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STATIC AND DYNAMIC CONTROLS OF SOIL MOISTURE VARIABILITY IN THE SHALE HILLS CATCHMENT

A Thesis in

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by

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ABSTRACT

Soil moisture is an important component of the hydrologic cycle. The spatial and temporal variability of soil moisture influences environmental processes at a wide range of spatial scales. This study utilized a four-year database consisting of soil moisture measurements at 106 locations from the surface down to 1.1-m depth within a forested catchment in central Pennsylvania to address the following objectives: 1) characterizing the relationship between soil moisture spatial variability and catchment-wide wetness to assess the uncertainty in estimating spatially-averaged soil moisture; 2) examining temporal changes in vertical soil moisture profile along a topographic gradient to identify processes that influence the above stated relationship; 3) compare the spatial organization of soil moisture at different measurement depths; 4) examine the correlation between soil moisture at different measurement depths and soil terrain indices. Our results showed that spatial variability (defined as the standard deviation) increased exponentially with increasing catchment-wide spatially-averaged soil moisture (R^2 = 0.863, p < 0.05). This relationship led to the widening of confidence intervals as spatially-averaged soil moisture increased at all depths (increased CI of 0.040, 0.038, 0.033, 0.037, 0.031, 0.029-m^3/m^3 between lowest and highest spatially-averaged soil moisture for 10, 20, 40, 60, 80 and 100-cm depths, respectively). Similarly, the number of samples required for obtaining 95% confidence interval in the estimates of spatially-averaged soil moisture increased as spatially-averaged soil moisture increased at all depths (number of samples increased by 23, 25, 24, 27, 19, and 16 between lowest and highest spatially-averaged soil moisture for 10, 20, 40, 60, 80 and 100-cm depths, respectively). Our analysis of temporal changes in the vertical soil moisture profile indicated that during the winter through early summer, the emergence of a shallow water table in the valley and spatially and temporally limited concentrated lateral flow along hillslopes, increased catchment-wide soil moisture spatial variability during wet periods. Conversely, during periods

of low soil moisture, an increase in hydrological processes operating across the watershed, particularly evapotranspiration, acted to decrease the catchment-wide soil moisture variability. The results of this analysis have implications for optimizing soil moisture monitoring in forested watersheds, particularly watersheds which exhibit strong seasonal fluctuations in water table height.

At the Shale Hills catchment, surface (<20-cm) soil moisture organization exhibited seasonal trends: during the winter through early summer, areas of high soil moisture were concentrated within convergent landforms, while during the summer through early fall, areas of high soil moisture were more randomly distributed throughout the catchment. This indicates that seasonal removal of soil moisture, primarily through evapotranspiration, had a significant influence on near-surface soil moisture organization under dry conditions, while topography was an important control on soil moisture organization under wet conditions. Sub-surface (>20-cm) soil moisture organization exhibited temporal persistence, with soil moisture above the catchment-wide average concentrated within convergent landforms under both wet and dry conditions. Deep soil profiles in convergent landforms provide a store of soil moisture that persisted even under dry conditions, indicating that soil moisture organization within the subsurface is a function of both topographic controls and soil depth. The results of linear regression between soil moisture and soil-terrain attributes indicate that terrain features generally outperformed soil textural properties in explaining the variability of soil moisture within the forested catchment. Slope, depth to bedrock, topographic wetness index (TWI) and rock fragments were significant ($\alpha = 0.05$) on at least 85% of the measurement days for all depth intervals measured. Intermediate depths (40 and 60-cm) exhibited the highest mean R^2 values for TWI and upslope contributing area, while mean R^2 values for slope and depth to bedrock increased with increased soil depth. No seasonal trend is present in the R^2 values for sub-surface soil moisture (60, 80 and 100-cm) and depth to bedrock and topographic wetness index, with depth to bedrock exhibiting high R^2 values throughout the four-year period. These results support our conclusion that both topography and soil depth are important in controlling soil moisture organization at depth, while seasonal fluctuations in evapotranspiration and topography are important controls on soil moisture organization at the near-surface.

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Chapter 1

Dynamic soil moisture spatial variability as a function of soil-landform units and soil depth in the Shale Hills Catchment

Introduction

Soil moisture is an important component of the hydrologic cycle. The spatial and temporal variability of soil moisture influences environmental processes at a wide range of spatial scales. At the regional scale, the spatial distribution of soil moisture provides an important feedback mechanism for climate dynamics and is an important control on the division of solar energy into latent and sensible heat (Koster et al., 2003; D'Odorico and Porporato, 2004). At the catchment scale, the distribution of soil moisture in space and time influences the non-linear behavior of a catchment's response to storm events and the partitioning of precipitation into stream runoff, infiltration, and storage within the soil zone (James and Roulet, 2007; Zehe and Bloschl, 2004; Meyles et al., 2003). Our ability to model these hydrological processes requires knowledge of how soil moisture varies across the landscape and vertically within the soil profile, and how this variability changes under different wetness conditions.

Physical (such as soil properties, underlying geology, topography, and vegetation cover) and hydrological (such as sources, sinks, and translocation of water in the vadose zone) characteristics of a field site exert a first order control on the spatial variability of soil moisture. Reynolds (1970) grouped the physical and hydrological characteristics that influence soil moisture variability into static and dynamic factors. Static factors generally do not change over the timescale of a research project and include topographic and most soil properties. Dynamic factors include precipitation, evapotranspiration, lateral surface and subsurface flow, and presence or absence of a groundwater table, which can vary in space and time over the length of a research project. Dynamic factors influence the overall wetness state of a catchment, and can interact with static factors to alter the spatial variability of soil moisture at the seasonal or storm event time scales. For example, Western et al. (1999) found that under wet conditions topographic indices were the best predictors of soil moisture, particularly specific contributing area that is related to lateral movement of soil water. Under dry conditions, they found that aspect, which is related to the amount of solar radiation that different portions of a catchment receive, is a good predictor of soil moisture spatial distribution. Famiglietti et al. (1998) found that under wet conditions soil total porosity and hydraulic conductivity were primary controls on the spatial variability of soil moisture, while under dry conditions, aspect, elevation and soil texture were important controls.

The complex interplay of dynamic and static factors at a field site leads to different relationships describing how soil moisture spatial variability (i.e., the standard deviation or coefficient of variation of soil moisture measured across the landscape) changes with catchment wetness (i.e., spatially-averaged soil moisture over the entire catchment) (Western and Blöschl, 1999; Brocca et al., 2007). This relationship has implications for optimal field sampling of soil moisture and the uncertainty estimation of spatially-averaged soil moisture. For example, Owe et al. (1982) used the standard deviation of soil moisture to determine that the number of samples required to be 95% confident of the true spatial mean was largest when mean spatial soil moisture was at intermediate values (θ = 0.15 – 0.25 m^3/m^3). Similarly, Famiglietti et al. (2008) used the relationship between spatially-averaged soil moisture and the standard deviation to calculate 95% confidence intervals for estimation of mean soil moisture based on different sample sizes. They found the 95% confidence intervals were widest within intermediate soil moisture values (θ = 0.10 – 0.35 m^3/m^3). On the other hand, Reynolds (1970), who observed a positive relationship between variability and spatially-averaged soil moisture, found that the required sample size to achieve a 95% confidence in the true spatial mean was positively related to catchment wetness.

Figure 1-1 illustrates two models that have emerged regarding the relationship between soil moisture variability and a catchment overall wetness: a convex upward relationship fitted using exponential functions (Owe et al., 1982; Western et al., 2003; Choi and Jacobs, 2007; Famglietti et al., 2008; Penna et al., 2009) and a curvilinear relationship (Reynolds, 1970; Famglietti et al., 1998; Western et al., 1998; Hupet and Vanclooster, 2004, Williams et al., 2009).

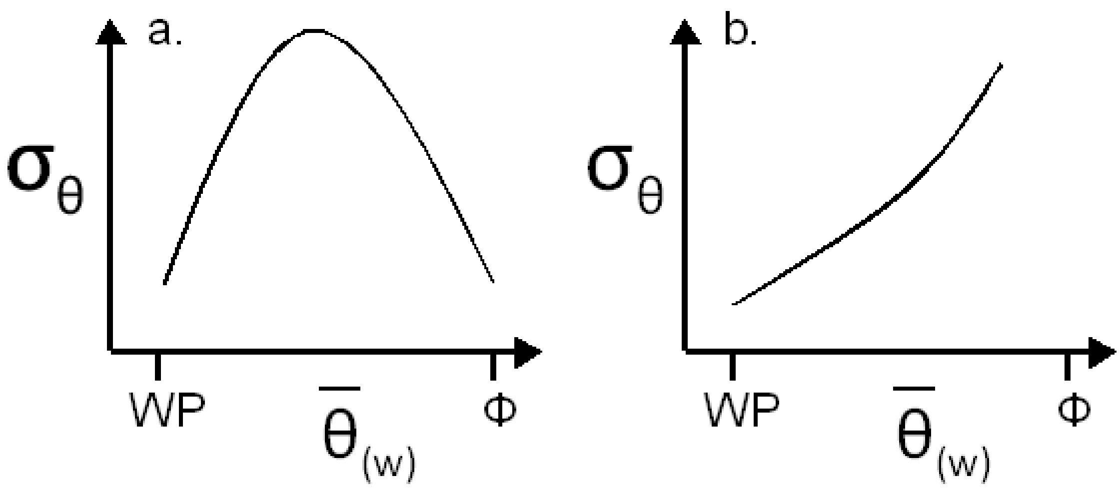

Figure 1-1: Conceptual diagram of observed relationships between catchment-wide spatially-averaged soil moisture ($\bar{\theta}_w$) and the standard deviation of all individual soil moisture measurements (σ_θ): a) convex upward relationship; b) positive curvilinear relationship. WP = wilting point of soil; Φ = total soil porosity. (Modified from Western et al., 2003).

Studies that have found an upward convex relationship between soil moisture variability and catchment wetness have attributed the shape to the slope of soil water retention curve, which is related to soil pore size distribution and soil textural properties (Veerbeken et al., 2008), heterogeneous precipitation fields and drainage rates at scales larger than 800-m (Famiglietti et al., 2008), and increased vertical and lateral redistribution of soil water during periods of high soil moisture (Owe et al., 1982). Studies that have found a positive relationship between soil moisture variability and catchment wetness have attributed the shape of the relationship to differences in hydraulic conductivity under wet conditions (Famiglietti et al., 1998), growing season spatial variability in evapotranspiration related to different vegetation covers (Hupet and Vanclooster, 2004), and soil textural differences that can inhibit soils from reaching uniform saturation during periods of high soil moisture (Williams et al.,2009). Knowledge of how spatial variability changes with catchment wetness require knowledge of how various factors control soil moisture variability.

Sources of soil moisture spatial variability operate not only spatially across a field site, but vertically within a soil profile. Monitoring vertical variability in soil moisture provides a more robust picture of the temporal and spatial dynamics of soil moisture, and help to constrain sources of soil moisture variability. Furthermore, our ability to model hydrological and environmental processes requires knowledge of both surface and subsurface soil moisture dynamics. For example, Stieglitz et al. (2003) found that mid-slope regions behave as a ridge-valley “cutoff switch” for shallow subsurface lateral flow. Increases in stream runoff associated with increases in shallow soil moisture in the midslope and increases in stream electrical conductivity closely coupled with an increase in deep soil moisture in the midslope. Similarly, McNamara et al. (2005) suggested that hydrologic connectivity is low during dry periods when deep soils are dry and prevent the transport of soil water from upper hillslopes to the stream. Only when these deep dry-soil barriers “wet up” do significant lateral flow from upslope soils contribute to stream discharge. Vereecken et al. (2008) highlighted the need for more catchment-scale monitoring of soil moisture at multiple depths, as these datasets can contain important information regarding hydrological fluxes. Many previous studies that examined the relationship between soil moisture variability and mean soil moisture were primarily conducted in the upper 0.30-m of soil for comparison to remotely-sensed data (e.g., Southern Great Plains Hydrology Experiments and Soil Moisture Experiments field campaigns). Monitoring soil moisture at multiple depths will allow a more complete picture of the spatial and temporal behavior of hydrological processes that affect both near-surface and subsurface soil moisture variability.

A four-year monitoring campaign of spatial and vertical soil moisture dynamics was conducted at the Shale Hills catchment, a 7.9-ha forested catchment in central Pennsylvania (Lin et al., 2006; Lin and Zhou, 2008). The combination of monitoring both spatial (lateral) and vertical soil moisture dynamics provides a unique opportunity to investigate how hydrological fluxes affect the relationship between soil moisture spatial variability and catchment-wide averaged moisture content at different soil depths. At the same time, this database provides an opportunity to examine how hydrological fluxes influence vertical soil moisture profiles and the relationship between near-surface and deeper soil moisture measurements. Specific objectives of this study were to: 1) characterize the relationship between spatial variability and catchment wetness to assess the uncertainty in estimating spatially-averaged soil moisture; and 2) examine temporal changes in vertical soil moisture profile along a topographic gradient to identify processes that influence this relationship.

Methodology

Site Description

The Shale Hills catchment, a National Critical Zone Observatory, is located in Huntingdon County, PA. The area of the catchment is 7.9-ha, and the elevation ranges from 256-m at the outlet of the catchment to 310-m at the highest ridge. The catchment is characterized by steep slopes (up to 25%–48%) and narrow ridges. Several species of maple, oak, and hickory are typical deciduous trees found on the sloping areas and on ridges, while the valley floor is encompassed by eastern hemlock coniferous trees (Lin, 2006). The catchment is underlain by medium-dark grey to olive colored, steeply bedded, highly fractured Rose Hill Shale exhibits reddish-brown iron oxidation stains. The Rose Hill Shale formation is estimated to be approximately 300-m thick and consists of interbedded shale and sandstone and some interbedded limestone in the upper portions of the formation (PA Department of Environmental Resources, Atlas 86, 1989).

A detailed soil survey of the catchment identified five soil series based on landform position and depth to bedrock (Lin, 2006). Weikert soil, described in the Official Soil Series Description (USDA-NRCS, 2003) as a shallow, well-drained soil formed from weathered gray and brown acid shale, siltstone and sandstone, is found on the steep planar hillslopes and summit regions within the catchment. Berks, a moderately deep, well-drained soil formed from residuum weathered from shale siltstone and fine grained sandstone, is found on the toe-slope positions and side-slopes of the concave hillslopes. Rushtown, a very deep, excessively drained soil found in colluvial deposits, is found in the concave hillslopes. Ernest soil, a very deep, moderately to well-drained soils with low permeability, is found in the valley bottoms and near stream zone. Blairton soil, a moderately deep, poorly to well drained soil found on uplands, is located within the valley bottom at the east portion the catchment. There is a clear relationship between soil type, depth to bedrock and topography. A map of the Shale Hills catchment which includes all soil moisture sampling locations and distribution of soil series is given in figure 1-2. Climate at the Shale Hills catchment is typical of central Pennsylvania, with the majority of precipitation falling as snow in the winter and rain during the spring through fall months. Precipitation during the summer months typically occurs during convective weather fronts which can produce high intensity, short duration storm events.

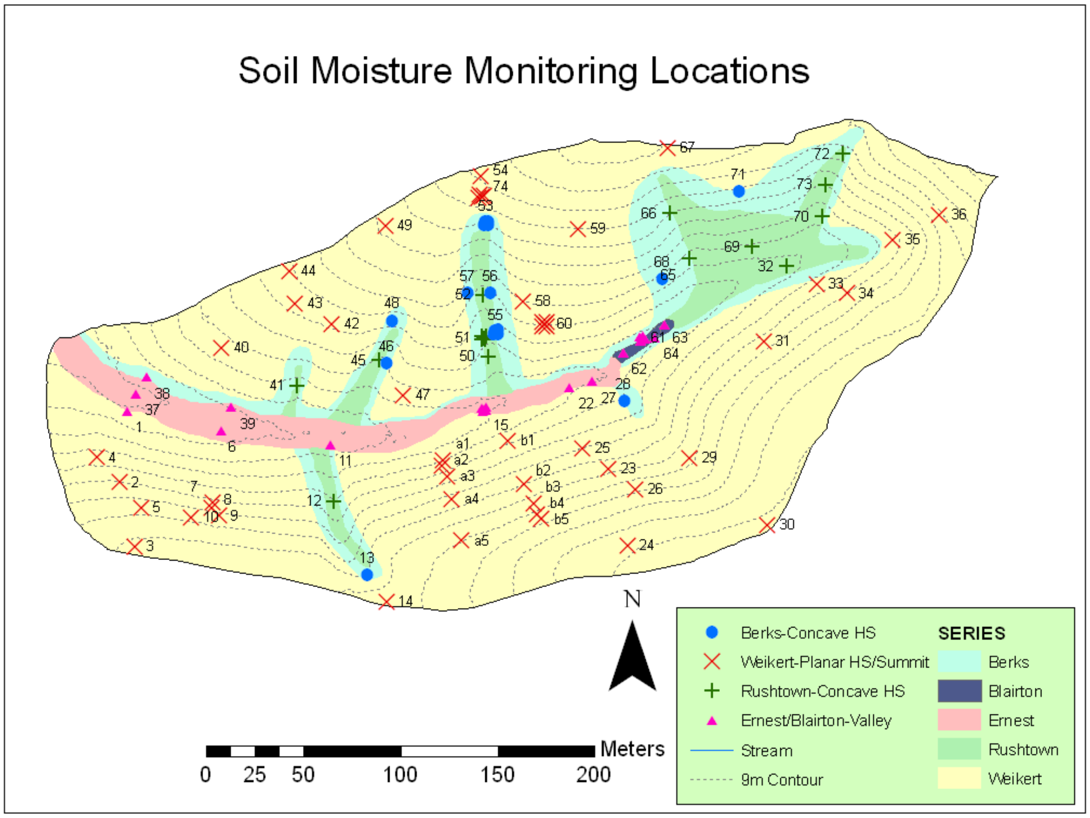

Figure 1-2: Map of the Shale Hills catchment showing soil moisture monitoring locations along with the soil-landscape unit (SLU) in which they belong. HS = hillslope.

Soil Moisture Monitoring Data Collection

This study utilized volumetric soil moisture data collected on an approximately weekly basis at the Shale Hills catchment over a four year period (September 10, 2004 to December 6, 2008). A total of 106 individual soil moisture monitoring locations were installed within the catchment between 2003 and 2006 (Fig. 1-2). Each monitoring locations consisted of a 0.051-m diameter PVC tube installed into the soil profile to a maximum depth of 1.1-m or to auger refusal, which ever came first. Each PVC tube was installed by first using a slide hammer to pound a 1.1-

m hollow metal soil sampler with a tapered bit and plastic soil core sampling sleeve into the soil. In this way, a 0.038-m diameter soil core was collected at each monitoring location and saved for later description and analysis. A second metal tube with a reversed tapered cutting bit and a diameter slightly smaller than that of the 0.051-m PVC tube was used to shape the hole and ensure a tight seal between the soil and the PVC tube. The PVC tube was capped at the bottom with a water tight seal and then placed in the augered hole. Finally, a removable cap was placed on top to prevent water from entering the tube. Volumetric water content (θ, units: m^3/m^3) was collected at 0-20, 10-30, 30-50, 50-70, 70-90 and 90-110-cm depth intervals (or to bedrock at shallow bedrock locations) at each soil moisture monitoring location using time domain reflectometry (TDR). Volumetric soil moisture was measured using a TRIME-T3 tube access probe with and a TRIME-FM3 mobile moisture meter (IMKO, Ettlingen, Germany). At each measurement depth, two to three readings were taken in orthogonal directions, and the mean θ was calculated and entered in the soil moisture database. Three to five hours were typically required for collection of soil moisture data at all soil moisture monitoring locations. In addition to measuring volumetric soil moisture during field data collection, water table height was measured in wells located adjacent to 35 soil moisture monitoring locations. Precipitation and climate data was collected beginning in 2006 at a meteorological station located at the summit of the south facing hillslope. Additional tipping bucket rain gauges were placed beneath the canopy to measure throughfall (model TE525-WS, Texas Electronics, Inc., Dallas, TX). During the summer of 2008, all soil moisture monitoring locations, water table monitoring locations, precipitation and climate instrumentation and streambed position was surveyed using a Sokkia® Set 5A total station (Sokkia, Inc., Olathe, KS).

The four-year soil moisture database consists of 157 individual measurement days. The measurement days analyzed for this study began on September 10, 2004 and continuing on an approximately weekly basis until December 6, 2008. Prior to September 2006, 77 individual monitoring locations were measured. In August 2006, an additional 20 monitoring locations were installed and beginning on September 6, 2006, 97 monitoring locations were measured. These additional 20 sites were arraigned in 5 clusters of 4 monitoring locations each, each cluster installed adjacent to automated soil moisture probes. One cluster was installed in the valley, three along an elevation gradient within a concave hillslope along the south-facing hillslope, and one located on the summit of the south facing hillslope. In late 2006, two more clusters comprised of 4 and 5 monitoring locations were installed in the valley and the summit of the south facing hillslope, respectively. These clusters were also adjacent to automated soil moisture probes. These most recent nine locations began being measured on January 8, 2006 and brought the total number of monitoring stations to 106. The number of locations measured on each measurement day varied due to the number of actual monitoring locations installed, personnel available to collect data and weather conditions, so the subsequent analysis included only 91 days where at least 35 soil moisture monitoring locations were measured. An examination of the 91 measurement days included in this study indicate that during the winter and spring soil moisture was monitored less frequently compared to the summer and fall. 3 measurement days were completed in the January and April, while 4, 5 and 6 measurement days were made in March, February and December, respectively. For the summer and fall months, September had the most measurement days with 17, followed by October and June with 12 and 11, respectively. July and November both had 8 measurement days while May and August both had 7. Figure 1-3 shows the temporal evolution of soil moisture over the 91 measurement days analyzed. Though the decision to use a minimum of 35 soil moisture monitoring locations was somewhat arbitrary, we determined it be an appropriate trade-off between having a sufficient number of monitoring sites to adequately represent spatial soil moisture within the catchment and allow for enough sampling days to have complete temporal coverage over all seasons.

Determination of Terrain Attributes

A digital elevation model (DEM) of the Shale Hills catchment was interpolated from light detecting and ranging (LIDAR) elevation data points flown over the Shale Hills catchment in 2006 (PAMAP Program, Bureau of Topographic and Geologic Survey, PA Department of Conservation and Natural Resources, 2006). The approximately 40,000 LIDAR elevation points were converted into a 1x1-m DEM using ArcGIS 9.2 (ESRI, Redland, CA). The quality of the LIDAR data and the resulting DEM is a function of the equipment used, aircraft speed/flying height, characteristics of the terrain surface as well as the density and distribution of the measured point source data (Fisher and Tate, 2006). All these factors introduce error, or "noise" into the DEM which needs to be accounted for. To reduce the amount of noise in the LIDAR data flown over Shale Hills and to better represent the primary topographic features within the catchment, a 9x9-m (9x9-cell) filter window was applied to the original DEM. The filter window used equal weighting to calculate the mean elevation of all cells within the window and applied the mean value to the center cell. This smoothed DEM was then use to derive four primary topographic attribute DEMs and one composite topographic attributes DEMs. Composite attributes are derived from the primary topographic attributes. The primary topographic attributes were elevation, slope, curvature, and upslope contributing area. The curvature value used in this study is the curvature of the surface fitted through all nine cells of the immediate neighborhood (ArcGIS 9.2 Spatial Analyst, ESRI, Redland, CA). The composite attribute was topographic wetness index (Beven and Kirkby, 1979), calculated using the ArcGIS 9.2 extension TauDEM (Tarboton, 1997). Terrain attributes were extracted from the DEM at all soil moisture monitoring locations using the coordinates derived from the total station survey.

Identification of Soil-Landform Units (SLUs) with the Catchment

Lin (2006) indentified four dominant landform groups within the Shale Hills catchment: valley, swale (concave hillslope), hillslope, and summit. There is a well-defined relationship between the five identified soil series and the dominant landform units (Fig. 1-2). An examination of the landform – soil relationship indicates that Ernest and Blairton soil series are located in the valley, Rushtown and Berks soil series are located in the swales, and the Weikert soil series is located in planar hillslope and summit landform units. As such, we define three dominant soil-landform units (SLUs) comprised of the five identified soil series and four dominant landforms units within the Shale Hills catchment: 1) Ernest/Blairton series-Valley floor, 2) Rushtown/Berks series-Concave hillslope, and 3) Weikert series-Planar hillslope/summit. Ernest and Blairton soils were combined into one soil-landform unit because of the very limited spatial extent of Blairton soils and its similar landform as the Ernest series. Similarly, Rushtown and Berks soils were combined because of their closely linked landform characteristics. Soil moisture locations were grouped into the most suitable SLU base on the 1-m DEM and detailed soil descriptions from soil cores and soil pits. Table 1-1 show pertinent terrain and soil characteristics for each soil-landform group and Figure 1-1 shows the soil moisture monitoring locations along with the group in which they belong. These three SLUs were used to compare soil moisture dynamics within the catchment. For the remainder of this paper, the three SLUs will be referred to by their landscape position: valley (VLY), concave hillslope (CHS), and planar hillslope or summit (PHS).

Table 1-1: Terrain characteristics for the three soil-landform units (SLUs) in the Shale Hills catchment based on the LIDAR data. Depth to bedrock was based on 223 field observation points. Different letters (a, b, c) after each mean value indicate a significant difference at $p < 0.05$ level.

Soil Unit	**Landform Unit**	**Mean Elevation (feet)**	**Mean Slope (%)**	**Mean Curvature (unitless)**	**Mean Upslope Contributing Area (feet^2)**	**Mean topographic wetness index (unitless)**	**Mean depth to bedrock (cm)**
Earnest/ Blairton	Valley	883.00^a	11.53^a	-1.076^a	5804.08^a	9.07^a	135.33^a
Rushtown/ Berks	Concave Hillslope	920.39^b	27.79^b	-0.959^b	306.46^b	5.98^b	103.21^b
Weikert	Planar Hillslope or Summit	931.11^b	29.61^b	0.133^b	40.62^c	4.61^c	44.52^c

Data Analysis

Determination of areas representative of catchment mean soil moisture

We define horizontal (spatial) variability of soil moisture (σ_h) to be the *standard deviation* of soil moisture measurements collected over all monitoring locations on a given day, or a subset of these monitoring locations in the case of SLU-based analysis. We also define depth-weighted mean soil moisture (θ_D) at an individual monitoring location for a more integrated representation of volumetric soil moisture content over the upper 1.1-m solum throughout the catchment:

$$\theta_{D(i)} = \frac{\sum_{z=1}^{n} \theta_z d_z}{L} \qquad [1]$$

where *i* represents an individual soil moisture monitoring location, θ_z is the volumetric soil moisture content at specific depth interval *z*, *n* is the total number of depth intervals measured at a monitoring location, d_z is the depth interval over which θ_z was made, and L is the sum over all d_z ($\leq$ 1.1 m in this study, the variation of which depends on depth to bedrock at each location). In this paper we refer to catchment-wide mean depth-weighted soil moisture content as $\overline{\theta}_{D(w)}$, and SLU-based mean depth-weighted soil moisture content as $\overline{\theta}_{D(SLU)}$ (where SLU may be substituted by specific units, VLY, CHS or PHS, where appropriate).

Results

Relationship between horizontal variability and spatially averaged soil moisture

Figure 1-3 compares the temporal evolution of spatially-averaged soil moisture within each SLU ($\overline{\theta}_{D(SLU)}$) over the four year period. When $\overline{\theta}_{D(w)}$ was greater that the 4-year mean, significant soil moisture differences formed between the SLUs, particularly with respect to the valley soil moisture that was strongly affected by the presence of a shallow water table during wet periods. During the dry months soil moisture became more uniform throughout the catchment and the overall soil moisture variability decreased, though $\overline{\theta}_{D(VLY)}$ and $\overline{\theta}_{D(CHS)}$ remain higher than $\overline{\theta}_{D(PHS)}$ (Fig. 1-3). Our results suggest that topography-based spatial organization of soil moisture exists in the Shale Hills catchment throughout the year, but the degree of which changes over time and is modified by other factors (such as soil type, vegetation growth, and the presence of a shallow water table in the near stream zone).

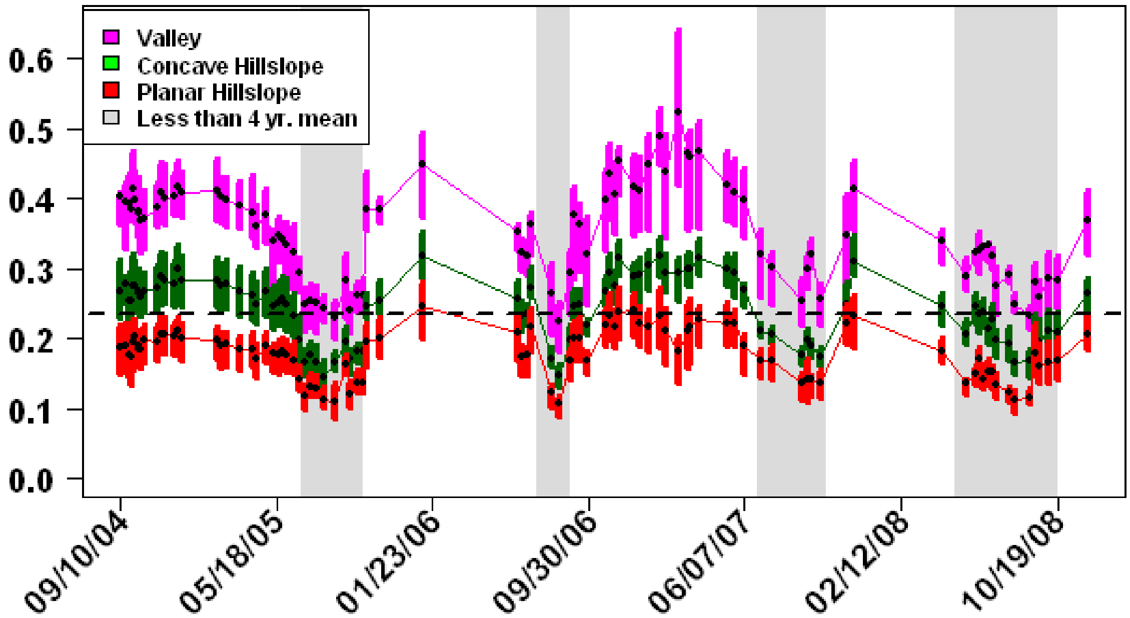

Figure 1-3: Box plot of the temporal evolution of soil moisture within the three soil-landform units (SLUs) over 91 measurement days from 2004 to 2008. The black dots represent mean soil moisture, the upper and lower bounds of the thick colored lines represents the 1st and 3rd quartiles of soil moisture measured in each SLU, respectively. Shaded areas indicate dry summer periods (06/16-10/02/2005, 06/30-08/31/2006, 06/06-10/06/2007, and 05/27-10/19/2008). Dashed line represents the 4-year catchment-wide mean soil moisture ($\bar{\theta}_{D(w)}$).

To examine the sources of spatial soil moisture variability and identify portions of the catchment which act to increase the variability of soil moisture under different wetness conditions, we examined two measurements days which represent wet (11/17/06, $\bar{\theta}_{D(w)}$ =0.280 m^3/m^3) and dry (08/02/05, $\bar{\theta}_{D(w)}$ = 0.169 m^3/m^3) conditions. Comparing the two measurement days, the wet measurement day shows a large spread of volumetric soil moisture values, indicative of high variability. On 11/17/06, the VLY SLU monitoring locations are located far to the right of the mean, particularly at near surface measurement intervals, creating a strong positive skew (skewness at 10-cm on 11/17/06 = 2.17). The positive skewness present during period of high soil moisture coincides with the presence of a shallow water table within the valley. On the dry measurement day (08/02/05), the distribution is less spread out and exhibits a clustering about the mean, indicating lower spatial variability. The VLY SLU remains to the left of the mean, but does not impart a significant positive skew to the shallow soil moisture distribution (skewness at 10-cm on 08/02/05 = 0.36) as the shallow water table has receded. These results indicate that during periods when the catchment has high spatially-averaged soil moisture, there is large spread to the soil moisture data, with valley monitoring locations producing a positively skewed distribution.

Figure 1-4 shows the horizontal variability (σ_h) plotted against depth-weighted volumetric soil moisture content over the entire catchment ($\bar{\theta}_{D(w)}$) from 2004 to 2008. The mean $\bar{\theta}_{D(w)}$ over these 91 days was 0.238 m^3/m^3, with a standard deviation of 0.046 m^3/m^3. Spearman correlation coefficient between $\bar{\theta}_{D(w)}$ and σ_h was 0.863 ($p < 0.001$).

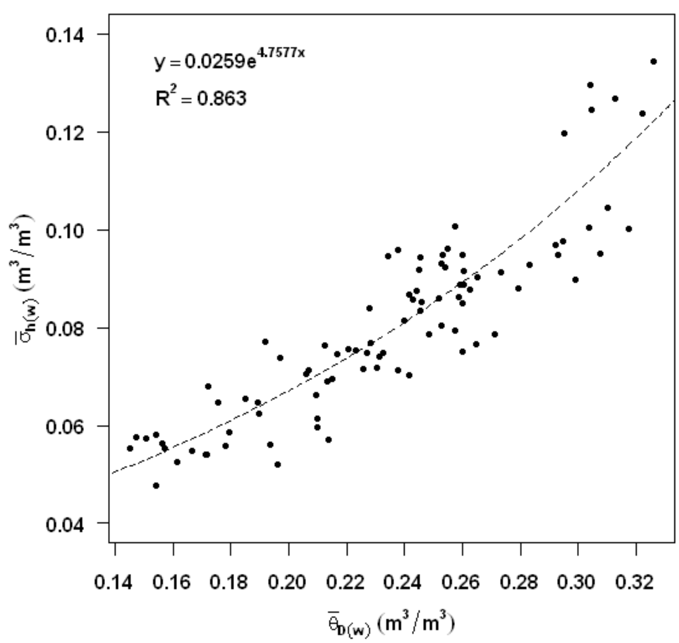

Figure 1-4: Catchment-wide horizontal variability (σ_h) plotted against mean catchment-wide depth weighted mean soil moisture ($\bar{\theta}_{D(w)}$).

This positive correlation indicates that during wet periods, the absolute variability (i.e., standard deviation) of soil moisture content within the catchment increases. A curvilinear relationship between $\bar{\theta}_{D(w)}$ and σ_h was best modeled by an exponential function: $\sigma_h = 0.0259e^{4.757\bar{\theta}_{D(w)}}$ (R^2 = 0.863, p< 0.001). Such a curvi-linear relationship was also evident within each of the measurement depths (Fig. 1-5), with a clear decline in the exponent from 6.10 at the 10-cm depth to 2.72 at the 100-cm depth and an increase in intercept from 0.0165 to 0.0444 m^3/m^3 from the surface down to 100-cm, indicating that changes in variability with changes in spatially-averaged soil moisture is dampened as depth increases. This is expected as the thick soil profile acts to retain deep soil moisture against removal by evaportranspiration, such that soil moisture at depth maintains relatively high soil moisture throughout much of the year and is more temporally persistent as compared to shallower soil depths.

We examine the confidence intervals associated with the estimation of areal mean soil moisture using the exponential equations shown in Fig. 1-5. Following the methods of Famiglietti et al. (2008), we compute the 95% confidence interval (CI) using a student *t*-distribution:

$$CI = \bar{\theta}_z \pm t_{\alpha/2,df} * s.e.(\bar{\theta}_z) \qquad [2]$$

where $\bar{\theta}_z$ is the spatially-averaged soil moisture at depth *z*, $t_{\alpha/2,df}$ is the student *t* distribution with exceedance α/2 and degrees of freedom, *df*, and *s.e.*($\bar{\theta}_z$) is the standard error of $\bar{\theta}_z$.

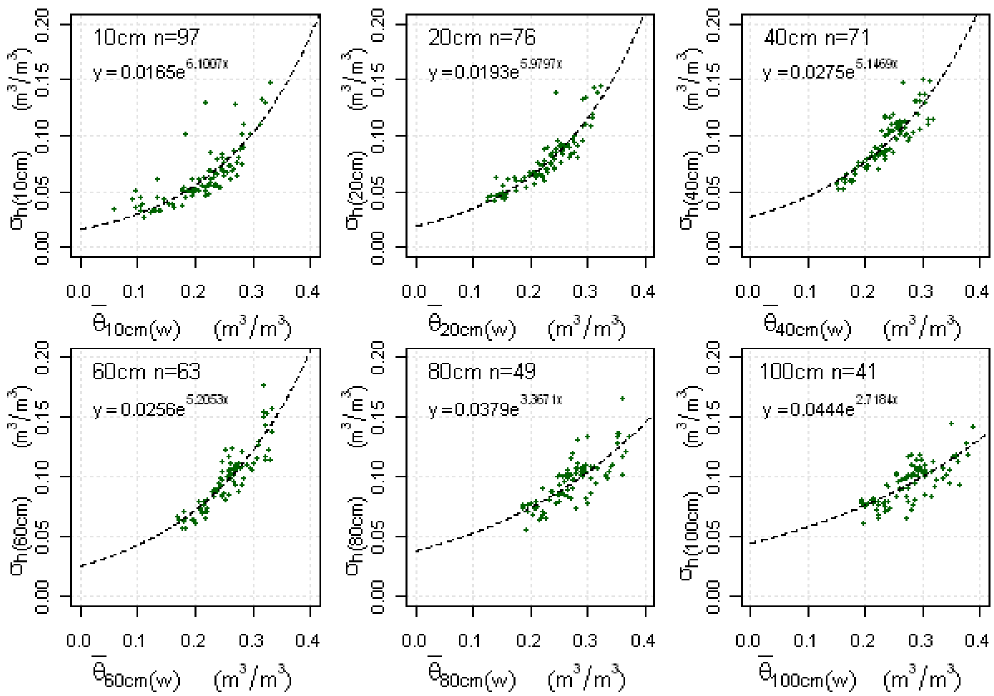

Figure 1-5: Horizontal variability (σ_h) of soil moisture verse catchment-wide mean soil moisture ($\overline{\theta}_{z(w)}$) measured at each measurement depth interval (represented by the central depth in cm). n is sample number for each depth.

Figure 1-6 shows the 95% confidence interval for different levels of $\overline{\theta}_z$ at the five monitoring depths (10, 20, 40, 60, 80 and 100-cm). For all measurement depths, as $\overline{\theta}_z$ increases, the 95% confidence intervals widen, indicating that our estimate of $\overline{\theta}_z$ becomes less certain. Our results indicate that the increase in the confidence interval between the respective lowest and highest measured $\overline{\theta}_z$ over the four-year monitoring period was 0.040, 0.038, 0.033, 0.037, 0.031 and 0.029-m^3/m^3 for 10, 20, 40, 60, 80 and 100-cm, respectively. Similarly, we calculate the number of soil moisture measurements required to achieve a tolerance of ±0.05 m^3/m^3 for the estimation of $\overline{\theta}_z$ at a significance level of 95%. Following the methods of Brocca et al. (2007) and Famiglietti et al. (2008), the required number of samples can be estimated by:

$$N = (t_{\alpha/2,df} * s.e.(\bar{\theta}_z)/e)^2 \quad [3]$$

Where N is the required number of samples, and *e* is the tolerance (±0.05 m^3/m^3 in this case). Results of this analysis is shown in figure 1-7. As expected we find that the as the spatially-average soil moisture increases, the number of samples required to accurately capture the mean increases. Comparing the number of samples required to achieve the desired confidence and tolerance at the respective lowest and highest values of $\bar{\theta}_z$ over the four-year monitoring period, our results indicate that the number of samples required increased by 23, 25, 24, 27, 19, and 16 for 10, 20, 40, 60, 80 and 100-cm, respectively.

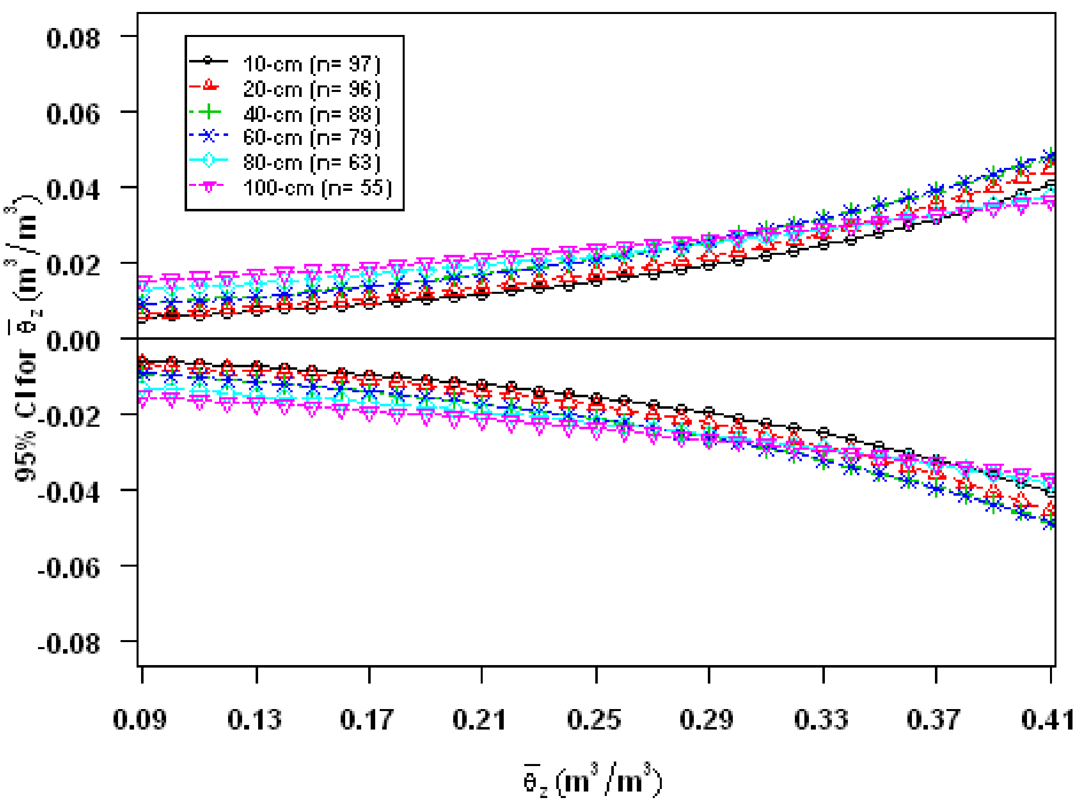

Figure 1-6: 95% confidence intervals (CI) for spatially-averaged mean soil moisture at each depth interval ($\bar{\theta}_z$) using the indicated number of sites (*n*).

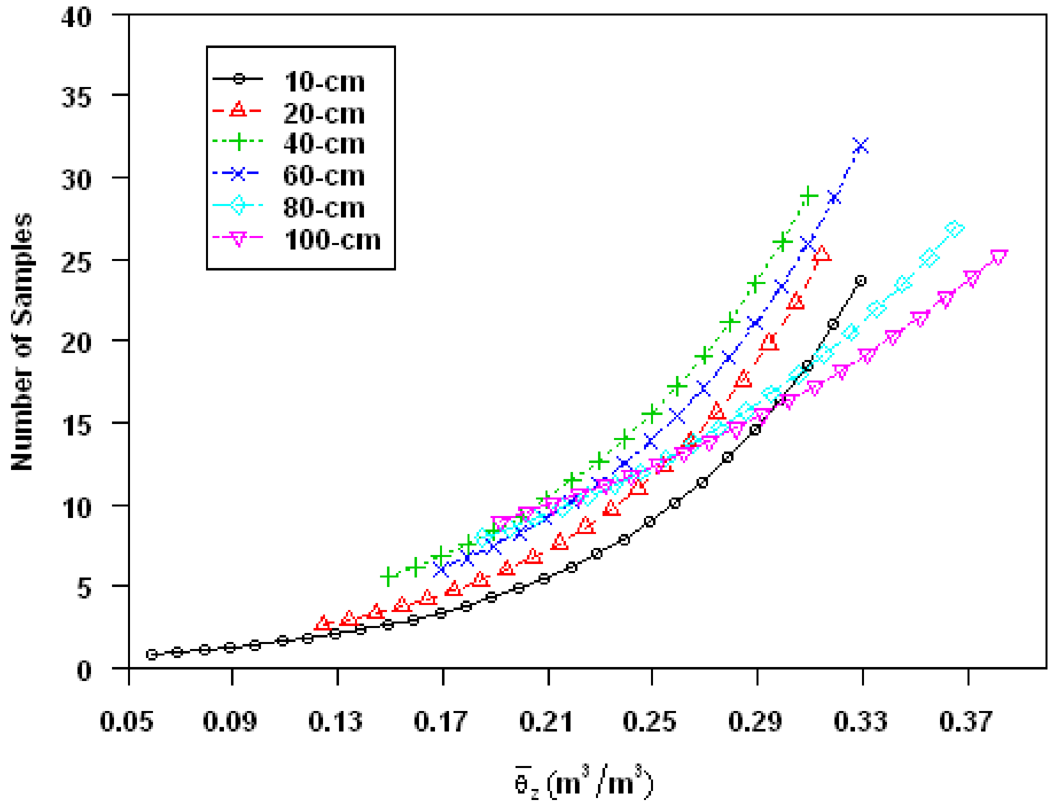

Figure 1-7: Numbers of samples required to achieve a ± 0.05 m^3/m^3 estimate of spatially-averaged soil moisture ($\bar{\theta}_z$) at each depth interval (z). The required number of samples was calculated for the range of $\bar{\theta}_z$ observed over the four-year monitoring period.

We next examined the the relationship between variability and spatial-averaged soil moisture for different soil-landform units. A positive curvi-linear relationship between $\sigma_{h(SLU)}$ and $\bar{\theta}_{D(SLU)}$ was also evident within each of the three SLUs (Figure 1-8). The concave hillslope had the smallest exponent (3.88) while the planar hillslope/summit had the largest exponent (7.06) and the valley's exponent falling in between (4.57). These suggested that soil moisture in concave and valley areas tended to change less over time with changes in the overall catchment wetness conditions, while that in the planar hillslope and summit areas tend to be more sensitive to the changes in whole catchment wetness conditions.

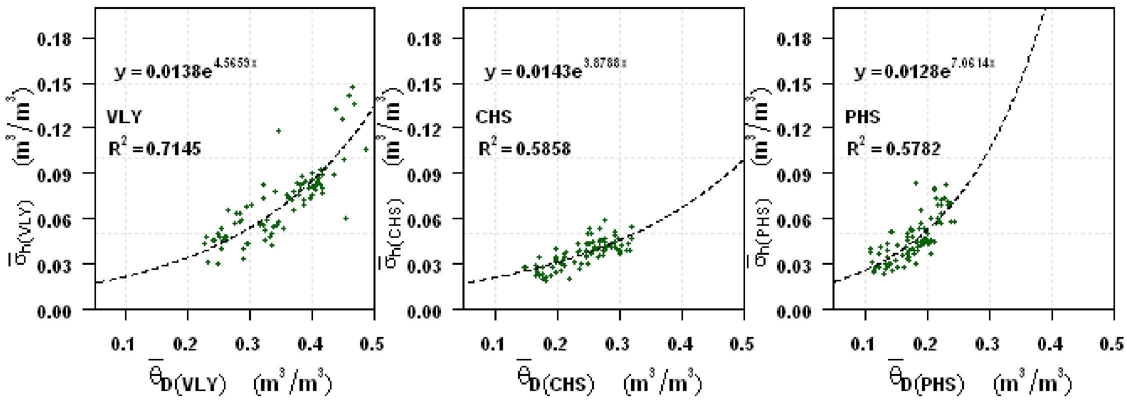

Figure 1-8: Horizontal variability ($\sigma_{h(SLU)}$) of soil moisture within each of the three soil-landform units (SLU) verses mean soil moisture ($\overline{\theta}_{D(SLU)}$) within each soil landform unit (SLU) (VLY = valley; CHS = concave hillslope; and PHS = planar hillslope). The dashed line is the fitted exponential equation shown.

Figure 1-9 shows the temporal evolution of each SLU's $\sigma_{h(SLU)}$ vs. $\overline{\theta}_{D(SLU)}$ in each month of a year. The horizontal blue line represents the 4-year mean (all 91 days) $\sigma_{h(w)}$ for the entire catchment, while the vertical blue line represents the 4-year (all 91 days) $\overline{\theta}_{D(w)}$ for the entire catchment.

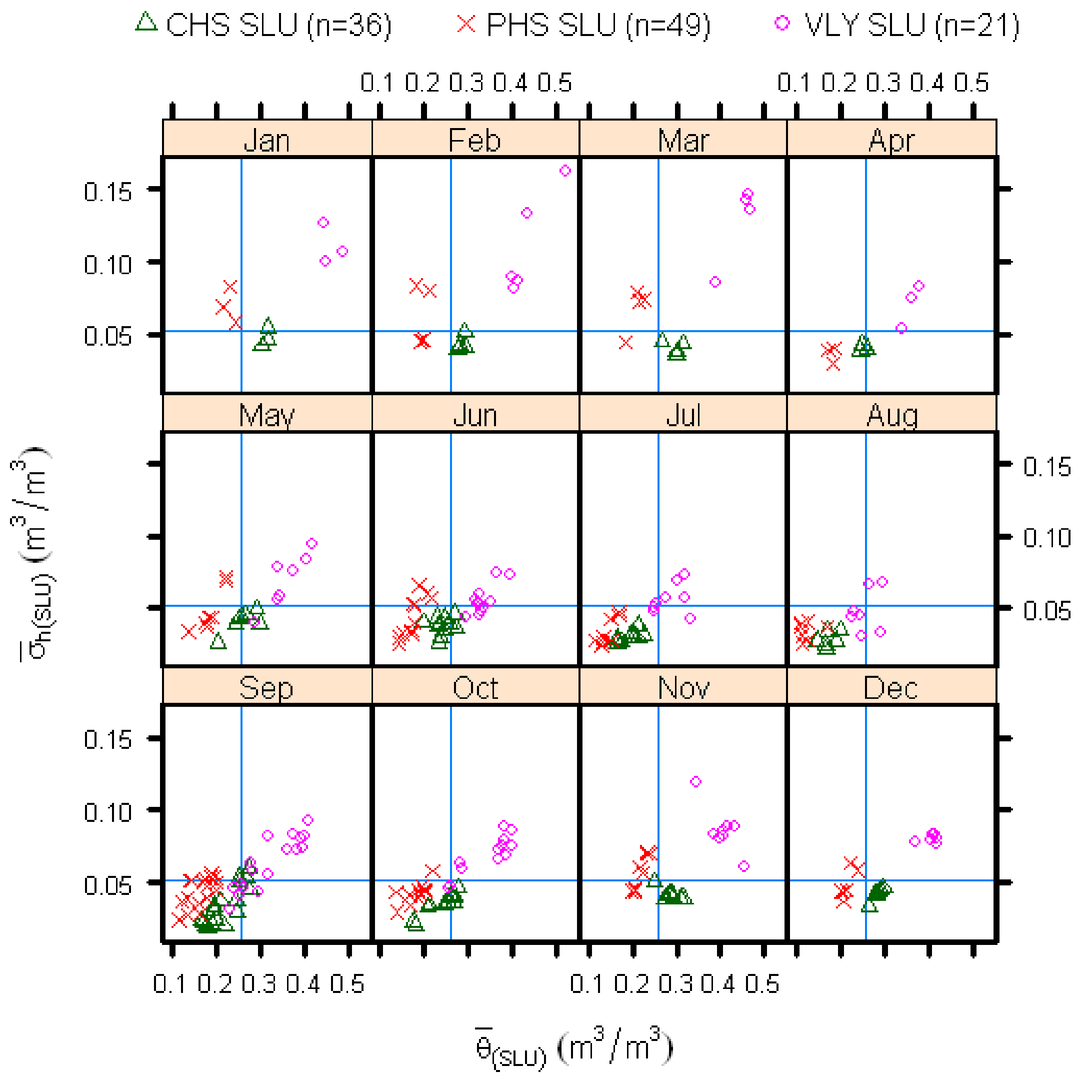

Figure 1-9: Temporal evolution of horizontal variability ($\sigma_{h(SLU)}$) plotted against depth-weighted mean soil moisture ($\bar{\theta}_{D(SLU)}$) within each soil-landform unit (SLU) (open triangle = concave hillslope; cross = planar hillslope; open circle = valley). The vertical blue line represents the four-year catchment-wide $\bar{\theta}_{D(w)}$. The horizontal blue line indicates the four-year catchment-wide $\bar{\sigma}_h$.

In this monthly changing sequence, the PHS SLU was predominantly located in the lower left quadrant (i.e., low $\bar{\theta}_{D(SLU)}$-low $\sigma_{h(SLU)}$) from April to October and exhibited the lowest daily $\bar{\theta}_{D(SLU)}$. Conversely, the VLY SLU was predominantly located in the upper right quadrant (i.e., high $\bar{\theta}_{D(SLU)}$ -high $\sigma_{h(SLU)}$), but exhibited the largest reduction in both $\bar{\theta}_{D(SLU)}$ and $\sigma_{h(SLU)}$ from late spring through summer (March-August). The CHS SLU exhibited the least fluctuation in $\sigma_{h(SLU)}$ among the three SLUs, but with a $\bar{\theta}_{D(SLU)}$ value between that of PHS and VLY SLUs. These results suggest that the VLY SLU contributed most significantly to the overall $\sigma_{h(w)}$ while the CHS SLU was closest to $\bar{\theta}_{D(w)}$ and contributed the least to overall $\sigma_{h(w)}$.

Temporal variability in the vertical soil moisture profile

We next analyzed the variability in vertical soil moisture profiles at the Shale Hills catchment. This can provide a more detailed characterization of hydrological processes (i.e. groundwater interactions, evapotranspiration) acting upon soil moisture. First. we compared the values of soil moisture measured at the surface (10-cm) to that of the soil moisture measured at depth (20-100-cm), by calculating the linear coefficient of determinations (R^2) for soil moisture measured at 10-cm with that at each of the deeper depth intervals within each location. Linear coefficient of determinations (R^2) between 20, 40, 60, 80 and 100-cm depth and surface soil moisture (10-cm) were 0.75, 0.54, 0.50, 0.48 and 0.47, respectively, with all R^2 values significant at the p<0.01 level. There is a negative relationship between R^2 and depth, indicating that subsurface soil moisture becomes less correlated with near-surface soil moisture as soil depth increased. We next examined the affect of dynamic hydrological factors on the vertical variability of soil moisture within different portions of the catchment. To accomplish this, we examined temporal changes in the soil moisture-depth profile at 3 different representative locations along a topographic gradient during a seasonal dry-down, wet-up sequence from March 5, 2007 to November 29, 2007 (Fig. 1-10). To improve the comparison between locations within different soil-landform groups, we use the degree of saturation, S, which is defined as:

$$S = \frac{\theta_z}{\phi} \qquad [3]$$

Where θ_z is the volumetric water content measured at depth *z*, and ϕ is the porosity of the depth interval reported in Lin (2006). Figure 1-10 shows the dry down sequence within the valley soil-landform unit for site 15, located along the valley floor at the base of a swale along the south-facing hillslope; site 51, which is located within the middle portion of the swale along the south-facing hillslope and site 53, which is located along the upper portion of the same swale along the south facing hillslope.

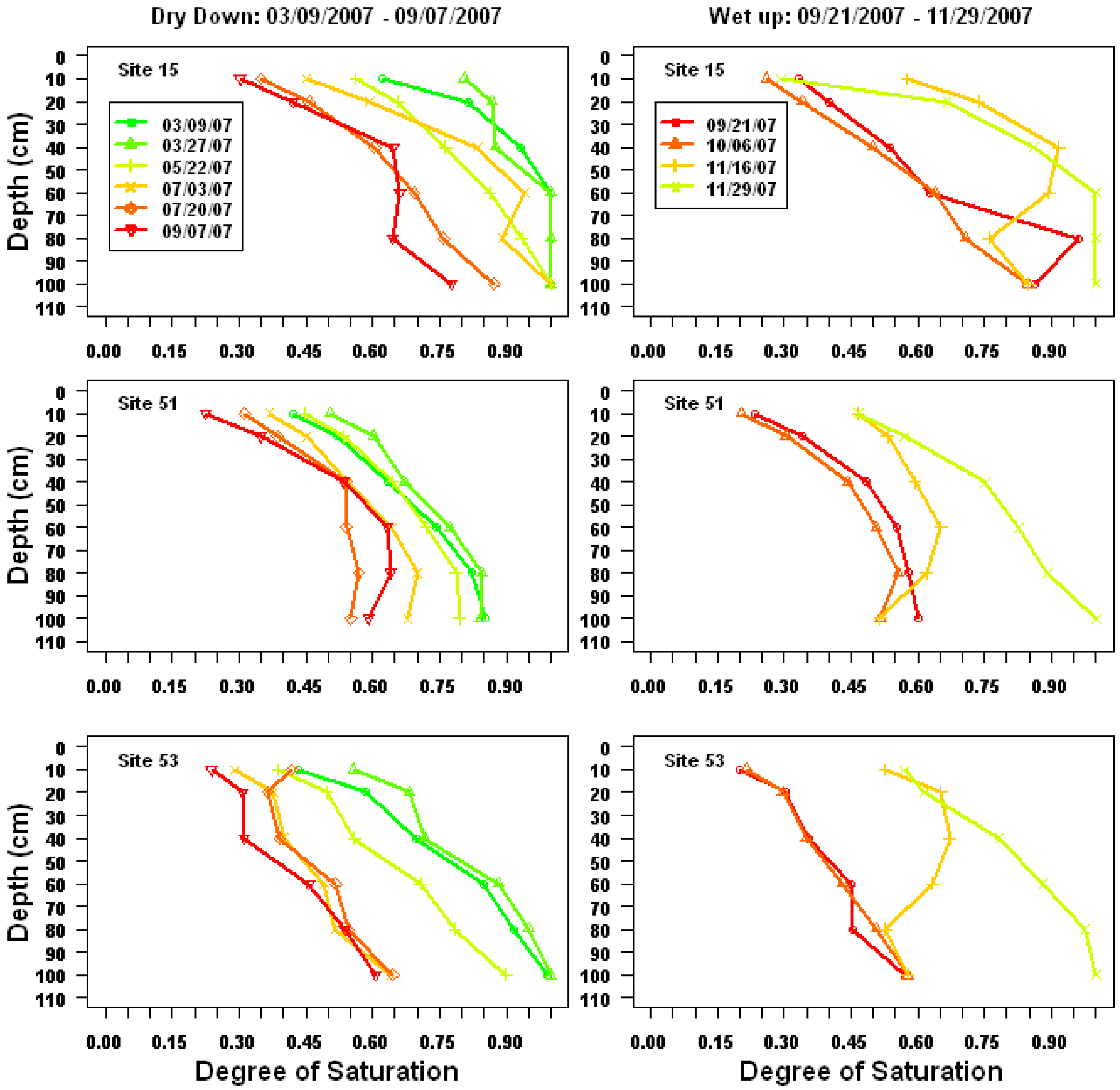

Figure 1-10: Example dry-down and wet-up sequence for three monitoring locations along a topographic gradient in the south-facing hillslope: Site 15 is in the valley, site 51 is in the mid-slope position of a concave hillslope, and site 53 is in the upper portion of the concave hillslope (see Fig. 1 for exact locations of these sites).

At the beginning of the dry down sequence (03/09/2007), the soil profile at location 15 is relative homogeneous, with saturated conditions (S = 1) present below ~60-cm due to the presence of a shallow water table within the valley. Saturated conditions at this location are consistent with field observations of a shallow water table. The saturated to nearly saturated condition persists until the end of May (05/22/2007) when a top-down drying sequence begins.

By the beginning of July, the entire profile has decreased below saturation and a negative relationship between soil moisture and depth exists. This relationship is consistent with higher removal rates of soil water by evapotranspiration at the near surface horizons compared to deeper soil horizons, and potentially the residual effect of the capillary rise from the receding water table. During the wet-up sequence, location 15 exhibited minimal rewetting of the profile on 09/21/2007 and 10/07/2007. Beginning on 11/16/2007, we see a rewetting of the middle portion of the soil profile, creating a "bulge" of soil moisture at the 40 and 60-cm depth. This may be indicative of a top-down rewetting of the soil profile as evapotranspiration begins to decrease. The lower portion of the soil moisture profile did not exhibit significant re-wetting on this date. By 11/29/2007, only 13 days later, we see that the lower portion of the profile (60, 80 and 110-cm depths) had again reached saturation due to the re-emergence of a shallow water table. On this day, the surface remained significantly drier than the deep soil horizons; it would be expected that as the shallow water table approached the surface during the winter and spring months, the soil profile would approach a homogeneous saturated to near-saturated profile.

Monitoring locations 51 and 53, located in the middle and upper portions of the swale, respectively, show similarities between their wet and dry down sequences. Both locations exhibit a persistent negative relationship between depth and degree saturation throughout the dry-down period. Unlike location 15, which exhibited a top-down dry-down sequence once vegetation began transpiring, location 53 exhibited a uniform dry-down through out the profile, maintaining a similar slope to the relationship between depth and degree of saturation throughout the summer. Location 51 exhibited larger dry-downs in the surface and deep horizons, with less dry-down within the intermediate horizon (40-cm). During the re-wetting phase beginning on 09/21/2007, we see similar behavior between locations 51 and 53. Both 51 and 53 exhibit a soil moisture "bulge" within the intermediate soil profile (20 to 60-cm) and a top-down re-wetting similar to location 15. By the 11/29/2007, only the deepest monitoring depth exhibited near-saturated conditions, suggesting the absence of any soil-groundwater interaction. Our results indicated that soil moisture within the valley is impacted by the presence of shallow water table during wet periods. The upslope positions (locations 51 and 53 in this case) don't exhibit saturated conditions at depth (within the upper 110-cm) due to the lack of soil-groundwater interaction. All three locations exhibit a similar wet-up sequence during the brief transition from dry to wet conditions during the late fall.

Discussion

Relationship between spatial and vertical soil moisture variability, mean spatial soil moisture and dominant hydropedologic processes

Previous studies investigating the relationship between spatial soil moisture and spatial variability have found a convex relationship with low variability at very high and very low soil moisture values (Owe et al., 1982; Choi and Jacobs, 2007; Famglietti et al., 2008; Penna et al., 2009). At our study site, we observed a positive relationship between the standard deviation of spatial soil moisture measurements and spatial averaged soil moisture. At the Shale Hills catchment, the increase in the spatial variability (ie. the standard deviation of soil moisture measurements across the catchment) with increase in catchment wetness (mean catchment-wide soil moisture), is due to spatially and temporally-limited dynamic factors (as defined by Reynolds (1970)). During periods of high soil moisture, the valley and concave soil-landform units become wetter than the surrounding planar hillslope landform unit. This creates soil moisture spatial organization along topographic features, particularly topographic convergent zones. Reinforcing this topographic organization is the close coupling of thicker soil in convergent areas, which create larger stores of soil moisture as compared to the planar and convex areas of the catchment.

Lateral subsurface water flow into convergent hillslopes and valley landform units, and associated loss of water from the thinner soil mantles on the planar upslope areas, act to increase soil moisture differences between landform units and increase the spatial variability. Our results agree with theoretical work by Albertson and Montaldo (2003) which found lateral flow from upslope areas to downslope areas increases the spatial variability of soil moisture, and lead to a positive relationship between the standard deviation of soil moisture and mean spatial soil moisture. Greyson et al. (1997) found that surface and subsurface lateral flow within the soil zone during periods when precipitation exceeded evapotranspiration acted to create soil moisture spatial organization within the Tarrawarra catchment in Australia. Accordingly, Western et al. (2004) observed a positive relationship between the standard deviation of soil moisture and mean soil moisture within the upper 30-cm of soil at the Tarrawarra catchment.

The presence of a shallow water table within the lower portions of the valley during periods of high soil moisture reinforces the increase in spatial variability due to lateral subsurface flow. The effect of a shallow water table on soil moisture variability can be seen when examining the histogram of soil moisture within individual depth intervals under wet and dry conditions (fig. 1-2). We found that when the catchment was in a wet soil moisture state, the soil moisture histogram for the shallow soil depths exhibited a positive skew, with valley monitoring locations comprising the elongated right tail. This indicates that the valley soils become significantly wetter than upslope slopes, due to the combination of lateral flow into convergent areas and input of groundwater into the valley soils. Conversely, during the dry wetness state during the summer, the skewness approaches zero (normal distribution) as the shallow water table retreats decreasing the soil moisture content in valley soils and the catchment as a whole is affected by soil moisture removal by evapotranspiration. The formation of a positively skewed distribution of soil moisture measurements under wet conditions is contrary to the soil moisture measurement distribution hypothesized by Western et al. (2003). They stated that under wet conditions, the distribution would be negatively skewed as the majority of measurements would be congregated toward saturation (upper bound of soil moisture values). Within Shale Hills, the limited areal extent of saturated areas around the stream coupling with a larger areal extent of a well-drained thin soil mantle along the steep planar upslope areas, lead to a limited number of points extending toward saturated soil moisture values and skewing the distribution to the right. The decrease seen in positive skewness as you move down the soil profile (fig. 1-2) may be due to the clustering of deep monitoring locations measured (>80-cm) within the convergent hillslopes and valley. These monitoring locations would experience a similar influence of lateral flow and groundwater-soil interactions described above. This agrees with our finding that deep soil moisture exhibits less change in variability (figure 1-6), with the coefficients of the fitted exponential function decreasing from 6.1 at 10-cm depth interval to 2.7 at the 100-cm depth interval.

Our results indicate that soil water removal processes, which include evapotranspiration, and reduced groundwater-soil interaction act to reduce the standard deviation and skewness in the distribution of soil moisture. Our results agree with Teuling et al. (2007) who found that at lower mean soil moisture values, vegetation acts to decrease soil moisture variability as transpiration removal rates will be higher where there is high soil moisture, and lower where there is lower soil moisture. Figure 1-6 indicates that when the catchment in is a dry soil moisture state, soil moisture spatial variability in the upper depth intervals will reach a minimum plateau where continued drying of the catchment does not result in significant decrease in soil moisture spatial variability. This minimum variability plateau may represent the variability of soil textural properties, which control the retention of soil water at large negative matric potentials. This finding agrees with Western et al. (2003) who suggested that at the lower limit of the spatial variability – mean soil moisture relationship, soil moisture variability approaches the spatial variability of soil textural differences.

Correctly modeling the relationship between spatially averaged soil moisture and the spatial variability of soil moisture measurements will enhance our estimation of uncertainty related to our estimates of spatially averaged soil moisture. Our results indicated that soil moisture variability increased with spatially averaged soil moisture. Accordingly, we found that the 95% confidence intervals increase with increasing catchment wetness, assuming in our case that a fixed number of monitoring locations were measured. We found that at high mean soil moisture content, the confidence intervals were largest for the near surface soil moisture depths, and decreased as you moved down the soil moisture profile. Conversely, at low mean soil moisture content, the confidence intervals were smallest for near surface soil moisture and increased as you moved down the soil profile. This suggest that near-surface soil moisture exhibits the highest spatial variability at high soil moisture values, which may be due to the saturated conditions of near-surface soil moisture measured in the valley and the relatively dry near-surface soil along the upslope areas. Comparing our results to previous investigations into the uncertainty of estimates of mean soil moisture, Famiglietti (2008) found that confidence intervals were largest within intermediate soil moisture values, and smallest at very low and very high soil moisture contents. Similar results were found by (Brocca et al., 2007), who observed a negative relationship between spatial variability and spatially averaged soil moisture. Differences between our results and earlier studies highlights the importance of correctly modeling the relationship between spatial variability and spatially averaged soil moisture and understanding how different hydrological fluxes influence the shape of the relationship. Our results indicate that soil-groundwater interaction leads to a positive relationship. This information may be useful for the optimal monitoring of future soil moisture measurement campaigns at locations where shallow water tables are present.

Conclusions

We observed an exponential increase in soil moisture spatial variability with an increase in catchment-wide averaged soil moisture. A consequence of this relationship is the widening of confidence intervals for estimating spatially-averaged soil moisture at all measurement depths (10, 20, 40, 60, 80 and 100-cm), and an increase in the number of samples required to obtain 95% confidence in estimating spatially-averaged soil moisture. Within the Shale Hills catchment, the 10-cm soil moisture exhibited the largest change in spatial variability with increase in catchment-wide wetness condition. Conversely, the soil moisture measured at the deepest depth (100-cm) exhibited the smallest change in variability. We attribute this to the ability of the deep soil profile to retain soil moisture against seasonal fluctuations, specifically evapotranspiration, therefore dampening seasonal changes in soil moisture variability with depth.

Soil moisture measurements at multiple depths along a topographic gradient allowed the examination of seasonal hydrological processes operating within the catchment. Temporal changes in vertical soil moisture profiles during seasonal dry-down and wet-up sequences indicated the influence of both a shallow water table in the valley and soil water removal by evapotranspiration on soil moisture variability. Spatially-limited hydrologic processes act to increase soil moisture variability, while spatially extensive hydrological processes act to decrease soil moisture variability. The results of this study would be particularly useful for future soil moisture monitoring campaigns at field sites where shallow water tables are present only seasonally during the year. Additionally, the results of this study has implications for remote sensing of soil moisture, particularly understanding how soil moisture variability changes with spatially-averaged soil moisture when hydrological processes such as soil groundwater interaction and lateral subsurface flow do not operate uniformly across the remote sensing footprint.

Chapter 2

Influence of topography and soil properties on near-surface and subsurface soil moisture organization within a forested catchment

Introduction

At the catchment scale, the organization of soil moisture spatially and vertically within the soil profile influences the non-linear behavior of a catchment's response to storm events (Stieglitz et al., 2003; Buttle, 2004; McNamara et al., 2005). High soil moisture within the soil profile can promote hydrologic connectivity between upslope areas and riparian zones and allow for the transport of nutrients and chemicals downslope via lateral subsurface water movement, overland flow, and flow along the bedrock-soil interface, altering the chemistry and quality of stream water and soil water (Lynch and Corbett, 1989; Hornberger et al., 1994; Boyer et al., 1997; McGlynn et al., 2003a,b, 2004). Therefore, our ability to model hydrological and environmental processes requires knowledge of both near-surface and subsurface soil moisture dynamics. Long term monitoring of surface and subsurface soil moisture provides a robust picture of the temporal and spatial dynamics of soil moisture and a means to identify the controls on soil moisture spatial organization throughout the year.

Physical (soil properties, underlying geology, topography and vegetation) and hydrological (sources, sinks and translocation of soil water) characteristics of a field site exert a first order control on the spatial organization of soil moisture. For example, soil water movement operates under the influence of gravity. Improvements in digital elevation models (DEM) and geographic information systems (GIS) have allowed detailed topographic analysis and correlation between soil moisture and terrain indices such as topographic wetness index (TWI, Beven and

Kirkby, 1979), profile and plan curvature, upslope contributing area and slope to name a few (e.g., Nyberg, 1996; Crave and Gascuel-Odoux, 1997; Western et al., 1999a; Lookingbill and Urban, 2004; Wilson et al. 2005). Soil properties, such as texture, rock fragments, and organic matter content, exert a first-order control on the ability of a soil to store water and transmit water laterally and vertically (e.g., Henninger et al., 1976; Yeakley et al., 1998; Maeda et al., 2006). Bedrock topography and depth to bedrock have also been recognized as important controls on the movement of water from upslope areas to riparian zones (Buttle et al. 2004; Tromp van Meerveld and McDonnell 2005). The ability of individual soil and terrain attributes to explain the spatial variability in soil moisture depends on the seasonal wetness state of the field site and dominant hydrological processes acting upon soil moisture (Grayson et al., 1997; Famiglietti et al.,1998; Western et al., 1999). For example, Western et al. (1999a) found that under dry conditions when soil fluxes are primarily vertical (ie. evapotranspiration and vertical drainage are dominant) and localized due to disconnected soil macropores, indices related to the amount of solar radiation soil receives (specifically cos(aspect) and potential solar radiation index) were important in predicting soil moisture distribution in the upper 30-cm of a pastureland catchment. Under wet conditions when soil fluxes have a lateral component (ie. lateral surface and subsurface flow) and are non-local due to connected soil macropores, they found topographic indices related to lateral movement of soil water (specifically upslope contributing area) are good predictors of soil moisture distribution. Seasonality of local and non-local hydrological fluxes in turn influences near-surface soil moisture organization (Grayson et al., 1997). Though studies have shown that the predictive ability of terrain characteristics alone to describe soil moisture patterns rarely exceed 50% (Western et al, 1999a), examining seasonal fluctuations in the ability of soil-terrain characteristics to explain soil moisture at different depths can provide information on the control physical attributes and hydrological fluxes exert on soil moisture organization.

Less well understood is whether observed seasonality in controls and seasonality in near-surface soil moisture organization is present at deeper soil depths. Previous studies have observed that the temporal stability of soil moisture increases with increasing soil depth (Hupet and Vanclooster, 2002; Pachepsky et al., 2005; DeLannoy et al., 2006). The persistence of soil moisture at depth suggests that the physical and hydrological characteristics controlling soil moisture organization may also be persistent through time and not necessarily exhibit seasonal changes. In this study, we attempt to identify controls on deep soil moisture organization. This will permit more realistic inclusion of soil moisture data into environmental and hydrological models. For example, Stieglitz et al. (2003) and McNamara et al. (2005) found that the absence of deep soil moisture in mid-slope regions can act to prevent the transport of soil water from upper hillslopes to the stream. Only when these deep soils "wet up" do significant lateral flow from upslope soils contribute to stream discharge. Previous research at the Shale Hills catchment suggests that a similar mechanism may operate at Shale Hills, specifically, that streamflow during the summer months is largely controlled by deep soil moisture stores as opposed to near-surface soil moisture storage (Leavesley, 1967).

Vereecken et al. (2008b) highlighted the need for more catchment-scale monitoring of soil moisture at multiple depths, as these datasets can contain important information regarding hydrological fluxes. To date, the majority of studies which examined the controls on soil moisture organization were primarily conducted in the upper 30cm of soil (eg. Hawley et al., 1983; Nyberg, 1996; Crave and Gascuel-Odoux, 1997; Grayson et al., 1997; Famiglietti et al., 1998; Western et al., 1999a) and often times related to the verification and assimilation of remotely sensed data (Famiglietti, 1999; Jacobs et al., 2004; Choi and Jacobs, 2007; Famiglietti et al., 2008). Monitoring of soil moisture at multiple depths is required to fully elucidate controls on both near-surface and subsurface soil moisture organization, as well as to determine whether the observed seasonality in controls on soil moisture at the near-surface is also present in subsurface soil moisture organization. The objective of this study was two-fold: 1) compare the spatial organization of soil moisture at different measurement depths under different wetness conditions; 2) examine the correlation between soil moisture at different measurement depths and soil-terrain indices and whether the strength of correlation is persistent under different wetness conditions.

Methodology

Site Description

The Shale Hills catchment, a National Critical Zone Observatory, is located in Huntingdon County, PA. The area of the catchment is 7.9-ha, and the elevation ranges from 256-m at the outlet of the catchment to 310-m at the highest ridge. The catchment is characterized by steep slopes (up to 25%–48%) and narrow ridges. Several species of maple, oak, and hickory are typical deciduous trees found on the sloping areas and on ridges, while the valley floor is encompassed by eastern hemlock coniferous trees (Lin, 2006). The catchment is underlain by medium-dark grey to olive colored, steeply bedded, highly fractured Rose Hill Shale exhibits reddish-brown iron oxidation stains. The Rose Hill Shale formation is estimated to be approximately 300-m thick and consists of interbedded shale and sandstone and some interbedded limestone in the upper portions of the formation (PA Department of Environmental Resources, Atlas 86, 1989).

A detailed soil survey of the catchment identified five soil series based on landform position and depth to bedrock (Lin, 2006). Weikert soil, described in the Official Soil Series Description (USDA-NRCS, 2003) as a shallow, well-drained soil formed from weathered gray and brown acid shale, siltstone and sandstone, is found on the steep planar hillslopes and summit regions within the catchment. Berks, a moderately deep, well-drained soil formed from residuum weathered from shale siltstone and fine grained sandstone, is found on the toe-slope positions and side-slopes of the concave hillslopes. Rushtown, a very deep, excessively drained soil found in colluvial deposits, is found in the concave hillslopes. Ernest soil, a very deep, moderately to well-drained soils with low permeability, is found in the valley bottoms and near stream zone. Blairton soil, a moderately deep, poorly to well drained soil found on uplands, is located within the valley bottom at the east portion the catchment. There is a clear relationship between soil type, depth to bedrock and topography. A map of the Shale Hills catchment which includes all soil moisture sampling locations and distribution of soil series is given in figure 1-2. Climate at the Shale Hills catchment is typical of central Pennsylvania, with the majority of precipitation falling as snow in the winter and rain during the spring through fall months. Precipitation during the summer months typically occurs during convective weather fronts which can produce high intensity, short duration storm events.

Soil Moisture Monitoring Data Collection

This study utilized volumetric soil moisture data collected on an approximately weekly basis at the Shale Hills catchment over a four year period (September 10, 2004 to December 6, 2008). A total of 106 individual soil moisture monitoring locations were installed within the catchment between 2003 and 2006 (Fig. 1-2). Each monitoring locations consisted of a 0.051-m diameter PVC tube installed into the soil profile to a maximum depth of 1.1-m or to auger refusal, which ever came first. Each PVC tube was installed by first using a slide hammer to pound a 1.1-m hollow metal soil sampler with a tapered bit and plastic soil core sampling sleeve into the soil. In this way, a 0.038-m diameter soil core was collected at each monitoring location and saved for later description and analysis. A second metal tube with a reversed tapered cutting bit and a diameter slightly smaller than that of the 0.051-m PVC tube was used to shape the hole and ensure a tight seal between the soil and the PVC tube. The PVC tube was capped at the bottom with a water tight seal and then placed in the augered hole. Finally, a removable cap was placed on top to prevent water from entering the tube. Volumetric water content (θ, units: m^3/m^3) was collected at 0-20, 10-30, 30-50, 50-70, 70-90 and 90-110-cm depth intervals (or to bedrock at shallow bedrock locations) at each soil moisture monitoring location using time domain reflectometry (TDR). Volumetric soil moisture was measured using a TRIME-T3 tube access probe with and a TRIME-FM3 mobile moisture meter (IMKO, Ettlingen, Germany). At each measurement depth, two to three readings were taken in orthogonal directions, and the mean θ was calculated and entered in the soil moisture database. Three to five hours were typically required for collection of soil moisture data at all soil moisture monitoring locations. In addition to measuring volumetric soil moisture during field data collection, water table height was measured in wells located adjacent to 35 soil moisture monitoring locations. Precipitation and climate data was collected beginning in 2006 at a meteorological station located at the summit of the south facing hillslope. Additional tipping bucket rain gauges were placed beneath the canopy to measure throughfall (model TE525-WS, Texas Electronics, Inc., Dallas, TX). During the summer of 2008, all soil moisture monitoring locations, water table monitoring locations, precipitation and climate instrumentation and streambed position was surveyed using a Sokkia® Set 5A total station (Sokkia, Inc., Olathe, KS).

The four-year soil moisture database consists of 157 individual measurement days. The measurement days analyzed for this study began on September 10, 2004 and continuing on an approximately weekly basis until December 6, 2008. Prior to September 2006, 77 individual monitoring locations were measured. In August 2006, an additional 20 monitoring locations were installed and beginning on September 6, 2006, 97 monitoring locations were measured. These additional 20 sites were arraigned in 5 clusters of 4 monitoring locations each,

each cluster installed adjacent to automated soil moisture probes. One cluster was installed in the valley, three along an elevation gradient within a concave hillslope along the south-facing hillslope, and one located on the summit of the south facing hillslope. In late 2006, two more clusters comprised of 4 and 5 monitoring locations were installed in the valley and the summit of the south facing hillslope, respectively. These clusters were also adjacent to automated soil moisture probes. These most recent nine locations began being measured on January 8, 2006 and brought the total number of monitoring stations to 106. The number of locations measured on each measurement day varied due to the number of actual monitoring locations installed, personnel available to collect data and weather conditions, so the subsequent analysis included only 91 days where at least 35 soil moisture monitoring locations were measured. An examination of the 91 measurement days included in this study indicate that during the winter and spring soil moisture was monitored less frequently compared to the summer and fall. 3 measurement days were completed in the January and April, while 4, 5 and 6 measurement days were made in March, February and December, respectively. For the summer and fall months, September had the most measurement days with 17, followed by October and June with 12 and 11, respectively. July and November both had 8 measurement days while May and August both had 7. Figure 1-3 shows the temporal evolution of soil moisture over the 91 measurement days analyzed. Though the decision to use a minimum of 35 soil moisture monitoring locations was somewhat arbitrary, we determined it be an appropriate trade-off between having a sufficient number of monitoring sites to adequately represent spatial soil moisture within the catchment and allow for enough sampling days to have complete temporal coverage over all seasons.

Determination of Terrain Attributes

A digital elevation model (DEM) of the Shale Hills catchment was interpolated from light detecting and ranging (LIDAR) elevation data points flown over the Shale Hills catchment in 2006 (PAMAP Program, Bureau of Topographic and Geologic Survey, PA Department of Conservation and Natural Resources, 2006). The approximately 40,000 LIDAR elevation points were converted into a 1x1-m DEM using ArcGIS 9.2 (ESRI, Redland, CA). The quality of the LIDAR data and the resulting DEM is a function of the equipment used, aircraft speed/flying height, characteristics of the terrain surface as well as the density and distribution of the measured point source data (Fisher and Tate, 2006). All these factors introduce error, or "noise" into the DEM which needs to be accounted for. To reduce the amount of noise in the LIDAR data flown over Shale Hills and to better represent the primary topographic features within the catchment, a 9x9-m (9x9-cell) filter window was applied to the original DEM. The filter window used equal weighting to calculate the mean elevation of all cells within the window and applied the mean value to the center cell. This smoothed DEM was then use to derive four primary topographic attribute DEMs and one composite topographic attributes DEMs. Composite attributes are derived from the primary topographic attributes. The primary topographic attributes were elevation, slope, curvature, and upslope contributing area. The curvature value used in this study is the curvature of the surface fitted through all nine cells of the immediate neighborhood (ArcGIS 9.2 Spatial Analyst, ESRI, Redland, CA). The composite attribute was topographic wetness index (Beven and Kirkby, 1979), calculated using the ArcGIS 9.2 extension TauDEM (Tarboton, 1997). Terrain attributes were extracted from the DEM at all soil moisture monitoring locations using the coordinates derived from the total station survey. Figure 2-1 shows the cumulative distribution of the four primary and one secondary terrain attribute derived from the smoothed 1x1m DEM and the cumulative distribution of the five terrain attributes calculated at each soil moisture monitoring location.

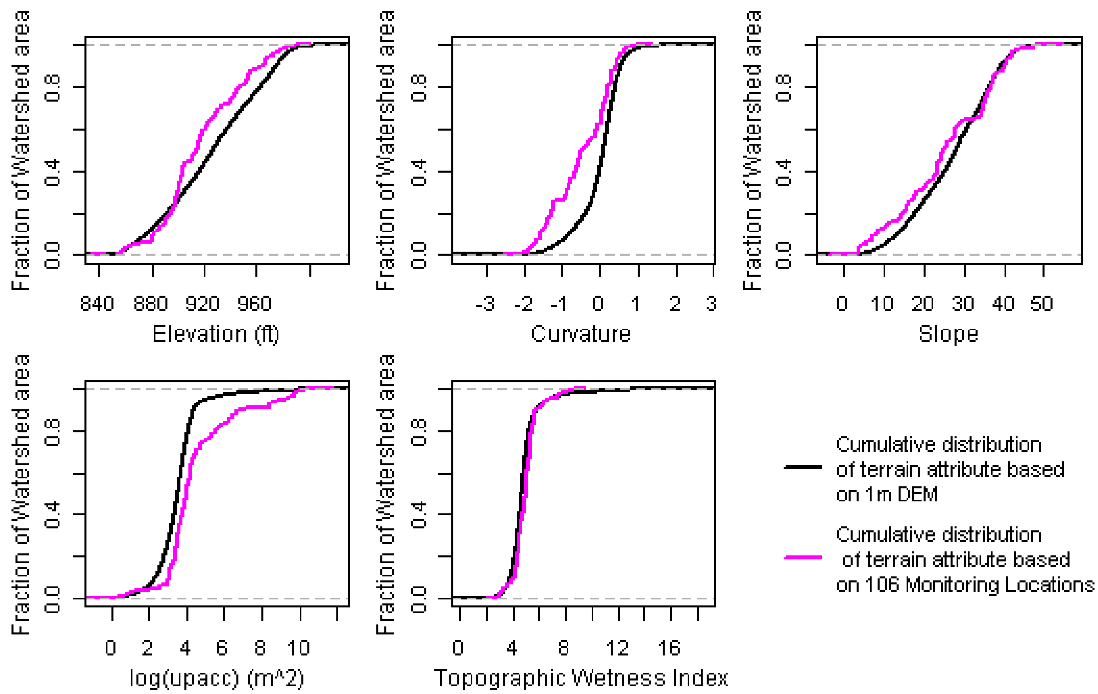

Figure 2-1: Cumulative distribution of attributes derived from 1x1m DEM and cumulative distribution of attributes derived from the soil moisture monitoring locations. Y-axis represents fraction of catchment less than the corresponding value of the terrain attribute.

The shape of the cumulative distribution for each of the four terrain attributes agrees with the cumulative distribution of the 1x1m DEM, suggesting that the manual soil moisture monitoring locations do a good job representing the spatial distribution of terrain attributes within the Shale Hills catchment.

Determination of Soil Properties

Determination of soil properties at Shale Hills was carried out on 58 intact soil cores which measured 0.038-m in diameter and up to 1.1-m in length, depending on depth to bedrock. Location of the soil cores described for this study is provided in figure 2-2.

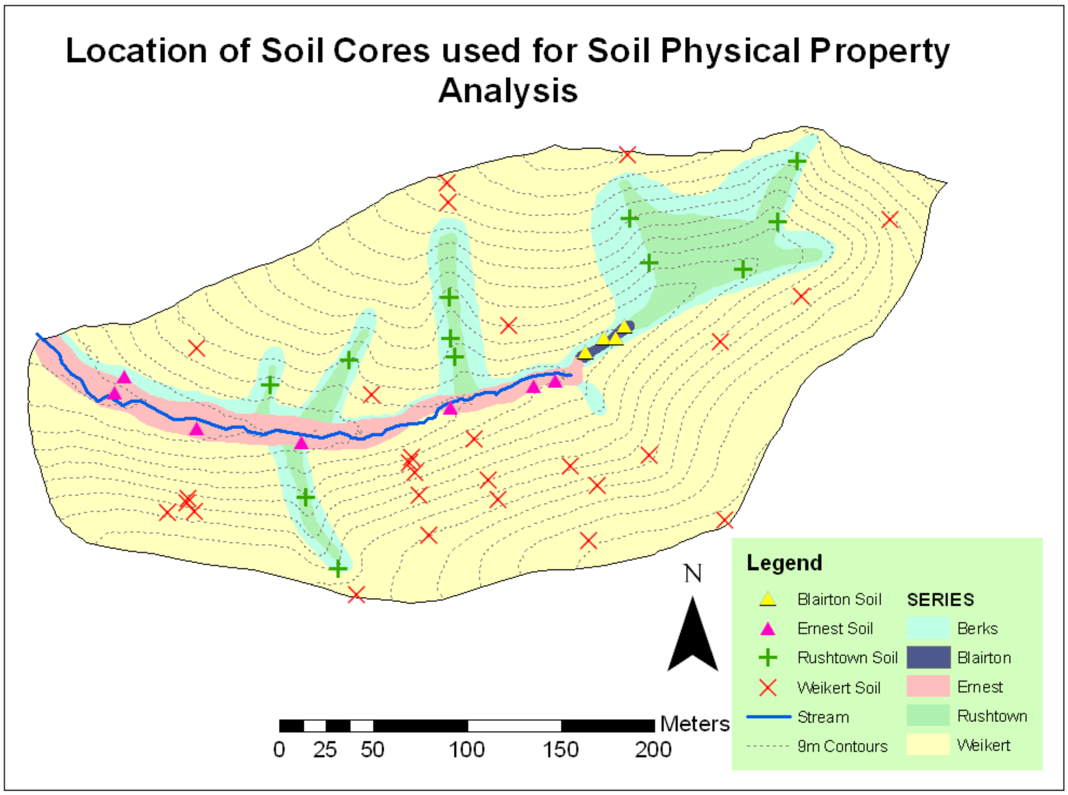

Figure 2-2: Map of the Shale Hills catchment showing locations of soil cores analyzed for this study.

Soil cores were collected between 2003 and 2006 during the installation of the manual soil monitoring locations (see previous section for details of soil core sampling). Each soil core was described using standard soil description techniques (Shoenberger et al., 2002). The description of the soil cores included color using the Munsell® soil color chart (Munsell® Color, GretagMacbeth, 2000), texture by feel, horizon thickness, soil structure, roots, and presence and amount of redoximorphic features. Photographic documentation of each soil core was also carried out. From the 58 soil cores described, 250 bulk soil samples were collected from the cores, corresponding to soil horizons. The number of bulk soil samples taken from an intact core varied from three to ten samples, depending on the length of the soil core and number of horizons identified. Prior to performing soil textural analysis, rock fragments defined as soil particles which did not pass through a 2mm sieve, were separated from the bulk sample and weighed to determine the percent rock fraction of each horizon. The less than 2mm soil fraction of each bulk sample was analyzed for soil texture using the rapid method outlined in Kettler et al. (2001). For this method, the <2mm soil fraction was first treated with calgon (hexametaphosphate) solution to deflocculate the soil aggregates. The sample was then passed through a 53-micron sieve to remove the sand fraction. The remaining solution was allowed to settle for between two and six hours, the exact time calculated using Stoke's Law and the height of the solution within a 1500-mL beaker. This allows the silt fraction to settle out and the suspended clay particles to be decanted. The remaining silt fraction was weighted and the clay fraction was calculated as the difference between the total weight of the <2mm soil fraction minus the sum of the silt and sand fraction. In addition to soil texture analysis, an unbiased subsample of each soil horizon was used for organic matter (OM) determination using the loss on ignition (LOI) method adapted from Storer (1984). Depth to bedrock was determined at 223 observations during soil mapping and installation of monitoring locations using a handheld auger. The bedrock – soil interface was assumed to be where the auger met refusal and could not be inserted further. Due to the highly fractured nature of the underlying shale bedrock, the refusal of the auger most likely represents the transition from the soil solum to fractured bedrock, and not competent bedrock. Depth to fractured bedrock varied from < 0.5m along the planar hillslopes to >2m along the valley floor. The results of our analyses are presented in Table 2-1.

Table 2-1: Mean soil properties for soil cores collected at soil moisture monitoring locations (n=58).

Soil Group	Soil Landform Unit	Number of Cores	Soil Horizon	Sand	Silt	Clay	Rock Fragments	Organic Matter
						% Weight		
Earnest/ Blairton	Valley	10	A	38.74	43.19	18.05	33.13	12.95
			Bw	31.99	43.88	24.11	28.41	3.93
			C	50.54	32.02	17.43	53.25	3.39
Rushtown/ Berks	Concave Hillslope	21	A	46.34	38.94	14.7	41.83	9.34
			Bw	47.73	35.1	17.16	41.37	3.78
			C	56.62	27.66	15.7	50.18	3.09
Weikert	Planar Hillslope/ Summit	27	A	43.89	43.02	13.08	51.3	11.13
			Bw	41.51	43.34	15.13	55.32	4.39
			C	46.2	38.66	15.12	71.47	3.65

Data Analysis

Correlation of soil-terrain attributes with soil moisture

Analysis of the correlation of soil moisture with terrain and soil properties was carried out at the fifty-eight monitoring locations where soil cores were described and analyzed (figure 2-2). We carried out a linear regression analysis to determine the ability of 11 different soil-terrain attributes to explain the variation in spatial soil moisture data at each measurement depth. Five terrain attributes were calculated from the 1x1m DEM: elevation (EL), curvature (CV), slope (SL), upslope contributing area (UC), and topographic wetness index (TW). Addtionally, the six soil attributes determined at the 58 soil core locations were: depth to bedrock (DB), weight percentages of clay (CL), silt (ST), sand (SD), organic matter content (OM), and rock fragments (RK, >2 mm soil fraction). Earlier studies found soil moisture data can be normally distributed (Bell et al., 1980; Owe et al., 1982; Nyberg, 1996) or exhibit a skewed distribution (Choi and Jacobs, 2007; Penna et al., 2009). Figure 2-3 is a plot of the skewness of soil moisture measurements at each depth verse the spatially averaged soil moisture at each depth ($\bar{\theta}_z$) on each measurement day.

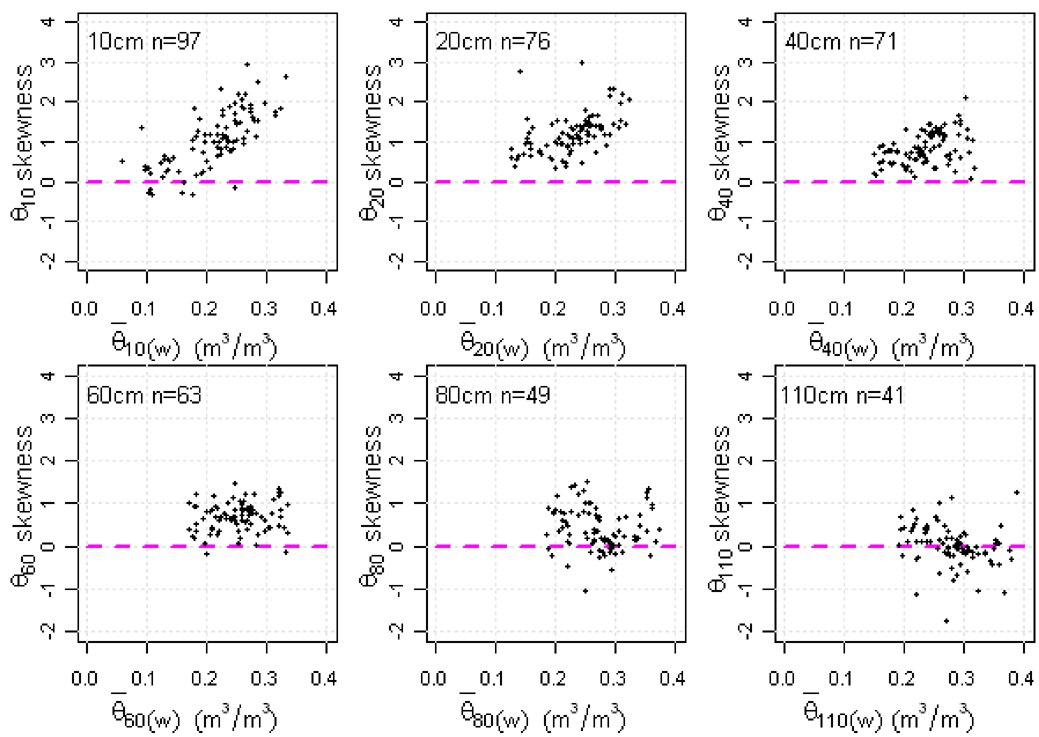

Figure 2-3: Skewness of soil moisture data verse mean soil moisture for each measurement day. Soil moisture data divided into the measurement depth intervals indicated. The horizontal dashed line represents zero skewness. n is the number of locations where the depth interval is measured.

A positive relationship between $\bar{\theta}_z$ and skewness is most evident in the upper depths (10-40 cm). Lower depths (80 and 100 cm) show a more normal distribution of soil moisture centered on zero skewness and lack a clear relationship with $\bar{\theta}_z$. Based on these results, soil moisture data collected at 10, 20 and 40-cm was first log-transformed to account for the non-normality of the soil moisture data. The statistical analyses were carried out using the statistical software *R*, v.2.8.1 (http://www.r-project.org).

Results

Temporal changes in soil moisture spatial organization

To examine the temporal changes in spatial organization of soil moisture at the Shale Hills catchment, we plotted soil moisture measurements at each depth for two cases: 1) a measurement day typical of wet conditions found during the spring (5/11/2007), when spatially-averaged soil moisture was above the long-term means for each depth, and 2) a measurement day typical of dry conditions during the summer months (9/7/2007) when spatially-averaged soil moisture was above the long-term means for each depth. Soil moisture measurements were grouped by whether the soil moisture measured was less than or greater than the spatial mean at the respective depth ($\bar{\theta}_z$) on the measurement day (fig. 2-4).

A visual assessment of soil moisture spatial organization indicates that under wet conditions (5/11/2007), soil moisture at 10 and 20-cm exhibit a strong relationship with topographic features. Locations with soil moisture greater than $\bar{\theta}_{10}$ ($\bar{\theta}_{10}$=0.262 on 5/11/2007) and $\bar{\theta}_{20}$ ($\bar{\theta}_{20}$=0.276 on 5/11/2007) were found within convergent landforms, particularly the swales along the north facing hillslope and valley floor. As you move vertically down the soil profile, locations which are above the spatially averaged mean congregate within the valley landform and lower swales (40 through 80-cm) and at the deepest depth interval (100-cm) the locations with soil moisture above the spatial mean were predominately located within the valley landform. Our results indicates that under wet conditions, locations with soil moisture above the spatially-averaged mean are concentrated within convergent landforms at both near-surface and subsurface depths.

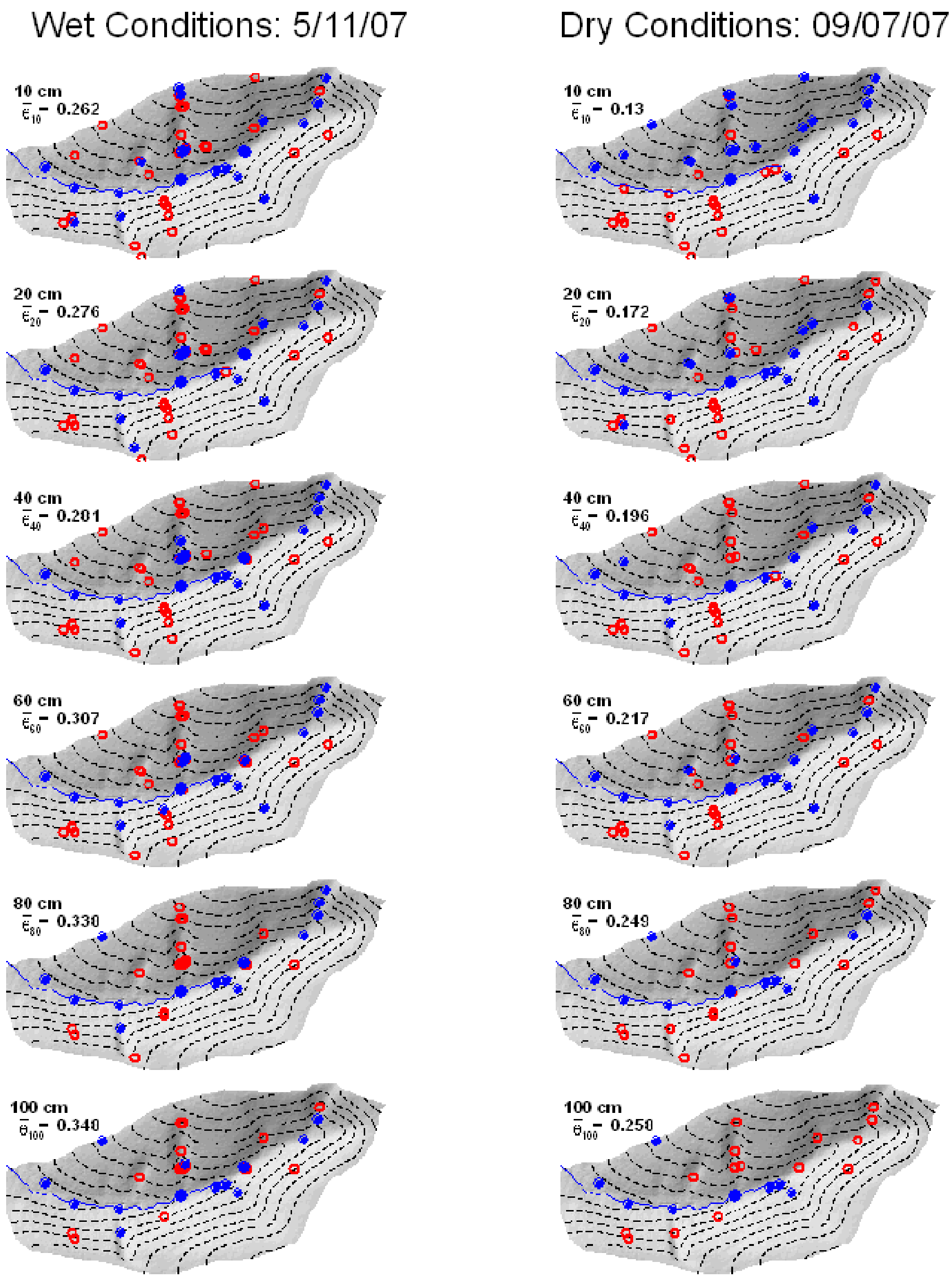

Figure 2-4: Map of soil moisture measurements made under wet (5/11/2007, $\overline{\theta}_{D(w)}$ = 0.280 m3/m3) and dry (9/07/2007, $\overline{\theta}_{D(w)}$ = 0.169 m3/m3) conditions. Solid blue circles represent locations which were above the spatial mean at the depth interval indicated ($\overline{\theta}_z$); hollow red circles represent locations which were below $\overline{\theta}_z$. Dashed lines represent 10-m contour lines.

On 9/7/2007, the soil moisture at 10 and 20-cm do not exhibit a strong relationship with topographic features, with locations greater than $\bar{\theta}_{10}$ ($\bar{\theta}_{10}$=0.130 on 9/7/2007) and $\bar{\theta}_{20}$ ($\bar{\theta}_{20}$=0.172 on 9/7/2007) distributed throughout the catchment, without clear organization around topographic features. In particular, locations with soil moisture values greater than $\bar{\theta}_{10}$ were located along the planar hillslope and concave hillslope landforms. Similarly, locations within the valley exhibit soil moisture greater than and less than $\bar{\theta}_{10}$, indicating that soil moisture at 10-cm is not topographically aligned with convergent landforms under dry soil moisture conditions. At 20-cm, we begin to see soil moisture align with convergent landforms, particularly along the valley, where monitoring locations are all above $\bar{\theta}_{20}$. As you vertically down the soil profile, we see soil moisture aligned with convergent landform features (40 and 60-cm) and at the deepest measurement depths (80 and 100-cm) soil moisture locations with values above $\bar{\theta}_{80}$ and $\bar{\theta}_{100}$ are predominately located with the valley landform, similar to soil moisture organization under wet conditions.

Comparing the spatial patterns under wet and dry conditions, differences are most pronounced at the near-surface soil moisture depths (10 and 20-cm). Under wet soil moisture conditions, surface (10-cm) soil moisture exhibits organization along topographic convergent features. Under dry soil moisture conditions, surface soil moisture does not exhibit clear organization along topographic convergent features. As you move vertically down the soil profile (40 to 100-cm), the soil moisture organization under wet and dry conditions became similar, with locations higher than the spatially average soil moisture remaining higher as you move vertically down, and locations below the spatially average soil moisture remaining lower. Our results indicate that near-surface soil moisture organization is more affected by seasonal change in hydrological fluxes than deeper depths, and as such, deeper soil moisture locations exhibit more temporal persistence in soil moisture values as compared to near surface locations.

Spatial Correlation between soil-terrain attributes and soil moisture

As demonstrated in figure 2-4, under wet conditions both surface and subsurface soil moisture organization aligns with topographic convergent areas (i.e. concave hillslopes and valley landforms). Under dry conditions, soil moisture at the near-surface (10-cm) does not show clear organization along convergent landforms while subsurface soil moisture exhibits persistent organization along topographic convergent areas. Under wet conditions, both near surface and subsurface soil moisture exhibit organization along topographic convergent features. Our results suggest that topographic attributes may be a good predictor of soil moisture spatial distribution for both near surface and subsurface depth measurements under wet conditions. Under dry conditions, however, topography may not be an effective predictor of soil moisture spatial distribution at the near-surface (10-cm), but may still be a good predictor of subsurface soil moisture (>20-cm). In this section, we first perform a linear regression analysis between the soil-terrain attributes and soil moisture measured at each depth interval and use the coefficient of determination (R^2) to assess the ability of individual soil-terrain attributes to describe the variability in soil moisture measurements. Second, we examine the seasonal variations in (R^2) between soil-terrain attributes and soil moisture and discuss how this is related to changes in the controls on soil moisture organization described above.

Table 2-2 shows mean R^2 values (averaged over all measurement days) for each depth and soil-terrain attribute. With the exception of percent weight clay and rock fragments, our results indicated that terrain features generally outperformed soil textural properties in explaining the variability of soil moisture distribution within the Shale Hills catchment.

Table 2-2: Mean coefficients of determination (R^2) between soil moisture measured at each depth interval and 11 soil-terrain attributes.

	Measurment Depth Interval					
Soil terrain Attribute	**10-cm**	**20-cm**	**40-cm**	**60-cm**	**80-cm**	**100-cm**
Elevation (m)	0.175	0.193	0.128	0.164	0.169	0.237
Slope	0.234	0.178	0.254	0.531	0.54	0.494
Curvature	0.15	0.188	0.221	0.228	0.149	0.197
Upslope Contributing Area (m^2)	0.18	0.217	0.266	0.275	0.145	0.158
Depth to Bedrock (cm)	0.258	0.286	0.25	0.432	0.439	0.394
Topographic Wetness Index	0.246	0.278	0.342	0.409	0.263	0.27
Sand (%)	0.042	0.041	0.063	0.129	0.164	0.18
Silt (%)	0.019	0.047	0.039	0.043	0.122	0.141
Clay (%)	0.166	0.216	0.355	0.404	0.351	0.432
Rock Fragments (%)	0.226	0.346	0.4	0.455	0.415	0.476
Organic Matter (%)	0.015	0.015	0.015	0.006	0.008	0.024

Percent weight sand, silt and organic matter had the lowest overall explanatory power of all soil-terrain attributes. We observed a positive trend between depth and mean R^2 for slope, depth to bedrock, clay and rock fragments. Conversely, we observed the highest mean R^2 values at intermediate depths for curvature, upslope contributing area, and topographic wetness index. An assessment of the direction of relationship (sign of the slope term in the linear regression equation) between soil moisture and soil-terrain attributes indicates that elevation, slope, curvature, percent weight sand and percent weight rock fragments were negatively related to soil moisture, while upslope contributing area, depth to bedrock, topographic wetness index, percent weight silt, percent weight sand and organic matter were positively related with soil moisture. Finally, mean R^2 values generally did not exceed 50% explanatory power, with the exception of the mean R^2 values for slope at depth intervals of 60 and 80-cm (R^2 = 0.531 and 0.540, respectively). The relatively low R^2 values agree with previous studies which found that the predictive ability of individual terrain characteristics to describe soil moisture patterns rarely exceed 50% (Western et al, 1999a).

Of the eleven soil-terrain attributes, only slope, depth to bedrock, topographic wetness index and percent weight rock fragments were significantly related to soil moisture measurements (using significance level, α, of 0.05) on at least 85% of the measurement days for all measurement depth intervals (Table 2-3). With the exception of percent weight clay and rock fragments, the R^2 values for terrain attributes were more often significant at $\alpha = 0.05$ than soil attributes.

Table 2-3: Percentage of days out of total days analyzed (n=91) when Coefficient of determination (R^2) between soil moisture measured at each depth interval and 11 soil-terrain attributes was significant at $\alpha = 0.05$.

	Measurment Depth Interval					
Soil terrain Attribute	**10-cm**	**20-cm**	**40-cm**	**60-cm**	**80-cm**	**100-cm**
Elevation (m)	82.4	95.6	71.4	81.3	59.3	72.5
Slope	96.7	95.6	98.9	100.0	100.0	97.8
Curvature	74.7	96.7	95.6	95.6	45.1	58.2
Upslope Contributing Area (m^2)	80.2	96.7	98.9	95.6	46.2	44.0
Depth to Bedrock (cm)	96.7	100.0	98.9	100.0	100.0	97.8
Topographic Wetness Index	86.8	100.0	100.0	98.9	94.5	85.7
Sand (%)	7.7	4.4	8.8	72.5	67.0	53.8
Silt (%)	3.3	5.5	2.2	2.2	33.0	25.3
Clay (%)	80.2	98.9	98.9	100.0	98.9	95.6
Rock Fragments (%)	84.6	100.0	100.0	100.0	98.9	96.7
Organic Matter (%)	1.1	0.0	0.0	0.0	0.0	0.0

Temporal evolution of coefficient of determination between soil moisture and soil-terrain attributes

We next examine how the R^2 values for slope, depth to bedrock, and topographic wetness index vary over the 91 measurement days analyzed and how they related to wet and dry conditions within the catchment. For consistency, we define wet conditions as measurement days when spatially-averaged soil moisture at depth *z* on day *i* ($\overline{\theta}_{z,i}$) is above the mean spatially-averaged soil moisture at depth *z* over the four-year monitoring period. Similarly, we define dry conditions as measurement days when spatially-averaged soil moisture at depth *z* on day *i* ($\bar{\theta}_{z,i}$) is below the mean spatially-averaged soil moisture at depth *z* over the four-year monitoring period. A comparison of the seasonal variability in R^2 values for each measurement depth interval indicated that the 10-cm depth interval exhibited the largest variability between wet and dry conditions with a general trend of decreasing seasonal variability as you move down the soil profile. This suggests a dampened influence of seasonal changes in hydrological fluxes, particularly evapotranspiration, on soil moisture spatial organization with increasing soil depth.

Figure 2-6a and 2-6b shows the correlation between topographic wetness index and soil moisture at 10, 20, and 40-cm (Fig. 2-6a) and 60, 80 and 100-cm (Fig. 2-6b). At the depth interval closest to the surface (10-cm), a seasonal trend is present in the data, with higher R^2 values under wet conditions (mean R^2 for 10-cm under wet conditions = 0.291) and lower R^2 values under dry conditions (mean R^2 for 10-cm under dry conditions = 0.179). This indicates that under dry conditions, near-surface soil moisture is not strongly aligned with topographic wetness. Subsurface soil moisture exhibited a decreasing seasonal variability as you moved vertically down the soil profile, with similar mean R^2 values under wet (mean R^2 under wet conditions = 0.293, 0.340, 0.406, 0.270 and 0.289 for 20, 40, 60, 80 and 100-cm, respectively) and dry conditions (mean R^2 under dry conditions = 0.260, 0.344, 0.410, 0.255, 0.249 for 20, 40, 60, 80 and 100-cm, respectively). This indicates that the ability of topographic wetness index to explain the spatial variability of near-surface soil moisture increases with catchment wetness, while the strength in the relationship between subsurface soil moisture and topographic wetness index is more temporally persistent through time and reflects temporally stable organization of soil moisture throughout the year.

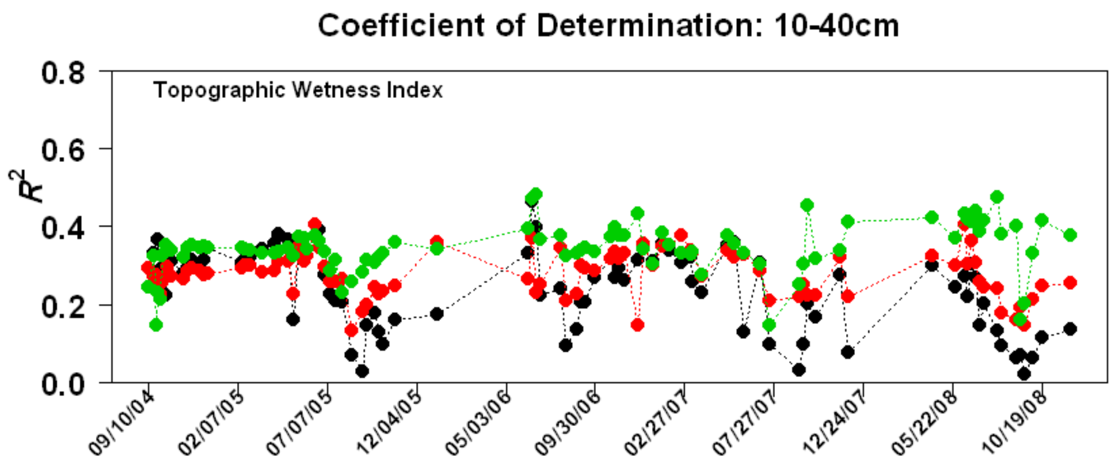

Figure 2-6a: Temporal variability in the coefficient of determination (R^2) between soil moisture and topographic wetness index. Black points are R^2 for soil moisture at 10-cm; red points are R^2 for soil moisture at 20-cm; green points are R^2 for soil moisture at 40-cm.

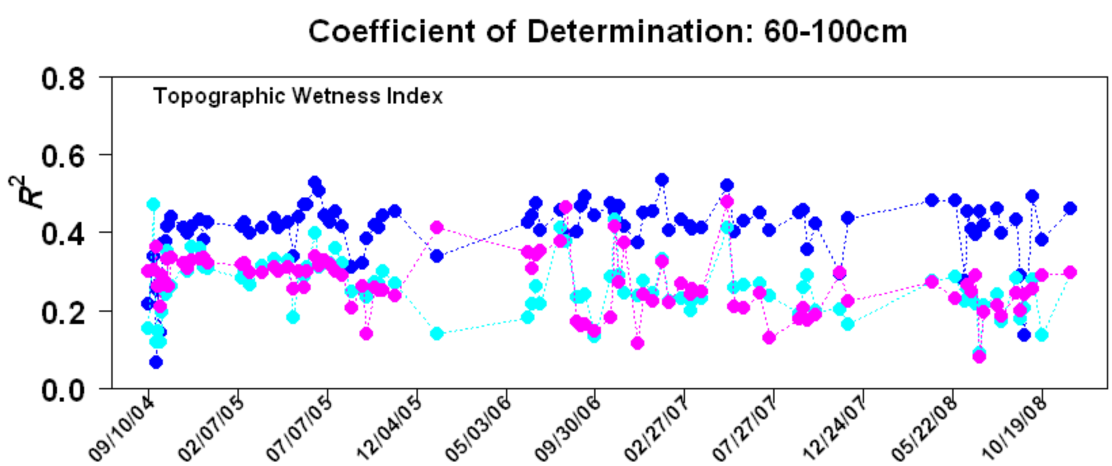

Figure 2-6b: Temporal variability in the coefficient of determination (R^2) between soil moisture and topographic wetness index. Blue points are R^2 for soil moisture at 60-cm; cyan points are R^2 for soil moisture at 80-cm; magenta points are R^2 for soil moisture at 100-cm depth intervals.

Similar results were found for R^2 values between soil moisture and depth to bedrock (Figure 2-7a and 2-7b). The R^2 values between near-surface soil moisture, particularly at 10-cm, and depth to bedrock also exhibit strong seasonal trends, with higher R^2 values under wet conditions (mean R^2 for 10-cm under wet conditions = 0.304) than under dry conditions (mean R^2 for 10-cm under dry conditions = 0.190). At depth, we again see decreasing seasonal variability as you moved vertically down the soil profile with the values of R^2 generally increasing with increasing soil moisture, indicating the ability of depth to bedrock to explain spatial variability in soil moisture increases with soil depth (mean R^2 for wet conditions = 0.311, 0.263, 0.435, 0.451 and 0.410 for 20, 40, 60, 80 and 100-cm, respectively; mean R^2 for dry conditions = 0.254, 0.233, 0.428, 0.426 and 0.376 for 20, 40, 60, 80 and 100-cm, respectively). The similar results between topographic wetness index and depth to bedrock may reflect the close coupling between deep soil profiles and topographic convergent areas.

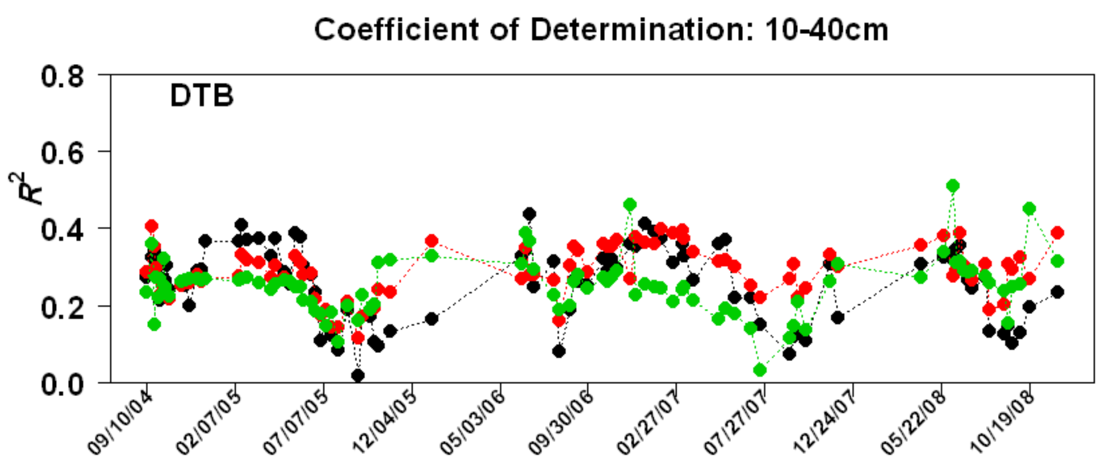

Figure 2-7a: Temporal variability in the coefficient of determination (R^2) between soil moisture and depth to bedrock (DTB). Black points are R^2 for soil moisture at 10-cm; red points are R^2 for soil moisture at 20-cm; green points are R^2 for soil moisture at 40-cm.

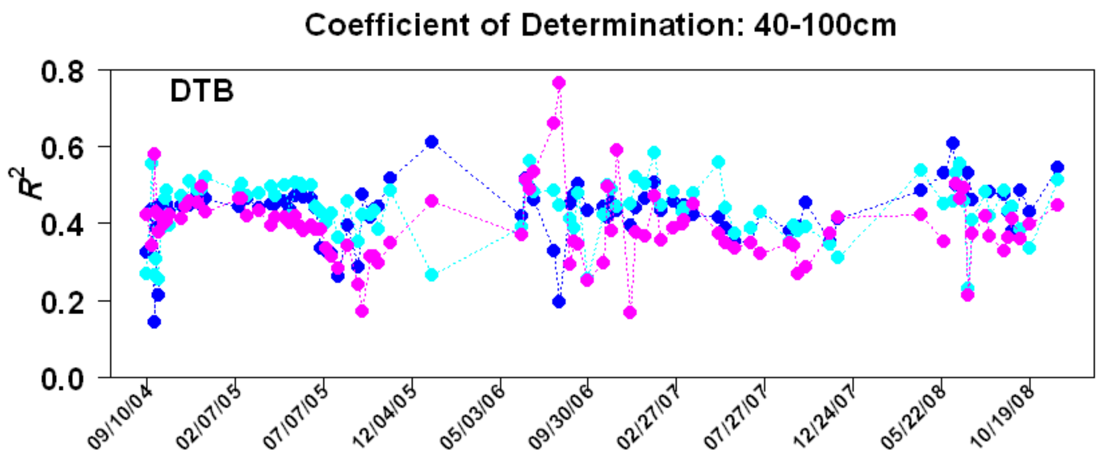

Figure 2-7b: Temporal variability in the coefficient of determination (R^2) between soil moisture and depth to bedrock (DTB). Blue points are R^2 for soil moisture at 60-cm; cyan points are R^2 for soil moisture at 80-cm; magenta points are R^2 for soil moisture at 100-cm depth intervals.

An analysis of R^2 values between soil moisture and slope (Figure 2-8a and 2-8b) did not indicate any seasonal trend in R^2 values at either the near-surface or subsurface depths (mean R^2 for wet conditions of 0.247, 0.185, 0.253, 0.521, 0.526 and 0.482 for 10, 20, 40, 60, 80 and 100-cm, respectively and mean R^2 for dry conditions of 0.214, 0.169, 0.253, 0.542, 0.554 and 0.506 10, 20, 40, 60, 80 and 100-cm, respectively). Similar to depth to bedrock, R^2 values tended to increase as you move vertically down the soil profile, indicating that the use of slope as a predictor of soil moisture improves with depth. This may be a consequence of the lack of deep soil profiles on the planar hillslopes and summits. In other words, measurement locations with a thick soil profile are generally located at lower elevations, where the valley contains low slope values and the highest soil moisture values. Conversely, the 10-cm depth interval is measured throughout the catchment and low slope values can be found within the valley as well as the upper planar hillslope and summit monitoring locations. This leads to low R^2 values for the slope attribute at near surface measurement intervals. The results of this analysis demonstrated clear seasonality in the spatial organization of soil moisture at the near surface (10-cm depth), with decreasing seasonality to spatial organization as you move vertically down the soil profile.

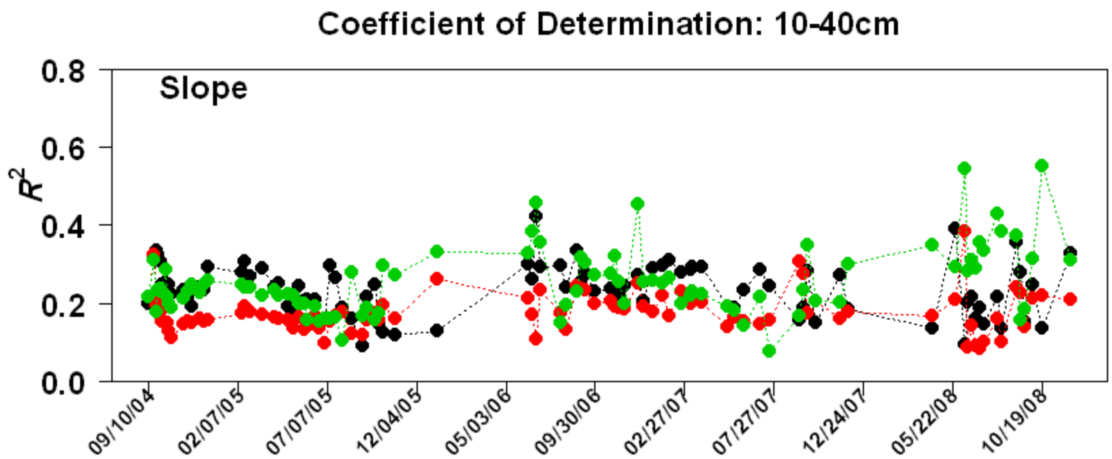

Figure 2-8a: Temporal variability in the coefficient of determination (R^2) between soil moisture and slope. Black points are R^2 for soil moisture at 10-cm; red points are R^2 for soil moisture at 20-cm; green points are R^2 for soil moisture at 40-cm.

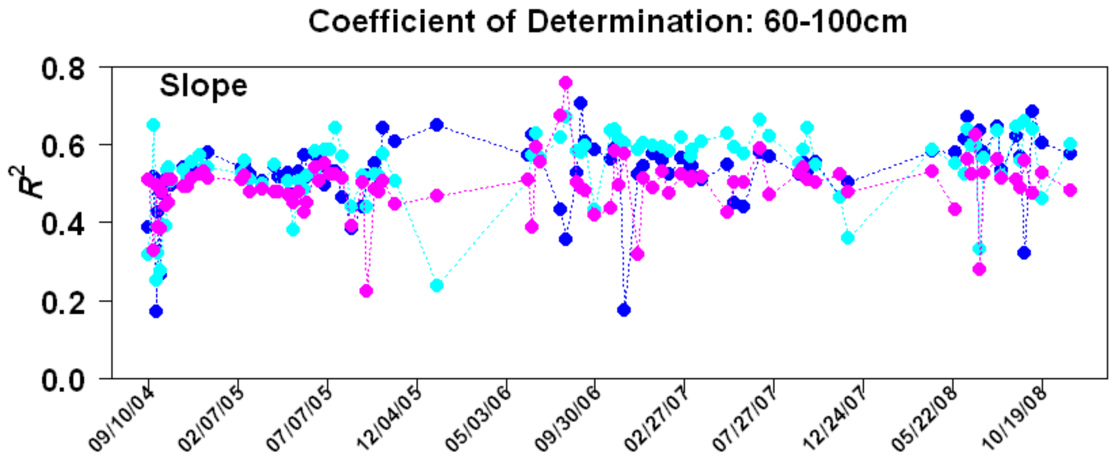

Figure 2-8b: Temporal variability in the coefficient of determination (R^2) between soil moisture and slope. Blue points are R^2 for soil moisture at 60-cm; cyan points are R^2 for soil moisture at 80-cm; magenta points are R^2 for soil moisture at 100-cm depth intervals.

Discussion

Near-surface (<20-cm depth interval) soil moisture organization within the Shale Hills catchment exhibits seasonal trends. Under wet conditions (late fall through spring), soil moisture above the spatial average was located within convergent landforms (ie. the valley and concave hillslopes). Under dry conditions (summer through early fall), near-surface soil moisture did not exhibit organization around convergent landforms and soil moisture above the spatial average was more randomly distributed throughout the catchment. On the other hand, deeper (>40-cm) soil moisture organization exhibited temporal persistence, with soil moisture above the spatial mean consistently located within convergent landforms under both wet and dry conditions. The seasonality in near-surface soil moisture organization at Shale Hills is in agreement with Grayson et al. (1997) who found that under conditions where precipitation exceeded evaporation, soil moisture within the upper 30-cm aligned with topographic depressions, while during periods when evaporation exceeded precipitation, soil moisture organization exhibited a more random appearance. Our examination of soil moisture organization within the upper 110-cm of soil indicate that near surface soil moisture organization does not reflect soil moisture organization at depth under dry conditions.

Source of the destruction of spatial organization under dry conditions may be due to variable rates of evapotranspiration by vegetation (Teuling and Troch, 2005; Hupet and Van Clooster, 2002), different rates of removal of soil moisture by evaporation due to slope aspect (Grayson et al., 1997, Western et al., 1999a), or the distribution of soil texture (Kim and Borros, 2002). Western et al. (2003) proposed that under dry conditions, soil moisture forms a positive skew with the majority of soil moisture measurements congregating toward the lower bound of the range of possible soil moisture values, typically the wilting point, as soil moisture in removed by evapotranspiration. In our case, under dry conditions soil moisture at 10-cm exhibited a normal distribution, but with considerable clustering around very low values (data not shown). This decrease in variability due to clustering reduces observed soil moisture organization and inhibits the ability of individual soil-terrain attributes to explain soil moisture distribution because drastically different topographic positions (planar hillslope and valley floor, for example) can exhibit essentially the same soil moisture behavior. Conversely, we do see an increase in the ability of terrain attributes, in particular topographic wetness index, to explain near-surface soil moisture variability under wet conditions. This is most likely a consequence of near-saturated to saturated conditions in the valley/near-stream zone due to the formation of a shallow water table. In-situ soil moisture monitoring and analysis of storm events found evidence of subsurface lateral flow into topographic convergent areas via soil macropores and at the interface between soil horizons (Zhu and Lin, 2008). Subsurface lateral flow can reinforce the organization of soil moisture and contribute to the increase in explanatory power of attributes related to topographic convergence. Our results indicate that seasonal removal of soil moisture, primarily through evapotranspiration, has a significant influence on the observed organization at the near-surface under dry conditions while topography is an important control on organization under wet conditions.

Unlike near-surface soil moisture organization, sub-surface soil moisture organization exhibits strong temporal persistence throughout the year. Williams et al. (2009) found that soil moisture generated from snowmelt tend to migrate downslope due to topographic controls and persist in the deep downslope soils. Within a predominantly agricultural watershed in central Pennsylvania, Henninger et al. (1976) found soil moisture increased as you moved toward the near-stream zone, and was a result of the combination of deep, moderately to poorly drained soils in the near-stream zone and topographic convergence. Similar to these studies, soil mapping at Shale Hills carried out by Lin et al. (2006) found that convergent landforms consist of deep, moderate to poorly drained soils (e.g. Ernest and Blairton soil series in the valley; Rushtown soil series in the concave hillslopes). These deep soil profiles provide a store of soil moisture which persisted even under dry conditions and reduces the effect that surface soil moisture removal processes have on deep soil moisture. This indicates that at Shale Hills, soil moisture organization within the subsurface is a function of both topographic controls and soil depth.

The results of our linear regression analysis between soil-terrain attributes and soil moisture indicate that both topography and soil depth are important in controlling soil moisture organization at depth, while controls on soil moisture organization at the near-surface seasonally fluctuate between evapotranspiration and topography. The mean coefficient of determination (R^2) for the depth to bedrock and percent clay content attributes increased as you moved down the soil profile (Table 2-1), indicating that the ability of these attributes to explain soil moisture variability generally increased with depth. Additionally, the R^2 for depth to bedrock did not show clear seasonal variation in it’s magnitude at depths greater than 60cm, and maintained a R^2 value similar that of near-surface soil moisture under wet conditions. This indicates that the ability of depth to bedrock to explain soil moisture variability remains consistent throughout the year. Furthermore, the high clay content within the deep soils allows for the retention of soil moisture under dry conditions, promoting persistence of soil moisture organization.

Examination of R^2 values for indices related to topographic convergence indicates that intermediate depths (40 and 60-cm) had the highest R^2 values throughout the year (Table 2-2), with R^2 for the 10 and 20-cm depths showing clear seasonal trends and 80 and 100-cm depths exhibiting the lowest R^2 throughout the year (Figure 2-6a and 2-6b). This indicates that lateral flow processes may be most influential at intermediate soil depths. Our results are in agreement with Lin et al. (2006), who proposed a conceptual model of surface and subsurface water movement within Shale Hills based on field observations and vertical soil moisture dynamics. Their model highlighted significant lateral preferential pathways along the A and A-B soil horizons, which coincide with intermediate soil depths (40-60-cm) within the deep valley and concave hillslope soils. Our results also corroborate earlier studies examining soil moisture at Shale Hills, which found lateral flow to be an important process in the movement of soil water downslope, particularly during periods of high antecedent soil moisture (Lynch, 1970; Corbett et al., 1975; Duffy, 1996).

Conclusions

Seasonal trends in near-surface (>10-cm) soil moisture organization indicate that seasonal removal of soil moisture, primarily through evapotranspiration, has a significant influence on the organization under dry conditions while topography is an important control on organization under wet conditions. Sub-surface (>20-cm) soil moisture organization exhibited temporal persistence, with areas of high soil moisture consistently located within convergent landforms under both wet and dry conditions. The combination of deep soil profiles in convergent landforms and lateral subsurface flow into convergent areas provide a store of soil moisture which persist even under dry conditions. Our results indicate that subsurface soil moisture organization is a function of both topographic controls and soil depth.

The results of our linear regression analysis between soil-terrain attributes and soil moisture indicate that terrain features generally outperformed soil textural properties in explaining the variability of soil moisture distribution within the Shale Hills. Our results indicates that R^2 values for near-surface soil moisture reflected the seasonal trends soil moisture organization, with higher R^2 values under wet conditions when soil moisture is organized with convergent landforms and lower R^2 values under dry conditions when soil moisture is more randomly distributed throughout the catchment. Similarly, the lack of a seasonal trend for subsurface soil moisture is reflected in the stability of R^2 values for sub-surface soil moisture (60, 80 and 100-cm).Topographic indices did not explain soil moisture variability at 80 and 100-cm as well as depth to bedrock or clay content; and indices related to topographic convergence generally explained the moisture variability of soil moisture at intermediate depths (40 and 60-cm) best. At the Shale Hills, both topography and soil depth are important in controlling soil moisture organization at depth, while seasonal fluctuations in evapotranspiration and topography are important controls on soil moisture organization at the near-surface. This work extends previous studies of soil moisture seasonal organization which focused primarily within the upper 30-cm of soil. We've demonstrated that seasonally of soil moisture organization decreases with increasing depth. This have implications for modeling soil moisture dynamics at multiple depths for inclusion in catchment-scale hydrological models.

Chapter 3

Conclusions

This study used spatially-extensive soil moisture dataset collected over four years to elucidate the spatial and temporal controls of soil moisture variability across a small forested catchment. We observed an increase in spatial variability of soil moisture with an increase in spatially-averaged soil moisture. During periods of high soil moisture, spatially-limited hydrologic processes, particularly groundwater-soil interactions in the valley and convergent subsurface flow in the valley and concave hillslopes, act to increase soil moisture variability. Conversely, during periods of low soil moisture, spatially extensive hydrologic processes operating across the watershed, particularly evapotranspiration, act to decrease soil moisture variability. A consequence of this positive relationship between spatial variability and spatially-averaged soil moisture is a widening of the confidence intervals for the estimation of spatially-averaged soil moisture at all measurement depths (10, 20, 40, 60, 80 and 100-cm), and an increase in the number of samples required to be 95% confident in estimates of spatially-averaged soil moisture. Correctly modeling the relationship between spatially averaged soil moisture and the spatial variability of soil moisture measurements will enhance our estimation of uncertainty related to estimates of spatially averaged soil moisture. This information may be useful for the optimal monitoring of future soil moisture measurement campaigns at locations where shallow water tables are present.

Seasonal trends in near-surface (>10-cm) soil moisture organization indicate that seasonal removal of soil moisture, primarily through evapotranspiration, has a significant influence on the organization under dry conditions while topography is an important control on organization under wet conditions. Sub-surface (>20-cm) soil moisture organization exhibited temporal persistence, with areas of high soil moisture consistently located within convergent landforms under both wet and dry conditions. The combination of deep soil profiles in convergent landforms and lateral subsurface flow into convergent areas provide a store of soil moisture which persist even under dry conditions. Our results indicate that subsurface soil moisture organization is a function of both topographic controls and soil depth.

The results of our linear regression analysis between soil-terrain attributes and soil moisture indicate that terrain features generally outperformed soil textural properties in explaining the variability of soil moisture distribution within the Shale Hills. Our results indicated that R^2 values for near-surface soil moisture reflected the seasonal trends soil moisture organization, with higher R^2 values under wet conditions when soil moisture is organized with convergent landforms and lower R^2 values under dry conditions when soil moisture is more randomly distributed throughout the catchment. Similarly, the lack of a seasonal trend for subsurface soil moisture is reflected in the stability of R^2 values for sub-surface soil moisture (60, 80 and 100-cm). These results support our conclusion that both topography and soil depth are important in controlling soil moisture organization at depth, while seasonal fluctuations in evapotranspiration and topography are important controls on soil moisture organization at the near-surface.

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