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Key Points:
- Terrain-based metrics were poor predictors of shallow soil water content
- Soil properties were strong predictors of shallow soil water content
- Spatial patterns in soil water content were persistent across seasonal variations in catchment wetness state

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The Influence of Local and Nonlocal Factors on Soil Water Content in a Steep Forested Catchment

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Abstract Surface topography can influence flow pathways and the location of runoff source areas and water transport in steep headwater catchments. However, the influence of topography on spatial patterns of residual soil moisture is less well understood. We measured soil volumetric water content (VWC) on 14 dates at 0–30 and 30–60 cm depth at 54 sites on a steep, 10 ha north-facing forested slope in the west-central Cascades Mountains of Oregon, USA. Spatial patterns in VWC were persistent over time, and contrary to expectations VWC at 30–60 cm depth was greater on divergent than convergent slopes, especially during wet periods ($R^2 = 0.27$, $p < 0.001$). Vegetation characteristics were assessed for all VWC monitoring locations and soil properties were determined for 13 locations as local factors that affect spatial patterns in VWC. Mean VWC over all dates was negatively correlated to gravimetric rock content ($R^2 = 0.28$, $p = 0.03$) and positively correlated to water storage at field capacity ($R^2 = 0.56$, $p < 0.01$). The variability in rock content in quick-draining soils influenced soil-water retention, and by extension, created spatially heterogenous but temporally persistent patterns in VWC. While spatial patterns were persistent, they were not easily explained by surficial topography in a steep, mountainous landscape with rocky, well-drained soils. Further research is needed to understand if combined soil-terrain metrics would be a more useful proxy for VWC than terrain-based wetness metrics alone.

Plain Language Summary Surface topography can direct the movement of water through the subsurface in ways that affect water availability for plants. When soils saturate, excess water may move downslope, leading to more water in hillslope hollows. However, in places where soils do not become saturated, the factors controlling the spatial patterns in water availability are less well understood. We designed our study to test if the redistribution of water, following surface topography, controlled the spatial patterns of soil moisture across a steep forested hillslope with well-drained soils. We found that spatial patterns of soil moisture were similar throughout the year, but the movement of water downslope was not responsible for these patterns because soils were drier in hillslope hollows and wetter on the intervening ribs. Additionally, we found that the amount of water in the soil was strongly related to rock content. Thus, the presence of rocks may contribute to the persistence in spatial patterns of soil moisture. We recommend future research focuses on understanding how spatial patterns in forest soil properties affect soil water storage. This will allow us to improve computer models that predict water stress in forest ecosystems, and thereby, help forest managers develop plans to mitigate water stress.

1. Introduction

Surface topography is commonly used as a proxy for soil water availability (Swetnam et al., 2017). This stems from our classic understanding that soil water is redistributed and organized in space via lateral and downslope movement. This can occur as saturation-excess surface runoff (Grayson et al., 1997; Western et al., 1999) or as subsurface flow along a bedrock-soil interface or an interface between soil horizons (Lin et al., 2006). Consequently, terrain-based wetness metrics are widely used to identify likely runoff flow paths at hillslope and catchment scales (Jencso & McGlynn, 2011; McDonnell et al., 1996). While these projections are commonly used to inform our understanding of streamflow source areas in montane forests (Nippgen et al., 2015), few studies have examined if and how terrain-mediated flow paths impact soil volumetric water content (VWC) available to vegetation in steep, variable terrain (Liang et al., 2017).

The influence of topography on surface and subsurface paths of lateral water movement, or the nonlocal control on VWC (Grayson et al., 1997), depends on overall catchment wetness/seasonality (Ali et al., 2014; Beven & Kirkby, 1979; McNamara et al., 2005), soil permeability (Rinderer et al., 2014), soil depth (Liang & Chan, 2017), and the spatial distribution of bedrock weathering (St. Clair et al., 2015). Nevertheless, the use of terrain-based wetness metrics as a proxy for water availability has become widespread for understanding ecosystem productivity, structure, and photosynthetic activity (Helman et al., 2017; Hoylman et al., 2018; Milledge et al., 2013). Terrain metrics include topographic wetness index (TWI), upslope accumulated area (UAA), Euclidean distance from stream, slope, slope curvature, and topographic position index (TPI). In many instances, these metrics have been useful for predicting VWC in the rooting zone where seasonal subsurface water movement is influenced by gradients in water potential that follow the surface topography. Terrain-based wetness metrics have also been used to predict catchment wetness in regions where water transport can occur as overland flow (Grayson et al., 1997; Western et al. 1999), and in semi-arid montane ecosystems where subsurface water flow is thought to occur along impermeable boundaries (Gómez-Plaza et al., 2001; Kaiser & McGlynn, 2018; McNamara et al., 2005; Williams et al., 2009). However, surface terrain can be a poor predictor of saturated flow paths where water flows along bedrock topography or within fractured geology, where the bedrock surface does not mirror surface topography (Freer et al., 2002). Further, if soils are deep and well-drained, near-surface soils may not receive laterally redistributed water. In those situations, the spatial patterning of VWC may be more strongly controlled by local factors, such as soil properties and vegetation (Grayson et al., 1997), rather than by topography.

When soils are dominated by vertical water fluxes, topography may exert considerable control on spatial patterns of VWC by indirectly controlling the organization of soil hydraulic properties and soil thickness (Baggaley et al., 2009; Lin et al., 2006; Pelletier et al., 2013). For example, terrain metrics can explain spatial variability in soil-water retention (Pachepsky & Timlin, 2001), predict soil morphological units with distinct water table regimes (Gannon et al., 2014; Gillin et al., 2015), and dictate permeability and distribution of bedrock fractures (St. Clair et al., 2015). Differences in evapotranspiration along topographic gradients may also create spatial patterns in VWC depending on vegetation species and rooting depths (Fatichi et al., 2015; Gómez-Plaza et al., 2001; Gwak & Kim, 2016; Ivanov et al., 2010; Traff et al., 2014; Tromp-van Meerveld & McDonnell, 2006a).

Understanding the mechanisms by which topography affects variability in VWC is important for future prediction of soil water availability in forest ecosystems. There is strong evidence that terrain-based wetness metrics can serve as a useful tool for predicting spatial patterns of near-surface VWC if boundary conditions and soil properties permit saturated water transport in shallow soils (Gevaert et al., 2014) or if soil hydraulic properties are mediated by surface topography (Lin et al., 2006). Our knowledge of the topographic controls on VWC was originally developed in a gently sloping grassland (Grayson et al., 1997). Since then, the concept has been extended to forest catchments with moderately sloped terrain (e.g., Kaiser & McGlynn, 2018, average = 10°, Gwak & Kim, 2016, average = 16°, Lin et al., 2006, range = 14–26°, and Penna et al., 2009, range = 12–42°). However, relatively few studies have investigated the controls on soil VWC in forest catchments where the average slope exceeds 30° (e.g., Liang et al., 2017, range = 6–64°, average = 41° and Kim et al., 2007, range = 30–45°). Thus, the degree to which terrain mediates VWC in steep, montane forests remains poorly understood.

Topography may not be useful in predicting near-surface VWC if lateral flow is negligible, if vertical movement via infiltration and evaporation controls soil moisture dynamics in the top meter of soil, or if soil hydraulic properties are not organized along topographic gradients (Hu & Si, 2014). In mountainous regions, high densities of roots and rocks can lead to well-drained, highly porous soils in which vertical preferential flow dominates (Beven & Germann 1982; Bundt et al., 2001; Liu & Lin, 2015; Wiekenkamp et al., 2016). Where soils drain quickly, saturation may be constrained to deeper subsurface soil layers (>1 m) (Zimmer & Gannon, 2018) or in fractured bedrock (Gabrielli et al., 2012). Water in forest soil layers below one meter can be a critical water source for vegetation, especially in regions that experience seasonal drought (Rempe & Dietrich, 2018). However, most direct measurement of VWC have occurred in the upper meter of soil due to the difficulty in accessing deeper soil layers. Liang et al. (2017) investigated the influence of topography, soil properties, and vegetation on VWC in the upper 20 cm of soil in a steep, humid catchment. They found that patterns in VWC were explained by the local saturated hydraulic conductivity of soils and vegetation density where rocky soils were underlain by fractured bedrock.

Understanding the relative effect of local and nonlocal factors can help determine the dominant mechanisms controlling near-surface soil water in steep, mountainous regions. The overall objectives of our study were to test whether common terrain metrics used in catchment scale hydrological models—TPI, TWI, upslope accumulation area, slope, and Euclidean distance from stream—explained the spatial patterns of VWC and how antecedent rainfall and soil depth altered the spatial patterns in VWC. Specifically, we asked:

1. How do attributes of topography, soils, and vegetation affect VWC across a range of antecedent rainfall amounts?
2. Are there spatial patterns in VWC and are these patterns persistent over time?
3. How does the variability of VWC change as a function of the spatial mean?

We hypothesized that topographic position would control VWC when antecedent rainfall was greatest. Specifically, we postulated that VWC would be greater along convergent slopes compared to divergent slopes due to downslope and lateral flows of water from adjacent areas. Additionally, we assumed this relationship would weaken during dry periods because soil properties and evapotranspiration would have a greater effect on spatial patterns of VWC when soils are below field capacity.

2. Site Description

Our study was located in Watershed 1, a 96 ha catchment at the H. J. Andrews Experimental Forest on the west slope of the central Cascade Mountains of Oregon, USA (44°12'18.8" N, 122°15'16.2" W). The average elevation of the study area is 576 m and the average slope is 37°. The study catchment was 100% clearcut from 1962–1966 and logging residues were burned in 1966 to expose a mineral soil seedbed. There were several efforts to re-establish vegetation in the watershed. The watershed was aerially seeded with Douglas-fir (*Pseudotsuga menziesii*) in 1967 and 10 ha were re-seeded in 1968. In 1969, 2-year-old Douglas-fir trees were planted across the entire watershed, and in 1971, 40 ha were re-planted with 2- and 3-year-old trees (Halpern, 1988). Forty to fifty-year-old Douglas-fir trees dominate the overstory. While much less common, both bigleaf maple (*Acer macrophyllum*) and western hemlock (*Tsuga heterophylla*) are also present. The understory includes vine maple (*Acer circinatum*), Oregon grape (*Mahonia aquifolium*), and sword fern (*Polystichum munitum*).

The average depth of the forest floor and organic horizon was 5 cm at our soil measurement points. Mineral soil in the top 100 cm was generally gravelly, silty clay loam with developed A and B horizons, which had gradual and poorly defined boundaries. Soils were underlain by unconsolidated, highly weathered saprolite and fractured bedrock (Gabrielli et al., 2012). Soil thickness ranged from 20 cm to more than 5 m. Parent materials primarily include tuffs and breccias, but basalts and andesites are also present (Halpern, 1988).

The regional climate is characterized by cool, wet winters and warm, dry summers. During the period of study, from August 2016 to October 2017, the site received 2,833 mm of rainfall, which was slightly more than the long-term average. The average rainfall total during the 15 month period from August to October during 1979–2015 was 2,450 mm, while the maximum total rainfall was 3,512 mm and minimum was 1,607 mm (Daly et al., 2019). The spatial variability of rainfall interception can create differences in VWC if measured under the canopy or under gaps in the canopy (Gray et al., 2002). Thus, we avoided locations under large canopy gaps when establishing soil moisture monitoring sites to minimize differences in VWC associated with interception.

3. Methods

3.1. Topographic Analysis

We used a map of classified TPI to guide the placement of soil monitoring sites. TPI was estimated from a 1×1 m digital elevation model (Spies, 2016) by subtracting the elevation of a grid cell from the mean elevation of all cells within a 30 m radius (Jenness, 2006). This method allowed us to classify slope position and landforms following the method of Weiss (2001). Positive TPI values represented divergent slope

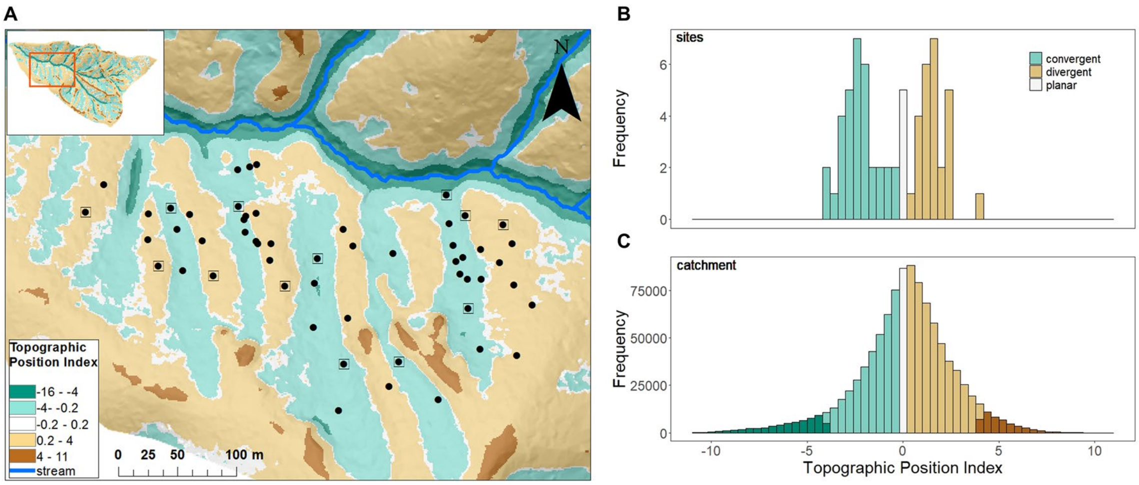

Figure 1. (a) Soil water content monitoring sites located on divergent (negative values) and convergent (positive values) slopes categorized from topographic position index (TPI) at 1 m resolution. We measured soil properties at 13 of the 54 monitoring sites (points with boxes). The distribution of TPI at monitoring sites (b) was representative of the distribution of TPI across the catchment (c). Extreme convergent slopes were perennial and ephemeral streams while extreme divergent locations were bedrock outcrops.

positions where the elevation of a pixel was high relative to the average surrounding locations. Conversely, negative TPI values represented convergent slope positions where the elevation of a pixel was low relative to surroundings. Locations where TPI was close to zero were relatively planar. Individual hillslopes were distinguished by a switch between negative and positive TPI along the same elevation contour (Figure 1a).

We used additional DEM-derived terrain metrics to test the effect of topography on soil water content. Other metrics used in our analysis were: slope gradient, UAA, TWI, and distance from stream. UAA represents the amount of land draining to each pixel and was estimated with the triangular multiple flow-direction algorithm developed by Seibert and McGlynn (2007). TWI was calculated as $\ln\left(\frac{UAA}{\tan(slope)}\right)$, as proposed by Beven & Kirkby (1979) in an effort to characterize the potential for nonlocal water subsidies and lateral water redistribution. Distance from stream was calculated as Euclidean distance from the site to the headwater perennial stream. We analyzed and visualized all terrain metrics using ArcGIS 10.5.1.

3.2. Quantification of Soil Water Content

We established 54 permanent soil water monitoring sites along alternating convergent and divergent hillslopes within a 10-ha north-facing area of the catchment in July 2016 (Jarecke et al., 2021). Sites were spaced roughly 30 m apart along transects. Once sites were established, we determined the GPS coordinates of each site using a Trimble GEoXT Global Positioning System. The TPI values at individual sites (Figure 1b) were representative of the range in TPI values estimated for each 1 × 1 m grid cell across the catchment (Figure 1c).

We measured soil VWC using time domain reflectometry (TDR; model No. 1502C, Tektronix Inc., Beaverton, OR). TDR is a standard method for obtaining VWC; it measures the propagation of electromagnetic waves in a pair of 3 mm diameter stainless steel rods. VWC was measured over two depths of mineral soil, 0–30 and 0–60 cm. We replicated measurements points at each site so there were two VWC measurements for each depth. A measurement point consisted of a pair of TDR rods installed vertically, 5 cm apart, in mineral soil (see Gray & Spies, 1995 for additional details on methods). The replicate measurement points were, on average, 2.5 m apart and the measurement volume of each point was 30 cm or 60 cm deep and 10 cm in diameter (Topp et al., 1980). There were multiple attempts to insert rods at approximately half of the sites because we encountered rocks that prevented the rods from penetrating the soil. We could not install the 60 cm rods at eight of the 54 sites due to high rock content below 30 cm. Rods remained in place over the entire study period.

We measured VWC on 18 dates from August 2016 to October 2017. The forest floor was removed prior to taking measurements and replaced between sampling dates. We converted the reflection trace from TDR to VWC using a calibration equation developed in a nearby watershed (Gray & Spies, 1995). We estimated VWC at 30–60 cm using the VWC from adjacent 0–30 and 0–60 cm probes after accounting for differences in volume sampled: $VWC_{30-60cm} = 2 \times VWC_{0-60cm} - VWC_{0-30cm}$. The sensitivity of the instrument was 0.01 cm^3 cm^{-3} as determined from repeat measurements less than one minute apart. Prior to analysis, we averaged VWC from the two replicate measurement points at each site. We chose to use the average because the difference between the two measurement points (average = 0.01 cm^3 cm^{-3}) was small relative to the variability among sites (standard deviation = 0.07 cm^3 cm^{-3}). Poor quality data occurred on four sampling dates during wet and cold conditions in winter and early spring; these data were not included in the analysis.

We also installed 10 shallow groundwater wells along two convergent hillslopes to understand the timing and duration of subsurface flows by driving a solid steel rod into the soil until refusal, which was generally ~2–2.5 m below the surface. We then inserted a 3.8 cm diameter screened PVC pipe. Wells were installed in late summer and all wells were dry at the time of installation. We used pressure transducers (Solinst Levelogger Junior Edge, model 3001) recording at an hourly time interval to identify if the soils became saturated, and if they did, the date, duration, and depth of soil saturation.

3.3. Measurements of Soils and Vegetation

We quantified soil hydraulic properties—saturated hydraulic conductivity and soil water retention—on intact soil cores collected at 13 of the 54 soil moisture monitoring sites (Figure 1a). Selection of the 13 sites was based on preliminary findings of high and low VWC measured on divergent and convergent slopes. Persistently wet and dry sites were selected to capture potential differences in soil properties that could control VWC on convergent versus divergent slopes. Soils were collected by digging a shallow pit and exposing an undisturbed soil face. Soils overlying each sampling depth, 15 and 45 cm, were removed and a 250 cm^3 metal cylinder (5 cm tall and 8 cm diameter) was pounded vertically into the soil. The intact soil cores were capped on both ends to preserve the soil structure and delivered to laboratory where they were stored at 4 °C.

Saturated hydraulic conductivity (K_s) was measured in the laboratory using the falling head method on the KSAT device (METER Group Inc.). See details on methods in Sarkar et al. (2019). The K_s was averaged from five repeated measurements from each soil core. Soil water retention was measured using the simplified evaporation method (Schindler et al., 2010) with HYPROP and WP4C Dewpoint PotentioMeter instruments (METER Group Inc.). The HYPROP system uses two tensiometers installed vertically into the soil core at 1.25 and 3.75 cm to measure matric potential. Change in the mass of the soil core is measured simultaneously for VWC, and measurements were recorded every 30 min. Measurements were stopped when air entered the lower tensiometer, which typically occurred around −81 kPa. After HYPROP measurements were complete, we immediately extracted five soil samples in 1 cm increments starting at the surface of the soil core. We then placed soil samples in the WP4C instrument to measure water potential of the dry soils using the chilled-mirror dewpoint technique (Scanlon et al., 2002). Data from the HYPROP and the WP4C were combined using HYPROP-Fit software and the data were fit using the unimodal constrained hydraulic function developed by van Genuchten (1980).

Soils from individual cores were subsequently dried at 105 °C for 24 h and the oven-dried weight was divided by the sample volume to determine the bulk density. We used the dried soil sample to quantify gravimetric coarse content and particle size. Coarse material consisted of 2–5 mm rock fragments, weathered saprolite fragments, roots, and wood. We placed the sample in a mortar and lightly tapped the soil with a pestle to break soil aggregates but preserve saprolite fragments. We then passed the sample through a 2 mm sieve to remove coarse material, including saprolite fragments. The sieved soil was mixed, a 5–7 g subsample was collected, and then organic carbon was removed from the subsample using the hydrogen peroxide method (Mikutta et al., 2005). The subsample was sent to the Critical Zone Lab at Virginia Tech for particle size analysis using laser diffractometry on a CILAS 1190 laser particle size analyzer (Miller & Schaetzl, 2012).

We measured depth to bedrock at 38 of the 54 soil moisture monitoring sites using a dynamic cone penetrometer, which is also known as a knocking pole (Shanley et al., 2003; Yoshinaga & Ohnuki, 1995). The pole consisted of 0.5 m graduated steel rod segments and a 20 mm long and 24 mm diameter cone tip, which was driven into the soil by repeated drops of a 5 kg weight onto a platform threaded on the upper segment of the pole. When the resistance to penetration became large (moving less than 1 cm in 15 or more knocks), we assumed the cone tip had reached bedrock. We calculated soil depth to bedrock at each site from the average of 2–3 repeat measurements taken approximately 5–10 m apart.

Vegetation, especially trees, is a local factor that can influence VWC through root uptake or canopy interception. We attempted to limit the influence of root water uptake and canopy interception by locating our soil monitoring sites along a uniform slope, with uniform aspect, in a single-aged, mono-specific stand with relatively uniform tree size and density. We calculated the total basal area and total distance-weighted basal area in a 5 m radius plot around each measurement point. Distance-weighted basal area was calculated using an equation from Tromp-van Meerveld & McDonnell (2006a) and Liang et al. (2017):

$$\text{Distance - weighted basal area} = \Sigma A_i \exp\left(-\delta d_i\right)$$

where A_i is the basal area of a tree (m^2), d_i is the corresponding distance to tree (m) measured with an IMPULSE laser (Laser Inc. Technologies), and δ is a constant set to 0.2 that determines the weight of the distance, such that the trees closer to the measurement point had greater weight than trees further away. We chose a 5 m radius plot around each measurement because this was the approximate crown radius of trees in our study area. We assumed that trees more than 5 m away would not be able to extend their roots to measurement points because the horizontal root systems of Douglas-fir, the dominant tree species at our site, do not typically reach beyond the crown projection of the tree (Mauer & Palátová, 2012).

3.4. Data Analysis

We assessed the effectiveness of terrain metrics for predicting VWC using regression relationships between VWC and the following terrain metrics: TPI, TWI, UAA, slope, and Euclidean distance from stream. TPI and UAA were weakly correlated (Pearson correlation = −0.5); however, other terrain metrics were not correlated to one another. The magnitude and range of the terrain metrics was highly variable, making direct comparisons of these metrics' effects on VWC difficult. Thus, we standardized the terrain metrics by subtracting the mean and dividing by the standard deviation. The resulting standardized slopes represented the change in VWC for a one standard deviation shift of the terrain metric. We compared the magnitude of the slopes to determine which of the terrain metrics might be most useful for explaining differences in VWC over our study area. We chose the terrain metrics with the greatest absolute slope to then repeat the regression analysis with the original/unstandardized metrics. We also used regression analysis to identify which local variables—soil and vegetation properties—were correlated to VWC.

We graphically assessed the relationship between VWC and each soil and vegetation property on each sampling date to identify which, if any, variables were correlated to VWC. Additionally, we were interested to know if the slope of the relationships depended on the antecedent rainfall amount. To determine this, we correlated 2-week antecedent rainfall to the predicted change in VWC for a one standard deviation (SD) shift for each local or nonlocal variable of interest. We also visually checked the pairwise relationship and Pearson correlation between these local and nonlocal variables.

We tested the spatial patterns of VWC for persistence over time. We first ranked sites from driest (1) to wettest (54) on each of the 14 measurement dates. We calculated the SD of the rank for each site over the study period, then compared the observed SDs to the expected SDs if the spatial patterns were entirely random. To do this, we randomly selected a rank from 1 to 54 for each site on each date, without replacement, and used these ranks to calculate a predicted SD from the random rankings. We repeated this process 1,000 times to create a distribution of predicted SD values. We then compared the observed SD at each site to the distribution of predicted SD of rank. If the observed SD of rank was less than the predicted values generated from random spatial patterns, the VWC at those sites had a persistent or stable rank over the study period. We set a threshold at the fifth percentile of the predicted distribution and considered observed values below that threshold to show evidence of stability in VWC over time.

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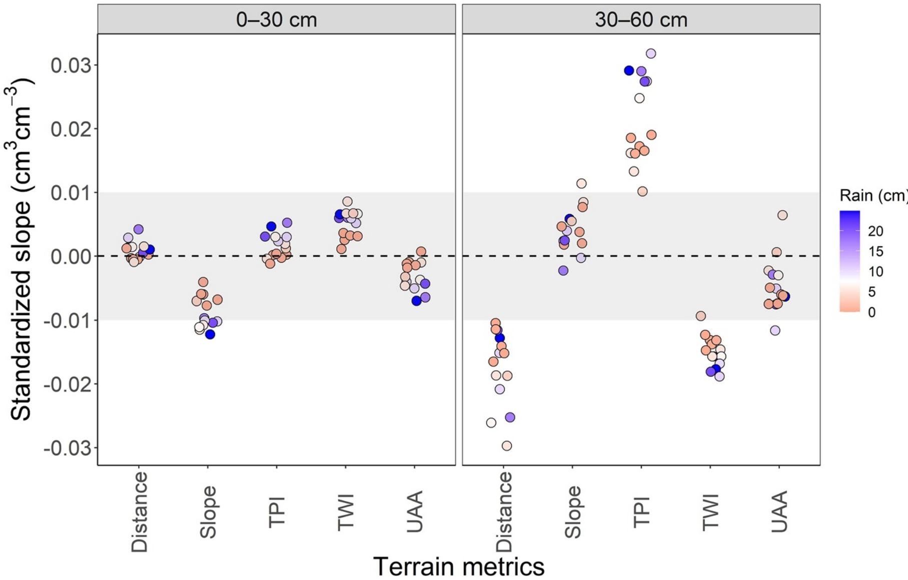

Figure 2. Standardized slopes represent the change in volumetric water content (VWC) for one standard deviation (SD) change in each of the terrain metrics. SD of distance from stream = 39 m; SD of slope gradient = 6°; SD of topographic position index (TPI) = 2; SD of topographic wetness index (TWI) = 10; SD of upslope accumulated area (UAA) = 610 m^2. The gray box indicates no detectable change in VWC (± 0.01 cm^3 cm^{-3}). TPI had the greatest effect on VWC when two-week antecedent rainfall was >10 cm, whereas seasonality did not alter the effect of distance from stream on VWC.

We examined how the variability of VWC across sites ($n = 54$) and difference in VWC between depths ($n = 2$) changed with overall catchment wetness. To characterize variability over space, we calculated the standard deviation (SD) of mean VWC on each measurement date ($n = 14$) and used a nonparametric smoothed spline regression to observe how the SD changed as the overall mean VWC increased. Additionally, we used a paired t-test to determine if the average difference in VWC between 0–30 and 30–60 cm at individual sites changed depending on 2-weeks antecedent rainfall, which ranged from 0 to 25 cm across measurement dates. We completed all data analysis using R statistical software (R Core Team, 2019) along with the R packages dplyr (Wickham et al., 2019), tidyr (Wickham & Henry, 2019), raster (Hijmans, 2019), ggplot2 (Wickham, 2016), cowplot (Wilke, 2019), GGally (Schloerke et al., 2020), and gridExtra (Auguie, 2017).

4. Results

4.1. Nonlocal and Local Controls

We found that topographic attributes were weakly correlated with spatial patterns of VWC across a range of antecedent rainfall amounts. VWC at 0–30 cm was not related to terrain metrics. However, VWC at the 30–60 cm changed by 0.01–0.03 cm^3 cm^{-3} for one standard deviation (SD) change in TPI and Euclidean distance from stream (Figure 2). When 2-week antecedent rainfall was high, VWC increased by 0.03 cm^3 cm^{-3} for a one SD increase in TPI, which represents a 2 m increase in elevation (more divergent) over the surrounding terrain (Figure 2). Conversely, VWC decreased 0.03 cm^3 cm^{-3} for a 39 m increase in distance from the stream during a period of intermediate wetness (Figure 2). We found a small decrease in VWC at 30–60 cm (0.01–0.02 cm^3 cm^{-3}) for one SD increase in TWI, but no detectable relationship between VWC and slope gradient or UAA. While these changes in the absolute VWC may seem small, we note that the change in the average VWC at 30–60 cm from the driest to the wettest sampling dates was only 0.10 cm^3 cm^{-3}. Thus, a 0.01 cm^3 cm^{-3} change in VWC was equivalent to 10% of the annual range in average VWC at our sites.

We further tested the strength and directionality of the relationship between VWC, TPI, and distance from stream. There was a significant positive linear relationship between TPI and VWC at 30–60 cm on 9 of 14 sampling dates ($p < 0.05$, Figure 3), suggesting divergent locations (positive TPI) were wetter, on average, than convergent (negative TPI) locations. The greatest slope and coefficient of determination occurred

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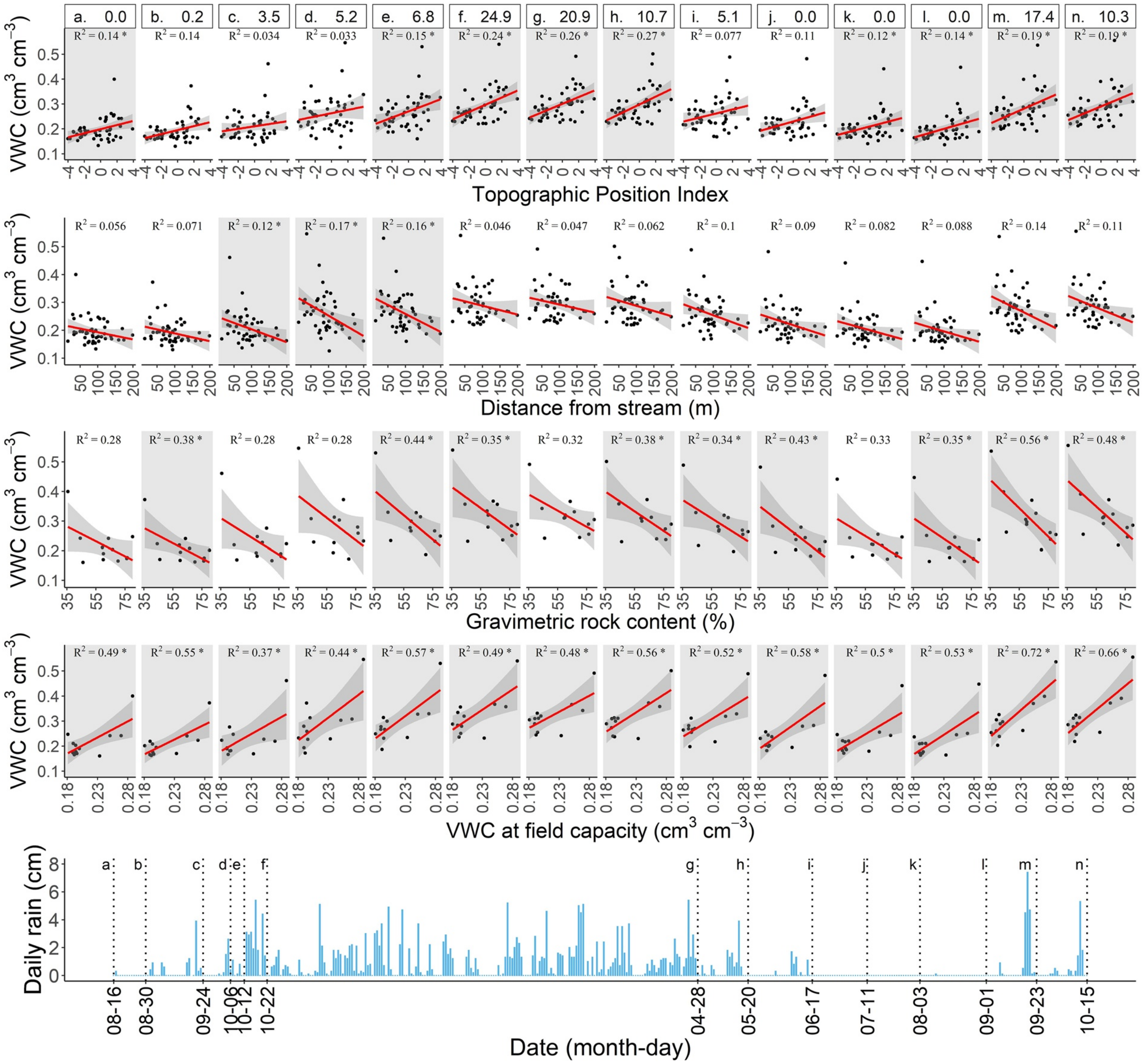

Figure 3. There was a significant positive linear relationship between topographic position index (TPI) and volumetric water content (VWC) at 30–60 cm on 9 of 14 sampling dates (a–n) and a significant negative linear relationship between distance from stream and VWC on 3 of 14 sampling dates. If the slope of the linear model was greater than 0 at a level of significance of $\alpha < 0.05$, it is indicated with * and panels are gray. Two-week antecedent rainfall (cm) is indicated above each column of regression plots for each sampling date. A greater amount of variability in VWC was explained by TPI when antecedent rainfall was >10 cm (panels f, g, h, m, and n) whereas the most variability was explained by distance from stream during low antecedent rainfall (panels c, d, and e). There was a significant negative linear relationship between percent rock content and VWC at 30–60 cm on 9 of 14 sampling dates and a significant positive linear relationship between VWC at field capacity and measured VWC on all sampling dates.

when 2-weeks antecedent rainfall was >10 cm (Figure 3 panels f, g, h, m, and n). VWC increased, on average, 0.01 cm^3 cm^{-3} (mean 95% CI = 0.001 to 0.02) for one standard deviation increase in TPI—this slope was strongly correlated to the 2-week antecedent rainfall ($R^2 = 0.69$, Figure 4a). Conversely, the relationship was weakest when antecedent rainfall was low (3–6 cm) during fall and spring (e.g., Figure 3 panels c, d, and i). In contrast, low antecedent rainfall conditions created the strongest relationship between VWC and distance from stream ($p < 0.05$, Figure 3 panels c, d, and e). VWC decreased, on average, 0.01 cm^3 cm^{-3} for one standard deviation increase in distance from stream (mean 95% CI = −0.02 to 0.001, Figure 4b).

Linear regression of VWC with each local factor (Table 1) indicated that gravimetric rock content and VWC at field capacity (−33 kPa) explained more of the variability in VWC at 0–30 cm (R^2 = 0.11–0.20; data not shown) and at 30–60 cm (R^2 = 0.28–0.72; Figure 3) than the other soil and vegetation properties

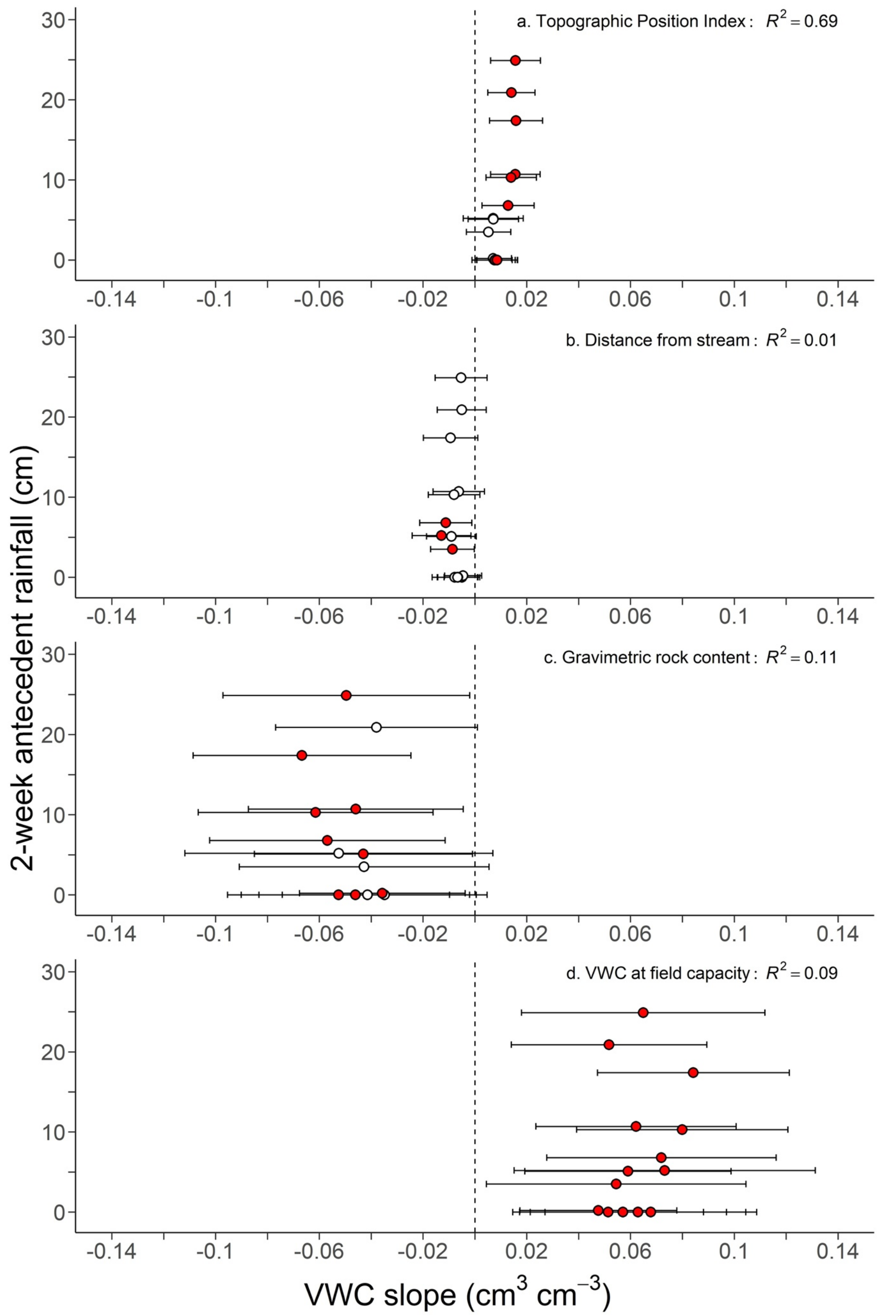

Figure 4. The slope for the change in volumetric water content (VWC) at 30–60 cm for one standard deviation increase in each variable (Topographic Position Index = 2, distance from stream = 39 m, gravimetric rock content = 13.9%, and VWC at field capacity = 0.04 cm^3 cm^{-3}). Red circles indicate the slope ≠ 0 at the $\alpha = 0.05$ level of statistical significance. Error bars represent the 95% confidence intervals The R^2 value was derived from the linear relationship between antecedent precipitation (cm) and the slope estimates ($n = 14$).

($R^2 = 0.001$–0.10; data not shown). Statistically, there was evidence that for 9 of 14 sampling dates VWC at 30–60 cm was related to the gravimetric rock content of soils and, for all sampling dates, was also related to the laboratory measurement of field capacity VWC ($p < 0.05$, Figure 3). While the estimated slopes were greater than those estimated from the regressions with TPI and Euclidean distance from stream, the 95% confidence intervals were much wider due to the relatively small number of sites where we measured soil properties ($n = 13$). VWC at field capacity and gravimetric rock content were highly correlated (Figure 5), and therefore, regression of VWC with these variables produced a similar, but directionally opposite, effect.

Table 1
Mean Values for Soil Properties From Soil Cores Taken at 15 and 45 cm Depth at a Subset of VWC Monitoring Sites (8 Convergent and 5 divergent)

		Convergent mean	Divergent mean	Overall mean ± standard deviation
Sand content	15 cm	11.4%	13.6%	12.3% ± 6.6%
	45 cm	12.5%	13.7%	13.0% ± 4.7%
Silt content	15 cm	52.7%	49.6%	51.5% ± 3.7%
	45 cm	49.9%	49.4%	49.7% ± 2.3%
Clay content	15 cm	35.8%	36.8%	36.2% ± 5.4%
	45 cm	37.6%	36.9%	37.3% ± 3.7%
Whole-soil dry bulk density	15 cm	1.0 g cm^{-3}	1.0 g cm^{-3}	1.0% ± 0.1 g cm^{-3}
	45 cm	1.1 g cm^{-3}	1.0 g cm^{-3}	1.1% ± 0.1 g cm^{-3}
Gravimetric rock content (diameters > 2 mm)	15 cm	66.3%	61.1%	64.3% ± 11.8%
	45 cm	63.1%	59.8%	61.9% ± 13.3%
Saturated hydraulic conductivity	15 cm	220 cm hr^{-1}	265 cm hr^{-1}	238 ± 113 cm hr^{-1}
	45 cm	207 cm hr^{-1}	249 cm hr^{-1}	223 ± 142 cm hr^{-1}
VWC at −33 kPa (field capacity)	15 cm	0.20 cm^3 cm^{-3}	0.20 cm^3 cm^{-3}	0.20 ± 0.04 cm^3 cm^{-3}
	45 cm	0.21 cm^3 cm^{-3}	0.22 cm^3 cm^{-3}	0.21 ± 0.03 cm^3 cm^{-3}
VWC at −2500 kPa (turgor loss point)	15 cm	0.13 cm^3 cm^{-3}	0.14 cm^3 cm^{-3}	0.13 ± 0.03 cm^3 cm^{-3}
	45 cm	0.14 cm^3 cm^{-3}	0.14 cm^3 cm^{-3}	0.14 ± 0.03 cm^3 cm^{-3}
Depth to bedrock		2.7 m	1.8 m	2.3 ± 1.2 m
Distance to nearest tree		2.0 m	2.0 m	2.0 ± 0.7 m
Total basal area within 5 m		0.33 m^2	0.33 m^2	0.33 ± 0.09 m^2
Total distance-weighted basal area within 5 m		0.16 m^2	0.17 m^2	0.17 ± 0.05 m^2
Basal area per hectare		31.8 m^2 ha^{-1}	33.8 m^2 ha^{-1}	32.7 ± 9.6 m^2 ha^{-1}

Soil depth to bedrock was measured at a subset of sites (n = 38) and vegetation properties were measured at all sites (n = 54).

VWC at 30–60 cm decreased, on average, 0.05 cm^3 cm^{-3} for one SD increase in rock content (mean 95% CI = −0.09 to −0.004 Figure 4c) and increased on average, 0.06 cm^3 cm^{-3} for one SD increase in field capacity VWC (mean 95% CI = 0.02 to 0.11, Figure 4d). Unlike TPI, the estimated slopes were poorly correlated to 2-week antecedent rainfall.

Soil properties were not correlated to TPI across the 13 sites (Figure 5). However, several soil properties were correlated with Euclidean distance from the stream. Soil clay content and water held at field capacity decreased with increased distance from the stream while sand content, bulk density, and rock content increased at locations further from the stream (Figure 5). Total depth to bedrock was not well correlated to any of the terrain metrics. However, we found the average depth to bedrock was 0.9 m greater on convergent slopes compared to divergent slopes (Table 1). Total soil depth to bedrock was also 0.8 m greater at locations within 80 m of the stream compared to locations further upslope.

4.2. Persistent Spatial Patterns

We found persistent spatial patterns in VWC across all sampling dates—some locations remained consistently wetter than the spatial average, while other locations remained consistently drier. When ranking individual sites according to VWC, the average rank, or relative wetness, of most sites varied little despite large seasonal differences in rainfall.

The SD of ranks for individual sites were distinct from those estimated from the permutation test on randomly assigned ranks. The SD of only five sites at 0–30 cm fell into the range of SDs that would be expected if ranking were entirely random (Figure 6). These few sites where rank was not as stable over time as the other sites, all had intermediate average rankings. For most sites, however, SDs of average ranks were lower

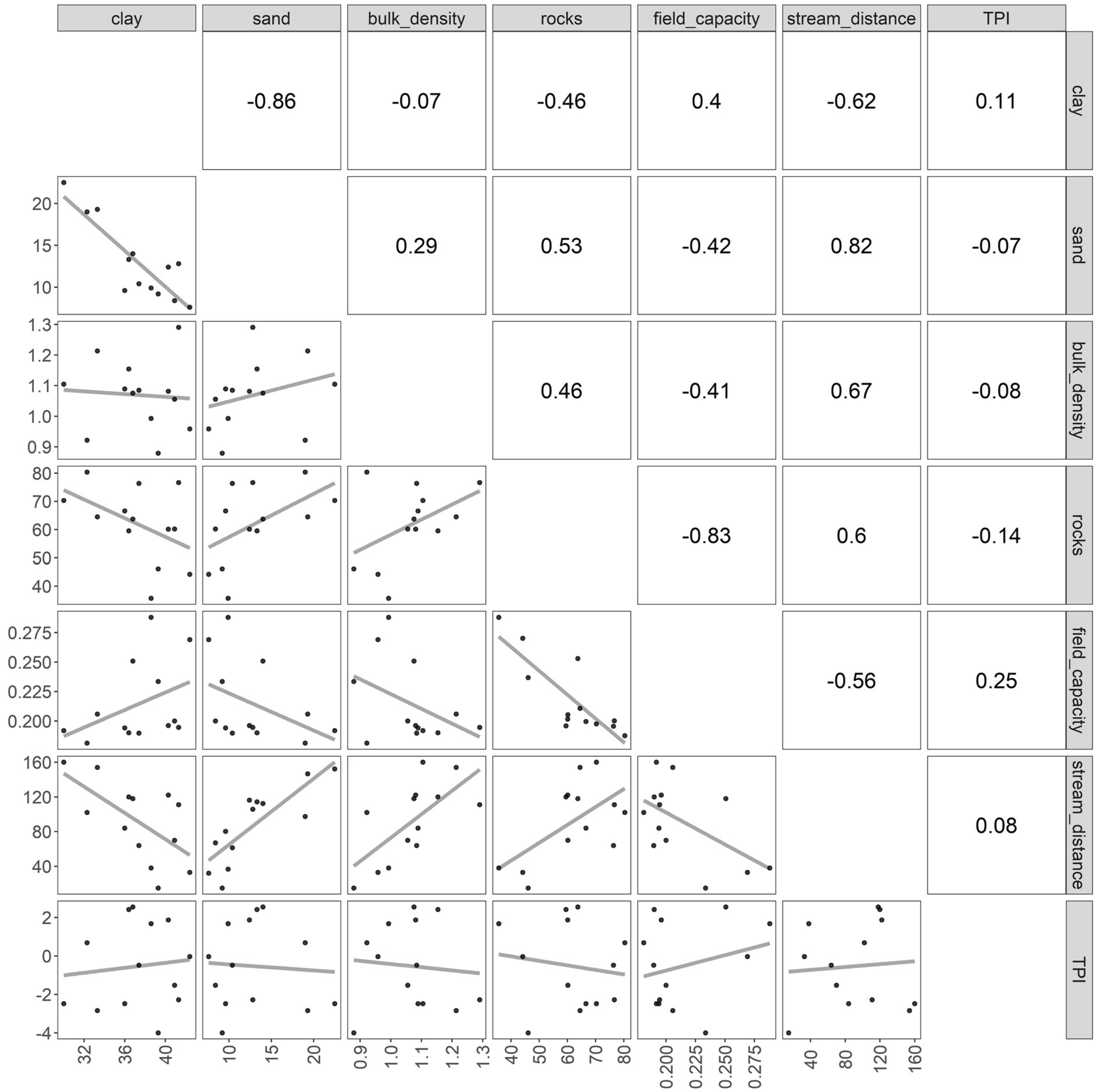

Figure 5. Linear relationships and the Pearson correlation coefficients among topographic variables—distance to stream (m) and topographic position index–and soil properties at 45 cm depth—clay content (%), sand content (%), bulk density (cm^3 cm^{-3}), rock content (%), and volumetric water content at field capacity (cm^3 cm^{-3}).

than the SDs generated by random assignment at both soil depths (SD at fifth percentile = 11.9 at 0–30 cm and 10.2 at 30–60 cm). The sites that were most stable in VWC over time—indicated by standard deviation <3—were either on the extreme dry or extreme wet end of the distribution of VWC, as indicated by high and low average rank.

4.3. Variability in Volumetric Water Content

VWC was spatially more variable at the deeper soil depth, 30–60 cm, compared to 0–30 cm. At both depths, the SD increased with mean VWC (Figure 7). The smallest variability in VWC occurred late in the dry season when 2-weeks antecedent rainfall was zero and soils were driest. The greatest variability occurred in October 2016 when 2-weeks antecedent rainfall was 24.9 cm and soils were at intermediate wetness. This led to a positive, convex relationship between the mean and SD at 30–60 cm (Figure 7).

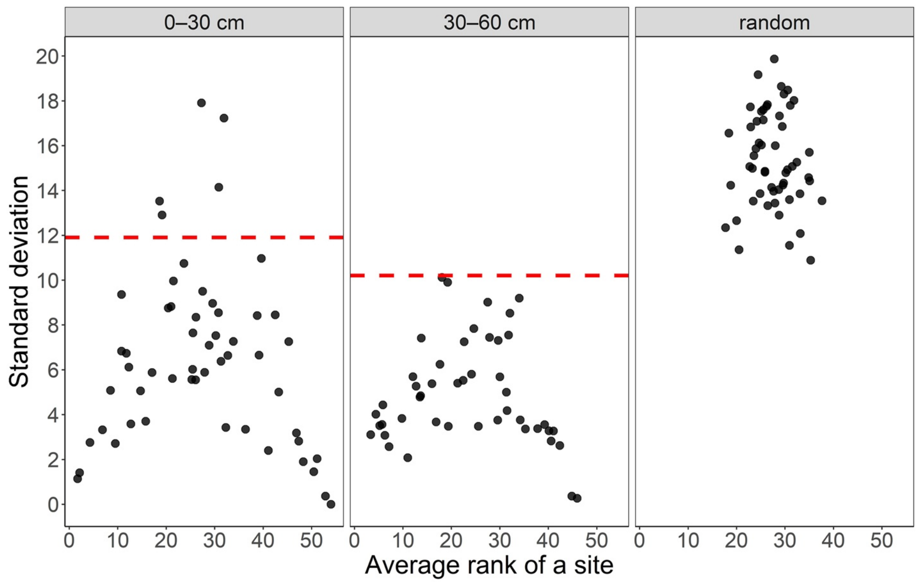

Figure 6. The distribution of the standard deviations versus the average rank of a site at both 0–30 and 30–60 cm was different from the distribution of the standard deviations of average rank of site wetness estimated from 1,000 simulations that randomly assigned rank to sites. The right panel is an example of one permutation under the null hypotheses of no spatial pattern or no stability in average rank. The red dashed line is the fifth percentile of the distribution of standard deviations estimated from 1,000 simulations that randomized ranks.

We observed small differences in VWC between 0–30 and 30–60 cm at individual sites where VWC was measured at both depths. The differences were, on average, greater during dry sampling dates (2-week antecedent rainfall <1 cm) than wet sampling dates (2-week antecedent rainfall >1 cm). Over all dates, VWC was, on average, 0.01 $cm^3 cm^{-3}$ greater at 30–60 cm than 0–30 cm ($t_{642} = -3.22$, $p = 0.02$, 95% CI = 0.012 to 0.003). However, during dry sampling dates, we found VWC was, on average, 0.02–0.03 $cm^3 cm^{-3}$ greater at 30–60 cm than 0–30 cm ($p \leq 0.02$; Table 2). In contrast, during wet sampling dates, VWC differed between depths for one date in April 2017 when it was 0.02 $cm^3 cm^{-3}$ greater at 0–30 than 30–60 cm ($p = 0.03$; Table 2). While the differences in VWC between depths at individual sites were generally small, a few sites had large differences—the maximum difference in VWC between the two depths at an individual site was 0.28 $cm^3 cm^{-3}$ (Figure 8).

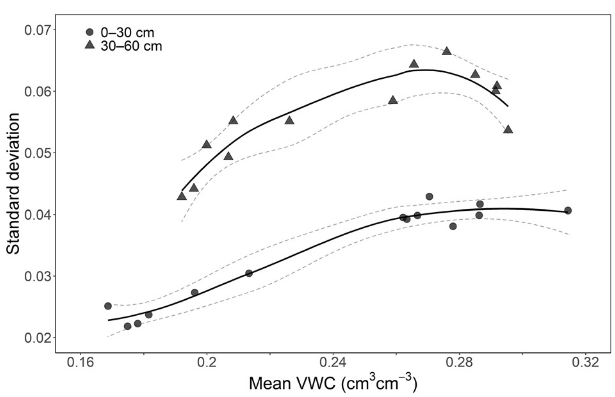

Figure 7. The standard deviation of volumetric water content (VWC) generally increased as mean VWC increased. The data were fit using a smooth local regression (solid line) with 95% confidence intervals (dashed line). The relation becomes asymptotic at high mean VWC at 0–30 cm, while the standard deviation peaks with the intermediate range of mean VWC and starts to decrease when overall mean VWC is the greatest at 30–60 cm.

5. Discussion

Our results showed the importance of soil properties in controlling the spatial variability of VWC in steep, quick-draining hillslopes. We expected spatial patterns in VWC would result from lateral redistribution of subsurface flow and therefore, be highly correlated to surface topography. Instead, we found that soil properties were an important control on VWC on all sampling dates. The temporal persistence of these relationships, as well as the overall spatial patterns during wet and dry seasons, suggested the effect of soil hydraulic properties may outweigh seasonally dynamic fluxes such as subsurface water redistribution from saturated flows in this watershed. Our results emphasized that spatial patterns in VWC, while persistent, are not easily explained by surface topography in steep, upland soils that are rocky and well-drained.

5.1. Nonlocal Controls

In our study in Watershed 1 at the H.J. Andrews Experimental Forest, soils at 30–60 cm depth on convergent slopes were, on average, drier than

Table 2
The Estimated Mean Difference in VWC Between 0–30 and 30–60 cm Using a Paired t-Test

Date	Two-week antecedent rainfall (cm)	Estimated difference in VWC	*p*-value	Lower, upper 95% CI
8/16/2016	0.0	**0.02**	**<0.01**	0.01, 0.03
8/30/2016	0.2	**0.02**	**<0.01**	0.01, 0.04
9/24/2016	3.5	0.00	0.62	−0.02, 0.01
10/6/2016	5.2	−0.01	0.40	−0.04, 0.02
10/12/2016	6.8	0.00	0.89	−0.02, 0.02
10/22/2016	24.9	0.01	0.63	−0.01, 0.02
4/28/2017	20.9	−0.02	0.03	−0.04, 0.00
5/20/2017	10.7	0.01	0.51	−0.01, 0.02
6/17/2017	5.1	−0.01	0.40	−0.03, 0.01
7/11/2017	0.0	**0.03**	**<0.01**	0.01, 0.05
8/3/2017	0.0	**0.03**	**<0.01**	0.01, 0.04
9/1/2017	0.0	**0.02**	**<0.01**	0.01, 0.04
9/23/2017	17.4	0.01	0.18	−0.01, 0.03
10/15/2017	10.3	0.01	0.49	−0.01, 0.03

VWC was greater, on average, at 30–60 cm than 0–30 cm during dry sampling dates (bold) but did not differ between depths during wet sampling dates except on April 28, 2017.

soils on divergent slopes. Conversely, we found no relationship between surface topography and VWC at the 0–30 cm soil depth. While the relationship at 30–60 cm was strongest when 2-week antecedent rainfall was high and soils were wet, it persisted across all sampling dates, including both dry and wet seasons (Figures 3 and 4). This relationship was opposite of our expectations, and clearly demonstrated that redistribution of soil water via subsurface flows, following flowpaths derived from the surface topography, could not explain the persistent spatial patterns in VWC in the top 60 cm of the soil.

The spatial redistribution of water by surface runoff or lateral subsurface flow following topographical features was previously defined as a nonlocal control on soil moisture by Grayson et al. (1997). Similarly, Western et al. (1999) found that surface soils became saturated and generated overland flow that accumulated in convergent areas. However, while saturation excess surface runoff has been described in some forested watersheds (e.g., Gomi et al., 2008), it is unlikely to have occurred at our field site because saturated hydraulic conductivity exceeded 200 cm hr^{-1}, which is far greater than precipitation intensity, even during the most intense rainstorms.

We expected subsurface lateral flows would be an important causal mechanism for spatial patterns of VWC at our study site. Subsurface flows have been observed in a nearby catchment (Gabrielli et al., 2012) and shown to influence spatial patterns in near-surface VWC especially during wet periods (Famiglietti et al., 1998; Grayson et al., 1997; Hoylman et al., 2019; Kaiser & McGlynn, 2018; McNamara et al., 2005; Takagi & Lin, 2011; Williams et al., 2009). Others have indicated that zones of saturation were better predicted by the topography of the bedrock than by surficial topography (Freer et al., 2002; Liang & Chan, 2017; Tromp-van Meerveld

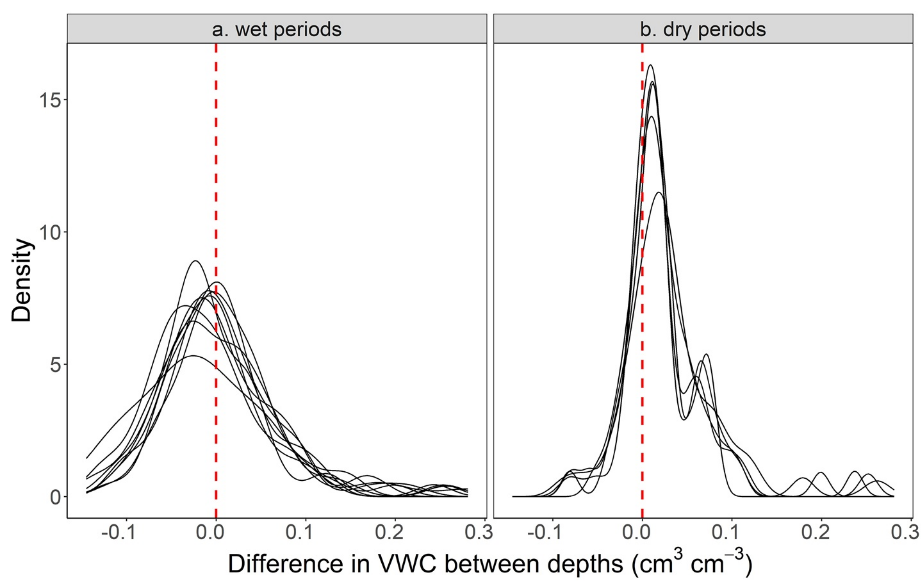

Figure 8. Distribution of differences in volumetric water content (VWC) between the two sampling depths (30–60 cm—0–30 cm) during wet sampling dates ($n = 9$) when two-week antecedent rainfall >1 cm and dry sampling dates ($n = 5$) when antecedent rainfall <1 cm. The distribution of differences was smoothed using a Gaussian kernel density estimate. The mean difference in VWC between the two depths was approximately zero during wet periods ($p = 0.81$), panel (a). However, VWC was 0.02 cm^3 cm^{-3} greater at 30–60 cm than at 0–30 cm during the dry periods ($p < 0.01$), panel (b).

& McDonnell, 2006b). In either case, however, subsurface flows must occur relatively near the surface to lead to a measurable relationship between topography and VWC. However, high rates of infiltration and hydraulic conductivity at our site allowed for rapid drainage through the first 60 cm of soil. Additionally, soils were, on average, more than 2 m deep and, in most locations, were underlain by highly weathered saprolite. Further, we never observed saturation in our 10 monitoring wells that penetrated over 2 m below the soil surface during more than two years of continuous monitoring. Thus, while saturation most likely occurred at our site, it occurred at depths too deep to influence spatial patterns of VWC in the upper 60 cm of soil.

We observed a significant relationship between VWC and distance from the stream, in which, soils closer to the stream were wetter than soils further upslope. We also found that upland soils within 80 m of the stream were approximately a meter deeper (mean depth = 2.7 m) than soils further upslope (mean depth = 1.9 m). Indeed, in our study area, the near-surface soils may be more likely to saturate where depth to bedrock was shallow. However, evidence of deep soils and lack of saturation in our 2 m deep hillslope wells suggested that saturated lateral flow and water table formation occurred much deeper than our measurement depths. Gabrielli et al. (2012) also found that subsurface saturation primarily occurred within highly weathered saprolite or fractured bedrock in a nearby watershed. Moreover, this is likely to occur during the wettest times of the year. However, we observed that VWC was most correlated with distance from stream during the fall when 2 weeks antecedent rainfall was low, soils were at intermediate wetness (Figures 3 and 4), and overall spatial variability in VWC was highest (Figure 7).

The spatial extent and scale of our study may be another reason why our results do not corroborate those of most studies, where convergent topographic positions are typically wetter than divergent ones. We used a 30 m radius to calculate TPI to represent hydrologic landforms in a 10 ha area while minimizing the effects of buried logs, tree tips, or other factors that create finer-scale surface roughness. Comparatively, TPI was estimated with a much larger radius in other studies where slope positions were classified (De Reu et al., 2013). For example, Hoylman et al. (2018) used a 150 m radius to classify slope positions in an 1,800 ha catchment in Montana. While their study design was similar to ours, the hydrologic landforms spanned a much larger spatial extent, resulting in larger upslope areas draining to the base of convergent slopes. Thus, the spatial extent used to test for relationships between terrain metrics and VWC can be quite variable depending on catchment structure and surface roughness. As a result, different studies might identify different hydrologic mechanisms as the primary control on patterns of VWC simply because of the differences in the spatial scale of the investigation.

The question of spatial scale is not independent of the landscape in which our study occurred. We expect that lithology and climate influence landform development—especially the size of hillslope hollows, the drainage area at which channels first form, and the overall drainage density (Montgomery & Dietrich, 1989). These factors interact with vegetation to control soil development, especially soil hydraulic properties and, along with disturbance, influence surface roughness. If these factors work together in such a way to promote water flow along hydraulic gradients that follow surface topography measured at the scale of a given study, then topographic metrics should be highly correlated with VWC (Ali et al., 2014; Bracken et al., 2013). Conversely, topographic metrics are unlikely to be well correlated with VWC at shallow depths if water flow is vertical rather than lateral in the upper meter of soil or if the mechanisms work at a scale substantially different than that measured in a given study.

5.2. Local Controls

The volumetric water content at our site was persistently and strongly influenced by soil physical properties—gravimetric rock content and water storage at field capacity—during both wet and dry seasons. When percent rock content increased by one standard deviation, VWC decreased by ~0.05 cm^3 cm^{-3}. In contrast, VWC changed only 0.01 cm^3 cm^{-3} when TPI and distance from stream changed by one standard deviation (Figure 4). Previous studies have illustrated that the amount and density of rocks can influence the storage and availability of water to plants after free drainage (Naseri et al., 2019; Parajuli et al., 2017). In general, rock content can be considered hydraulically inactive in soils. The presence of rocks decreases the pore space available to store water when soils have drained to field capacity. This also explains why the amount of water in the soil, following free drainage to field capacity, was highly correlated to the measured VWC at our sites over the duration of our study (Figure 3).

Porous, highly weathered rocks are likely to hold some water, and if ignored, could lead to underestimation of VWC particularly during dry conditions (Parajuli et al., 2017; Rempe & Dietrich, 2018). Because fragments of weathered rock or saprolite were observed when digging soil pits at our sites, rocks may have contributed to measured VWC when located near TDR probes. We know neither the amount nor the mobility of the water stored in these rocks, so we do not know exactly how rock moisture influenced our measurements of VWC. Nevertheless, we measured lower VWC in rocky soils, suggesting that the volume of bulk soil occupied by rocks limited the water storage capacity of the soil after free drainage and that these effects can persist over time.

None of the vegetation metrics we employed appeared to be related to the spatial patterns in VWC. However, we controlled for vegetation factors in our study design to isolate the effects of topography. We established our study area in a ~50 years old plantation forest on a north-facing hillslope with uniform aspect where tree density and size were also relatively uniform. Thus, it was not surprising that VWC was not influenced by the average distance to the nearest tree, tree density, or either total, or distance-weighted total basal area at our sites. Additionally, these vegetative metrics did not change with changes in TPI and distance from the stream. Although we did not measure canopy cover at our sites, interception can decrease VWC under canopies compared to nearby soils under canopy gaps (Gray et al., 2002).

Evapotranspiration from trees can interact with soil moisture availability and soil depth to change spatial patterns in VWC. This was demonstrated by Tromp-van Meerveld & McDonnell (2006a) who found that trees transpired more soil water during the growing season at sites with deep soils ($\bar{x}$ = 93 cm) than sites with shallow soils ($\bar{x}$ = 51 cm). However, despite greater ET losses at the sites with deep soils, VWC measured at 30 cm depth decreased more slowly than at sites with shallow soils (Tromp-van Meerveld & McDonnell, 2006a). They attributed this to differences in soil depth, which determined the total amount of water that was available for transpiration during the growing season. However, our data suggest the spatial patterns in VWC at 30–60 cm were not likely to result from differences in total soil depth or from differences in ET. First, soils at our site are much deeper than those studied by Tromp-van Meerveld & McDonnell (2006a), averaging 1.8 m deep on divergent and 2.7 m deep on convergent slopes. Thus, root water uptake from deep soils or the hydraulic redistribution of deeper soil moisture to shallower soil layers (Brooks et al., 2006) would likely be similar between slope types. Further, convergent slopes, which had deeper soils were drier at 30–60 cm than divergent slopes, which is opposite of Tromp-van Meerveld & McDonnell's (2006a) results. Second, spatial patterns in VWC were persistent across both wet and dry seasons even though most plant water uptake occurs during the dry summer months, suggesting that the spatial patterns in VWC were not determined by ET, but rather dictated by differences in soil properties among sites.

5.3. Temporal Persistence

We observed strong temporal stability in spatial patterns of volumetric water content at our field site. Despite large seasonal changes in mean VWC from the wet winter season to the long, dry summer, the wettest sites were the wettest sites on every sampling date and the driest sites were the driest sites on every sampling date. Temporal stability of spatial patterns in soil water content has been observed in numerous studies and, in general, is attributed to feedbacks between soil water fluxes and water storage (Vanderlinden et al., 2012). This can occur due to nonlocal water redistribution (Takagi & Lin, 2011), local plant water uptake (Gómez-Plaza et al., 2001), and local soil properties such as bulk density and texture (Cosh et al., 2008). However, these factors either seem not to apply (nonlocal water redistribution) or are insufficient to explain the persistence of the spatial patterns we observed over the extreme seasonality in both precipitation and mean soil moisture (Figure 6). Moreover, results from other studies suggest that the combined effects of controlling factors rather than single factors are responsible for the temporal stability of VWC patterns (Vanderlinden et al., 2012).

We would expect spatial patterns of VWC to change seasonally because the relative influence of local and nonlocal factors also changes with season. For example, differences in rock content should generate spatial patterns in VWC that persist over the wet season when soil moisture remains at or near field capacity with frequent rainfall events. Conversely, the interaction of soil properties, soil depth, and ET would be expected to influence the development of a new spatial pattern during the dry season (Gómez-Plaza et al., 2001; Hu & Si, 2014; Tromp-van Meerveld & McDonnell, 2006a; Western et al., 1999). Given that we did not observe shifts in the spatial pattern in VWC, suggests that differences in ET across our sites were not large enough to influence spatial patterns of relative soil wetness among sites. This is notable because it is widely accepted that soil moisture availability is often a critical control on evapotranspiration (Feddes et al., 2001; Jassal et al., 2009; Klein et al., 2014). As such, without substantial precipitation over the long dry summer, we would expect that total ET would be greater in the wettest locations and lesser in the driest locations, which would obscure existing spatial patterns in VWC (or produce new ones).

Evapotranspiration responds to two primary controls—soil moisture availability and atmospheric water demand. Research by Novick et al. (2016) showed that ET from Douglas-fir forests in the Pacific Northwestern USA was more strongly regulated by atmospheric water demand than by soil moisture availability. We would expect similar atmospheric conditions across the full extent of our study site because it was small (10 ha), had relatively uniform slope and aspect, and the range in elevation was relatively modest. If both atmospheric conditions and the forest canopy are uniform, then regulation of tree water use by atmospheric water demand could lead to similar magnitude and timing of plant water uptake among our sites. Under these conditions, the spatial patterns in VWC that were present at the end of the wet season could persist through the long summer dry season.

5.4. Relationship Between Local Factors and Topographic Metrics

While we found strong and persistent correlations between local soil properties and VWC, the local factors did not appear to differ strongly between convergent and divergent hillslopes as measured by TPI (Figure 5). Thus, we were unable to explain why divergent locations were wetter than convergent locations. Unfortunately, we did not have sufficient resources to dig soil pits and sample and analyze the soil at all 54 VWC monitoring sites. Rather, we chose to compare the wettest and driest sites, expecting that this contrast would most likely demonstrate the mechanisms controlling differences correlated to topography. However, with only 13 sample locations for soil properties, our statistical power was low. Despite that, we saw no evidence that rock content differed between convergent and divergent slopes (Table 1, Figure 5). Thus, while others find soil properties and surface topography may jointly control VWC (Hu & Si, 2014), soil properties do not appear to be an explanation for the observed differences in VWC with TPI. We did, however, find that rock content, sand content, and bulk density were greater at sites further from the stream at 45 cm depth (Figure 5). Additionally, VWC at field capacity and clay content decreased with increased distance from stream (Figure 5). This suggested that soil physical and hydraulic properties may vary along hillslope lengths.

Total depth to bedrock was measured at 38 of our 54 VWC monitoring sites and results indicated that soils were slightly shallower at divergent locations than at convergent ones (Table 1). However, soil depth itself, was unrelated to VWC. We commonly encountered an increase in resistance with the knocking pole before reaching an impenetrable bedrock layer. Thus, we assumed most soils were underlain by highly weathered saprolite with a porous and friable consistency whereas a few locations were underlain with andesitic intrusions that were resistant but still highly fractured (Gabrielli et al., 2012). In both cases, the underlying bedrock likely contributed to deep drainage and prevented formation of shallow saturated zones. Thus, the difference in total depth to bedrock among our measurement sites do not appear to be sufficient to control spatial patterns in VWC.

The mean and range in the values of our vegetation metrics also did not differ among convergent and divergent hillslopes. As described above, this study was designed to isolate topographic effects from potential confounding factors such as vegetation—by selecting a study site located in a relatively uniform plantation forest. The comparison of vegetation metrics between convergent and divergent locations suggests that we were, in fact, successful. But consequently, there were no differences in vegetation metrics measured with the spatial grain and extent of our study.

Our results clearly showed that the effect of rock content on soil hydraulic properties altered VWC in measurable ways (Figures 3 and 4). Furthermore, the change in soil properties including bulk density, rock content, and soil texture with change in distance from the stream (Figure 5) may partially explain the positive linear relationship between VWC and distance from the stream (Figure 3). The delineation of landforms based on pedology and hydrologic processes could be a useful, albeit complex, framework for exploring the mechanisms that control VWC patterns (Baggaley et al., 2009; Gillin et al., 2015; Lin, 2010). Unfortunately,

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we often lack detailed soil maps that could otherwise be used to understand variability in soil properties and how soils alter hydrological processes at pedon and landscape scales. Thus, the spatial extent at which soils and topography interact to modify hydrological processes remain poorly understood in many landscapes (Western & Blöschl, 1999). While we did not have enough information to confidently discern how soil properties (e.g., rock content) are distributed in space, others have shown through model simulation that accounting for the effect of rock content on soil hydraulic properties improved predications of VWC (Lai et al., 2018). Thus, improved understanding of how rock content changes across horizontal and vertical space would likely be necessary to predict spatial patterns of VWC in our study area and in other steep mountainous catchments with rocky soils.

5.5. Study Limitations and Future Work

Given the high variability in the fraction of coarse material including rocks, roots, and buried wood (Table 1), the small measurement volume of our TDR sensors may exacerbate the effects of these factors on the observed spatial variability in VWC among sites. For example, if the TDR probes were inserted next to large pores created by rocks and roots, then macropores would likely decrease VWC relative to nearby soils free of large air-filled pores once soils drained to field capacity. Conversely, large pieces of decomposing wood can remain wetter than the adjacent soil and result in measurements of unusually high VWC. It was common to find buried wood and charcoal when extracting soil samples at 15 and 45 cm. This may explain why VWC differed by as much as 0.3 $cm^3\ cm^{-3}$ between the 0–30 and 30–60 cm depths at a few sites (Figure 8). However, because TDR probes were installed vertically from the surface, it was impossible to know the specific local conditions that each pair of probes encountered. Nevertheless, we expected to observe high spatial variance in VWC relative to other studies given the abundance of rocks, coarse roots, and buried wood. However, we found that the range in the standard deviations over 14 sampling dates (SD = 0.02–0.07 $cm^3\ cm^{-3}$, Figure 7) was well within the range reported in other studies (Tague et al., 2010; Takagi & Lin, 2011). We also found the positive convex relationship between the mean and SD of VWC was reported in other studies (Brocca et al., 2010; Famiglietti et al., 2008; Tague et al., 2010). Thus, while these issues might account for some of the extreme variability among sites or between soil depths, the spatial variability appears typical of most soils and is an unlikely explanation for greater VWC on divergent slope positions versus convergent ones, or greater VWC at sites near the stream versus those further away. Additionally, we have no reason to expect that our site selection would have biased our results, especially with a sample of 54 soil moisture sites. We recommend that a subset of sites be evaluated for small-scale variability in VWC given the heterogeneity of macropore structure found to be influential in forest soil hydrology (De Vries & Chow, 1978). This is a potential limitation of our study as we had only two measurement points for each depth, which were spaced roughly 2 m apart at each site. However, the variability between points was usually small relative to the variability among sites on any given sample date.

We recommend future work couple measurements of soil properties and hydraulic properties with measures of VWC at multiple spatial extents, and ideally, use a combination of point and spatially continuous measurements techniques to assess relative soil wetness. We also recommend researchers identify how soil hydraulic properties influence the temporal stability of spatial patterns at multiple depths. Doing so, could improve models of soil water storage and soil moisture availability for plants in landscapes with deep, fast-draining soils such as the ones studied here.

6. Conclusions

Our study was designed to test if the horizontal redistribution of water, following surface topography, controlled the spatial patterns of VWC across steep, highly dissected terrain. Spatial patterns of VWC are often characterized with metrics like the TPI or the TWI. Most of the relationships between terrain metrics and VWC have been described for catchments with gentle to moderate slopes and, to a lesser extent, in catchments with steep terrain (Liang et al., 2017). Terrain metrics were developed to characterize source areas for streamflow generation models and, more recently, have been related to the VWC of the soil and used as a proxy to determine the potential availability of water for plant growth. In our study, we found persistent spatial patterns in VWC, which were weakly related to topography. However, contrary to expectations, divergent hillslopes were actually wetter than convergent hollows. VWC was more strongly related to soil properties—specifically, the abundance of coarse fragments and the amount of water stored in the soil after draining to field capacity. Soils at the site were relatively deep ($\bar{x}$ = 2.3 m), well-drained, and underlain by porous, highly weathered saprolite. Moreover, we did not find saturated conditions within 2 m of the soil surface over two winters during which we continuously monitored 10 hillslope wells. These conditions are unlikely to be conducive to the horizontal redistribution of water at depths sufficiently shallow to influence VWC of the upper soil profile. The conditions at our site are common in steep, mountainous terrain worldwide. Unfortunately, we lack detailed information on soil properties and their spatial variability in most locations, which challenges our ability to understand how soils alter hydrological processes from pedon to landscape scales. Thus, we recommend that future research test the spatial extent and depths at which soils and topography interact to modify hydrological processes in steep, complex topography.

Data Availability Statement

Soil data are publicly available via the Andrews Forest database (http://andlter.forestry.oregonstate.edu/data/abstract.aspx?dbcode=SP036) in addition to the LiDAR-based DEM (http://andlter.forestry.oregonstate.edu/data/abstract.aspx?dbcode=GI010) and meteorological data (http://andlter.forestry.oregonstate.edu/data/abstract.aspx?dbcode=MS001).

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References

Ali, G., Birkel, C., Tetzlaff, D., Soulsby, C., McDonnell, J. J., & Tarolli, P. (2014). A comparison of wetness indices for the prediction of observed connected saturated areas under contrasting conditions. *Earth Surface Processes and Landforms*, *39*(3), 399–413. https://doi.org/10.1002/esp.3506

Auguie, B. (2017). *GridExtra: Miscellaneous functions for "grid" graphics*. Retrieved from https://cran.r-project.org/package=gridExtra

Baggaley, N., Mayr, T., & Bellamy, P. (2009). Identification of key soil and terrain properties that influence the spatial variability of soil moisture throughout the growing season. *Soil Use and Management*, *25*(3), 262–273. https://doi.org/10.1111/j.1475-2743.2009.00222.x

Beven, K., & Germann, P. (1982). Macropores and water flow in soils. *Water Resources Research*, *18*(5), 1311–1325. https://doi.org/10.1029/WR018i005p01311

Beven, K. J., & Kirkby, M. J. (1979). A physically based, variable contributing area model of basin hydrology. *Hydrological Sciences Bulletin*, *24*(1), 43–69. https://doi.org/10.1080/02626667909491834

Bracken, L. J., Wainwright, J., Ali, G. A., Tetzlaff, D., Smith, M. W., Reaney, S. M., & Roy, A. G. (2013). Concepts of hydrological connectivity: Research approaches, pathways and future agendas. *Earth-Science Reviews*, *119*, 17–34. https://doi.org/10.1016/j.earscirev.2013.02.001

Brocca, L., Melone, F., Moramarco, T., & Morbidelli, R. (2010). Spatial-temporal variability of soil moisture and its estimation across scales. *Water Resources Research*, *46*(2). https://doi.org/10.1029/2009WR008016

Brooks, J. R., Meinzer, F. C., Warren, J. M., Domec, J. C., & Coulombe, R. (2006). Hydraulic redistribution in a Douglas-fir forest: Lessons from system manipulations. *Plant, Cell and Environment*, *29*(1), 138–150. https://doi.org/10.1111/j.1365-3040.2005.01409.x

Bundt, M., Widmer, F., Pesaro, M., Zeyer, J., & Blaser, P. (2001). Preferential flow paths: Biological 'hot spots' in soils. *Soil Biology and Biochemistry*, *33*(6), 729–738. https://doi.org/10.1016/S0038-0717(00)00218-2

Cosh, M. H., Jackson, T. J., Moran, S., & Bindlish, R. (2008). Temporal persistence and stability of surface soil moisture in a semi-arid watershed. *Remote Sensing of Environment*, *112*(2), 304–313. https://doi.org/10.1016/j.rse.2007.07.001

Daly, C., Schulze, M., & McKee, W. (2019). Meteorological data from benchmark stations at the HJ Andrews experimental forest, 1957 to present. Long-Term Ecological Research. In *Forest science data bank*. Corvallis, OR: Available. https://doi.org/10.6073/pasta/c021a2ebf1f91adf0ba3b5e53189c84f. http://andlter.forestry.oregonstate.edu/data/abstract.aspx?dbcode=MS001

De Reu, J., Bourgeois, J., Bats, M., Zwertvaegher, A., Gelorini, V., De Smedt, P., et al. (2013). Application of the topographic position index to heterogeneous landscapes. *Geomorphology*, *186*, 39–49. https://doi.org/10.1016/j.geomorph.2012.12.015

De Vries, J., & Chow, T. L. (1978). Hydrologic behavior of a forested mountain soil in coastal British Columbia. *Water Resources Research*, *14*(5), 935–942. https://doi.org/10.1029/WR014i005p00935

Famiglietti, J. S., Rudnicki, J. W., & Rodell, M. (1998). Variability in surface moisture content along a hillslope transect: Rattlesnake Hill, Texas. *Journal of Hydrology*, *210*(1–4), 259–281. https://doi.org/10.1016/S0022-1694(98)00187-5

Famiglietti, J. S., Ryu, D., Berg, A. A., Rodell, M., & Jackson, T. J. (2008). Field observations of soil moisture variability across scales. *Water Resources Research*, *44*(1). https://doi.org/10.1029/2006WR005804

Fatichi, S., Katul, G. G., Ivanov, V. Y., Pappas, C., Paschalis, A., & Consolo, A., et al. (2015). Abiotic and biotic controls of soil moisture spatiotemporal variability and the occurrence of hysteresis. *Water Resources Research*, *51*(5), 3505–3524. https://doi.org/10.1002/2014WR016102

Feddes, R. A., Hoff, H., Bruen, M., Dawson, T., De Rosnay, P., Dirmeyer, P., et al. (2001). Modeling root water uptake in hydrological and climate models. *Bulletin of the American Meteorological Society*, *82*(12), 2797–2809. https://doi.org/10.1175/1520-0477(2001)082<2797:MRWUIH>2.3.CO;2

Freer, J., McDonnell, J. J., Beven, K. J., Peters, N. E., Burns, D. A., Hooper, R. P., et al. (2002). The role of bedrock topography on subsurface storm flow. *Water Resources Research*, *38*(12), 5–1. https://doi.org/10.1029/2001wr000872

Gabrielli, C. P., McDonnell, J. J., & Jarvis, W. T. (2012). The role of bedrock groundwater in rainfall-runoff response at hillslope and catchment scales. *Journal of Hydrology*, *450*, 117–133. https://doi.org/10.1016/j.jhydrol.2012.05.023

Gannon, J. P., Bailey, S. W., & McGuire, K. J. (2014). Organizing groundwater regimes and response thresholds by soils: A gramework for understanding runoff generation in a headwater catchment. *Water Resources Research*, *50*(11), 8403–8419. https://doi.org/10.1002/2014WR015498

Gevaert, A. I., Teuling, A. J., Uijlenhoet, R., DeLong, S. B., Huxman, T. E., Pangle, L. A., et al. (2014). Hillslope-scale experiment demonstrates the role of convergence during two-step saturation. *Hydrology and Earth System Sciences*, *18*(9), 3681–3692. https://doi.org/10.5194/hess-18-3681-2014

Gillin, C. P., Bailey, S. W., McGuire, K. J., & Gannon, J. P. (2015). Mapping of hydropedologic spatial patterns in a steep headwater catchment. *Soil Science Society of America Journal*, *79*(2), 440–453. https://doi.org/10.2136/sssaj2014.05.0189

Gómez-Plaza, A., Martínez-Mena, M., Albaladejo, J., & Castillo, V. M. (2001). Factors regulating spatial distribution of soil water content in small semiarid catchments. *Journal of Hydrology*, *253*(1–4), 211–226. https://doi.org/10.1016/S0022-1694(01)00483-8

Gomi, T., Sidle, R. C., Miyata, S., Kosugi, K. i., & Onda, Y. (2008). Dynamic runoff connectivity of overland flow on steep forested hillslopes: Scale effects and runoff transfer. *Water Resources Research*, *44*(8). https://doi.org/10.1029/2007WR005894

Gray, A. N., & Spies, T. A. (1995). Water content measurement in forest soils and decayed wood using time domain reflectometry. *Canadian Journal of Forest Research*, *25*(3), 376–385. https://doi.org/10.1139/x95-042

Gray, A. N., Spies, T. A., & Easter, M. J. (2002). Microclimatic and soil moisture responses to gap formation in coastal Douglas-fir forests. *Canadian Journal of Forest Research*, *32*, 332–343. https://doi.org/10.1139/x01-200

Grayson, R. B., Western, A. W., Chiew, F. H. S., & Blöschl, G. (1997). Preferred states in spatial soil moisture patterns: Local and nonlocal controls. *Water Resources Research*, *33*(12), 2897–2908. https://doi.org/10.1029/97WR02174

Gwak, Y., & Kim, S. (2016). Factors affecting soil moisture spatial variability for a humid forest hillslope. *Hydrological Processes*, *31*(2), 431–445. https://doi.org/10.1002/hyp.11039

Halpern, C. B. (1988). Early successional pathways and the resistance and resilience of forest communities. *Ecological Society of America*, *69*(6), 1703–1715. https://doi.org/10.2307/1941148

Helman, D., Osem, Y., Yakir, D., & Lensky, I. M. (2017). Relationships between climate, topography, water use and productivity in two key Mediterranean forest types with different water-use strategies. *Agricultural and Forest Meteorology*, *232*, 319–330. https://doi.org/10.1016/j.agrformet.2016.08.018

Hijmans, R. J. (2019). *Raster: Geographic data analysis and modeling*. Retrieved from https://cran.r-project.org/package=raster

Hoylman, Z. H., Jencso, K. G., Hu, J., Holden, Z. A., Martin, J. T., & Gardner, W. P. (2019). The climatic water balance and topography control spatial patterns of atmospheric demand, soil moisture, and shallow subsurface flow. *Water Resources Research*, *55*, 2370–2389. https://doi.org/10.1029/2018WR023302

Hoylman, Z. H., Jencso, K. G., Hu, J., Martin, J. T., Holden, Z. A., Seielstad, C. A., & Rowell, E. M. (2018). Hillslope topography mediates spatial patterns of ecosystem sensitivity to climate. *Journal of Geophysical Research: Biogeoscience*, *123*(2), 353–371. https://doi.org/10.1002/2017JG004108

Hu, W., & Si, B. C. (2014). Revealing the relative influence of soil and topographic properties on soil water content distribution at the watershed scale in two sites. *Journal of Hydrology*, *516*, 107–118. https://doi.org/10.1016/j.jhydrol.2013.10.002

Ivanov, V. Y., Fatichi, S., Jenerette, G. D., Espeleta, J. F., Troch, P. A., & Huxman, T. E. (2010). Hysteresis of soil moisture spatial heterogeneity and the "homogenizing" effect of vegetation. *Water Resources Research*, *46*(9). https://doi.org/10.1029/2009WR008611

Jarecke, K., Wondzell, S., & Bladon, K. (2021). Soil moisture and soil properties in watershed 1 of the HJ Andrews experimental forest, 2016–2020. Long-term ecological research. In *Forest science data bank*. Corvallis, OR: Available. https://doi.org/10.6073/pasta/d4764b05a9aa95f7cfc5514dfcacc6a3. http://andlter.forestry.oregonstate.edu/data/abstract.aspx?dbcode=SP036

Jassal, R. S., Black, T. A., Spittlehouse, D. L., Brümmer, C., & Nesic, Z. (2009). Evapotranspiration and water use efficiency in different-aged Pacific Northwest Douglas-fir stands. *Agricultural and Forest Meteorology*, *149*(6–7), 1168–1178. https://doi.org/10.1016/j.agrformet.2009.02.004

Jencso, K. G., & McGlynn, B. L. (2011). Hierarchical controls on runoff generation: Topographically driven hydrologic connectivity, geology, and vegetation. *Water Resources Research*, *47*(11), W11527. https://doi.org/10.1029/2011WR010666

Jenness, J. (2006). Topographic position index (tpi_jen.avx) extension for arcView. *Jenness Enterprises*

Kaiser, K. E., & McGlynn, B. L. (2018). Nested scales of spatial and temporal variability of soil water content across a semiarid montane catchment. *Water Resources Research*, *54*, 7960–7980. https://doi.org/10.1029/2018WR022591

Kim, S., Lee, H., Woo, N. C., & Kim, J. (2007). Soil moisture monitoring on a steep hillside. *Hydrological Processes*, *21*(21), 2910–2922. https://doi.org/10.1002/hyp.6508

Klein, T., Rotenberg, E., Cohen-Hilaleh, E., Raz-Yaseef, N., Tatarinov, F., Preisler, Y., et al. (2014). Quantifying transpirable soil water and its relations to tree water use dynamics in a water-limited pine forest. *Ecohydrology*, *7*(2), 409–419. https://doi.org/10.1002/eco.1360

Lai, X., Zhu, Q., Zhou, Z., & Liao, K. (2018). Rock fragment and spatial variation of soil hydraulic parameters are necessary on soil water simulation on the stony-soil hillslope. *Journal of Hydrology*, *565*, 354–364. https://doi.org/10.1016/j.jhydrol.2018.08.039

Liang, W.-L., & Chan, M.-C. (2017). Spatial and temporal variations in the effects of soil depth and topographic wetness index of bedrock topography on subsurface saturation generation in a steep natural forested headwater catchment. *Journal of Hydrology*, *546*, 405–418. https://doi.org/10.1016/j.jhydrol.2017.01.033

Liang, W.-L., Li, S.-L., & Hung, F.-X. (2017). Analysis of the contributions of topographic, soil, and vegetation features on the spatial distributions of surface soil moisture in a steep natural forested headwater catchment. *Hydrological Processes*, *31*, 3796–3809. https://doi.org/10.1002/hyp.11290

Lin, H. (2010). Earth's Critical Zone and hydropedology: Concepts, characteristics, and advances. *Hydrology and Earth System Sciences*, *14*(1), 25–45. https://doi.org/10.5194/hess-14-25-2010

Lin, H. S., Kogelmann, W., Walker, C., & Bruns, M. A. (2006). Soil moisture patterns in a forested catchment: A hydropedological perspective. *Geodermatology*, *131*(3–4), 345–368. https://doi.org/10.1016/j.geoderma.2005.03.013

Liu, H., & Lin, H. (2015). Frequency and control of subsurface preferential flow: From pedon to catchment Scales. *Soil Science Society of America Journal*, *79*(2), 362–377. https://doi.org/10.2136/sssaj2014.08.0330

Mauer, O., & Palátová, E. (2012). Root system development in Douglas fir (Pseudotsuga menziesii [Mirb.] Franco) on fertile sites. *Journal of Forest Science*, *58*(9), 400–409. https://doi.org/10.17221/94/2011-jfs

McDonnell, J. J., Freer, J., Hooper, R., Kendall, C., Burns, D., Beven, K., & Peters, J. (1996). New method developed for studying flow on hillslopes. *Eos, Transactions American Geophysical Union*, *77*(47), 465–472. https://doi.org/10.1029/96EO00306

McNamara, J. P., Chandler, D., Seyfried, M., & Achet, S. (2005). Soil moisture states, lateral flow, and streamflow generation in a semi-arid, snowmelt-driven catchment. *Hydrological Processes*, *19*(20), 4023–4038. https://doi.org/10.1002/hyp.5869

Mikutta, R., Kleber, M., Kaiser, K., & Jahn, R. (2005). Organic matter removal from soils using hydrogen peroxide, sodium hypochlorite, and disodium peroxodisulfate. *Soil Science Society of America Journal*, *69*(1), 120–135. https://doi.org/10.2136/sssaj2005.0120

Milledge, D. G., Warburton, J., Lane, S. N., & Stevens, C. J. (2013). Testing the influence of topography and material properties on catchment-scale soil moisture patterns using remotely sensed vegetation patterns in a humid temperate catchment, northern Britain. *Hydrological Processes*, *27*(8), 1223–1237. https://doi.org/10.1002/hyp.9292

Miller, B. A., & Schaetzl, R. J. (2012). Precision of soil particle size analysis using laser diffractometry. *Soil Science Society of America Journal*, *76*(5), 1719–1727. https://doi.org/10.2136/sssaj2011.0303

Montgomery, D. R., & Dietrich, W. E. (1989). Source areas, drainage density, and channel initiation. *Water Resources Research*, *25*(8), 1907–1918. https://doi.org/10.1029/wr025i008p01907

Naseri, M., Iden, S. C., Richter, N., & Durner, W. (2019). Influence of stone content on soil hydraulic properties: experimental investigation and test of existing model concepts. *Vadose Zone Journal*, *18*, 1–10. https://doi.org/10.2136/vzj2018.08.0163

Nippgen, F., McGlynn, B. L., & Emanuel, R. E. (2015). The spatial and temporal evolution of contributing areas. *Water Resources Research*, *51*, 4550–4573. https://doi.org/10.1002/2015WR017273.Received10.1002/2014wr016719

Novick, K. A., Ficklin, D. L., Stoy, P. C., Williams, C. A., Bohrer, G., Oishi, A. C., et al. (2016). The increasing importance of atmospheric demand for ecosystem water and carbon fluxes. *Nature Climate Change*, *6*(11), 1023–1027. https://doi.org/10.1038/nclimate3114

Pachepsky, Y. A., Timlin, D. J., & Rawls, W. J. (2001). Soil water retention as related to topographic variables. *Soil Science Society of America Journal*, *65*, 1787–1795. https://doi.org/10.2136/sssaj2001.1787

Parajuli, K., Sadeghi, M., & Jones, S. B. (2017). A binary mixing model for characterizing stony-soil water retention. *Agricultural and Forest Meteorology*, *244*(1), 1–8. https://doi.org/10.1016/j.agrformet.2017.05.013

Pelletier, J. D., Barron-Gafford, G. A., Breshears, D. D., Brooks, P. D., Chorover, J., Durcik, M., et al. (2013). Coevolution of nonlinear trends in vegetation, soils, and topography with elevation and slope aspect: A case study in the sky islands of southern Arizona. *Journal of Geophysical Research: Earth Surface*, *118*(2), 741–758. https://doi.org/10.1002/jgrf.20046

Penna, D., Borga, M., Norbiato, D., & Dalla Fontana, G. (2009). Hillslope scale soil moisture variability in a steep alpine terrain. *Journal of Hydrology*, *364*(3–4), 311–327. https://doi.org/10.1016/j.jhydrol.2008.11.009

R Core Team (2019). *R A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing.

Rempe, D. M., & Dietrich, W. E. (2018). Direct observations of rock moisture, a hidden component of the hydrologic cycle. *Proceedings of the National Academy of Sciences*, *115*(11), 2664–2669. https://doi.org/10.1073/pnas.1800141115

Rinderer, M., van Meerveld, H. J., & Seibert, J. (2014). Topographic controls on shallow groundwater levels in a steep, prealpine catchment: When are the TWI assumptions valid? *Water Resources Research*, *50*, 6067–6080. https://doi.org/10.1002/2013WR015009.Received

Sarkar, S., Germer, K., Maity, R., & Durner, W. (2019). Measuring near-saturated hydraulic conductivity of soils by quasi unit-gradient percolation-2. Application of the methodology. *Journal of Plant Nutrition and Soil Science*, *182*, 535–540. https://doi.org/10.1002/jpln.201800383

Scanlon, B. R., Andraski, B. J., & Bilskie, J. (2002). 3.2.4 Miscellaneous methods for measuring matric or water potential. In J. H. Dane, & G. C. Topp (Eds.), *Methods of soil analysis, Part 4: Physical methods* (pp. 643–670). Madison, WI: Soil Science Society of America. https://doi.org/10.2136/sssabookser5.4.c23

Schindler, U., Durner, W., von Unold, G., Mueller, L., & Wieland, R. (2010). The evaporation method: Extending the measurement range of soil hydraulic properties using the air-entry pressure of the ceramic cup. *Journal of Plant Nutrition and Soil Science*, *173*(4), 563–572. https://doi.org/10.1002/jpln.200900201

Schloerke, B., Cook, D., Larmarange, J., Briatte, F., Marbach, M., Thoen, E., et al. (2020). *GGally: Extension to ggplot2*. Retrieved from https://cran.r-project.org/package=GGally

Seibert, J., & McGlynn, B. L. (2007). A new triangular multiple flow direction algorithm for computing upslope areas from gridded digital elevation models. *Water Resources Research*, *43*(4). https://doi.org/10.1029/2006WR005128

Shanley, J. B., Hjerdt, K. N., McDonnell, J. J., & Kendall, C. (2003). Shallow water table fluctuations in relation to soil penetration resistance. *Ground Water*, *41*(7), 964–972. https://doi.org/10.1111/j.1745-6584.2003.tb02438.x

Spies, T. (2016). LiDAR data (August 2008) for the Andrews experimental forest and Willamette national forest study areas. Long-term ecological research. In *Forest science data bank*. Corvallis, OR: Available. https://doi.org/10.6073/pasta/c47128d6c63dff39ee48604ec-c6fabfc. http://andlter.forestry.oregonstate.edu/data/abstract.aspx?dbcode=GI010

St. Clair, J., Moon, S., Holbrook, W. S., Perron, J. T., Riebe, C. S., Martel, S. J., et al. (2015). Geophysical imaging reveals topographic stress control of bedrock weathering. *Science*, *350*(6260), 534–538. https://doi.org/10.1126/science.aab2210

Swetnam, T. L., Brooks, P. D., Barnard, H. R., Harpold, A. A., & Gallo, E. L. (2017). Topographically driven differences in energy and water constrain climatic control on forest carbon sequestration. *Ecosphere*, *8*(4), e01797. https://doi.org/10.1002/ecs2.1797

Tague, C., Band, L., Kenworthy, S., & Tenebaum, D. (2010). Plot- and watershed-scale soil moisture variability in a humid Piedmont watershed. *Water Resources Research*, *46*(12). https://doi.org/10.1029/2009WR008078

Takagi, K., & Lin, H. S. (2011). Temporal dynamics of soil moisture spatial variability in the Shale Hills Critical Zone Observatory. *Vadose Zone Journal*, *10*(3), 832–842. https://doi.org/10.2136/vzj2010.0134

Topp, G. C., Davis, J. L., & Annan, A. P. (1980). Electromagnetic determination of soil water content: Measurements in coaxial transmission lines. *Water Resources Research*, *16*(3), 574–582. https://doi.org/10.1029/WR016i003p00574

Traff, D. C., Niemann, J. D., Middlekauff, S. A., & Lehman, B. M. (2014). Effects of woody vegetation on shallow soil moisture at a semiarid montane catchment. *Ecohydrology*, *8*, 935–947. https://doi.org/10.1002/eco.1542

Tromp-van Meerveld, H. J., & McDonnell, J. J. (2006a). On the interrelations between topography, soil depth, soil moisture, transpiration rates and species distribution at the hillslope scale. *Advances in Water Resources*, *29*(2), 293–310. https://doi.org/10.1016/j.advwatres.2005.02.016

Tromp-van Meerveld, H. J., & McDonnell, J. J. (2006b). Threshold relations in subsurface stormflow: 2. The fill and spill hypothesis. *Water Resources Research*, *42*(2). https://doi.org/10.1029/2004WR003800

Vanderlinden, K., Vereecken, H., Hardelauf, H., Herbst, M., Martínez, G., Cosh, M. H., & Pachepsky, Y. A. (2012). Temporal stability of soil water contents: A review of data and analyses. *Vadose Zone Journal*, *11*, vzj2011.0178. https://doi.org/10.2136/vzj2011.0178

van Genuchten, M. T. (1980). A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society of America Journal*, *44*, 892–898. https://doi.org/10.2136/sssaj1980.03615995004400050002x

Weiss, A. (2001). Topographic position and landforms analysis. *Poster Presentation, ESRI User Conference, San Diego, CA*. http://www.jennessent.com/downloads/TPI-poster-TNC_18x22.pdf

Western, A. W., & Blöschl, G. (1999). On the spatial scaling of soil moisture. *Journal of Hydrology*, *217*(3–4), 203–224. https://doi.org/10.1016/S0022-1694(98)00232-7

Western, A. W., Grayson, R. B., Blöschl, G., Willgoose, G. R., & McMahon, T. A. (1999). Observed spatial organization of soil moisture and its relation to terrain indices. *Water Resources Research*, *35*(3), 797–810. https://doi.org/10.1029/1998wr900065

Western, A. W., Grayson, R. B., & Green, T. R. (1999). The Tarrawarra project: High resolution spatial measurement, modelling and analysis of soil moisture and hydrological response. *Hydrological Processes*, *13*(5), 633–652. https://doi.org/10.1002/(SICI)1099-1085(19990415)13:5%3C633::AID-HYP770%3E3.0.CO;2-8

Wickham, H. (2016). *ggplot2: Elegant graphics for data analysis. Springer-Verlag New York*. Retrieved from https://ggplot2.tidyverse.org

Wickham, H., François, R., Henry, L., & Müller, K. (2019). *dplyr: A grammar of data manipulation*. Retrieved from. https://doi.org/10.1201/9781351201315

Wickham, H., & Henry, L. (2019). *tidyr: Tidy messy data*. Retrieved from https://cran.r-project.org/package=tidyr

Wiekenkamp, I., Huisman, J. A., Bogena, H. R., Lin, H. S., & Vereecken, H. (2016). Spatial and temporal occurrence of preferential flow in a forested headwater catchment. *Journal of Hydrology*, *534*, 139–149. https://doi.org/10.1016/j.jhydrol.2015.12.050

Wilke, C. O. (2019). *cowplot: Streamlined plot theme and plot annotations for ggplot2*. Retrieved from. https://doi.org/10.1515/9783748602224

Williams, C. J., McNamara, J. P., & Chandler, D. G. (2009). Controls on the temporal and spatial variability of soil moisture in a mountainous landscape: The signature of snow and complex terrain. *Hydrology and Earth System Sciences*, *13*(7), 1325–1336. https://doi.org/10.5194/hess-13-1325-2009

Yoshinaga, S., & Ohnuki, Y. (1995). Estimation of soil physical properties from a handy dynamic cone penetrometer test. *Journal of the Japan Society of Erosion Control Engineering*, *48*, 22–28. https://doi.org/10.11475/sabo1973.48.3_22

Zimmer, M. A., & Gannon, J. P. (2018). Run-off processes from mountains to foothills: The role of soil stratigraphy and structure in influencing run-off characteristics across high to low relief landscapes. *Hydrological Processes*, *32*, 1546–1560. https://doi.org/10.1002/hyp.11488