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Observed spatial organization of soil moisture and its relation to terrain indices

Andrew W. Western,[1] Rodger B. Grayson,[1] Günter Blöschl,[2] Garry R. Willgoose,[3] and Thomas A. McMahon[1]

Abstract. We analyze the degree of spatial organization of soil moisture and the ability of terrain attributes to predict that organization. By organization we mean systematic spatial variation or consistent spatial patterns. We use 13 observed spatial patterns of soil moisture, each based on over 500 point measurements, from the 10.5 ha Tarrawarra experimental catchment in Australia. The measured soil moisture patterns exhibit a high degree of organization during wet periods owing to surface and subsurface lateral redistribution of water. During dry periods there is little spatial organization. The shape of the distribution function of soil moisture changes seasonally and is influenced by the presence of spatial organization. Generally, it is quite different from the shape of the distribution functions of various topographic indices. A correlation analysis found that $\ln(a)$, where a is the specific upslope area, was the best univariate spatial predictor of soil moisture for wet conditions and that the potential radiation index was best during dry periods. Combinations of $\ln(a)$ or $\ln(a/\tan(\beta))$, where β is the surface slope, and the potential solar radiation index explain up to 61% of the spatial variation of soil moisture during wet periods and up to 22% during dry periods. These combinations explained the majority of the topographically organized component of the spatial variability of soil moisture a posteriori. A scale analysis indicated that indices that represent terrain convergence (such as $\ln(a)$ or $\ln(a/\tan(\beta))$) explain variability at all scales from 10 m up to the catchment scale and indices that represent the aspect of different hillslopes (such as the potential solar radiation index) explain variability at scales from 80 m to the catchment scale. The implications of these results are discussed in terms of the organizing processes and in terms of the use of terrain attributes in hydrologic modeling and scale studies. A major limitation on the predictive power of terrain indices is the degree of spatial organization present in the soil moisture pattern at the time for which the prediction is made.

1. Introduction

Natural catchments exhibit spatial variability of soil moisture at a range of scales [*Rodríguez-Iturbe et al.*, 1995; *Schmugge and Jackson*, 1996]. At the small catchment and hillslope scales, soil moisture varies as a result of water-routing processes [*Dunne and Black*, 1970a; *Dunne et al.*, 1975; *Zavlaski and Sinai*, 1981; *Beven and Kirkby*, 1979; *Moore et al.*, 1988], radiative (aspect) effects [*Moore et al.*, 1993], and heterogeneity in vegetation and soil characteristics. Partial area saturation excess runoff has been observed to be an important runoff-producing process in many catchments [*Dunne and Black*, 1970a, b; *Dunne et al.*, 1975; *Anderson and Burt*, 1978a, b]. This runoff is believed to be associated with systematic or organized spatial variation in soil moisture, particularly saturated areas associated with topographic convergence [*Dunne et al.*, 1975; *Anderson and Burt*, 1978a, b; *O'Loughlin*, 1981, 1986; *Anderson and Kneale*, 1982; *Moore et al.*, 1988; *Barling et al.*, 1994]. Integrated catchment behavior (runoff) depends on this small-scale systematic behavior. However, it may not be necessary to model this small-scale behavior deterministically to describe integrated catchment behavior at larger scales. Rather, larger-scale descriptions could be developed with effective parameters that account for the smaller-scale processes. Understanding the organizational and statistical characteristics of this small-scale behavior is critical to understanding and predicting integrated catchment behavior and its relationship with scale [*Blöschl and Sivapalan*, 1995; *Willgoose*, 1996; *Blöschl*, 1999]. This paper examines (1) the degree of spatial organization of soil moisture in a small catchment during different seasons and (2) how well that organization can be predicted using terrain indices.

Hydrologic processes can vary in space in an organized way or randomly or in a combination of the two [*Gutknecht*, 1993; *Blöschl et al.*, 1993; *Blöschl*, 1999]. We use "randomness" to refer to variability that is not predictable in detail but that has predictable statistical properties, and "organization" to refer to regularity or order. Spatial organization implies variation characterized by consistent spatial patterns [*Blöschl*, 1999]. In the context of this paper most of the organization is related to topography. *Blöschl* [1999] noted that natural systems can vary from completely disorganized (disordered, random) to highly

[1]Centre for Environmental Applied Hydrology and Cooperative Research Centre for Catchment Hydrology, Department of Civil and Environmental Engineering, University of Melbourne, Parkville, Australia.

[2]Institut für Hydraulik, Gewässerkunde und Wasserwirtschaft, Technische Universität Wien, Vienna, Austria.

[3]Department of Civil, Surveying and Environmental Engineering, University of Newcastle, Newcastle, Australia.

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organized; that is, systems can exhibit some degree of organization. The ultimate in disorder is white noise. With increasing organization, processes may exhibit (1) continuity (which is captured statistically by the variogram or the autocorrelation function); (2) connectivity (i.e., connected thin bands such as high conductivity flow paths); or (3) convergence (i.e., a branching structure of drainage lines and hillslopes). The proper representation of the degree of spatial organization can be critically important for hydrologic prediction. For example, incorporating connectivity into antecedent moisture patterns has a dramatic effect on simulated runoff, even if the spatial correlation structure (variogram) is unchanged [e.g., *Grayson et al*., 1995, Figure 19.9]. Whether these differences are likely to be seen in reality is unknown since so far there have been too few data on soil moisture distribution to be certain of the true patterns that exist in nature.

Representation and prediction of the spatial variability of soil moisture are needed for a range of purposes over a range of scales from small catchments to whole continents. Spatial variability can be represented either explicitly by using distributed models or statistically. Distributed models often suffer from problems of poor parameter identifiability and data constraints, among others [*Hillel*, 1986; *Beven*, 1989; *Grayson et al*., 1992a]. Statistical approaches usually rely on some form of distribution function, and models based on this approach are referred to as distribution models. Distribution models are simpler and have the advantage of needing fewer data and fewer model parameters that are easier to identify. The distribution function used in distribution models is often an empirical function based on surrogates for hydrologic processes such as terrain indices.

Terrain indices aim to represent the key hydrological processes controlling the spatial distribution of soil moisture in a simplified but realistic way. Terrain indices are used in hydrologic prediction in two ways. First, the cumulative distribution function of the terrain index can be used to obtain a lumped estimate of the contributing area. This is the way terrain indices were initially used in models like Topmodel [*Beven and Kirkby*, 1979]. Secondly, it is possible to map the distribution function back into space to predict the soil moisture (or saturation deficit) pattern. In addition to enabling distribution model predictions to be interpreted spatially, these patterns can be used to provide antecedent moisture patterns for event models [*Grayson et al*., 1992b] and to generate qualitative soil moisture maps to aid in environmental decision making [*Moore et al*., 1993]. The spatial nature of terrain indices makes them particularly attractive for use in geographic information systems [*Grayson et al*., 1993; *Meijerink et al*., 1994].

Topographic indices assume that topography is dominant in controlling and modifying the hydrologic processes operating in the landscape. Most of the indices currently in use allow some interpretation of the physical rationale behind them. Terrain indices can be grouped into primary terrain attributes, such as slope, aspect, curvature, and specific catchment area, and compound attributes that are combinations of primary attributes [*Moore et al*., 1991]. Surface slope, $\tan(\beta)$, influences the hydraulic gradient driving any surface flows and also subsurface flows when the water table has a similar slope to the ground surface. Surface slope and aspect together influence both rainfall input [*Sharon*, 1980] and radiation influx. Radiation influences the energy available to drive evapotranspiration (and processes such as snowmelt [*Dozier*, 1980; *Blöschl et al*., 1991]). Tangent curvature provides a measure of the local convergence or divergence of lateral flow paths. Profile curvature reflects how the hydraulic gradient and flow velocities change. Mean curvature is the mean of tangent and profile curvature and is a measure of the overall convexity or concavity of the landscape. Specific catchment area, a, is the upslope area above a contour segment divided by the length of that contour segment. It is a measure of the potential area that can contribute lateral flow through a unit contour length.

Compound topographic indices such as the steady state wetness index of *Beven and Kirkby* [1979], $\ln(a/\tan(\beta))$, and a similar index developed by *O'Loughlin* [1986] have been widely applied in hydrology. Wetness indices essentially predict organized spatial fields of soil moisture. The topographic wetness indices were originally developed to predict zones of surface saturation but these indices have also been used to predict patterns of soil moisture and saturation deficit [e.g., *Bárdossy and Lehmann*, 1998]. The steady state assumption in the Beven and Kirkby and the O'Loughlin wetness indices has been criticized as being unrealistic for many climates. This assumption implies that the entire catchment upslope of a point contributes water to that point by subsurface lateral flow, which is a very slow process [*Barling et al*., 1994]. Barling's field observations and modeling by *Barling et al*. [1994] and *Hemanatha and Willgoose* [1996] suggest that this results in spatial patterns of soil moisture and zones of saturation that are significantly different from those predicted using steady state assumptions.

The index approach can be used to characterize other processes that influence the spatial distribution of soil moisture. Local variations in potential evapotranspiration can be characterized by indices such as the potential solar radiation index that quantifying solar energy inputs to different topographic locations. The potential solar radiation index is the ratio of the potential solar radiation (i.e., the solar radiation in the absence of an atmosphere) on a sloping surface to that on a horizontal surface [*Moore et al*., 1991]. Spatial variations in humidity are unlikely to be significant at small (500 m) catchment scales owing to mixing in the atmospheric boundary layer. Topographically controlled spatial variations in rainfall also occur [*Sharon*, 1980] owing to wind effects which can be predicted using topographic and meteorological data in an index context.

While valid heuristic considerations suggest the usefulness of terrain indices for hydrologic modeling, their success depends ultimately on their predictive power, that is, how much of the spatial variability they can explain. *Moore et al*. [1988] found that the wetness index, $\ln(a/\tan(\beta))$, explained 26% to 33% of the spatial variation in soil moisture in a 7.5 ha catchment in New South Wales, Australia. A multiple regression with wetness index and aspect provided the best predictor, explaining 31% to 41% of the variance. A study by *Ladson and Moore* [1992] suggested for a 38 ha catchment in Kansas an explained variance of less than 10% for soil moisture. *Burt and Butcher* [1985] found that on a 1.4 ha hillslope in South Devon, United Kingdom, the wetness index explained less than 50% of the variance of the depth to saturation on 46 out of 47 occasions. Typically, it explained less than 25% of the variance (35 out of 47 occasions). For slope discharge the wetness index explained between 17% and 31% of the variation. Other indices ($a \times$ plan curvature, $(a/\tan(\beta)) \times$ plan curvature, a/β) often performed better than the wetness index for predicting saturation depth and, particularly, slope discharge. *Moore and Thompson* [1996] found that the relationship between depth to water table and wetness index was poor (explained variance of 26%) in lower-slope convergent zones in a 4 ha catchment in

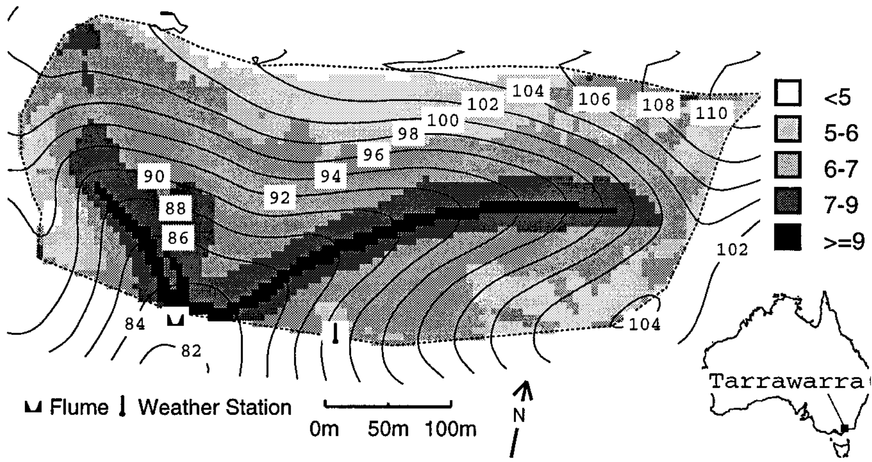

Figure 1. The Tarrawarra Catchment. The contours (2 m interval) show the topography of the catchment and the raster map shows the variation of $\ln(a)/\tan(\beta)$. The locations of the flume and weather station are also shown.

British Columbia, Canada. In a 0.63 ha Swedish catchment *Nyberg* [1996] found that the wetness index explained 34% to 42% of the spatial variation in soil moisture. The logarithm of the specific area was an equally good predictor. *Jordan* [1994] found coefficients of determination between depth to water table and the wetness index of between 3% and 79% on seven occasions in a 12.5 km^2 catchment on the Swiss Plateau. On five of the seven occasions, less than 25% of the variance was explained by the wetness index. *Zavlaski and Sinai* [1981] did not consider the wetness index, but found that curvature (∇^2 elevation) explained 81% of the variation in soil moisture near Beer-Sheba, Israel, two weeks after rainfall (250 mm). In this last case the lateral flow probably occurred in an unsaturated state [*Zavlaski and Sinai*, 1981]. Clearly, terrain indices have performed well in some circumstances but poorly in many others. Whether this is due to the processes leading to topographic organization being incorrectly represented or whether it is due to limited topographic organization is uncertain.

Owing to the small number of point samples used, all of these studies have been limited in terms of assessing any organization in the spatial patterns of soil moisture. Point values are notoriously poor in identifying spatial organization. *Williams* [1988] and *Schmugge and Jackson* [1996], among others, point out that the apparent randomness sometimes observed for hydrologic variables is largely a consequence of using point measurements. What is needed are high-resolution observations of soil moisture patterns based on a large number of point samples. These would allow reliable examination of whether spatial organization of soil moisture is present in the landscape and how much of that organization can be predicted with terrain indices. Also, the predictive power of wetness indices has not been fully assessed in the literature. Many of the studies have relied on measurements of soil water within a thin surface layer, have examined only one particular season of the year without analyzing seasonal variability, and/or have used measurements on a single hillslope only. Also, the small number of samples as used in most studies may compromise the reliability of the estimates of the predictive power of the indices. Finally, the shapes of distribution functions derived from indices have rarely been compared to those measured in the field.

The aim of this paper therefore is to examine (1) to what degree soil moisture in a small catchment exhibits spatial organization and (2) whether that organization can be predicted using terrain indices. In terms of the predictive capability we examine how well the indices represent the shape of the distribution function of soil moisture, how well they represent the spatial patterns of soil moisture, and at which scale the indices are best at predicting the spatial organization of soil moisture. This paper goes beyond the existing literature in a number of ways. The data we use are significantly more detailed in space (over 500 sampling sites in a 10.5 ha catchment), they extend over a catchment with a variety of topography and aspect rather than a single hillslope, and they cover a wider range of moisture conditions than previous studies. This data set allows us to examine the seasonal change in the topographic organization of soil moisture and what features of organization terrain indices can predict. It also allows the importance of the degree of spatial organization in determining the predictive power of indices to be assessed.

The rest of the paper is arranged as follows. First, we briefly describe the field site and the analysis methods used in this study. Then we present measured patterns of soil moisture and discuss the nature of the observed spatial organization. Next we examine the ability of a number of terrain indices to reproduce the distribution function of soil moisture and to reproduce the spatial patterns of soil moisture. The latter is done by a correlation analysis, and the effect of seasonality is examined. We then examine the spatial statistics and spatial patterns of the residuals of the correlation analysis to determine the scale at which the terrain indices work best and to indicate what features of the patterns are not well captured by the indices and how these could be improved. Finally, we discuss the implications of our findings from hydrologic process and modeling perspectives.

2. Field Description and Data Set

The data used to examine the spatial characteristics of soil moisture and the predictive ability of various terrain attributes come from the 10.5 ha Tarrawarra catchment [*Western and Grayson*, 1998]. Tarrawarra is an undulating catchment located

Table 1. Summary of the 13 Soil Moisture Patterns and Antecedent Precipitation at Tarrawarra

	Soil Moisture, % vol/vol					Antecedent Precipitation	
Date	Mean	Variance	Coefficient of Variation	10th Percentile	90th Percentile	10 Days, mm	40 Days, mm
Sept. 27, 1995	37.7	24.1	0.13	31.3	44.9	16	63
Feb. 14, 1996	26.2	10.6	0.12	21.5	29.9	58	98
Feb. 23, 1996	20.8	5.3	0.11	17.8	23.7	0	97
March 28, 1996	23.9	7.1	0.11	20.2	27.0	7	89
April 13, 1996	35.2	12.3	0.10	29.9	38.7	65	145
April 22, 1996	40.5	14.6	0.09	36.9	46.0	71	215
May 2, 1996	41.4	19.4	0.11	36.8	46.9	6	172
July 3, 1996	45.0	14.0	0.08	39.9	48.6	20	25
Sept. 2, 1996	48.5	13.9	0.08	45.3	53.8	22	108
Sept. 20, 1996	47.3	15.2	0.08	42.7	52.3	36	117
Oct. 25, 1996	35.0	19.2	0.13	29.6	39.4	15	84
Nov. 10, 1996	29.3	10.8	0.11	25.4	33.5	35	71
Nov. 29, 1996	23.9	6.28	0.11	20.8	26.6	12	61

on the outskirts of Melbourne, Australia (Figure 1). It has a temperate climate, and the average soil moisture is high during winter and low during summer. The data used in this paper are the topographic data, which are based on a detailed ground survey, and soil moisture data from 13 soil moisture surveys. Eleven of these surveys consist of approximately 500 measurements of soil moisture on a 10 m by 20 m sampling grid. The remaining two are more spatially detailed (approximately 1000 and 2000 points). Table 1 provides a summary of the 13 surveys. The soil moisture surveys used in this paper cover the range of soil moisture conditions typically observed in this landscape. The measurements were made using time domain reflectometry equipment mounted on an all terrain vehicle. Each measurement represents a point measurement of the moisture in the top 30 cm of the soil profile.

The soils at Tarrawarra have a 20- to 35-cm-deep A horizon. Perched water tables form in the A horizon during winter months, and the soil profile dries to a depth of approximately 1 m during summer. Analysis of soil moisture profile data from 20 sites in the catchment indicates that the top 30 cm of the soil profile accounts for 40% to 60% of the total active profile moisture storage, depending on the measurement site. Furthermore, during wet periods nearly all the temporal variation in the soil moisture profile occurs in the A horizon of the soil profile. This is due to relatively low permeability in the B horizon. Thus, from a runoff process perspective, the soil moisture in the top 30 cm of the soil profile is a key variable. The Tarrawarra catchment is used for cattle grazing and has pasture vegetation throughout the catchment. The catchment and data collection methods are described in detail by *Western and Grayson* [1998].

3. Analysis Methods

The terrain attributes for the Tarrawarra catchment were obtained as follows. A 5 m grid-based digital elevation model was developed from a detailed topographic survey of the catchment [*Western and Grayson*, 1998] using a thin-plate spline method for interpolation [*Hutchinson and Gessler*, 1994; *Mitasova and Mitas*, 1993]. Table 2 summarizes the methods used to calculate the terrain indices considered in this analysis.

The analysis presented in this paper consists of two main parts. The first is a qualitative discussion of the degree of organization observed under different moisture conditions. The discussion is based on a visual examination of the observed spatial patterns of soil moisture and on indicator plots. Two indicator plots for each occasion were derived by thresholding the observed moisture patterns at the 75th and 90th percen-

Table 2. Summary of the Terrain Indices Used in Our Analysis

Index	Formula	Reference	Note
Slope	$\tan \beta = \sqrt{f_x^2 + f_y^2}$	*Mitasova and Hofierka* [1993]	1
Cos(aspect)	cos(aspect)		
Tangent curvature	$k_t = \dfrac{f_{xx} f_y^2 - 2 f_{xy} f_x f_y + f_{yy} f_x^2}{p \sqrt{q}}$	*Mitasova and Hofierka* [1993]	1
Profile curvature	$k_p = \dfrac{f_{xx} f_y^2 + 2 f_{xy} f_x f_y + f_{yy} f_x^2}{p \sqrt{q^3}}$	*Mitasova and Hofierka* [1993]	1
Mean curvature	$k_m = \dfrac{k_t + k_p}{2}$	*Mitasova and Hofierka* [1993]	···
Specific area, a	DEMON algorithm	*Costa-Cabral and Burgess* [1994]	···
Wetness index	$\ln(a/\tan\beta)$	*Beven and Kirkby* [1979]	···
Potential solar radiation index	R_s/R_o	*Moore et al.* [1993], *Dingman* [1994]	2
Rainfall index	equation (8)	*Sharon* [1980]	3

(1) Elevation, z, is obtained from a regularized spline with tension such that $z = f(x, y)$. Derivatives of z are obtained from the fitted spline: $f_x = \partial f/\partial x$, $f_y = \partial f/\partial y$, $f_{xx} = \partial^2 f/\partial x^2$, $f_{yy} = \partial^2 f/\partial y^2$, $p = \sqrt{f_x^2 + f_y^2}$, $q = p + 1$. (2) R_s is the potential solar radiation on a sloping plane, R_o is the potential solar radiation on a horizontal plane. (3) Drop size intensity [*Laws and Parsons*, 1949] and drop size terminal velocity [*Gunn and Kinzer*, 1949] relationships, and 6 min wind and rainfall data were used to calculate a rainfall weighted average for the preceeding 28 days.

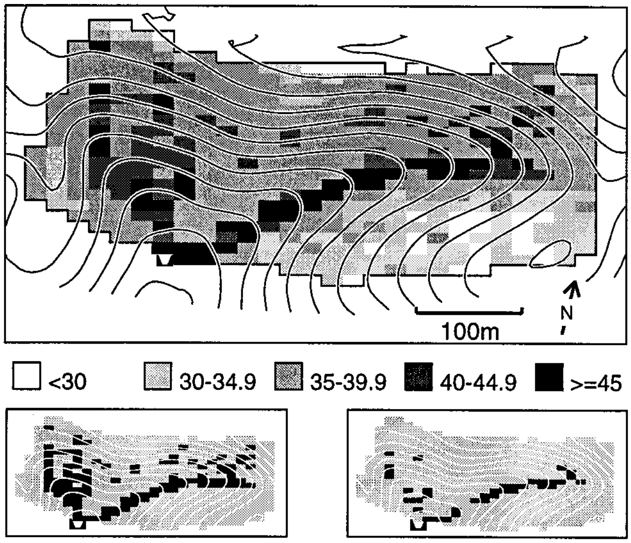

Figure 2. Soil moisture variation at the Tarrawarra Catchment on September 27, 1995. Each raster cell represents a single point measurement of the percent volumetric soil moisture in the top 30 cm of the soil profile. The 75th percentile indicator plots (lower left) and 90th percentile indicator plots are also shown.

tiles, respectively. For a more detailed analysis of the indicator properties of the Tarrawarra soil moisture data see work by *Western et al.* [1998a].

The second part analyzes three aspects of the predictive performance of terrain indices. First we examine the ability of different terrain indices to reproduce the distribution function of soil moisture. The rationale for this analysis is that some hydrologic models use distribution functions based on terrain indices to estimate the statistical distribution of soil moisture (or storage deficit) within a catchment and hence to estimate the runoff coefficient for simulating runoff. Here cumulative distribution functions (cdf's) of soil moisture are plotted against the cdf's for various terrain indices. The mean was removed from each cdf prior to plotting. If the shape of the cdf of soil moisture and the cdf of the terrain index were the same, the plots would consist of straight lines passing through the origin. This is important because many distribution models assume a linear relationship between the two cdf's. Second we examine the ability of a number of terrain indices to predict the spatial patterns of soil moisture. This is based on a correlation analysis and on residual patterns. Scatter plots of soil moisture and the different terrain indices were drawn, and correlation coefficients and coefficients of determination were calculated. Some multivariate cases were also considered, for which the coefficient of determination was calculated using multiple regression. Spatial patterns of residuals from the correlation analysis were plotted and examined to determine how well the topographically organized component of the spatial variation of soil moisture was predicted. Third, we examine the ability of a number of terrain indices to predict spatial soil moisture variability at different scales. We calculate the variograms for the residuals and compare these variograms to the variogram for the soil moisture. This gives us an indication of the scale or lag at which the indices are able to explain the spatial variance. Standard geostatistical techniques were used to estimate the variograms [*Isaaks and Srivastava*, 1989; *Western et al.*, 1998b]. *Western et al.* [1998b] provide a detailed geostatistical analysis of the soil moisture patterns. For comparison, a similar analysis was performed in the spectral domain using a standard fast Fourier transform algorithm [*Press*, 1990].

4. Results

4.1. Observed Spatial Organization

In this section we examine how the degree of organization of soil moisture changes between seasons using data from four surveys. Figures 2–5 show four of the 13 soil moisture patterns and the corresponding 75th and 90th percentile indicator plots. The indicator plots show where the relatively wet areas are located. Figures 2–5 represent a range of moisture conditions from dry to very wet that are representative of the conditions encountered throughout the year.

The first soil moisture pattern (September 27, 1995; Figure 2) represents wet conditions at Tarrawarra. There is a strong relationship between topographic location and soil moisture (topographic organization), which indicates a significant degree of lateral redistribution of water. An important feature of this organization is the connection of the wet areas to the catchment outlet. This means that there is little potential for runon infiltration of saturation excess runoff before it reaches the catchment outlet. While lateral redistribution is important, there is also a relationship between the observed moisture and aspect. The northwest facing hillslope in the southeastern part of the catchment is somewhat drier than other parts of the catchment. This may result from variations in evapotranspiration. As well as the organization present, there is some randomness as evidenced by the short-scale variability.

The second moisture pattern (February 23, 1996; Figure 3) illustrates dry conditions within the catchment. In contrast to Figure 2, the only organization that is apparent is a weak relationship between aspect and soil moisture. Again, it is the northwest facing hillslope that is somewhat drier than other

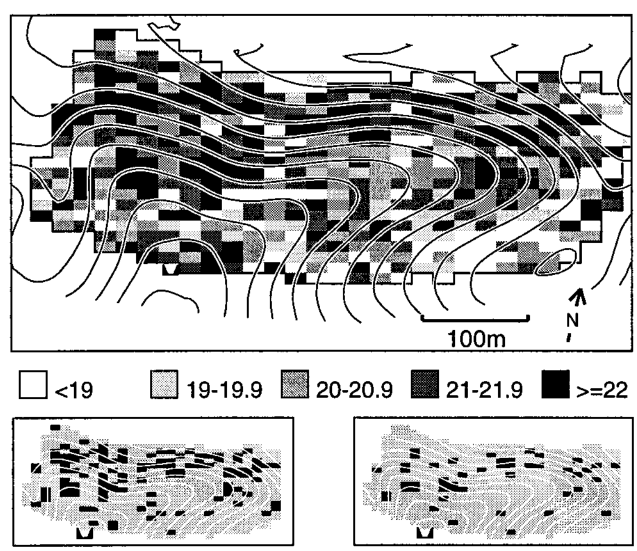

Figure 3. Soil moisture variation at the Tarrawarra Catchment on February 22, 1996. Each raster cell represents a single point measurement of the percent volumetric soil moisture in the top 30 cm of the soil profile. The 75th percentile indicator plots (lower left) and 90th percentile indicator plots are also shown.

parts of the catchment. The small range in soil moisture (14–27% vol/vol) reflects the limiting effect of high soil suction on evapotranspiration. Much of the variation appears random.

The third pattern (April 13, 1996; Figure 4) represents the transition from dry to wet conditions. It exhibits topographic organization, but the form of that organization is quite different than that observed under wet conditions (Figure 2). The wettest areas in the catchment are focused in the areas with high local convergence, reflecting the early stages of topographic redistribution of moisture. Other areas are more random. A significant difference between the transitional and the wet condition moisture pattern is that connectivity between the wettest areas and the catchment outlet has not yet developed, the lower parts of the drainage lines are relatively dry, and there is significant potential for runon infiltration of runoff produced in the wettest parts of the catchment. This is true even though the average catchment moisture status is similar in the two cases (September 27, 1995, and April 13, 1996; see Table 1).

The fourth pattern (July 3, 1996; Figure 5) is for very wet conditions. In many parts of the catchment the soil is saturated and soil moisture is being limited by soil porosity. The topographic organization of the soil moisture is much reduced compared to September 1995 (Figure 2). The organization that does exist is related partly to topography and partly to spatial heterogeneity in porosity.

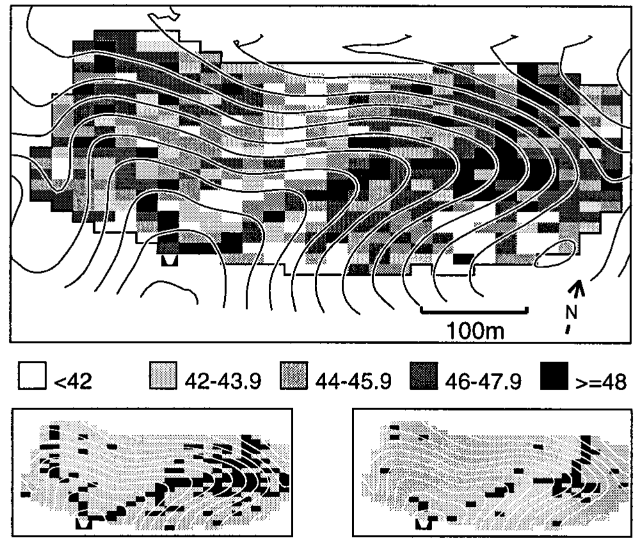

Figure 5. Soil moisture variation at the Tarrawarra Catchment on July 3, 1996. Each raster cell represents a single point measurement of the percent volumetric soil moisture in the top 30 cm of the soil profile. The 75th percentile indicator plots (lower left) and 90th percentile indicator plots are also shown.

4.2. Performance of Terrain Indices: Distribution Functions

In this section we examine the ability of different terrain indices to predict the shape of the cdf of soil moisture. Figure 6 shows the cdf of soil moisture plotted against the cdf of (1) the wetness index, (2) tangent curvature, and (3) the potential radiation index. Each point on the curves in Figure 6 has the same exceedance probability in terms of the terrain index and the soil moisture. The markers on the lines indicate deciles. If the shape of the cdf of soil moisture is the same as that of the terrain index, the plots would consist of straight lines through the origin. The cdf of the soil moisture distribution is predicted most closely by the cdf of tangent curvature (the straightest lines) (Figure 6b). The temporal changes in the spatial variability of the soil moisture (Table 1) are evident in the different slopes of the four curves in Figure 6b. Changes in the shapes of the curves in Figure 6b mean that the shape of the soil moisture distribution is changing over time. There is also a tendency for a marked "step up" (increase) in the soil moisture cdf, relative to the tangent curvature cdf, for the upper (10–20%) tail of the distributions.

The relationship between the soil moisture cdf and the wetness index cdf is curvilinear because of the highly skewed shape of the wetness index distribution compared to the soil moisture distribution. Again the changing variability and the step up in the upper tail of the soil moisture cdf, relative to the wetness index cdf, are evident. The relationship between the soil moisture cdf and the potential radiation cdf tends to have a backwards 'S' shape, which reflects differences in kurtosis between the two distributions. In addition to temporal changes in the variability of the soil moisture, there are also temporal changes in the variability of the potential radiation index, reflecting seasonal changes in the solar declination. The relationships between the cdfs of other indices and the cdf of soil moisture were also examined. The behavior of profile and mean curvature was qualitatively similar to, but quantitatively poorer than tangent curvature. The behavior of cos(aspect) was similar to the potential radiation index and ln(a) was similar to the wetness index, though the curvature was less pronounced.

There is a general tendency for the cdf of soil moisture to be predicted better during dry periods than during wet periods. This is related to the changing nature of the cdf of soil moisture. In summer the cdf of soil moisture is normal or slightly skewed [*Western et al.*, 1998b] and there is little topographic organization. In winter and spring the wet band in the gullies

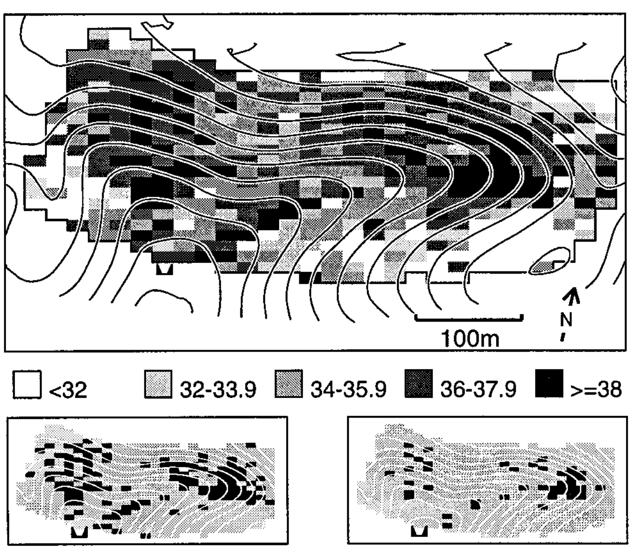

Figure 4. Soil moisture variation at the Tarrawarra Catchment on April 13, 1996. Each raster cell represents a single point measurement of the percent volumetric soil moisture in the top 30 cm of the soil profile. The 75th percentile indicator plots (lower left) and 90th percentile indicator plots are also shown.

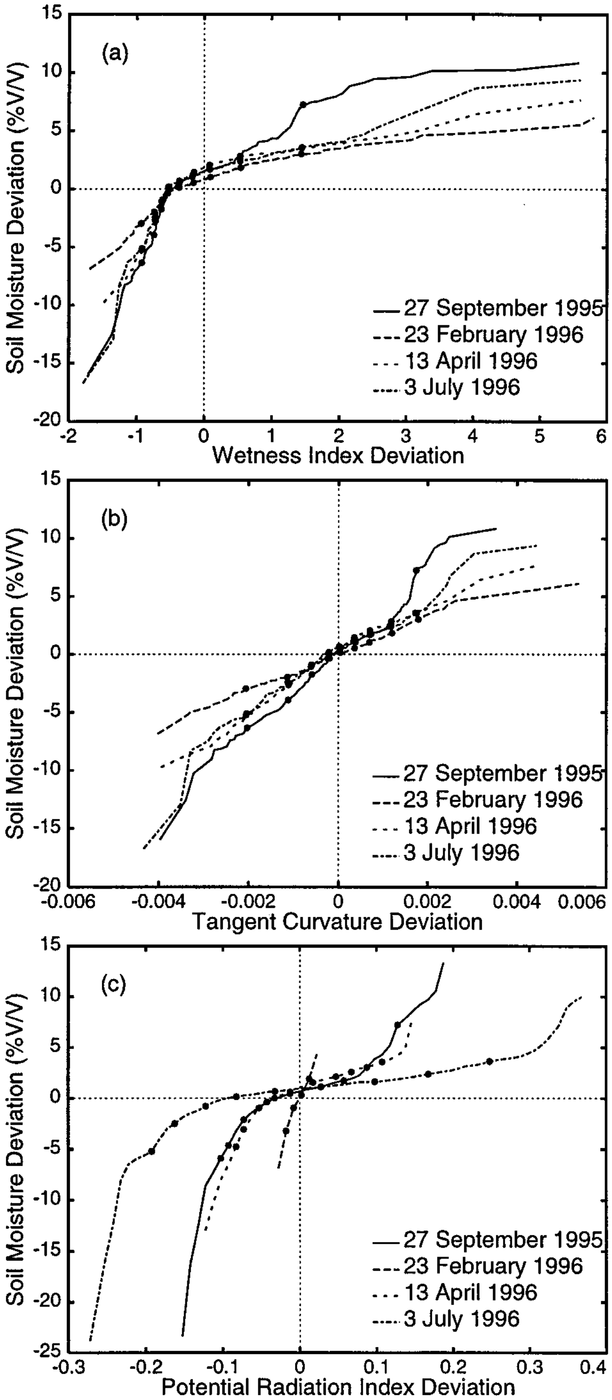

Figure 6. Cumulative distribution functions of soil moisture plotted against the cumulative distribution functions of three terrain indices: (a) wetness index ln(*a*/tan(*β*)), (b) tangent curvature, and (c) potential radiation index. Each value represents the same exceedance frequency for soil moisture and the terrain index. The cdf's are presented as deviations from the mean (i.e., the mean has been subtracted). The markers indicate deciles.

leads to the rapid increase in moisture in the upper one to two deciles.

4.3. Performance of Terrain Indices: Spatial Patterns

We now analyze how well different terrain attributes can predict the spatial pattern of soil moisture and how this explanatory power changes seasonally. The attributes considered here are shown in Table 2. These attributes were chosen because they represent processes that play some role in either the flow of water through the catchment or the spatial variation in the meteorological forcing of the catchment. The effect of measurement errors on these correlations is discussed in the appendix.

Figure 7 shows scatter plots between the wetness index, tangent curvature, the potential radiation index, and soil moisture, for September 27, 1995. The soil moisture pattern on this occasion (Figure 2) is typical of those when the topographic organization of soil moisture is greatest. It is clear from Figure 7 that for organized conditions, the soil moisture is related to the wetness index, although the relationship is nonlinear. There is some relationship between tangent curvature and soil moisture with the convergent parts of the catchment (negative curvature) being wetter than the divergent parts. There is also some relationship between the potential radiation index and soil moisture with the parts of the catchment receiving more solar radiation being drier than the other parts of the catchment.

The seasonal changes in the correlation between a range of terrain attributes and soil moisture are shown in Figure 8 and Table 3. It should be noted that the explained variance was not significantly improved by using a LOWESS regression [*Hirsh et al.*, 1993], which uses an arbitrary functional form and provides an optimal smoothing of the data. For example, the R^2 for the relationship between soil moisture and wetness index on September 27, 1995 (Figure 8a) improved from 0.42 to 0.44 when a LOWESS regression was used instead of a linear regression. This indicates that the assumed exponential decrease in hydraulic conductivity with depth is not causing poor correlations. The seasonal variation in mean soil moisture is also shown in Figure 8. Three different indices shown in Figure 8 relate to lateral redistribution of soil moisture. These are the logarithm of specific area, the wetness index, and tangent curvature. The seasonal pattern of performance of these three indices is similar, and they explain up to 50%, 43%, and 36% of the spatial variation, respectively, when the catchment is sufficiently wet to allow significant lateral redistribution. Correlations between mean curvature and soil moisture are similar to those between tangent curvature and soil moisture. Those between profile curvature and soil moisture are generally smaller than those between tangent curvature and soil moisture. During extremely wet conditions, the correlations with the lateral flow indices are slightly reduced. This is probably due to the increased area of saturated soil and the soil moisture being controlled by soil porosity rather than the local water balance in these areas. During dry conditions, cos(aspect) and the potential solar radiation index are the best predictors and explained up to 12% and 14% of the spatial variation in soil moisture, respectively, during these periods. These correlations reduce during periods when evapotranspiration is low. The rainfall index never fell outside the range [0.95–1.05], owing to the gentle topography at Tarrawarra, and it is only correlated with soil moisture when there is a strong cross correlation between it and the potential radiation index.

Lateral redistribution and evapotranspiration both affect the soil moisture pattern. Therefore linear combinations of wetness index and potential radiation index and of ln(a) and potential radiation index were considered. These performed similarly and explained up to 61% of the spatial variation in soil moisture during wet conditions (Figure 8). However, they

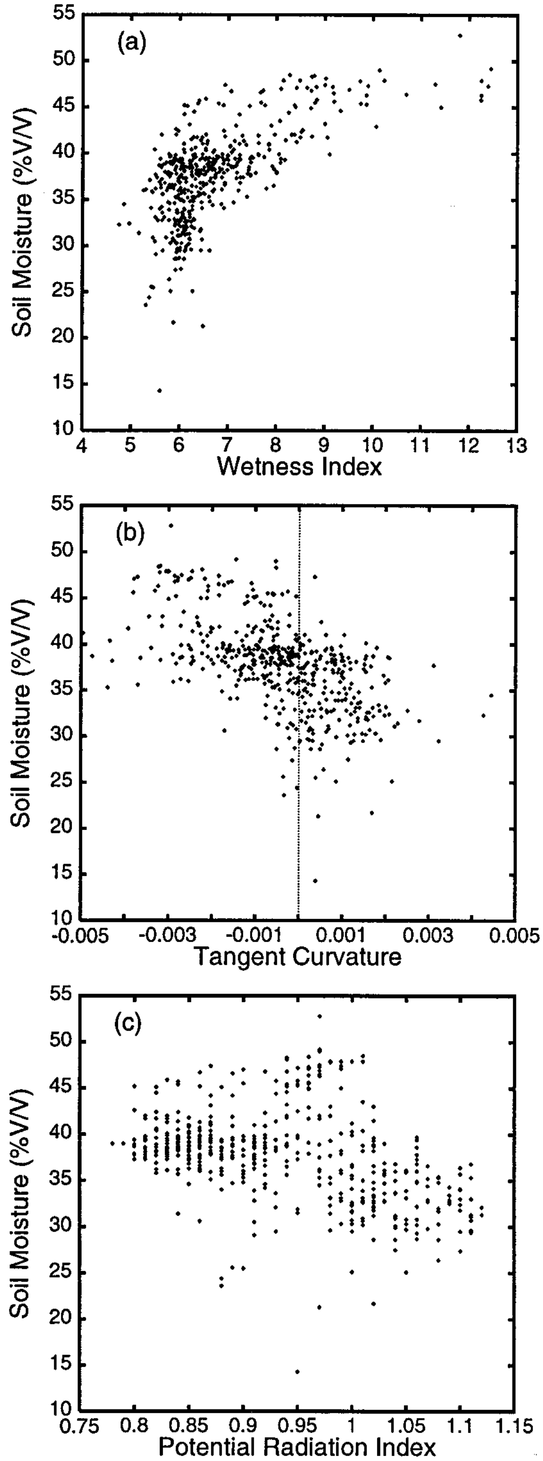

Figure 7. Scatter plots showing the relationship between volumetric soil moisture in the top 30 cm of the soil profile and wetness index, tangent curvature and potential solar radiation index for September 27, 1995.

explained only up to 22% of the spatial variation in soil moisture during dry conditions. The potential radiation index and wetness index are highly independent, and they therefore explain different parts of the spatial variation in soil moisture. When cos(aspect) was substituted for the potential radiation index, explained variance decreased slightly. The seasonal pattern of correlation between soil moisture and the combination of wetness index and potential solar radiation index is complicated. Generally, it is highest when the topographic organization is greatest, that is, during autumn and spring. It is reduced during summer owing to the local soil and evapotranspiration control on soil moisture and during winter owing to extensive saturation and soil porosity control.

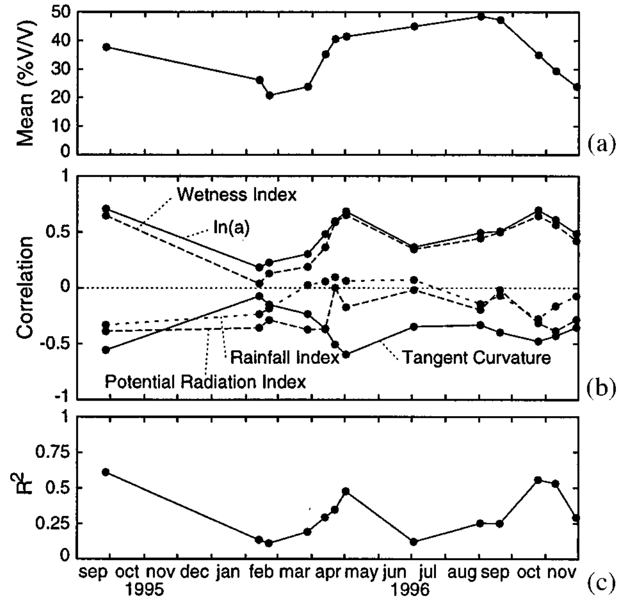

Figure 8. (a) Seasonal variations of mean catchment soil moisture, (b) correlation coefficients between spatial soil moisture patterns and various terrain indices, and (c) coefficients of determination between spatial soil moisture patterns and a combination of wetness index and potential radiation index (by multiple regression).

4.4. Performance of Terrain Indices: Residual Patterns

In this section we analyze the errors in the soil moisture patterns predicted by the terrain indices in order to determine how well the terrain indices explain the spatial organization. Residual maps were plotted and examined qualitatively. Figure 9 shows residual error maps for three different occasions. Light gray relates to pixels for which predicted soil moisture is lower than measured. Dark gray relates to pixels for which predicted soil moisture is higher than measured. We are interested in how well the spatial pattern of soil moisture is explained. If the topographic indices capture the key topographic controls on soil moisture, the residuals should appear random. An organized pattern in the residuals related to topographic position indicates that the terrain attributes used here are not capturing all the topographically related soil moisture variation. The characteristics of that pattern may give some indication of the processes that are not being captured by the terrain indices.

Figure 9a is the residual error map for soil moisture predictions made using a regression relationship between wetness index and soil moisture for September 27, 1995. There is a clear relationship between aspect and the residual. Soil moisture on northerly facing (high radiation) slopes is overpredicted, and that on southerly slopes is underpredicted. This confirms that spatially variable evapotranspiration is important in determining the spring soil moisture pattern. Also, only part of the spatial organization of soil moisture is being explained.

Table 3. Coefficients of Determination for Volumetric Soil Moisture in the Top 30 cm of the Soil Profile and a Range of Terrain Indices

Date	Slope	Cos(aspect)	Tangent Curvature	Profile Curvature	Mean Curvature	ln(a)	ln(a/tanβ)	Potential Solar Radiation Index	Rainfall Index	Potential Solar Radiation Index and ln(a)/tan(β)	Potential Solar Radiation Index and ln(a)
Sept. 27, 1995	0.00−	0.21−	0.31−	0.13−	0.28−	0.50+	0.42+	0.15−	0.11−	0.61	0.61
Feb. 14, 1996	0.12+	0.07−	0.01−	0.04−	0.03−	0.03+	0.00+	0.13−	0.06−	0.14	0.15
Feb. 23, 1996	0.06+	0.04−	0.02−	0.01−	0.02−	0.05+	0.02+	0.08−	0.03−	0.11	0.13
March 28, 1996	0.04+	0.12−	0.06−	0.06−	0.08−	0.09+	0.04+	0.14−	0.00+	0.19	0.22
April 13, 1996	0.04+	0.15−	0.13−	0.12−	0.18−	0.23+	0.13+	0.14−	0.00+	0.29	0.34
April 22, 1996	0.01−	0.00−	0.26−	0.09−	0.23−	0.36+	0.35+	0.00+	0.01+	0.35	0.36
May 2, 1996	0.01−	0.06−	0.36−	0.15−	0.33−	0.47+	0.43+	0.03−	0.00+	0.48	0.48
July 3, 1996	0.00−	0.00−	0.12−	0.02−	0.07−	0.13+	0.12+	0.00−	0.01+	0.12	0.13
Sept. 2, 1996	0.00+	0.06−	0.11−	0.07−	0.13−	0.24+	0.20+	0.04−	0.02−	0.25	0.27
Sept. 20, 1996	0.01−	0.00−	0.16−	0.07−	0.15−	0.26+	0.25+	0.00−	0.01−	0.25	0.26
Oct. 25, 1996	0.00−	0.15−	0.23−	0.10−	0.22−	0.48+	0.42+	0.10−	0.08−	0.56	0.55
Nov. 10, 1996	0.00−	0.21−	0.18−	0.09−	0.19−	0.37+	0.32+	0.15−	0.03−	0.53	0.49
Nov. 29, 1996	0.01+	0.08−	0.13−	0.08−	0.14−	0.24+	0.18+	0.08−	0.00−	0.29	0.30

The sign of the correlation is indicated by the plus or minus following the coefficients of determination.

When a multiple regression including the wetness index and the potential solar radiation index is used to predict soil moisture (Figure 9b), the aspect effect is removed and the residual pattern appears almost random. This suggests that most of the spatial organization is being captured by the terrain indices. Similar results were obtained for all spring and summer patterns (September 27, 1995; and February 14 and 23, March 28, September 20, October 25, and November 10 and 29, 1996) but are not shown here. Figures 9c and 9d are residual maps for multiple regressions of soil moisture against the wetness index and the potential solar radiation index for transition and very wet conditions. Early in the transition from dry to wet (Figure 9c) the soil moisture in the upper end of the eastern drainage line and along the lower part of the main north facing slope is underpredicted. The soil moisture on the upper part of the main north facing slope is overpredicted on this occasion. On April 22, May 2, and July 3, 1996 (Figure 9d), there is a slight tendency for the soil moisture in divergent parts of the catchment to be overpredicted and for that in convergent areas to be underpredicted.

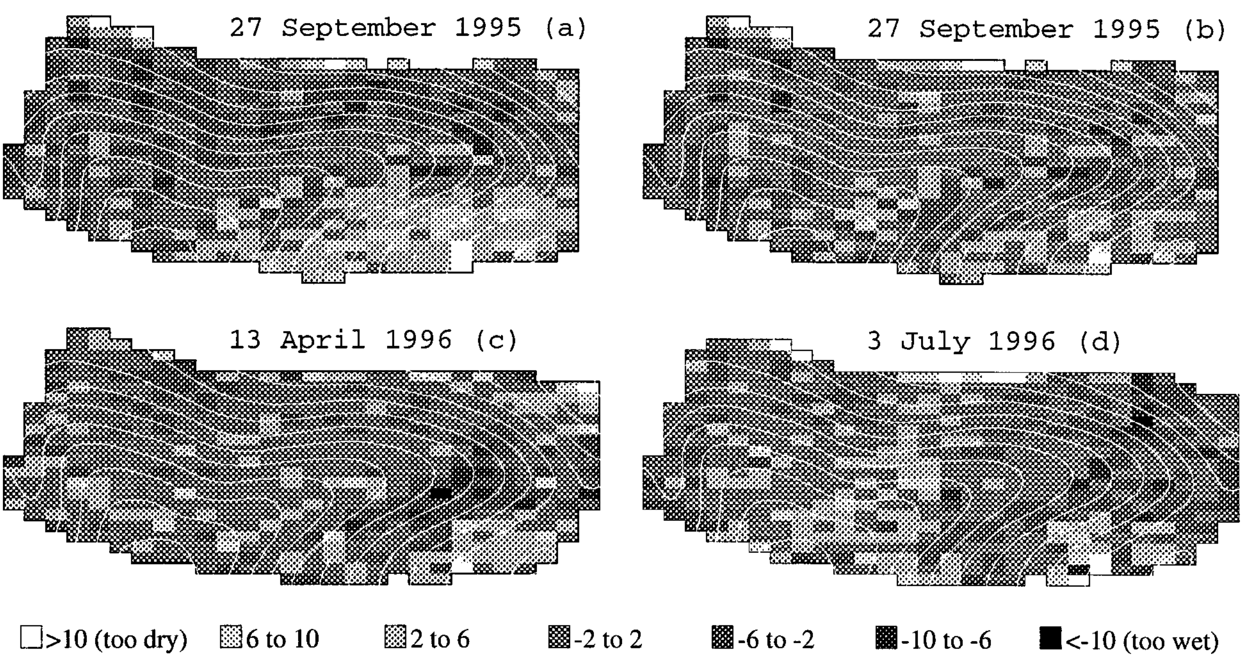

Figure 9. Residual maps for soil moisture predictions made using a regression relationship between soil moisture and various terrain indices. Light gray relates to an underprediction of soil moisture and dark gray relates to an over-prediction of soil moisture. Terrain indices and surveys used are (a) wetness index for September 27, 1995; (b) wetness index and potential solar radiation index for September 27, 1995; (c) wetness index and potential solar radiation index for April 13, 1996; and (d) wetness index and potential solar radiation index for July 3, 1996.

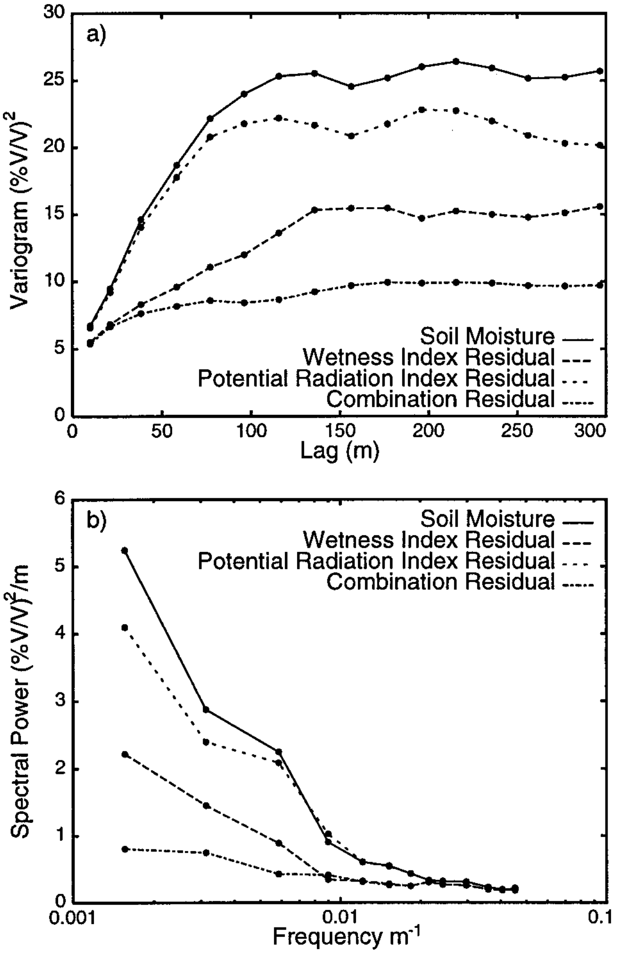

Figure 10. (a) Variograms of soil moisture and variograms of the residuals from a regression with various terrain indices for 27 September, 1995. (b) Same as Figure 10a but represented as a power spectrum.

4.5. Performance of Terrain Indices: Scale Analysis

In this section a scale analysis of the errors is undertaken. This provides information on how well the soil moisture variation at different scales is being predicted by the terrain indices. Figure 10a shows variograms of soil moisture and of the residuals from regressions of soil moisture against different terrain attributes for September 27, 1995. The value of the variogram of the soil moisture at a given lag represents the total variance at that lag, while the value of the variogram of the residual represents the unexplained variance at that lag. The difference between the value of the variogram for soil moisture and that for the residual at a given lag represents the explained variance at that lag. If the variogram of the soil moisture is increasing more quickly (i.e., is steeper than) than the variogram of the residual, part of the variance at that lag is being explained. The existence of random measurement errors means that the residual variogram for a perfect predictor of the soil moisture pattern would consist of a pure nugget effect (horizontal variogram) equal to the measurement error variance. The wetness index explains some of the spatial variance in soil moisture at all the scales ($\geq$10 m) considered here, and it explains a substantial proportion (about 50%) of the variability at scales greater than approximately 50 m. Using the logarithm of the specific area as the predictor gave very similar results. The potential radiation index explains very little of the variation for scales less than approximately 80 m, but for scales greater than 80 m it explains approximately 15% of the variance in soil moisture. When soil moisture is predicted using a multiple regression against the wetness index and the potential radiation index, a substantial reduction in the unexplained variance is obtained, compared to the wetness index alone. It is interesting that this improvement in soil moisture prediction occurs for scales greater than 40 m, while the potential radiation index was only useful at scales greater than 80 m, when it was used as the sole predictor.

Figure 10b shows the same information as Figure 10a; however, it is in the spectral domain rather than in the lag domain. In comparing Figure 10a and Figure 10b it is important to note that the variogram gives the total variance integrated over all scales less than or equal to a given lag while the power spectrum gives the spectral variance per unit frequency (i.e., for a scale class). Again, the effect of measurement error needs to be accounted for. Most of the variance in the soil moisture is concentrated at frequencies less than 0.01 m^{-1} (wavelengths greater than 100 m). Again, it is clear that the wetness index explains at least some of the variance at frequencies less than 0.02 m^{-1} (wavelengths greater than 50 m) but that the potential solar radiation only explains variations at lower frequencies (i.e., wavelengths greater than 170 m). The improvement in prediction at wavelengths greater than 110 m when the potential radiation index is combined with the wetness index is also evident.

5. Discussion and Implications

5.1. Processes Leading to Organization

The degree of topographic organization of soil moisture varies seasonally at Tarrawarra. In the terminology of *Blöschl* [1999], soil moisture in summer exhibits a low degree of organization (i.e., continuity only), while in winter it exhibits a high degree of organization (connectivity and convergence in addition to continuity). The varying degree of organization is related to variations in the relative importance of different processes. Subsurface lateral flow occurs and is important in the hydrology of Tarrawarra, especially in the development of the organization observed in the wet patterns. However, the organization observed in the soil moisture patterns actually results from a combination of both surface and subsurface pathways. After sufficient rain on the dry catchment, subsurface flow leads to wet areas high up in the strongly convergent areas during the autumn (Figure 4). The wetness index underpredicts soil moisture in these areas (Figure 9c). This effect, which is related to the dynamics of the subsurface flow, has been recognized by *Barling et al.* [1994]. Field observations during a runoff event on April 14 show that this in turn activates surface flow and runon infiltration processes, which dominate the lateral redistribution of water downstream of the initial source areas. The observed changes in the soil moisture pattern between March 28 and April 13 and between April 13 and 22 also suggest that wet areas grow from upstream, not downstream as predicted by the steady state wetness index [*Grayson et al.*, 1997].

The second organizing process is related to spatial variations in evapotranspiration. In summer, when only a small amount of topographic organization is present, the potential radiation index shows the strongest relationship with soil moisture. This effect is also evident in spring (e.g., September 27, 1995), when the catchment is drying, and in early autumn (April 13, 1996) as the catchment wets up. This is consistent with the findings of *Moore et al*. [1988]. This effect is only apparent when evapotranspiration is important in the local water balance (drying and dry periods), and it disappears during periods of low evapotranspiration compared to rainfall (wetting and wet periods).

5.2. Predictive Ability of Terrain Indices

Many index-based hydrologic models only make use of a distribution function for their water balance calculations. Our analysis of the distribution functions of soil moisture suggests that several different terrain indices capture their general shape. The ability of an index to predict the soil moisture distribution function is not necessarily the same as its ability to predict the spatial soil moisture pattern. For example, tangent curvature is a significantly better predictor of the distribution function than the wetness index is; however, the wetness index is a slightly better predictor of the soil moisture pattern. There is a considerable amount of temporal variability in the shape of the soil moisture distribution function that cannot be captured by a single static index. This temporal variability leads to a step up in the upper 10–20% of the moisture distribution. This step up in the soil moisture is up to 5% compared to the dry case (February 23, 1996). When integrated over the 300 mm measurement depth, this is equivalent to 15 mm of water. Given that these differences occur in the wet end of the moisture cdf, they are likely to be significant from a runoff perspective.

There is also temporal variability in the variance (a factor of 4.5) and, to a lesser degree, the coefficient of variation of soil moisture (a factor of 1.6). Both lateral redistribution and spatial variations in evapotranspiration related to insolation appear to be important in determining the spatial pattern of soil moisture. Methods for representing the combination of these two processes, that account for changes in their relative importance, need to be developed. One possible approach is to use a weighted combination of existing indices with the weighting based on average soil moisture storage. By using this approach, temporal variability in the distribution function would be introduced in two ways: first, through the variable weighting, and second, through seasonal variations in the index representing spatially variable radiation effects.

Combinations of various indices may also improve the predictions of spatial patterns of soil moisture. Using a combination of the wetness index and potential radiation index, it was possible to explain the majority of the topographically related part of the spatial organization (Figures 9b–9d) at Tarrawarra. This was not generally possible when using a single index. However, here the relative importance of the two indices was determined by multiple regression against observed data, that is, a posteriori. While we have demonstrated the potential of a combination of terrain indices to characterize the topographic organization of soil moisture, we need to develop methods for determining a priori the relative importance of the indices that account for lateral flow and topographically related evapotranspiration.

It is clear that the degree of spatial organization of soil moisture is an important limit on the predictive power of terrain indices. The degree of spatial organization in the soil moisture patterns is lowest in summer, increases to a maximum during moderately wet periods, and decreases again during extremely wet periods (Figures 2–5). The predictive ability of the combination of wetness index and potential radiation index has a similar seasonal pattern (Figure 8). This is consistent with the results of other workers who have considered a range of conditions [e.g., *Burt and Butcher*, 1985]. Also, the spatial pattern of residuals from the combination of wetness index and potential radiation index indicate that these indices are capturing most of the topographic organization on each occasion (residual maps appear random), yet there is a wide range in the predictive power of the indices over time.

To summarize, there are three factors that limit the predictive ability of terrain indices. First, the spatial variation of soil moisture includes both organized and random components and, by its nature the random component is not predictable in detail. This randomness sets an upper limit to the predictive power, which never exceeds 61% at Tarrawarra and rarely exceeds 50% in the literature. Second, current indices do not represent all the processes that are important in determining the spatial pattern of the soil moisture. Third, the spatial pattern and the distribution function of soil moisture change over time and these temporal changes can not be captured by a static index. Nevertheless, our results show that it is possible to improve terrain index–based predictions such that the organized component of the soil moisture is predicted well, at least a posteriori.

5.3. Terrain Indices, Modeling, and Scale

There are many sources of variation in hydrologic systems operating over an extremely wide range of scales (see work by *Seyfried and Wilcox* [1995] for some excellent examples of the range of scales and nested nature of spatial variability). Some of these sources are topography related and might be expected to result in topographically organized variation; others are not related to topography. This raises two important questions. First, how much variation can we expect to explain by using (large-scale) topography alone? This really depends on what proportion of the spatial variation is topographically organized and how much is random. This varies seasonally, as discussed above. We cannot predict the details of random variation.

Second, what are the scales at which topography can be used to explain spatial variation? There are four ranges of scale we will consider here. At the very small scales (smaller than the 10 m resolution of the moisture data used here) microtopographic variations exist because of soil disturbance by cattle (at a scale of approximately 150 mm) and there is likely to be small-scale heterogeneity in soil characteristics. Vegetation varies at the individual plant scale and at a patch scale of 1–10 m. These small-scale sources of variability, along with measurement error contribute to the nugget effects in variograms of both the soil moisture and the residuals. They are not predictable using terrain indices that describe variations at scales from the digital elevation model (DEM) scale (5 m) up to the catchment scale. From a practical perspective the details of this small-scale variability are unknowable, at least at the present time. However, if necessary, their statistical properties could be determined and represented statistically by making the appropriate measurements. These very small-scale variations contribute significantly to the poor performance of the indices. In Figure 10a the variogram for the residuals of the combination of wetness index and potential radiation index shows that there is 5.4 $(\% \text{ vol/vol})^2$ unexplained variance at the 10 m scale (about half of it being measurement error) out of a total of 9.4 $(\% \text{ vol/vol})^2$ unexplained variance. That is, more than half the unexplained variance results from variability in soil moisture at very small (<10 m) scales. Between the 10 m (DEM) scale and the hillslope scale there is variation due to topographically routed lateral flow. Topographic indices representing lateral flow (wetness index, upslope area) are able to capture this source of variability. At slightly larger scales there are variations due to contrasts between hillslopes (e.g., different aspect in this case). Topographic indices representing these contrasts (potential radiation index) are able to capture this source of variability. Clearly, these indices represent the variations from hillslope to hillslope. These are the scales that are resolved by the DEM. There is a small amount of unexplained variability at scales between the DEM scale and the catchment scale. This is probably related to variability in soils and vegetation. At still larger scales that are beyond the maximum scale examined in this study, one may expect that other sources of variability come in. One important source may be different land use types. Land use is relatively uniform at Tarrawarra. Indices representing soil moisture at larger scale are therefore likely to require some sort of representation of the prevailing land use.

These scale considerations have important implications for representing the spatial organization of soil moisture in distributed (process-based dynamic) models. These implications vary depending on whether the spatial organization is resolved at the model element scale. For large model elements, compared to the scale of the spatial organization, some sort of representation of the processes within a model element is necessary (subgrid parameterization). One simple way of representing subgrid processes is to use effective parameters which reflect some sort of average behavior within a model element [e.g., *Wen and Gómez-Hernández*, 1996]. Often it is assumed that these parameters can be related uniquely to the underlying detailed distribution (of soil moisture or topography in this case or of hydraulic conductivity in other cases). This relationship is termed the "scaling rule" [e.g., *Blöschl*, 1999]. However, if the nature of the organization changes throughout the year, it is clear that not only will the parameters change but also the scaling rule will change. This may compromise the reliability of the model. What are needed are methods that account for the changing degree of organization within model elements.

For small model elements, compared to the scale of the spatial organization, the organization can be explicitly resolved by the model; however, there will always be some random subgrid variability. Also, it is well recognized [e.g., *Stephenson and Freeze*, 1974] that specifying the antecedent moisture for each model element is critical to accurate simulations. Usually, some simple assumption is made such as using a uniform distribution or a distribution based on the steady state wetness index. Contrasting Figure 1 with Figures 2–5 demonstrates how erroneous the wetness index would be at Tarrawarra during summer and autumn. *Grayson et al*. [1995, Figure 19.9, p. 690] show that the difference in runoff response between random and organized initial saturation deficit is not only profound but dependent on the intensity or total rainfall depth. Differences of similar importance can be expected to occur at Tarrawarra and in other catchments.

Similarly, for distribution function models, the changing degree of organization of soil moisture can be important. It is interesting that the wetness index has been shown to be a useful tool in modeling the size of saturated source areas [e.g., *Beven and Kirkby*, 1979; *Moore et al*., 1986; *Ambroise et al*., 1996], even though it is generally a poor predictor of spatial patterns and, at least at Tarrawarra, the distribution function. There are several reasons why this might be so. First, it is not necessary to represent the spatial variability of soil moisture over the entire landscape. From a water balance perspective it is sufficient to represent the variability of soil moisture within the parts of the landscape that act as variable source areas. It is likely that model calibration will ensure that this part of the distribution function is adequately represented, at least in situations where the variable source areas are not highly dynamic. However, it is also fair to say that models that use empirical distribution functions not related to terrain (e.g., the HBV model [*Bergström*, 1995]) also perform well when properly calibrated based on runoff.

6. Conclusions

In this paper we address two questions: To what degree does soil moisture exhibit spatial organization? and Can that organization be predicted using terrain attributes? An analysis of 13 soil moisture patterns, each based on over 500 individual measurements of soil moisture, from the Tarrawarra experimental catchment indicates that soil moisture does exhibit spatial organization. The degree of spatial organization varies seasonally. During moderately wet periods (winter) the spatial pattern of soil moisture is strongly controlled by the topography, which influences the lateral redistribution and evapotranspiration processes. Wet areas are focused on the drainage lines and convergent areas. This produces a high degree of spatial organization. In summer, when the catchment is dry, there is only a small amount of topographic organization related to spatial variation in evapotranspiration. As the catchment wets up during the autumn, the amount of topographic organization increases, but the character of that organization is different from that later in the winter in that wet areas are focused in convergent areas at the upper end of the drainage lines. When the catchment becomes extremely wet, extensive (near) saturated conditions exist, and the degree of organization decreases. Similar seasonal changes in behavior are likely to occur in a wide range of landscapes where there is significant seasonality [*Grayson et al*., 1997].

The predictive capability of terrain attributes is examined in terms of (1) how well the indices represent the shape of the distribution function of soil moisture, (2) how well they represent the spatial patterns of soil moisture, and (3) at which scale the indices are best at predicting the spatial organization of soil moisture.

1. The distribution function of the spatial variability of the soil moisture is temporally variable and is influenced by the presence of organization. The shape of the soil moisture distribution function is generally quite different from that of various terrain indices. Tangent curvature was the best predictor of the general shape of the soil moisture distribution function. The steady state wetness index and $\ln(a)$ were poor predictors of the soil moisture distribution function. Static indices are not able to capture the temporal variability in the soil moisture distribution, especially in the wet 10–20% of the moisture cdf.

2. How well a particular terrain index performs in terms of predicting the spatial pattern of soil moisture depends on the degree of organization and on how well it represents (acts as a surrogate for) the processes controlling the organized component of the spatial distribution of water. During wet conditions $\ln(a)$ was the best univariate predictor of the spatial pattern of soil moisture (explained variance of up to 50%), and the wet-

ness index (explained variance of up to 42%) and tangent curvature (explained variance of up to 36%) were almost as good. During dry conditions cos(aspect) (explained variance of up to 12%) and the potential solar radiation index (explained variance of up to 14%) were the best univariate predictors of the spatial pattern. Combinations of $\ln(a)$ and the potential solar radiation index, and of the steady state wetness index and the potential solar radiation index produced similar results and were able to explain up to 61% of the spatial variation of soil moisture during wet conditions and up to 22% during dry conditions. These combinations were generally able to predict the majority of the organized component of the spatial variability and therefore represent upper limits to the predictive power of terrain indices for Tarrawarra. Seasonal changes in the predictive ability of the indices are due to seasonal changes in the degree of topographic organization. Such changes are likely where ever there is significant seasonality in soil moisture.

3. Indices such as $\ln(a)$ or $\ln(a/\tan(\beta))$ explained some of the spatial variability at all scales from 10 m up to the catchment scale (i.e., they represent variability within the hillslope). Indices such as the potential solar radiation index explain some of the spatial variability at scales from 80 m up to the catchment scales (i.e., they represent variation between different hillslopes). There is a significant amount of random behavior, especially at small scales, that cannot be predicted using terrain indices. This is likely to be the case elsewhere.

We strongly believe that wetness indices should be based on considerations of the actual processes occurring in a particular catchment under a particular climate. Ultimately, we need to consider a modified range of indices for the spatial prediction of soil moisture that can represent the changes in dominant processes that occur through the year. Even then we must recognize that the predictive power of topographic indices is limited by the nontopographically organized component of the spatial variation and the unexplained variance will always be significant, rarely less than 50% based on this study and the literature.

Appendix: Measurement Errors

Measurement errors can influence the predictive performance of the terrain indices by reducing the calculated correlations. The effect of the soil moisture measurement error is considered here. The TDR equipment used at Tarrawarra has a quoted error of ±2% vol/vol or less and our own calibrations suggest an error standard deviation of ±1.7% vol/vol. Thus we would expect a variance of 2.9 $(\%\ \text{vol/vol})^2$ if the soil moisture was completely uniform. The total variance in the soil moisture is given in Table 1 for each sampling occasion. The smallest is 5.3 $(\%\ \text{vol/vol})^2$ (February 23, 1996), which is only twice the expected error variance. Other occasions with low soil moisture variance are March 28 and November 29, 1996. For these three occasions the correlations between the soil moisture and the terrain attributes may be artificially reduced. If we assume that all of the measurement error contributes to the unexplained variance of the spatial soil moisture patterns we can estimate a corrected coefficient of determination. For example, on February 23, 1996, the observed spatial variance was 5.3 $(\%\ \text{vol/vol})^2$ and the explained variance was 0.7 $(\%\ \text{vol/vol})^2$ (i.e., 13% of the observed variance was explained by a combination of upslope area and potential radiation index; Table 2). When allowing for a measurement error variance of 2.9 $(\%\ \text{vol/vol})^2$, the total variance is 2.4 $(\%\ \text{vol/vol})^2$ and now the explained variance of 0.7 $(\%\ \text{vol/vol})^2$ represents 29% of the total variance. An increase of 16% to 29% of the explained variance is an upper limit as not all of the error may contribute to the unexplained variance. While this is a significant increase in explained variance it does not change the overall pattern in Figure 8. On the other dry occasions the effect of measurement errors is smaller. On the wet occasions the effect of measurement errors is negligible since the spatial variances of soil moisture are large as compared to the measurement error variance.

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G. Blöschl, Institut für Hydraulik, Gewässerkunde und Wasserwirtschaft, Technische Universität Wien, Karlsplatz A-1040, Vienna, Austria.

R. Grayson, T. A. McMahon, and A. W. Western, Centre for Applied Hydrology and Cooperative Research Centre for Catchment Hydrology, Department of Civil and Environmental Engineering, University of Melbourne, Parkville, Victoria 3052, Australia. (western@civag.unimelb.edu.au)

G. R. Willgoose, Department of Civil, Surveying and Environmental Engineering, University of Newcastle, Callagham 2308, Australia.

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