope locations.

While the various topographic attributes considered in this study work to redistribute moisture under the wet conditions associated with storms and early inter-storm periods, taken together, Figs. 4, 6–9 show that most of these attributes (with the exception of slope) are increasingly correlated with moisture content *later* into a dry down sequence. This suggests that some other environmental factor (e.g. soil properties,

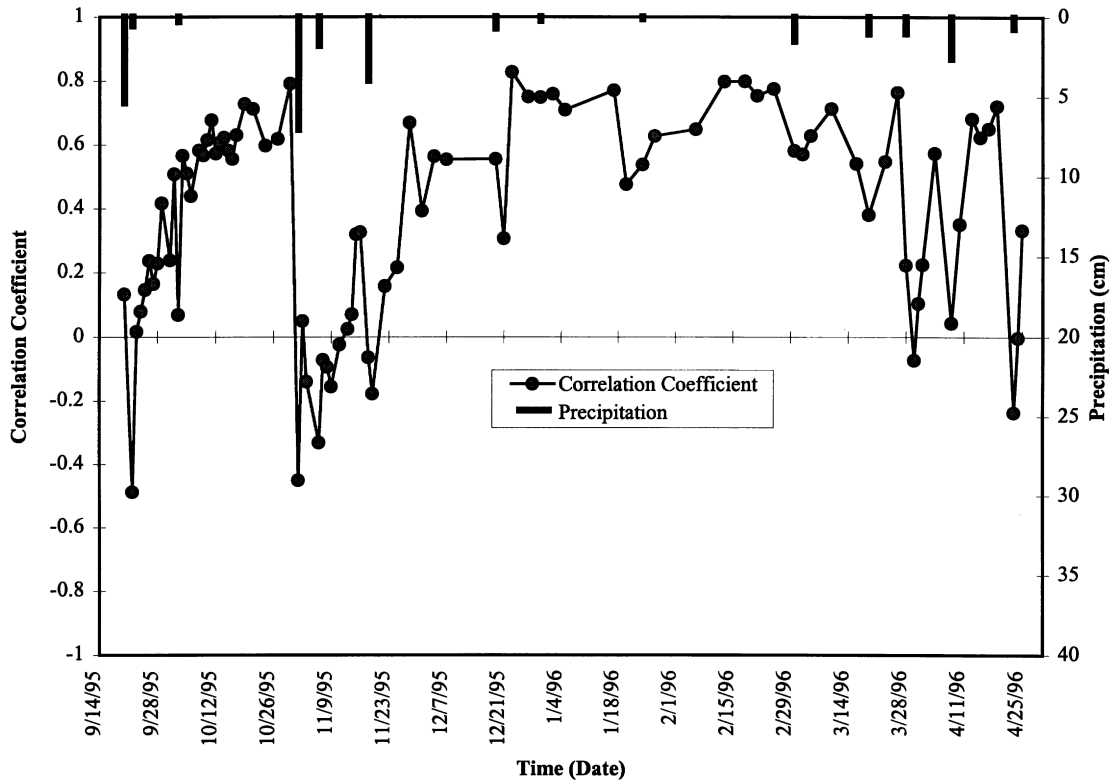


Fig. 9. Daily correlation coefficient between $\cos(\text{aspect})$ and moisture content versus date. Also shown is daily precipitation depth (cm).

vegetation, meteorology) influences variability *earlier* in a dry down. These results suggest further that the greater the precipitation depth and the resulting surface wetness, the stronger the decorrelation with topography, and the more important other environmental factors become in influencing moisture content variability early in an interstorm period.

At least two factors suggest that heterogeneity in soils is the dominant influence on soil moisture variability under wet conditions. The first is that no significant variations in vegetation and precipitation were observed along the transect. However, two distinct soil types are found along the transect, and the transition between the two, which occurs between 60 m and 100 m from the transect origin (see Fig. 1), directly coincides with the transition between the more variable moisture conditions upslope and the less variable conditions downslope observed under wet conditions (see Fig. 4). Second, the tendency towards positive correlation between relative elevation and moisture content after heavy rain events

(see Fig. 6) is indicative of an environmental control that varies jointly with topography, such as soil properties. For example, under saturated conditions, a positive correlation between relative elevation and moisture content would be expected if porosity decreased systematically downslope.

The relationship between soil heterogeneity and moisture content variability was further explored by means of particle size analysis and porosity measurements at each of the 21 sampling locations. Results of these analyses (Fig. 10) indicate that particle size distributions are highly variable upslope and relatively constant downslope. These textural differences can be expected to yield large variations in hydraulic conductivity, which would be maximized under wet conditions (owing to the nonlinear relationship between moisture content and hydraulic conductivity in the unsaturated zone), thus explaining the differences in upslope versus downslope moisture content variations and the higher degree of soil moisture variability under wet conditions than dry. Unfortunately, we

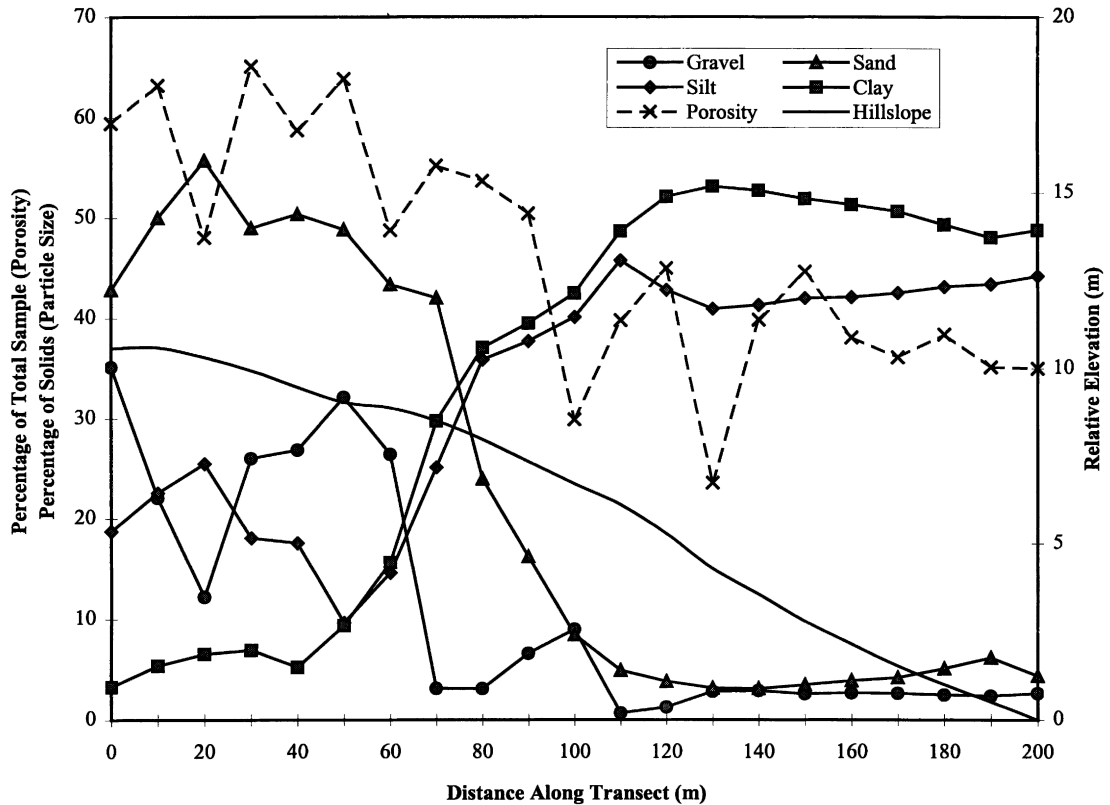


Fig. 10. Particle size distribution (%) and porosity (%) at each sampling location versus distance of sampling location along transect (m).

were unable to obtain reliable estimates of hydraulic conductivity along the transect, so that no correlation between surface moisture content and hydraulic conductivity was possible.

Like the particle size distributions, porosity (Fig. 10) shows a systematic (decreasing) trend downslope, which explains the increasing positive correlation between moisture content and relative elevation with increasing precipitation depth described above. In fact, the relationship between porosity and surface moisture content is shown more clearly in the time series of their correlation coefficient, shown in Fig. 11a. As expected, positive correlation is at a maximum (moderate level) following rain events; and the wetter the soil, the stronger the correlation.

Fig. 11a also shows that the correlation between moisture content and porosity becomes increasingly negative, approaching moderate levels (correlation coefficients between -0.6 to -0.7) as dry down sequences progress, so that the influence of soil

heterogeneity on surface moisture content variability is not strictly limited to early in dry down sequences. The downslope decrease in porosity (and the other systematic textural variations shown in Fig. 10) is likely associated with coincident decreases in hydraulic conductivity, so that negative correlation would arise due to slower drainage and evapotranspiration rates, and thus higher surface moisture contents at the foot of the transect.

This point is further supported by the time series of the correlation coefficient between clay content and surface moisture content shown in Fig. 11b. In general, positive correlation increases with time in a dry down sequence, and reaches high levels (correlation coefficients greater than 0.8) during the winter months. This increase in positive correlation is consistent with the increasingly negative correlation shown in Fig. 11a, since increasing clay content downslope likely results in decreasing hydraulic conductivity, slower drainage and evapotranspiration

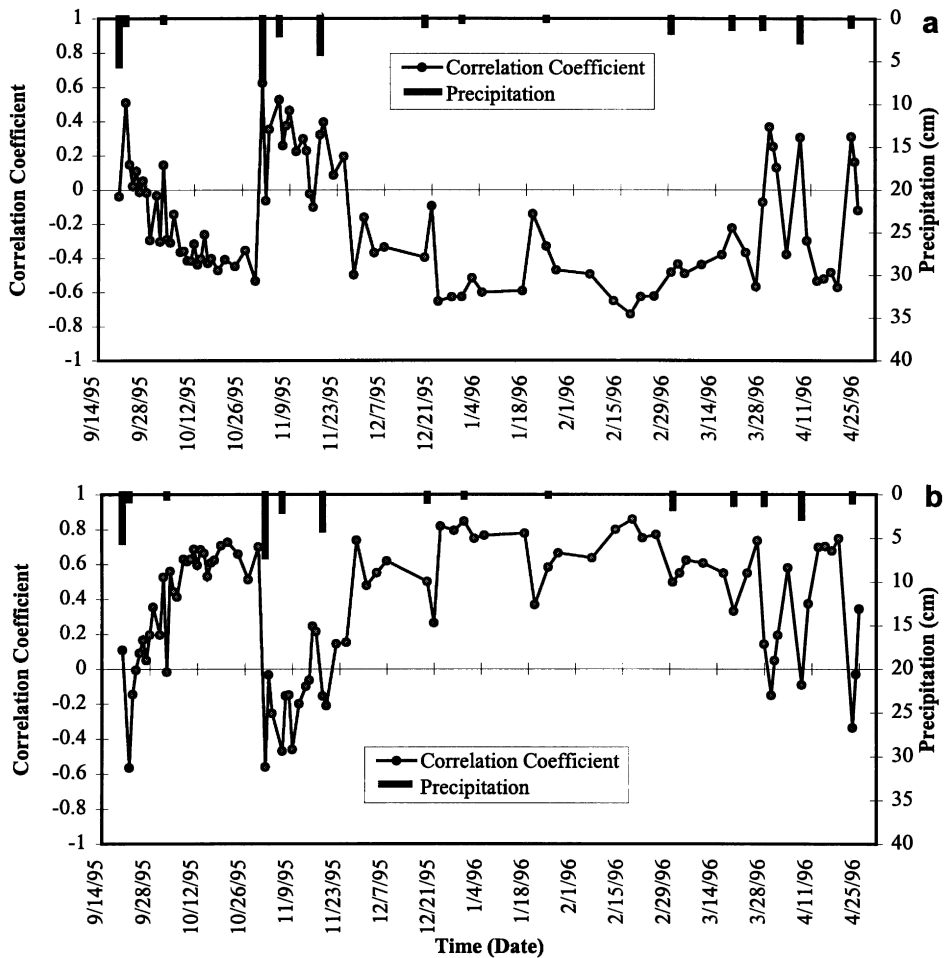


Fig. 11. Daily correlation coefficient between moisture content and (a) porosity; (b) clay content. Both versus date. Also shown is daily precipitation depth (cm).

rates, and hence higher moisture retention along the lower portion of the transect.

5.4. Summary of mechanistic controls on surface soil moisture variability at Rattlesnake Hill

Because both topographic and soil characteristics vary systematically in the downslope direction, distinguishing between the relative roles of topographic and soil attributes in influencing surface moisture content variability would require intensive field monitoring that is beyond the scope of this work. Additionally, since only a limited range of these attributes are observed along the single transect, their influence on surface moisture content variations

may be over or underestimated with respect to the larger hillslope area. With these caveats in mind, we offer a conceptual model of the mechanistic controls on surface soil moisture variability along the Rattlesnake Hill transect.

Under the wettest conditions, the surface layer will be saturated, and consequently, we propose that variations in moisture content are strongly influenced by the spatial distribution of porosity. Although topography is playing an important role in driving lateral redistribution under saturated and wet conditions, its impact on moisture content variability may not yet be evident while the thin soil layer is at or near saturation. Our results indicate that under the wettest conditions encountered during the study (22 September

and 1 November 1995), at which time the surface soil layer along the lower half of the transect was saturated, surface moisture content is moderately correlated to porosity, clay content, relative elevation and aspect. Correlation to relative elevation has been previously explained in the context of its covariance with porosity; correlation with clay content and aspect can be similarly explained, since they are each highly correlated with relative elevation (see Table 2). Correlation between surface moisture content and all of the remaining topographic indices is weak.

The high moisture contents following significant storm events result in active vertical and lateral redistribution. Under wet, but not saturated conditions, soil moisture variability is likely controlled by variations in hydraulic conductivity, the heterogeneity in which will have a greater impact on moisture movement, and thus moisture content variations, under wet conditions than dry. Unfortunately, as previously mentioned, no reliable measurements of hydraulic conductivity were obtained in this study. However, we believe that the increased variability in the along-transect moisture content profiles under wet versus dry conditions is a direct result of the measured variations in particle size distribution and porosity (Fig. 10), which serve as indirect measures of hydraulic conductivity.

As the hillslope dries, soil properties and topography continue to jointly influence moisture movement, and the impact of topography on soil moisture variability becomes more apparent. Results of the particle size analysis indicate that clay content increases and porosity decreases in the downslope direction. Both of these are consistent with a systematic decrease in hydraulic conductivity along the transect. This would result in more rapid drainage upslope, more moisture retention downslope, and the emergence of along-transect moisture content profiles in which moisture content increases downslope.

Topography also contributes to the downslope increase in moisture content, in at least two ways. First, topographically-driven lateral flow redistributes moisture towards areas of topographic convergence, and from upslope to downslope areas. Consequently, in addition to draining more slowly than upslope areas, downslope locations receive more lateral moisture inputs from (at least while lateral redistribution is active), and thus remain wetter than, their upslope neighbors. Second, as shown in Fig. 1, aspect changes

systematically along the transect, from south upslope to east–southeast downslope, and as a result, upslope areas receive greater daily total solar radiation input than those downslope. This likely encourages greater evaporative drying upslope than down, further contributing to the increasingly negative correlation of moisture content with relative elevation seen in the time series of hillslope moisture content transects shown in Fig. 4. Our results show that with progressive drying, for example, by the end of the fall and winter dry down sequences, correlation with moisture content is strong for relative elevation, clay content and $\cos(\text{aspect})$; is moderate for specific contributing area, porosity, $\ln(a/\tan b)$, and profile curvature; is weak for planform and mean curvature, and is essentially zero for slope.

5.5. Implications for surface soil moisture estimation

The results of this study have the following implications for modeling and predicting variations in surface soil moisture content at Rattlesnake Hill. These implications may also have relevance to soil moisture estimation in different geographical and climatological regimes. First, small scale variations in both soil and topographic properties control the evolution of surface moisture content variability along the transect. Hence, in hillslope-scale applications, these various attributes must be incorporated at high resolution into distributed hydrological models, or into the derivation of other predictive measures of surface moisture content.

Second, the topographic and soil attributes with which variability in surface moisture content is most correlated, change with the degree of hillslope wetness, from porosity and hydraulic conductivity under wet conditions, to relative elevation, $\cos(\text{aspect})$ and clay content under drying conditions. This suggests that no one predictive index (e.g. the wetness index), can be expected accurately to predict surface moisture content throughout an entire dry down sequence. Rather, different predictive indices for wet versus dry conditions may be required. Western et al. (1997) reached a similar conclusion, but for the 30 cm surface soil layer, rather than the 5 cm layer considered in this study.

Third, it is worth noting that under drying conditions, several other topographic and soil attributes

were better correlated with surface moisture content than $\ln(a/\tan b)$ (relative elevation, clay content, $\cos(\text{aspect})$, specific contributing area and porosity). This is likely due to the fact that the wetness index was developed to predict the soil water deficit in the entire unsaturated zone profile, not just the upper 5 cm soil layer. In spite of this theoretical mismatch, the wetness index is often invoked as a predictor of surface moisture content, and this research suggests that other topographic and soil attributes are better suited at Rattlesnake Hill and perhaps elsewhere.

A final and related point for discussion is the high correlation of relative elevation with moisture content under dry conditions. At Rattlesnake Hill, several of the topographic and soil attributes investigated in this work vary systematically with relative elevation, and are consequently strongly or moderately correlated with it (Table 2). As such, we believe that its strong correlation to moisture content results because it integrates along-transect variability in important controls (e.g. porosity, hydraulic conductivity, aspect, clay content, specific contributing area, wetness index, curvature) into one easily and accurately measured variable. Because of the ease with which relative elevation is measured (i.e. it does not need to be derived from a high resolution DEM, which may not exist in a location of interest) we suggest that its utility as a predictive index of surface moisture content be explored beyond the context of Rattlesnake Hill.

6. Summary

Variability in surface soil moisture content was studied along a 200 m downslope transect on a hill-slope in central Texas. For the seven-month period beginning on 20 September 1995, soil samples were collected on a near-daily basis at 10 m intervals along the transect, and gravimetric moisture contents were determined. Results for the 0–5 cm surface soil layer indicate that significant variability in moisture content exists along the length of the transect; that following rain events, variability is greater upslope than downslope; that these differences decrease with time; and that in general, moisture content variability decreases with time between rain events as the transect-mean moisture content decreases.

The dominant influences on soil moisture

variability were inferred by correlation analyses. Though cross-correlation between soil and topographic attributes complicated identification of causality, results suggest that the dominant influences on soil moisture variability along the transect are dependent upon the status of surface moisture content. Under wet conditions, variation in soil properties (porosity, hydraulic conductivity) exerts a controlling influence on surface moisture content variability. Under dry conditions, surface soil moisture content is most strongly related to relative elevation, aspect and clay content. Consequently, the dominant influence on soil moisture variability gradually changes from soil heterogeneity to joint influence by topography and soil properties as the transect dries following rain events.

Acknowledgements

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