Journal of Hydrology 376 (2009) 378–391

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Connectivity at the hillslope scale: Identifying interactions between storm size, bedrock permeability, slope angle and soil depth

L. Hopp *, J.J. McDonnell

Department of Forest Engineering, Resources and Management, Oregon State University, Corvallis, OR, USA

ARTICLE INFO

Article history:
Received 18 October 2008
Received in revised form 10 July 2009
Accepted 19 July 2009

This manuscript was handled by P. Baveye Editor-in-Chief, with the assistance of S. Christensen, Associate Editor

Keywords:
Connectivity
Interaction
Threshold
Virtual experiment
Hillslope hydrology
Water

SUMMARY

The links between soil water movement at the plot scale and runoff generation at the hillslope scale are highly non-linear and still not well understood. As such, a framework for the general characterization of hillslopes is still lacking. Here we present a number of virtual experiments with a 3D physically-based finite element model to systematically investigate the interactions between some of the dominant controls on subsurface stormflow generation. We used the well-studied Panola experimental hillslope to test our base case simulation and used the surface and subsurface topography and the stormflow data of this site as a framework for a subsequent series of virtual experiments. The parameterization of the soil and bedrock properties was based on field measurements of soil moisture and saturated hydraulic conductivity. After calibration and testing against multiple evaluation criteria including distributed trench flow data and internal tensiometric response, we varied slope angle, soil depth, storm size and bedrock permeability across multiple ranges to establish a set of response surfaces for several hillslope flow metrics. We found that connectivity of subsurface saturation was a unifying descriptor of hillslope behavior across the many combinations of slope type. While much of the interplay between our four hillslope variables was intuitive, several interactions in variable combinations were found. Our analysis indicated that, e.g. interactions between slope angle, soil depth and storm size that caused unexpected behavior of hydrograph peak times were the result of the interplay between subsurface topography and the overlying soil mantle with its spatially varying soil depth distribution. Those interactions led to new understanding of process controls on connectivity .

Introduction

Field studies in hillslope hydrology in upland humid areas continue to characterize and catalogue the enormous heterogeneity and complexity of rainfall–runoff processes at different sites around the world. Nevertheless, the ability to generalize these findings to ungauged regions still remains largely out of reach (McDonnell et al., 2007). Hillslopes exhibit a baffling array of heterogeneity in landscape properties and complexity of their responses to fixed hillslope attributes (e.g. slope, soil depth, etc.) and temporally varying precipitation inputs. One common emergent feature at the hillslope scale appears to be the threshold response to storm rainfall and snowmelt inputs. These thresholds have been noted for decades (for early review see Dunne, 1978) and reported more recently at various hillslope trench investigations in Japan (e.g. Tani, 1997), New Zealand (e.g. Woods and Rowe, 1996), North America (e.g. Hutchinson and Moore, 2000) and Europe (e.g. Scherrer and Naef, 2003). Only recently have the process controls on threshold response been examined. Tromp-van Meerveld and McDonnell (2006a,b) demonstrated that connectivity of patches of transient saturation were a necessary prerequisite for exceeding the rainfall threshold necessary to drive lateral flow at the Panola Mountain research watershed in Georgia, USA. Since then, such connectivity has been modeled with percolation theory (Lehmann et al., 2007) and subsurface saturated connectivity has been shown to control hillslope response at other sites (Spence, 2007; van Verseveld et al., 2008).

Connectivity appears to be a possible unifying concept and theoretical platform for moving hillslope and watershed hydrology forward. Bracken and Croke (2007) have made compelling arguments for how connectivity may contribute, conceptually, to understanding surface runoff-dominated geomorphic systems. Their work follows similar calls in ecology for connectivity-based understanding of water-mediated transfers of matter, energy and organisms (Pringle, 2001). While biologists often define connectivity as the degree to which a landscape facilitates or impedes the movement of individuals (Taylor et al., 1993), a hillslope hydrological definition may be linked to how the hillslope architecture controls the filling and spilling of isolated patches of saturation,

* Corresponding author. Address: Department of Forest Engineering, Resources and Management, Oregon State University, 204 Peavy Hall, Corvallis, OR 97331-5706. Tel.: +1 541 737 8719; fax: +1 541 737 4316.
E-mail address: Luisa.Hopp@oregonstate.edu (L. Hopp).

0022-1694/$ - see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.jhydrol.2009.07.047

leading to whole-slope connectedness of areas with high relative saturation. While this filling and spilling appears to be the mechanistic basis for threshold response in many landscapes (Gomi et al., 2008; Spence and Woo, 2006; Tromp-van Meerveld and McDonnell, 2006b; Buttle et al., 2004), these findings have been largely based on single case studies of individual hillslopes with little synthesis among and across sites. Such synthesis is made extremely difficult because the measurements made at different locations are often unique to that site.

Buttle (2006) pointed out the need to consider interactions between controls on hydrologic response instead of looking at controls and their effects individually. One possible way forward for synthetic work aimed at understanding the controls on hillslope connectivity and interactions among the many control factors are virtual experiments. Weiler and McDonnell (2004) defined virtual experiments as "numerical experiments driven by a collective field intelligence". We argue here that such an approach may help us begin to understand how different hillslope variables control the disposition of storm rainfall at the hillslope scale and influence ultimately whole-slope connectivity. While the list of possible variables is very long, some of the more important variables from recent field-based study of hillslope connectivity is soil depth (Buttle and McDonald, 2002), bedrock permeability (Onda et al., 2001) and topography (both surface and subsurface) (Freer et al., 2002). How different values and combinations of these static attributes combine with temporally varying storm rainfall characteristics is a major open research question in hydrology today. Virtual experiments offer a way to address such a question, where single-realization field study sites are unable to achieve this. More importantly, the virtual experiment approach may help identify and understand the interactions among these variables – something that hydrologists have not yet explored, yet clearly seen in nature.

Here we present a series of virtual experiments aimed at identifying the hillslope controls on connectivity. We use a physics-based model (Cloke et al., 2006; Ebel et al., 2008) to systematically explore the interactions between controlling hillslope variables and to surface the possible combinations of factors that might promote subsurface hydrological connectivity. We base our virtual experiments on a real hillslope that exhibits complex system behavior – the Panola experimental hillslope described previously by Freer et al. (2002) and many others – by first demonstrating that the model reproduces the hillslope response to a storm event from integrated flow measures at the slope base to internal, spatially distributed, process behavior within the hillslope. We then use that parameterization of the model for addressing questions aimed at understanding the interactions among what we consider to be some of the key variables controlling hillslope connectivity response to storm rainfall:

– How do factors inhibiting the generation of subsurface stormflow (e.g. the permeability of the underlying bedrock) interact with factors forcing the generation of subsurface stormflow (e.g. slope angle)?
– Is subsurface stormflow generation always positively correlated with slope angle and storm size, negatively correlated with bedrock permeability and soil depth or are there interactions between these factors?
– How does the connectivity of a transient water table at the soil–bedrock interface relate to interactions between factors?

We systematically varied each of our chosen variables to obtain 72 combinations for interaction analysis. Clearly, this list of variables is not complete and many other possible hillslope variables could be explored (e.g. spatial patterns of the rainfall input, rainfall intensity; slope length, topographic variability of the subsurface; macroporosity, antecedent wetness, different soil types and hydraulic properties, soil layering, etc.). We chose our four factors as a starting point based on two constraints: findings from our previous field experiences at the Panola site (and elsewhere as noted above) and the realistic limitations of the model and associated computational time. This second aspect is somewhat analogous to decisions made in the field, where the extent of monitoring (in time and space) is decided based upon financial and manpower limitations.

Materials and methods

Study site and selected rainstorm event

The study hillslope that we used to define the geometry and the soil hydraulic properties of the model domain is part of the Panola Mountain Research Watershed (PMRW), situated in the Georgia Piedmont, 25 km southeast of Atlanta. The climate is subtropical-humid, with a mean annual air temperature of 16.3 °C and a mean annual rainfall of 1240 mm, distributed uniformly over the year. The study hillslope and the subsurface stormflow collection system have been described in detail elsewhere (Freer et al., 2002; Tromp-van Meerveld and McDonnell, 2006a,b). Here we only briefly describe the hillslope characteristics that are crucial for setting up the base case scenario of our virtual model environment.

The study hillslope has a slope angle of 13°. The upslope boundary consists of a small bedrock outcrop; the lower hillslope boundary is formed by a 20 m wide trench where subsurface stormflow from ten 2 m wide slope sections is continuously measured. Five soil pipes that have most likely developed from root decay are plumbed individually. The trench extends vertically to the interface between soil and bedrock. Lateral subsurface stormflow collected at the trench exfiltrates from the trench face through soil immediately overlying the bedrock (based on field observations by C. Graham, pers. com.). Surveyed surface and bedrock topography used in the model domain covers an area of 28 m by 48 m. The surface topography is relatively planar whereas the bedrock topography is highly irregular (Fig. 1b), resulting in variable soil depths ranging between 0 and 1.86 m, with a mean soil depth of 0.63 m and a coefficient of variation of 56%. The soil is a sandy loam, devoid of discernible structure or layering and overlain by a 0.15 m deep organic-rich horizon. The bedrock directly underlying the soil consists of 2–3 m of porous saprolite (soft disintegrated granite derived from the Panola granite beneath).

The model base case scenario that we used as a starting point for the virtual experiments was calibrated to the hydrologic response of the hillslope to a rainstorm that occurred on 6–7 March 1996. This is one of our best-studied storms in the Panola dataset (Burns et al., 2001; Freer et al., 2002; McDonnell et al., 1996). This 3-year return interval storm had a total precipitation amount of 87 mm over 31 h in two separate pulses (Fig. 1a). For this rainstorm, continuous pressure head readings exist from a tensiometer network distributed across the length of the trench and up to 30 m upslope of the trench (Freer et al., 2002). Fig. 1 shows the location and depth of tensiometers that were used for testing the model.

Virtual experiments

Base case scenario

We used the well known finite element model Hydrus-3D (Simunek et al., 2006) for our virtual experiments. This model numerically solves the Richards' equation for water flow in variably saturated porous media and has been used extensively in 1D and 2D forms for a variety of hydrological application (e.g. Buczko and Gerke, 2006; Kampf and Burges, 2007; Keim et al., 2006;