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Changing controls of soil moisture spatial organization in the Shale Hills Catchment

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ABSTRACT

Modeling hydrological processes often requires the identification of dominant controls on soil moisture spatial organization under different climatic conditions at various soil depths. In this study, we utilized a four-year database consisting of soil moisture measurements at 106 locations from near-surface down to 1.1 m depth across a forested catchment in central Pennsylvania, USA. Our objectives were to 1) compare the spatial organization of soil moisture within different soil–landform units and its temporal persistence at different depths under varying catchment wetness conditions and 2) investigate correlation strength between soil moisture content and 11 soil–terrain attributes and the temporal change of such correlation. Our results showed that the catchment's near-surface (<0.3 m) soil moisture organization exhibited clear seasonal trends: during winter through early summer, areas of high soil moisture were concentrated within convergent landforms; while during summer through early fall, soil moisture was more uniformly distributed throughout this complex terrain catchment. This suggests that under dry conditions soil moisture removal (primarily through evapotranspiration) had a significant influence on the organization of near-surface soil moisture, while topography was an important control on soil moisture spatial organization under wet conditions. Subsurface (>0.3 to 1.1 m) soil moisture organization, however, exhibited increasing temporal persistence with depth, and subsoil moisture above the catchment-wide average was concentrated within convergent landforms under both wet and dry conditions. Topographic wetness index, slope, depth to bedrock, and percent (by weight) clay and rock fragment were significant ($p<0.05$) factors influencing soil moisture content on at least 80% of 91 measurement days analyzed for all soil depths. Intermediate depths (>0.3 to <0.7 m) exhibited the highest coefficient of determination (R^2) in linear regression for topographic wetness index, suggesting that lateral subsurface flow may be an important driver of soil moisture dynamics at these depths in this catchment. Mean R^2 values for slope, depth to bedrock, and percent clay and rock fragment increased with increasing depth, confirming the importance of deep soil moisture storage on subsoil moisture organization. We conclude that the controls on this catchment's soil moisture spatial organization at the near-surface (<0.3 m) fluctuates seasonally between evapotranspiration and topography; that at intermediate depths (0.3 to 0.7 m) the soil moisture organization is controlled significantly by lateral subsurface flow; and that the organization at deeper depths (>0.7 m) becomes more temporally persistent and is primarily a function of both topography and soil depth.

1. Introduction

The spatial organization of soil moisture, both horizontally across the landscape and vertically within the soil profile, influences the non-linear behavior of a catchment's response to precipitation events (Buttle et al., 2004; McNamara et al., 2005; Stieglitz et al., 2003). 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 other chemicals downslope via lateral subsurface flow, overland flow, and/or flow along the soil–bedrock interface (Boyer et al., 1997; Hornberger et al., 1994; Lin, 2006a; Lynch and Corbett, 1989; McGlynn and McDonnell, 2003a,b; McGlynn et al., 2004). Thus, understanding near-surface and subsurface soil moisture spatio-temporal organization is required for validating hydrological models and for proper management of nutrients in close proximity to riparian zones. Combining long-term monitoring of surface and subsurface soil moisture can provide a comprehensive picture of the spatial–temporal pattern of soil moisture dynamics, and allow the identification of influential factors through time.

Improvements in digital elevation models (DEM) and geographic information systems (GIS) have allowed detailed topographic analysis of soil moisture and have demonstrated some correlations between soil moisture and terrain indices (Beven and Kirkby, 1979; Crave and Gascuel-Odoux, 1997; Lookingbill and Urban, 2004; Nyberg, 1996; Western and Bloschl, 1999; Wilson et al., 2005). Soil properties, such as texture, rock fragment, and organic matter content also exert a first-order control on the ability of a soil to store and transmit water (Henninger et al., 1976; Maeda et al., 2006;

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Yeakley et al., 1998). Additionally, depth to bedrock and bedrock topography have been increasingly recognized as important controls on hillslope and catchment water movement (Buttle et al., 2004; Lin and Zhou, 2008; Tromp van Meerveld and McDonnell, 2005). The ability of individual soil and terrain attributes to explain the spatial variability in soil moisture, however, depends on the wetness of a field site and dominant hydrological processes acting at a given space and time, which may change at the seasonal or event time scales (Famiglietti et al., 1998; Grayson et al., 1997; Western et al., 1999a,b). For example, Grayson et al. (1997) found that under dry conditions when soil moisture fluxes were primarily vertical (i.e., evapotranspiration and vertical drainage) and localized due to disconnected soil macropores, indices related to the amount of solar radiation that a soil receives (aspect and potential solar radiation index) were important in predicting soil moisture distribution in the upper 0.3 m of a pasture catchment in Australia. In contrast, under wet conditions when soil water fluxes have a lateral component (i.e., lateral surface and subsurface flow) and are "non-local" due to connected soil macropores, topographic indices related to lateral movement of soil water (such as upslope contributing area) were good predictors of soil moisture distribution. Because of such temporal dynamics, numerous studies have shown that static, terrain-derived indices alone rarely explained more than 50% of soil moisture variability (Famiglietti et al., 1998; Western et al., 1999a; Williams et al., 2009). Though climate seasonality and local or non-local hydrological fluxes exert a strong influence on *surface* or *near-surface* soil moisture organization (Grayson et al., 1997; Western et al., 1999a), less is understood regarding how the *subsurface* (>0.3 m) soil moisture spatial pattern may change with climate seasonality and seasonal hydrological fluxes. Though some studies have observed that the temporal stability of soil moisture spatial pattern would increase with increasing soil depth with damped effect from seasonal climate (De Lannoy et al., 2006; Hupet and Vanclooster, 2002; Lin, 2006; Pachepsky et al., 2005), it remains to be better understood how the explanatory power of terrain and soil characteristics on soil moisture may vary with depth and time.

The importance of subsurface soil moisture content is increasingly recognized as a key control on subsurface water movement and stream flow. For example, Stieglitz et al. (2003) and McNamara et al. (2005) found that the absence of high soil moisture at depth in mid-slope regions acted to prevent the transport of soil water from upper hillslopes to the riparian zone. Only when these deep soils "wet up" do significant lateral flow from upslope soils contribute to stream discharge. Similarly, Tromp van Meerveld and McDonnell (2005) argued that transient saturated zones that formed along the soil–bedrock interface were a primary control on the delivery of hillslope water to the stream. Previous research based on a limited number of soil moisture monitoring locations suggested that a similar mechanism might exist at the Shale Hills Catchment (Leavesley, 1967), which was later confirmed (Lin, 2006; Lin and Zhou, 2008).

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 and allow for space–time geostatistical modeling (e.g., Jost et al., 2005). To date, the majority of studies that examined the controls on soil moisture spatial organization were primarily conducted in the upper 0.3 m of soils (Crave and Gascuel-Odoux, 1997; Famiglietti et al., 1998; Grayson and Western, 1998; Hawley et al., 1983; Nyberg, 1996; Western et al., 1999a), which were often related to the verification and assimilation of remotely-sensed soil moisture data (Choi and Jacobs, 2007; Famiglietti et al., 1999; Famiglietti et al., 2008; Jacobs et al., 2004). In this study, we carried out an intensive catchment-

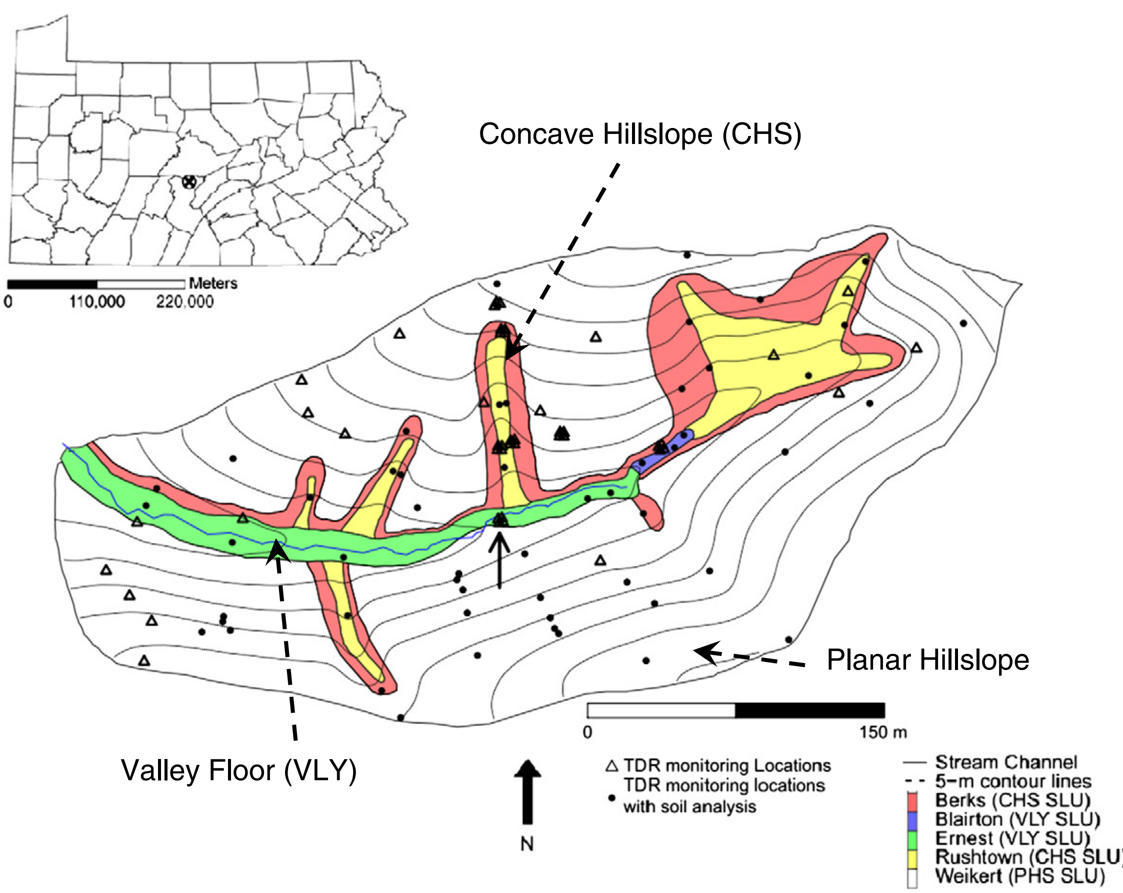

Fig. 1. Location of the Shale Hills Catchment in Pennsylvania, United States, and the site map showing soil moisture monitoring locations along with the soil–landform units. Solid arrow indicates water table monitoring location (site #15).