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Interflow dynamics on a low relief forested hillslope: Lots of fill, little spill ☆

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SUMMARY

We evaluated the occurrence of perching and interflow over and within a sandy clay loam argillic horizon within first-order, low-relief, forested catchments at the Savannah River Site (SRS) in the Upper Coastal Plain of South Carolina. We measured soil hydraulic properties, depths to the argillic layer, soil moisture, shallow groundwater behavior, interflow interception trench flows, and streamflow over a 4-year period to explore the nature and variability of soil hydraulic characteristics, the argillic "topography", and their influence on interflow generation. Perching occurred frequently within and above the restricting argillic horizons during our monitoring period, but interflow was infrequent due to microtopographic relief and associated depression storage on the argillic layer surface. High percolation rates through the argillic horizon, particularly through soil anomalies, also reduced the importance of interflow. Interflow generation was highly variable across eleven segments of a 121 m interception trench. Hillslopes were largely disconnected from stream behavior during storms. Hillslope processes were consistent with the fill-and-spill hypothesis and featured a sequence of distinct thresholds: vertical wetting front propagation to the argillic layer; saturation of the argillic followed by local perching; filling of argillic layer depressions; and finally connectivity of depressions leading to interflow generation. Analysis of trench flow data indicated a cumulative rainfall threshold of 60 mm to generate interflow, a value at the high end of the range of thresholds reported elsewhere.

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1. Introduction

Subsurface stormflow or interflow (defined here as shallow slope-parallel flow over an impeding horizon) has been studied on forested hillslopes since Engler (1919) (Bachmair and Weiler, 2011; Weiler et al., 2005). Hewlett (1961) demonstrated the potential importance of interflow to watershed processes by examining interflow and drainage dynamics on re-packed hillslope troughs. Subsequently, early conceptualizations of hillslope flow processes assumed that the topography of the impeding layer was similar to that of the soil surface as in the classic schematic by Atkinson (1978) or the seminal simulations by Zaslavsky and Sinai (1981). Hewlett and Hibbert (1967) later used a multi-catchment comparison to show the overarching importance of soil depth on interflow magnitude and catchment runoff production. Since then, studies have examined the role of topographic convergence on interflow patterns (Anderson and Burt, 1978), the role of soil pipes (Mosley, 1979), and interflow mixing and displacement (Pearce et al., 1986). A continuing issue for physically-based hydrologic modeling is the need to understand how the mismatch between

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our knowledge of surface and subsurface topography affects our predictions of hillslope behavior.

In the past two decades, the use of geophysical techniques to study hillslopes has revealed that subsurface topography can differ substantially from surface topography (McDonnell et al., 1996). This realization led to new concepts of interflow generation via filling and spilling of depressions created by subsurface topography (Spence and Woo, 2003). Tromp van Meerveld and McDonnell (2006c) demonstrated for the instrumented hillslope at the Panola Mountain Research Watershed, Georgia, USA that downslope flow proceeded along subsurface interfacial dendritic drainage networks that had to fill, spill, and connect as later modeled by Hopp and McDonnell (2009). Since then, others have observed fill and spill processes in other environments and found that bedrock topography more strongly controls hydraulic gradient than surface topography in flat terrain (Devito et al., 2005). Similarly, Ali et al. (2011) found that subsurface storage is a more sensitive surrogate for discharge in a steep headwater catchment than surface storage. Spatial analysis of runoff source area in moderately sloping catchments revealed that runoff production is controlled by connectivity of shallow groundwater among the hillslope, riparian zone, and stream (Jencso et al., 2009). These findings indicate subsurface topography of the impeding layers may play a more important role than surface topography on storm water partitioning and redistribution in moderately sloping catchments.

While the factors causing interflow are well studied in steep catchments, the dynamics of interflow in low-angle forested catchments are less understood. Experimental work has shown that interflow in low to moderate angle topography can occur over Bt and Bw horizons (layers of clay or iron accumulation, respectively) (Beasley, 1976; Newman et al., 1998; Wilson et al., 1990) and fragipans (McDaniel et al., 2008; Parlange et al., 1989). Modeling studies have shown that the effect of subsurface concavities is diminished as slope increases (Hopp and McDonnell, 2009) as water spills more readily over the downslope lip of each concavity. In low angle forested slopes with deep (e.g., >100 m) underlying bedrock, the subsurface topography has not been defined by differential weathering or shallow landsliding but rather by biological processes such as windthrow (Gabet and Mudd, 2010; Ulanova, 2000) and animal burrowing (Neary et al., 2009) and also irregularities in soil weathering and illuviation of fine particles. Thus, the spill pathways connecting local concavities are likely to be random and dissimilar to fluvial pathways. If, however, subsurface pathways are dominated by macropore networks created by root systems, then subsurface topography likely becomes a control on flow networks (Tromp van Meerveld and McDonnell, 2006b). Because of these complexities, interflow influenced by the presence of an argillic clay horizon (Bt horizons) ranges from frequent and substantial (Beasley, 1976; Wilson et al., 1990) to rare and inconsequential (Buttle and McDonald, 2002; Redding and Devito, 2010). Evaluating the contrasts in flow behavior among hillslopes with different steepness and lithology allows us to understand and predict the relative balance of fill and spill (McDonnell, 2013).

Here we present new work that examines the controls on perching (here defined as a subsurface water table that builds up temporarily over restricting layers) and interflow generation over and within a sandy argillic horizon on low angle slopes (less than 5%) within forested catchments in the Sandhills of the Upper Coastal Plain, South Carolina, USA. We quantified the variability of the argillic topography and saturated hydraulic conductivities of both the Bt horizon and the overlying A and E horizons, the spatial variability of interflow across a 120 m long interflow interception trench divided into 11 segments, as well as perching within and on the argillic layer using piezometers on the hillslope above the trench. The following questions guided our research: (1) Do low angle slopes exhibit similar threshold and fill-and-spill behavior as steeper hillslopes? (2) How variable are the subsurface topography and hydraulic characteristics of the impeding argillic layer? (3) Does surface topography predict the frequency of perching and interflow production across the slope?

2. Study site

The study was conducted in three adjacent first order catchments, with the majority of research conducted on a single catchment and most data collected from 2008 to 2011. All three catchments are tributaries to Fourmile Branch on the U.S. Department of Energy (DOE) Savannah River Site (SRS) within the Aiken plateau of the Upper Atlantic Coastal Plain (Fig. 1) in South Carolina, USA. The SRS site was in row-crop, agriculture, featuring terracing and shallow gullies prior to acquisition and reforestation by the Atomic Energy Commission (a predecessor to DOE) in 1950 (Kilgo and Blake, 2005). Annual precipitation at the site is approximately 1220 mm distributed evenly throughout the year, while potential evapotranspiration is approximately 1400 mm. The weather is characterized by long, hot summers with an average daily maximum temperature of 32.3 °C and high intensity thunderstorms and relatively mild winters with an average temperature of 8.6 °C (Rebel, 2005) and frontal rainfall.

The headwater catchments are characterized by gently rolling hills with average slopes of 2–3%. Upland and bottomland areas are nearly level. The steepest slopes reach 55%, but comprise only small areas on the valley margins. The primary study catchment (R) drains 45 hectares of forested area and features a 300 m long, flat, unchanneled valley of a forested wetland above the channel head. The adjacent B and C catchments, where additional soil and groundwater measurements were made, are larger (169 and 117 hectares, respectively) and also feature long, flat, forested wetland valleys as well as Carolina Bay wetlands typical of the Upper Atlantic Coastal Plain (Fig. 1). There is field evidence of previous terracing, gully erosion, and downslope soil movement that occurred during the farming period prior to the establishment of the current timber stand.

The hillslopes and ridges are covered by longleaf pine (*Pinus palustris*), loblolly pine (*Pinus taeda*), and slash pine (*Pinus elliottii*) first established in the late 1950s, now in the second or third rotation. Mixed hardwoods dominate the riparian areas, mainly sweet gum (*Liquidambar styraciflua*). The soils are well-drained, loamy, siliceous, thermic Grossarenic Paleudults (Rasmussen and Mote, 2007), featuring a thin loamy sand A horizon overlying a deep loamy sand E horizon that grades into an argillic Bt horizon of sandy clay loam. Herein the A and E horizons will be referred to as mineral soils. The surface soils contain 80–90% sand, and clay content increases to 35% or more in the Bt horizon (Kilgo and Blake, 2005).

3. Methods

The hydrological measurements are focused in the R catchment where a 121 m interflow interception trench was excavated along the contour at mid-slope in 2009. Slopes above the trench range from about 6% to 12%. The open trench (covered by a tarped structure to prevent precipitation input) is 1.5–2.0 m deep and consists of eleven separate 11 m long trench drains constructed within the clay layer. Within each segment, a perforated pipe was covered with gravel and landscape cloth to intercept lateral flow moving above and within the argillic layer from an upslope contributing area of 5.7 ha (13% of the R catchment). Intercepted water from each drain was piped downhill into a v-notch weir box in which water level was measured by an Odyssey capacitance probe at