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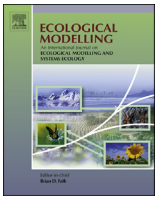

A stochastic approach to modelling and understanding hillslope runoff connectivity dynamics

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ABSTRACT

Runoff generation at the hillslope scale is an important component of the hydrological cycle. Recent work has shown that a common hillslope runoff response mechanism is driven by connectivity of saturated patches in the subsurface (via filling and spilling) to a threshold initiation of lateral flow at the hillslope base. Here, we show that directed percolation theory is able to represent this key runoff process including the details of dynamical flowpath development and filling and spilling processes at the soil-bedrock interface. We then use the directed percolation model to investigate how changes in slope angle, soil depth, and subsurface microtopography influence stormflow response. We map the evolving subsurface flow network under different hillslope classes and compare them to the natural system response. Our results suggest that the natural system sheds water more efficiently than randomly generated systems providing some insights into key hydrogeomorphic controls on water shedding in the environment.

1. Introduction

The mechanisms by which hillslopes store and release water affect many ecological processes through biogeochemical and nutrient cycling (Stieglitz et al., 2003). There is a developing consensus that filling and spilling of infiltrated rainfall at a soil-bedrock interface or along other subsurface impeding layer(s) is a dominant process leading to hillslope runoff in a variety of hydrological systems (Spence, 2010; McDonnell, 2013). Connectivity of saturated patches in the subsurface via filling and spilling leads to threshold flow activation at the hillslope base, and associated material transfer (McGlynn and McDonnell, 2003).

While several new quantitative measures of connectivity have been developed for hillslopes and catchments (e.g. Western et al., 2001; Reaney et al., 2006; Bracken and Croke, 2007; Ali and Roy, 2009), spatially explicit modelling of the connectivity and dis-connectivity that dynamically occurs at a confining layer in the subsurface has proved very challenging. Traditional Darcy-Richards solvers have been used (Ebel et al., 2008; Hopp and McDonnell, 2009; James et al., 2010) but are very computationally expensive and limit the scenarios that can be explored. Simpler conceptual models have been used (e.g. Weiler and McDonnell, 2003; Tromp-van Meerveld and Weiler, 2008) but they still require more site information (antecedent soil moisture profiles, hydraulic parameters, etc.) than is often available. More problematic is the inherent stochastic nature of fill and spill, connectivity and threshold response—something that defies both physically based and conceptual modelling approaches.

One approach that shows considerable promise for capturing the dynamics of lateral connectivity-associated thresholds is percolation theory. Lehmann et al. (2007) showed that with a small set of simple rules they could match observed threshold response and runoff ratio when modelling subsurface stormflow at the hillslope scale. In other words, percolation theory subsumed the considerable process complexity that is usually described deterministically, linking a stochastic pattern of spatial connectivity with the lateral outflow behaviour.

While useful and certainly a step forward, the traditional percolation theory approach of Lehmann et al. (2007) was perhaps too abstract a stochastic modelling approach because it did not account for the spatial distribution of subsurface topography and soil depth—two key controls on subsurface stormflow dynamics that we have known about since Hewlett and Hibbert (1967). Recent physics-based modelling work (Tromp-van Meerveld and Weiler, 2008) shows how critically important such information is for prediction. The question now is: how can we use a stochastic approach like percolation theory, which is both parsimonious and

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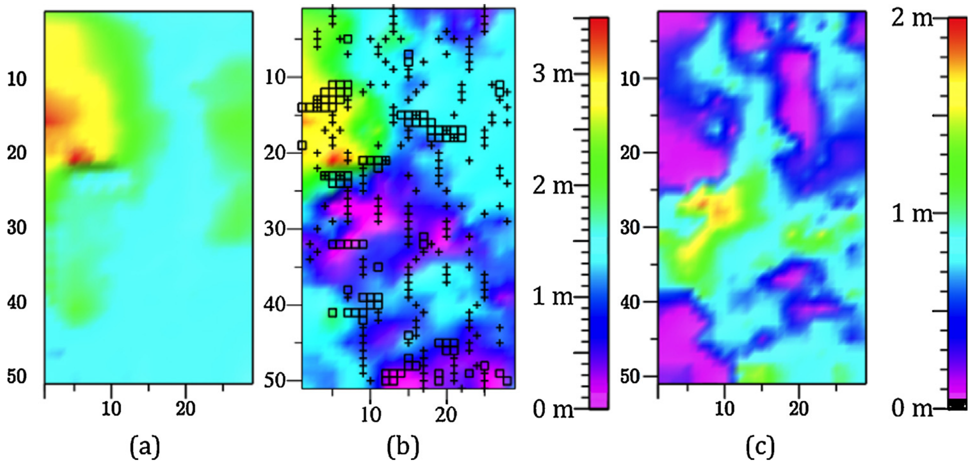

Fig. 1. Panola experimental hillslope physical characteristics, with the average hillslope angle, 13.1°, relaxed in order to generate a map of topographic relief. The top of the hillslope is at the top of the figure. The three plots show (a) surface relief, (b) bedrock relief, and (c) soil thickness, in metres over the 29 m × 51 m hillslope section. In (b), cells which are lower than their downslope neighbour are highlighted with squares, and cells which are lower than their left and right neighbours are highlighted with crosses—so it is readily apparent where water following the global gradient will typically pool along ridges, and also which preferential spillways will be taken.

inherently suited to capture the observed linkage between subsurface saturation connectivity and runoff threshold that we aim to describe, but more directly incorporate features that are known to be of critical importance, such as topography and soil depth distribution?

Here we apply the principles of directed percolation to bring process realism into a stochastic, pattern-focused modelling approach for gaining new insights into the dynamics of hillslope connectivity and threshold response, using it as the basis for a description of the movement of water along a subsurface confining layer. Directed percolation theory is a special case, first posed by Broadbent and Hammersley (1957), in which a direction of flow is prescribed at each bond between neighbouring cells on a grid. The advantage of directed percolation is that the direction of flow can be based on the topography of the flow layer (in our case, the topography of the soil-bedrock interface), allowing for more realistic representations of spatial connectivity. Indeed, in accounting for this detail we shall be able to describe naturally connecting flowpaths along heterogeneous surfaces where local gradients do not always follow the global gradient (cf. Fig. 1b), much as Ambegaokar et al. (1971), and particularly Pollak (1972), did in the original papers which used percolation theory to describe electrical conduction within random resistor networks exhibiting similar heterogeneity.

While directed percolation has previously been considered in descriptions of infiltration-excess runoff on rough surfaces (Davy et al., 2001), we are unaware of any previous application to the problem of modelling subsurface stormflow in hillslopes where runoff occurs at a confining layer beneath highly permeable soil, where the non-uniform delivery of water through heterogeneous soil exceeds the infiltration capacity of the lower (e.g. fractured bedrock) layer. In this case, the spatial variability of soil depth adds a significant layer of complexity to the dynamical process of infiltration-excess fill-and-spill at the impeding surface.

This paper outlines how a model based on directed percolation can be used to represent what we call "essential hillslope realism" (following Dietrich et al., 2003), thereby bridging the gap between the abstract statistical realism of modelling approaches like that of Lehmann et al. (2007), which incorporate little detail of the real world, and the detailed realism that process-deterministic approaches are unable to achieve (e.g. due to CPU and resolution limits). Our objectives are: (i) to examine the ability of directed percolation to match observed fill, spill, connectivity, threshold dynamics for a well-characterised hillslope, (ii) to use the model as a virtual experiment tool (following Weiler and McDonnell, 2003) to explore the effects of slope angle on fill and spill, connectivity and threshold response, and (iii) to examine the effects of soil depth and subsurface topography on connectivity dynamics via the virtual experiment approach.

2. Background on the Panola hillslope

In order to realistically capture the observed process of perched stormflow along soil-mantled bedrock, we develop our directed percolation approach based on field-measured runoff dynamics at the Panola experimental hillslope, located within the Panola Mountain Research Watershed near Atlanta, Georgia, USA. Fig. 1 shows the bedrock and surface relief at Panola along with a map of soil depth. The hillslope angle is 13.1°, with a trench dug at its base (at the bottom of Fig. 1) in order to capture runoff, as described in Tromp-van Meerveld and McDonnell (2006a) and Tromp-van Meerveld et al. (2008).

During storm events which are typically of long duration and low intensity, rain infiltrates vertically into thin (∼0–2 m) sandy-loam soil that varies in depth, and therefore reaches storage capacity at different times across the hillslope. When the soil's storage threshold has been reached, water begins filling depressions along the bedrock surface, and eventually spills laterally downslope (cf. the organisation of rills and spillways along the bedrock surface in Fig. 1b, as described in the figure's caption), all while a percentage infiltrates further into the bedrock (Tromp-van Meerveld and McDonnell, 2006a,b). Tromp-van Meerveld et al. (2007) measured a 91% bedrock infiltration loss rate on the Panola hillslope in a series of sprinkling experiments.

The main factor that limits whether any appreciable flow will be observed at the base of the slope is the cumulative rainfall amount, since a certain volume must always go towards saturating the lower part of the soil profile and filling the bedrock depressions before flow in the trench at the base of the hillslope is observed (Tromp-van Meerveld and McDonnell, 2006a). Given a large enough event to produce stormflow, the main physical controls on the process development are then: antecedent soil moisture deficit, bedrock loss rate and bedrock topography.

The antecedent soil moisture deficit depends on both the soil depth, which varies across the hillslope, and the antecedent soil moisture. Data records from 123 storm events at Panola (as reported by Tromp-van Meerveld and McDonnell, 2006a,b) indicate that the antecedent soil moisture does not exceed ∼0.41 vol/vol,

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