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INVESTIGATING NONLINEAR RAINFALL-RUNOFF RESPONSE FROM A TRENCHED HILLSLOPE USING TOUGH2 3-D SIMULATIONS

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ABSTRACT

In this short paper we describe the Panola Mountain Experimental Watershed trenched hillslope field site, the existing experimental dataset and a preliminary simulation of the hillslope rainfall-runoff response using the Panola hillslope 3-D TOUGH2 model. Extensive previous field studies on this experimental hillslope have formed a valuable reference dataset to which simulation of the development of subsurface lateral flow during storm events can be compared. The most recent studies of Tromp-van Meerveld and McDonnell (2006a,b,c) observed a threshold 'fill and spill' response during storms events resulting from the irregular bedrock topography of depression storage of transient groundwater pockets that eventually spilled over a small bedrock ridge to form connected subsurface stormflow. Here we describe preliminary simulations with the Panola hillslope 3-D TOUGH2 model and present a test simulation of a 63 mm storm event compared to experimental data. This storm is above the 55 mm size at which 'fill and spill' behavior has been observed. Further application of the Panola hillslope model will extend to an investigation of hillslope classification.

INTRODUCTION

Runoff generation in upland watersheds is poorly understood. In many hillslope settings in humid climates, subsurface stormflow is a dominant runoff generating mechanism, particularly when slopes are steep, soils are transmissive and rainfall amounts are large. While many different mechanisms have been proposed to explain the myriad subsurface response mechanisms (lateral preferential flow, transmissivity feedback, organic layer interflow—see review in Weiler et al., 2005), recent intercomparison efforts of experimental hillslopes have observed threshold behavior as a common link to diverse internal water processing. Indeed, the nonlinear hydrologic response to rainfall observed on many hillslope experimental sites has recently been suggested to be a universal property of water flow from hillslopes (McDonnell, 2003; Lehmann et al. 2006). This phenomenon is receiving an increasing amount of attention because of its potential to define emergent behavior at the hillslope scale and in so doing, improve our ability to predict runoff generation in poorly gauged areas.

In this study, we use the TOUGH2 simulator (Pruess, 1991) to model water flow at a trenched hillslope at the Panola Mountain Research Watershed (PMRW), Georgia, USA in an investigation of the development of this nonlinear response. Extensive previous experimental work on this trenched hillslope has shown that formation of transient groundwater in bedrock depressions during storm events is a precondition for the generation of subsurface stormflow. For storms over 55 mm in size, the pockets of transient groundwater spill over, hydrologically connecting transient saturation to other downslope pockets and ultimately, to the down-slope trench. Tromp-van Meerveld and McDonnell (2006b) call this the fill-and-spill hypothesis where, for these larger storms, a threshold-like change in trench outflow (i.e. subsurface stormflow) is observed. Field observations of hillslope water balance indicate significant (> 20%) losses of water to permeable bedrock (Tromp-van Meerveld et al., 2006), a component of the water balance that has traditionally been neglected by assuming an impermeable lower boundary to the hillslope. Questions of the importance of water loss to bedrock and the limitations on our abilities to observe it in the field is one example of the value of developing a 3-D TOUGH2 model of the Panola hillslope.

Recent hillslope modeling efforts at PMRW using the Tromp-van Meerveld and McDonnell (2006a) data have focused on examining the importance of changing spatial connectivity of lateral preferential flow paths as one of the controls of threshold response by explicitly including pipeflow into the model structure (e.g. Weiler and McDonnell, 2006) or on using percolation theory to simulate the random distribution of connectivity on a 2-D hillslope (e.g. Lehmann et al. 2006). In this present modeling study, we examine the development of subsurface runoff within the hillslope using a 3-D matrix continuum approach in an exploration of the observed nonlinear rainfall-runoff response. The TOUGH2 model incorporates the mapped irregular bedrock topography of the Panola hillslope in which transient groundwater can form and a permeable bedrock formation into which water can infiltrate.

Spatial heterogeneities of bedrock topography, soil depth and throughfall input could potentially produce threshold response in the absence of discrete preferential flow paths. The objectives of this study are to model the rainfall-runoff response of the Panola hillslope and compare simulated spatial patterns of subsurface saturation with published field observations. We also test the ability of the continuum approach to describe the non-linear response of this hillslope. We take advantage of the extensive experimental dataset and the iTOUGH2 (Finsterle, 1993) capabilities for model-data comparison and sensitivity analysis. In this paper we limit our simulations to scenarios of subsurface flow runoff generation (excluding overland flow). This is not an unreasonable constraint considering that overland flow on well-drained hillslopes such as the Panola hillslope is a rare runoff generation mechanism.

This short paper describes the extensive spatial and temporal Panola hillslope dataset and illustrates a preliminary simulation of the outflow at the downslope trench. The further use of the Panola hillslope model in an exploration of hillslope classification is outlined as a future research objective.

STUDY SITE

The Panola Mountain Research Watershed (PMRW) is a forested watershed located near Atlanta, Georgia in the humid, sub-tropical climate of the south-eastern USA. Monthly precipitation of 104 mm is uniform throughout the year (1240 mm annual) and is delivered by both winter frontal storms (long duration, low intensity) and shorter more intense summer thunderstorms (Tromp-van Meerveld and McDonnell, 2006b). Annual mean air temperature is 16.3 ˚C (NOAA, 1991).

The experimental hillslope, described in detail by Tromp-van Meerveld and McDonnell (2006a) measures 46 m in length and is bounded downslope by a 20 m long excavated trench that intercepts subsurface lateral flow moving towards an ephemeral stream channel. Sandy-loam soil ranging in depth between 0 to 1.86 m overlies the Panola Granite bedrock that outcrops at the top of the hillslope. On the hillslope, average slope is 13˚ degrees. Significant variation in bedrock topography (Figure 1) forms depressions and ridges that control subsurface flow. Generally, a water table is not present on the hillslope between storm events. During events, transient saturation will form and depending on the size of the storm, lead to the 'fill and spill' behavior of transient subsurface flow (Tromp-van Meerveld and McDonnell, 2006b).

HILLSLOPE EXPERIMENTAL DATASET

Extensive experimental work has been performed at the Panola Mountain Research Watershed (PMRW) using the trench face collection system as a window on the development of subsurface lateral flow (McDonnell et al., 1996; Freer et al. 1997; 2002; Burns et al., 1998). We will use the recent 2002 observations of Tromp-van Meerveld and McDonnell (2006a,b,c) as reference against which to test our TOUGH2 3-D hillslope model. The dataset and analysis is described in detail in Tromp-van Meerveld and McDonnell (2006a,b,c). Here, we briefly summarize the data with which our TOUGH2 hillslope model will be tested (Table 1).

The 2002 dataset of rainfall-runoff response at the Panola hillslope includes a continuous times series of rainfall and resulting outflow at the downslope trench face from January through June 2002. The 20 m long trench is divided into 2m sections allowing for observation of spatial variation in outflow response related to flowpaths dominating the irregular bedrock surface. The dataset not only includes observation of outflow from the soil matrix but monitors outflow from five distinct soil pipes derived by decayed roots. Within the hillslope itself, the temporal build up of saturated conditions was monitored by a series of 29 recording wells installed along two down-valley transects and within a bedrock hollow. Maximum water table elevation during storm events was collected over a grid of 135 crest stage recorders. Soil moisture conditions were measured using an Aqua-pro capacitance sensor (Aqua-pro Sensors, Reno, NV) on a 4m x 4m grid of the upper portion of the hillslope and a 4m x 2m grid of the lower hillslope (Tromp-van Meerveld and McDonnell, 2006c).

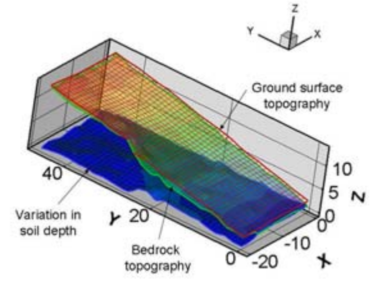

Figure 1. Surface and bedrock topography and variation in soil depth used to generate the 3-D TOUGH2 Panola hillslope mesh.

Table 1. 2002 Panola hillslope experimental data to which modeling results will be compared.

Data Type	Details
Rainfall time series	Tipping buckets (mm/15 min)
Subsurface lateral flow time series (matrix versus pipeflow)	20 m trench collector system; divided in 4 m sections; pipeflow monitored separately from matrix flow; (mm/15 min)
Water table elevation (time series)	29 recording wells with capacitance rods (mm/5 min)
Water table elevation (maximum rise)	Crest state gauges with cork dust
Hillslope average soil moisture	Aqua-pro capacitance sensor, Reno, NV

3-D TOUGH2 HILLSLOPE MODEL

We use the TOUGH2 simulator (Pruess 1991) to model the Panola hillslope rainfall-runoff response. Based on the 2 m grid surveys of surface and subsurface elevation (Tromp-van Meerveld and McDonnell, 2006a) illustrated in Figure 1, a TOUGH2 mesh has been built to describe the variable surface and subsurface topography of the Panola hillslope and the resulting variation in depth to soil-bedrock interface.

Hillslope infiltration during storm events is simulated by injecting water into the top soil layer at rates determined by field observations of throughfall (mm/15 min). Water within the soil domain can percolate into a lower bedrock layer prescribed as a Dirichlet boundary condition. Although this water is lost from the hillslope, it contributes to recharge at a larger catchment scale (and is not included in the simulation). Water within the soil domain can move downslope under variably saturated conditions to the trench boundary. The trench boundary is simulated by a second Dirichlet boundary condition with high porosity, permeability, and no capillarity.

In this preliminary simulation, the soil domain is characterized as an isotropic sandy-loam using average permeability, porosity and van Genuchten capillary pressure function parameters described in Table 2 from Carsel and Parrish (1988). Bedrock is similarly characterized but with reduced permeability two orders of magnitude smaller (1E-14 m^2) than the soil domain. Based on Aqua-pro soil moisture measurements of hillslope average soil moisture, antecedent moisture conditions within the hillslope soil are initialized at 30% volumetric moisture content or 0.7 liquid saturation.

Table 2. General characterization of the Panola hillslope.

Model Parameter	Soil Domain
$k_{\text{horizontal}}$	1E-12 m^2
k_{vertical}	1E-12 m^2
Porosity	0.41
Van Genuchten, m	0.47
Van Genuchten, α	0.075

SIMULATION OF A 63 MM THUNDERSTORM

A thunderstorm on 30-Mar-02 delivered a total of 63 mm of throughfall to the hillslope within 48 hours (Figure 2). Observed subsurface lateral flow in the form of outflow from the entire 20 m trench accumulated to 5.8 mm or 9.3 % of total throughfall. Comparison of the TOUGH2 simulated and observed trench outflow for this event is illustrated in Figure 2. No calibration has been performed for this simulation except for the manual adjustment of bedrock permeability. Although simulated total trench flow is similar in value (5.3 mm or 8.3% of throughfall) to observations, there are clear differences between peak instantaneous flow rates. Simulated outflow of water to the trench is damped and lagged in time compared to observations. Continued work will compare simulated spatial extent of the water table formation within the hillslope to experimental results of Tromp-van Meerveld and McDonnell (2006b).

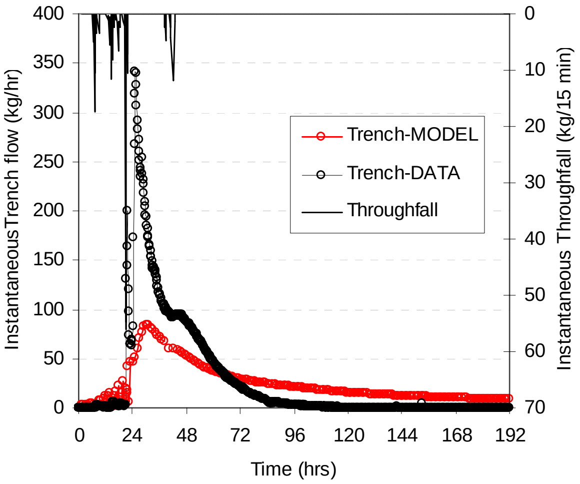

Figure 2. Throughfall and observed trench outflow during a 63 mm storm event on March 30, 2002.

FUTURE OBJECTIVES

We wish to apply the Panola hillslope model to the investigation of hillslope classification. The recent SLope InterComparison Experiment (SLICE) Workshop held in September 2006 at the HJ Andrews Experimental Forest, Oregon, assembled researchers from around the world working on hydrology and biogeochemistry of trenched-hillslopes. These experimental sites span a vast range of climatic, geologic and geographic environments from Japan, New Zealand, Europe, eastern and western North America. Inter-comparison studies such as Uchida et al. (2005) have posed the question of how to compare experimental results across these varied sites, a fundamental challenge to hillslope hydrologists.

To explore the varied conditions observed at different experimental sites using the Panola hillslope model, we organize variables of interest into categories of hillslope domain characteristics, event characteristics and model structure. Domain characteristics define the soil and bedrock parameters within the TOUGH2 model, and include some overlap with model structure (e.g. exponential decrease in soil k, slope, irregular soil depth) where alteration to the mesh would be required. Event characteristics identify storm magnitude, duration, intensity, and spatial variation that are input within the GENER block of a TOUGH2 simulation. This category also includes antecedent moisture conditions and the temperature of the input, distinguishing snowmelt water from a rainstorm. Sensitivity analyses and grid search methods of iTOUGH2 will allow us to explore the effects of these domain and event characteristics and model structure on simulated hillslope rainfall-runoff.

Table 3. Variables of interest in the study of hillslope classification.

Parameter	Domain characteristics	Event characteristics	Model Structure
k soil	√		
k bedrock	√		
k soil anisotropy	√		
k soil:exponential decrease	√		√
Pcap: (m,α, Slr)	√		
krel: (m, Slr)	√		
porosity	√		
Slope	√		√
Irregular soil depth	√		√
AMC*		√	
Storm magnitude		√	
Storm duration		√	
Spatial variation in input		√	
Temperature of input: Melt water versus rainstorm		√	

* AMC – Antecedent moisture conditions

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