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Spatial and temporal occurrence of preferential flow in a forested headwater catchment

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SUMMARY

The highly dynamic nature of preferential flow in time and space makes it challenging to identify and analyze its occurrence at the catchment scale. Novel analysis methods using soil moisture sensor response times offer an opportunity to investigate catchment-wide controls on preferential flow. The aim of this study was to identify factors that control preferential flow occurrence based on 3-year soil moisture monitoring using a wireless sensor network in the Wüstebach catchment, Germany. At 101 locations, the sensor response times at three depths (5, 20, and 50 cm) were classified into one of four classes: (1) non-sequential preferential flow, (2) velocity-based preferential flow, (3) sequential flow, and (4) no response. A conceptual model, postulating that preferential flow in the Wüstebach catchment is dominated by differences in soil type, landscape position, and rainfall input, was proposed for hypothesis testing. To test the conceptual model, the classification results were combined with spatial and event-based data to understand and identify controlling factors. Spatial parameters consisted of hydrological, topographical, and soil physical and chemical parameters. Temporal factors included precipitation characteristics and antecedent soil moisture conditions. The conceptual model as proposed could only be partly confirmed. Event-based occurrence of preferential flow was highly affected by precipitation amount, with a nearly catchment-wide preferential response during large storm events. During intermediate events, preferential flow was controlled by small-scale heterogeneity, instead of showing catchment-wide patterns. The effect of antecedent catchment wetness on the occurrence of preferential flow was generally less profound, although a clear negative relationship was found for precipitation events with more than 25 mm. It was found that spatial occurrence of preferential flow was however governed by small-scale soil and biological features and local processes, and showed no obvious relationship with any of the selected spatial parameters. Overall, the results demonstrate that sensor response time analysis can offer innovative insights into the spatial–temporal interrelationship of preferential flow occurrence.

1. Introduction

Preferential flow involves water bypassing a large portion of the soil matrix and is widely considered to be a common phenomenon in hydrology (Flury et al., 1994; Lin, 2010). Accelerated water movement through a small fraction of the soil can drastically affect nutrient transport (Alaoui et al., 2011), the residence time of water and pollutants (Blackwell, 2000; Jarvis, 2007), stormflow generation (Tromp-van Meerveld and McDonnell, 2006a, 2006b), and groundwater recharge (Beven and Germann, 2013; Bonell, 1993).

Numerous studies exist that relate the spatial occurrence of preferential flow to soil properties and hydrological conditions (Flury et al., 1994; Ghafoor et al., 2013; Jarvis, 2007; Koestel and Jorda, 2014; van Schaik, 2009). A variety of local factors can control the occurrence of preferential flow, such as hydrophobicity, plant root growth, swelling and shrinking behavior of clays, and soil fauna burrows (Allaire et al., 2009; Blackwell, 2000; Ghafoor et al., 2013; Lin, 2010). At the landscape scale, the distribution of soil types and their properties, topographic features, and vegetation cover also influence the occurrence of preferential flow (Flury et al., 1994; Koestel and Jorda, 2014; Liu and Lin, 2015; van Schaik, 2009). Temporal factors affecting the initiation of preferential flow include total precipitation, precipitation intensity,

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and initial soil moisture conditions (Graham and Lin, 2011; Hardie et al., 2011; Koestel and Jorda, 2014; Williams et al., 2003).

Several studies have attempted to understand spatial variability of preferential flow occurrence at the hillslope to the catchment scale using a limited number of local-scale measurements (e.g. Ghafoor et al., 2013; van Schaik, 2009). van Schaik (2009) related tracer-infiltration patterns to predetermined site characteristics at the catchment scale to generate predictive maps of four flow parameters (uniform front depth, maximum infiltration, total stained area, and preferential flow index). This study revealed that 50–66% of the spatial variability in infiltration patterns could be explained by selected site characteristics (vegetation, texture, slope, and location). Ghafoor et al. (2013) investigated the susceptibility to preferential flow on tilled soils in east-central Sweden using non-reactive solute breakthrough experiments on 45 columns of contrasting soils. Their work concluded that preferential flow was weakly correlated to saturated hydraulic conductivity, but more strongly correlated to the size of the largest water-filled pores.

Despite previous research, no general set of rules exists that clearly explains the spatial and temporal patterns of preferential flow at the landscape scale. The lack of understanding concerning factors that promote preferential flow at the landscape scale is at least partly related to the fact that monitoring the occurrence of preferential flow through time and in space remains a challenging task (Allaire et al., 2009; Beven and Germann, 2013; Lin and Zhou, 2008). Although there is an arsenal of available methods to study preferential flow, methods for landscape-wide quantification across space and time remain lacking (Allaire et al., 2009). For example, dye tracers have been used to visualize water movement in the subsurface. However, the destructive nature of this method prohibits the investigation of the temporal dynamics of preferential flow at a specific site. For this purpose, geophysical measurement methods such as ground penetrating radar and electrical resistivity tomography offer non-destructive alternatives to characterize preferential flow (Greve et al., 2012; Guo et al., 2014; Kim et al., 2010; Moysey and Liu, 2012). However, such geophysical methods often lack sufficient spatial extent to cover large catchment areas.

A promising alternative method to study spatial and temporal variability of preferential flow at the catchment scale is the use of soil moisture sensor response times (Graham and Lin, 2011; Hardie et al., 2013; Lin and Zhou, 2008; Liu and Lin, 2015). After determining the sequence of soil moisture sensor response times at different depths, the spatial occurrence of preferential flow and other flow regimes can be identified for individual precipitation events. Lin and Zhou (2008) identified lateral and vertical preferential flow by applying this method at seven monitoring sites in the Shale Hills catchment. Graham and Lin (2011) extended this study by evaluating soil moisture response at the hillslope scale for 175 events and found that the frequency of preferential flow occurrence ranged from 17% to 54% of all the precipitation events. Liu and Lin (2015) extended the spatial extent of this approach to the catchment scale and revealed a subsurface flow network in the catchment and some degree of topographic control. Although such work in the Shale Hills catchment is promising, similar investigations of preferential flow occurrence in different soils and climate conditions are clearly needed.

The aim of this study is to investigate the dominant controls on preferential flow at the catchment scale using sensor response times determined from a dense wireless soil moisture sensor network in the Wüstebach catchment, Germany. The data set comprises three-year long soil moisture time series measured at three depths at 101 locations. A conceptual model that represents our initial understanding of preferential flow occurrence within the catchment was proposed for hypothesis testing. To test our conceptual model and to better understand the factors and processes that cause spatial and temporal variability in preferential flow, results of the sensor response time analysis were related to site (soil and topographic features) and event characteristics (total precipitation, precipitation intensity, antecedent wetness conditions).

2. Materials and methods

2.1. The TERENO test site Wüstebach

The Wüstebach catchment is part of the Eifel/Lower Rhine Valley Observatory of TERENO (Terrestrial Environmental Observatories) in Germany (Zacharias et al., 2011). The catchment has a mean annual precipitation and temperature of 1100 mm and 7 °C, respectively, and covers an area of 38.5 ha (Bogena et al., 2015). Altitude ranges from 595 m a.s.l. in the northern part of the catchment to 628 m in the southern part. Vegetation consists of Norway spruce (*Picea abies* (L.)) and Sitka spruce (*Picea sitchensis*) that were planted at the end of the 1940s (Etmann, 2009).

The soil types in the Wüstebach catchment vary from Cambisols and Planosols in the groundwater distant areas to Gleysols and Histosols in the riparian zone (Figs. 1 and 2). The soil texture is characterized by silty clay loam with a medium to high fraction of coarse material (>2 mm up to several centimeters). The underlying bedrock consists of fractured Devonian shale (lightly silty, strongly schistose) with occasional fine to medium grained sandstone inclusions (Graf et al., 2014; Rosenbaum et al., 2012). The Wüstebach site is highly instrumented to obtain information on hydrological, chemical, and meteorological states and fluxes (Bogena et al., 2015). To investigate the occurrence and effects of preferential flow, we mainly rely on soil moisture and precipitation data here.

2.2. Conceptual model

For hypothesis testing, we propose a conceptual model of preferential flow occurrence (Fig. 3) that integrates site-specific knowledge and concepts taken from the literature. We expected that preferential flow occurs mainly in the riparian zone during lower intensity storm events (area C), because water accumulates here due to its topographic position. This creates wetter conditions that facilitate preferential flow. For storms with moderate intensity or during wetter initial moisture conditions, it was expected that the slopes of the Wüstebach catchment become increasingly wet, thus activating preferential flow paths particularly in the more susceptible Planosols on the lower hillslopes (area B). The remaining part of the catchment (area A) was expected to react only during high intensity storm events. This area mainly consists of Cambisols, which are expected to be the least susceptible to preferential flow. Nonetheless, earlier research proves that even less susceptible soils can show a preferential response during high intensity rainfall events (e.g. Graham and Lin, 2011).

2.3. Soil moisture measurements

Soil moisture has been monitored since August 2009 using the wireless soil moisture sensor network SoilNet with a temporal resolution of 15 min. Sensors were installed at three depths at 150 locations (Bogena et al., 2010; Rosenbaum et al., 2012). At each individual measurement location, one ECHO-5TE and one ECHO-EC-5 sensor (Decagon, Devices Inc., Pullman, USA) were installed at 0.05 and 0.5 m depth and two ECHO-EC-5 sensors were installed at 0.2 m (Fig. 1). For sensor installation, we prepared a borehole with a diameter of 20 cm and a depth of 70 cm. During installation,