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Combined soil-terrain stratification for characterizing catchment-scale soil moisture variation

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ABSTRACT

Soil properties and terrain characteristics influence spatiotemporal patterns of soil moisture across a watershed. To improve the predictive power of landscape hydrologic models, it is essential to consider both soil and terrain attributes when stratifying a catchment into similar hydrologic functional units. In this study, we developed and validated a new catchment-scale stratification scheme for the Shale Hills watershed by combining soil and terrain attributes in an attempt to delineate soil-landscape units with similar soil moisture dynamics. Terrain was combined with soils information by first using a Random Forest supervised classification algorithm to predict a detailed soil map using 47 field soil samples and terrain variables derived from 1-m LiDAR. A slope class map generated from the LiDAR-derived digital elevation model (DEM) was overlaid on the predicted soil map to delineate areas of similar slope value across the catchment. We compared the performance of this new stratification scheme with two classical stratification schemes, a soil map developed from detailed field survey and a landform unit map based on the DEM, for estimating soil moisture time-series across the forested watershed. The combined soil-terrain method outperformed classical stratification schemes in estimating soil moisture time-series over a 4-year period. Our results demonstrate that combining soil and terrain attributes can help improve the stratification of a catchment into similar soil hydrologic functional units, which is valuable to distributed hydrology modeling and other applications.

1. Introduction

Understanding the link between soil moisture patterns and landscape features is critical to improving landscape hydrologic modeling (Band et al., 1993; Pauwels et al., 2001; Yu et al., 2014). A common assumption in catchment hydrology is that terrain places a dominant control on hydrologic functions (Beven and Kirkby, 1979; Winter, 2001). This assumption leads many researchers to parameterize hydrologic models based on landforms or sub-catchment units using terrain alone. Since topographic information in the form of digital elevation models (DEM) has been increasingly available, stratifying catchments into similar hydrologic functioning units with terrain has been widespread (Moore et al., 1991; Blöschl and Sivapalan, 1995; Winter, 2001). However, field-based soil properties are often not directly included in these stratification schemes, and terrain is assumed to be a proxy for inferring soil properties. These assumptions remain largely unchallenged, since many catchment hydrologic studies do not validate terrain-based sub-catchment units using *in situ* collected soil moisture data or compare model performance with actual soil distributions.

Topographically-based stratification approaches have been continuously improved over time with advancements in GIS and remote sensing technologies. Following the conceptual work by Beven and Kirkby (1979) and Dooge (1986), hydrologic response units (HRUs) have been developed by dividing a catchment into units of similar topography (Leavesley and Stannard, 1990). Park and van de Giesen (2004) used topographic variables (surface curvature and upslope contributing area) derived from DEM to stratify the Terrawarra Catchment and validated their landform units with a general linear modeling approach using *in situ* soil moisture measurements. Gharari et al. (2011) used a terrain-based index, called height above nearest drainage, along with slope value to stratify a catchment in Luxembourg into similar hydrologic functioning units.

Soil properties may have even higher correlations with catchment-wide soil moisture measurements than terrain variables, as Gomez-Plaza et al. (2001) have shown, where sand content was the most correlated variable with soil moisture content for both wet and dry conditions in semi-arid Spain. This suggests that combining soil and terrain attributes within a single stratification would be better for predicting catchment-scale soil moisture dynamics. Temporal patterns of soil moisture have been assessed with terrain and soil characteristics across a watershed (Canton et al., 2004) and some terrain variables are more related to the temporal structure of soil moisture patterns than others.

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Given this finding, an analysis that addresses how well different terrain variables represent spatio-temporal patterns of soil moisture would be beneficial to any combined soil and terrain stratification study.

There is evidence that combining soil and terrain attributes can further improve catchment hydrologic stratifications (Lin et al., 2006). Takagi and Lin (2012) found that field soil moisture content was highly correlated with terrain variables, depth to bedrock, and clay content in the forested Shale Hills catchment at multiple depths, indicating that both soil and terrain properties are important attributes for defining sub-catchment units with similar soil hydrologic function. Devito et al. (2005) refined existing HRU boundaries by including information about soil texture and peatland cover, which improved catchment water flow predictions. Although a stratification that combines soil and terrain attributes is likely to better characterize catchment-scale soil moisture patterns, a combined soil-terrain stratification in predicting soil moisture patterns has yet to be developed and validated using *in situ* soil moisture data.

Given the importance of catchment stratification for scaling soil moisture and parameterizing distributed hydrologic models and the relative scarcity of the validation and comparison of different stratification methods with catchment-wide *in situ* soil moisture measurements, our objectives in this study are to: (1) uncover terrain variables that are significantly correlated with temporal structure of soil moisture across a catchment, and (2) compare the skill of a newly developed soil-terrain stratification scheme with two classical stratification schemes in predicting catchment-wide soil moisture with *in situ* data.

2. Materials and methods

2.1. Study site

The Shale Hills Catchment is a 7.9-ha forested watershed characterized by steep slopes (ranging from 25 to 48%) and narrow ridges, with elevation ranging from 256 to 310 m. The catchment valley is oriented in an east–west direction, which divides the catchment into two almost true north- and south-facing hillslopes. Several species of maple (*Acer* spp.), oak (*Quercus* spp.), and hickory (*Carya* spp.) are typical deciduous trees found on the sloping areas and on the ridges, while the valley floor is dominated by eastern hemlock (*Tsuga canadensis Carriére*) (Lin, 2006; Naithani et al., 2013). Oaks species are spread throughout the hillslope area, while maples and hickory are mostly situated on the south-facing slope. The climate at the Shale Hills is typical of humid temperate region, with long-term (>100 yr) mean monthly temperatures reaching a minimum of −3 °C in January and a maximum of 22 °C in July. Annual precipitation is about 980 mm (National Weather Service, State College, PA), with the majority of precipitation falling as rain during the spring through fall months (about 70–100 mm/month) and as snow in the winter (about 70 mm/month).

The soils at the Shale Hills were formed from Silurian-age shale residuum and colluvium. The soils are generally silt loams and silty clay loams in texture, with some clay loams and sandy clay loams. All soil types have an approximately 0.05 m thick litter layer (Oe horizon) due to the presence of forested cover over the entire catchment. The catchment is underlain by >200 m thick Rose Hill shale, a Silurian formation frequently associated with the iron-rich Clinton Ore. Many gravelly shale fragments (2–150 mm) are found throughout soil profiles, and the near surface shale is characterized as fractured bedrock.

2.2. Soil moisture monitoring

Volumetric soil water content (hereafter, “soil moisture”; unit: $cm^3\ cm^{-3}$) was collected manually at a weekly to bi-weekly interval from 106 sites (varied from 46 to 106 sites depending on weather and available field assistants) during 2007–2010. Soils were drilled down to 1.1 m or the beginning of bedrock (whichever is shallower), so that 5.1 cm diameter Schedule 40 PVC tubes could be installed vertically into the soil. During each data collection period, soil moisture was recorded at up to six depths (10, 20, 40, 60, 80, 100 cm) using a TRIME-FM Time Domain Reflectometry (TDR) probe (IMKO, Germany), which was inserted within the PVC access tube at each site. Site locations are distributed across the entire catchment (Fig. 1) representing all soil types and landforms and were chosen based on the field surveyed soil map. A total of 17,464 moisture measurements (Weikert = 5221, Berks = 3446, Rushtown = 4601, Blairton = 1345, and Ernest = 2851) recorded from 2007 to 2010 were used in this study.

2.3. Field surveyed soil map

The Hydropedology group at Penn State conducted a detailed soil survey throughout the catchment in cooperation with the USDA Natural Resources Conversation Services personnel (see Lin et al., 2006 for details). Transects were placed 50 m apart and aligned perpendicularly to the catchment's bedrock southwest to northeast orientation. During the survey, a total of 289 samples were taken, and five soil types were identified in the catchment. Soil thickness, landscape position, and depth to redoximorphic features were the main criteria used to differentiate these soil types.

The Weikert (loamy-skeletal, mixed, active, mesic Lithic Dystrudept) is the predominant soil type in the catchment, comprising 78% of the catchment, and is characterized as a thin soil on hilltops, planar, and convex hillslopes. The Rushtown (loamy-skeletal, over fragmental, mixed, mesic Typic Dystrochrept) is mostly located in the center of four dominant concave hillslopes and a large portion of the upper 100 m of the catchment valley. The Berks soil type (loamy-skeletal, mixed, active, mesic Typic Dystrudept) is well drained and largely distributed along the slope transitional zones between the shallow Weikert and the deep Rushtown soils. The Blairton soil type (fine-loamy, mixed, active, mesic Aquic Hapludult) is located in the valley bottom, with an argillic horizon at 0.2–0.8 m depth and few (2–5%) redox features starting at 0.8–1.1 m depth. The Ernest soil type (fine-loamy, mixed, superactive, mesic Aquic Fragiudults) is a very deep (>3 m depth to bedrock), poorly to moderately well-drained soil on the valley floor around the first-order stream with many redox features and a fragipan-like layer starting at 0.3–0.5 m depth.

2.4. Digital terrain, depth to bedrock, and landform units

A LiDAR flyover in February 2011 was used to generate a high-resolution 1 × 1 m DEM raster dataset for the Shale Hills. During preprocessing, TerraScan software (Terrasolid) classified raw LiDAR point data and ground points were interpolated across space using ordinary kriging (Guo and Si, 2008). A Gaussian filter was applied with a 4.5 × 4.5 m smoothing window to reduce noise in the DEM. Topographic variables derived from the LiDAR DEM included local slope value (Fig. 2a), vertical distance to stream (VDS, Fig. 2c; Olaya and Conrad, 2009), upslope contributing area (Fig. 2d; Tarboton, 1997), topographic wetness index (TWI, Fig. 2e; Beven and Kirkby, 1979), and surface curvature (Fig. 2f; Zevenbergen and Thorne, 1987) using SAGA GIS (Conrad et al., 2015). Local slope value [$m\ m^{-1}$], upslope contributing area [m^2], surface curvature [−], and TWI [−] were developed using the Basic Terrain Analysis module, and VDS [m] was calculated with the Vertical Distance to Channel Network module.

A depth to bedrock map (Fig. 2b) was obtained from catchment-wide auger sampling. A total of 318 auger data points were used in a regression kriging (Isaaks and Srivastava, 1989; Odeh et al., 1995) to interpolate depth to bedrock across the catchment. During the regression kriging, a backwards-stepwise algorithm (Venables and Ripley, 2002) was used to select a multiple linear regression model with DEM-derived terrain variables as covariates. The regression with the lowest Akaike's Information Criterion (AIC) was selected for regression kriging. The best multiple linear regression model contained surface curvature ($p = 0.008$) and TWI ($p < 0.001$) as covariates.