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Variability and persistence of hillslope initial conditions: A continuous perspective on subsurface flow response to rain events

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SUMMARY

Runoff response to rain events depends on the initial moisture conditions in the subsurface. This study explores subsurface stormflow response to initial conditions within the context of a continuous hillslope water balance. A hypothetical hillslope with three-dimensional variably saturated subsurface flow is developed using the HYDRUS model forced with a year-long sequence of hourly precipitation and transpiration from Seattle, WA, USA. Using six different soil hydraulic parameter sets, test simulations examine (1) variability of hillslope initial conditions prior to rain events, (2) persistence of initial conditions in a continuous simulation, and (3) effects of initial conditions on subsurface stormflow during rain events. Results show that hillslope initial conditions vary seasonally, producing bimodal distributions of storage values with preferred storage ranges for wet and dry seasons. Preferred storage ranges differ by soil texture and by hydraulic conductivity. Wet season initial conditions are most frequently at storage values above hillslope field capacity, with higher preferred ranges of storage for scenarios with lower saturated hydraulic conductivity. Dry season hillslope storage values converge to minimum values below field capacity, and these minimum values vary with soil texture but not with saturated hydraulic conductivity. Tests of initial condition convergence show that scenarios with different initial storages can eventually converge under either persistent wetting or persistent drying until hillslope storage reaches the wet or dry preferred states. Dry preferred states are unlikely to produce subsurface stormflow, as test rain events generate hillslope outflow only when initial storage is at or above an event and parameter-specific threshold near the hillslope field capacity. Above this flow threshold, all simulations show a nonlinear increase in subsurface stormflow with increasing initial storage, with the steepest rates of increase for scenarios with the highest values of saturated hydraulic conductivity. Simulation experiments present a quantitative approach for deriving functional relationships between event response, initial storage, and hillslope water retention.

1. Introduction

Hydrologic response is frequently analyzed for isolated events, which are discrete intervals of time in which a period of rain or snowmelt causes runoff. Most hydrometric measurement networks monitor both precipitation and discharge, so events are often considered logical subdivisions for analyzing hydrologic response. However, each individual event can be preceded by a different set of initial conditions, defined as the distributions of moisture within the domain that contributes to runoff. As a result, in any given location, identical rain events preceded by different initial conditions could result in distinct runoff responses.

This dependence of runoff on initial conditions has been observed in many environments, but the nature of reported relations between initial conditions and event response is variable. Studies of hillslopes with rapid subsurface stormflow have identified rainfall–runoff relationships that appear to be linear for events larger than a site-specific precipitation threshold (Tani, 1997; Carey and Woo, 2001). The antecedent wetness of a slope can also shift both the type of runoff response (Montgomery and Dietrich, 1995) and the runoff magnitude (Whipkey, 1965; Sidle et al., 1995). Different degrees of antecedent wetness can also be associated with variable patterns of soil moisture organization (Grayson et al., 1997; Ivanov et al., 2010). The patterns of soil moisture organization within a hillslope can affect runoff response in some settings (Merz and Plate, 1997; Zehe and Blöschl, 2004), whereas they may be less important in other settings (James and Roulet, 2007). Clearly, initial conditions play a role in event response, and both climate and hillslope characteristics interact to control the flow processes and moisture patterns that develop in a particular location.

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2. Background

To understand event response to initial conditions, a first challenge lies in measuring the initial conditions for the domain of interest. No measurement method is currently available for sensing the three-dimensional, time-varying moisture distributions in a hillslope subsurface volume. Instead, initial conditions must be inferred through indirect techniques that under-sample space, time or both. While detailed spatial surveys of moisture have been conducted in many locations (e.g. Famiglietti et al., 1998; Western et al., 2004), these surveys measure near-surface soil moisture, so even with a dense measurement grid, such surveys do not give fully three-dimensional moisture distributions. Technologies such as ground penetrating radar (Huisman et al., 2003) and electromagnetic induction (Sheets and Hendrickx, 1995) may help measure moisture distributions at greater depth, but these techniques are typically not available for continuous measurement of moisture distributions through time. A new technology for monitoring moisture via cosmic ray neutrons (Zreda et al., 2008) shows promise for sampling soil moisture continuously over $\sim$300 m areas, but this technique does not characterize the distribution of moisture at a finer spatial resolution.

Coupled with measurement challenges are equally significant challenges in identifying the processes that affect the fate of event precipitation. Hillslope configuration, stratigraphy, water retention characteristics, vegetation characteristics, and climatic setting all interact to create a wide range of runoff behaviors over time and space. While efforts to tabulate and categorize rainfall–runoff behaviors across study sites do find similar flow behaviors in hillslopes with similar characteristics and climate (Dunne, 1978), experimental results from individual sites are difficult to compare to one another because measurement sites are so variable in configuration (McDonnell et al., 2007).

As a complementary approach to field measurements, multiple studies explore event response using hydrologic models. Freeze (1972) used a transient variably saturated flow model to simulate hillslope response to varying rainfall, antecedent moisture, and geologic configuration. He saw these model-based experiments as a useful tool for understanding runoff mechanisms, but at the time, computer limitations inhibited conducting the experiments in great detail. Even in a model-based study, the complexity of runoff generation led Freeze (1972) to conclude that there should be no reason to expect event response to behave in any consistent way. Beven (1977) followed this work by using a subsurface flow model to explore hillslope event response to variable initial conditions, topography, and soil characteristics. Subsequent studies have also used modeling experiments to explore runoff variability with different catchment and rainfall characteristics (Loague, 1988; Gan and Burges, 1990), test hypotheses about flow processes (Weiler and McDonnell, 2004), identify flow response regimes based on climate and catchment characteristics (Harman and Sivapalan, 2009), or develop hypothetical realities of hydrologic response for use in model testing (Mirus et al., 2009). Modeling studies have consistently identified the importance of initial moisture states to simulated event response (Gan and Burges, 1990; Castillo et al., 2003; Zehe and Blöschl, 2004; Brocca et al., 2008), but as with field-based studies, results from different models are difficult to compare to one another without a common organizing framework.

This study uses hillslope subsurface flow simulations to explore interactions between hillslope characteristics, initial conditions, and event response. These interactions are placed in the context of a continuous water balance, so individual events can be examined relative to time variability in hillslope storage. To enable multiple scenario tests, the study employs a physically-based model of subsurface flow through a hypothetical hillslope. The advantage of a hypothetical slope is that, unlike a natural slope, its initial conditions prior to rain events are fully known both at the scale of in situ point measurements and at the scale of the hillslope as a whole. While even the most detailed model is an approximation of reality, a physically-based model is a useful tool for revealing interactions and nuances in flow behaviors that may be difficult to discern from measurements alone (Loague et al., 2006) and for developing a rigorous theoretical foundation for subsequent field measurements (Dunne, 1983). Following this philosophy, the specific objectives of the study are to identify for a hypothetical hillslope: (1) the variability of hillslope initial conditions, (2) controls on initial condition persistence, and (3) the effects of initial conditions on event response.

3. Methods

3.1. Simulation configuration and supporting measurements

The hypothetical slope for this study has relatively a simple geometry, which is convergent in plan form and planar in profile form. The hillslope is designed to represent the general characteristics of a soil-mantled hillslope in a humid climate. The slope is 10 m long, and it converges from a width of 7 m at the ridge line to a width of 3 m at the base of the slope (Fig. 1). The soil depth is 1 m, and the entire convergent slope is inclined at 10%. This configuration gives a domain volume of 50 m^3, which is small relative to natural hillslopes but large enough to represent essential features of space–time variability in soil moisture and runoff. The hypothetical slope is created using the HYDRUS-3D model (Šimůnek et al.,

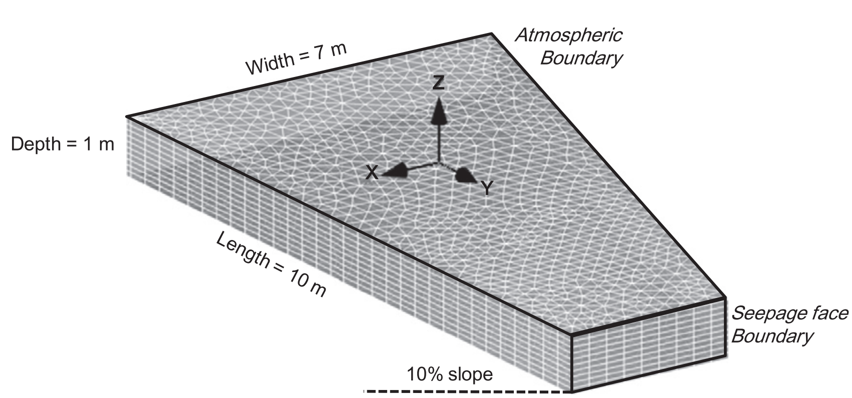

Fig. 1. Domain configuration for the hypothetical hillslope in HYDRUS-3D. All unlabeled boundaries have no-flow boundary conditions.