Journal of Hydrology 393 (2010) 77–93

Contents lists available at ScienceDirect

Journal of Hydrology

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

Hillslope threshold response to rainfall: (2) Development and use of a macroscale model

Chris B. Graham [a,*], Jeffrey J. McDonnell [b,c]

[a] Department of Crop and Soil Sciences, The Pennsylvania State University, University Park, PA, USA
[b] Department of Forest Engineering, Resources and Management, Oregon State University, Corvallis, OR, USA
[c] University of Aberdeen, School of Geosciences, Aberdeen, Scotland, UK

ARTICLE INFO

Keywords:
Preferential flow
Hillslope hydrology
Numeric models
Model calibration
Virtual experiments

SUMMARY

Hillslope hydrological response to precipitation is extremely complex and poorly modeled. One possible approach for reducing the complexity of hillslope response and its mathematical parameterization is to look for macroscale hydrological behavior. Hillslope threshold response to storm precipitation is one such macroscale behavior observed at field sites across the globe. Nevertheless, the relative controls on the precipitation–discharge threshold poorly known. This paper presents a combined model development, calibration and testing experiment study to investigate the primary controls on the observed precipitation–discharge threshold relationship. We focus on the dominant hydrological processes revealed in part one of this two-part paper and with our new numerical model, replicate the threshold response seen in the discharge record and other hydrometric and tracer data available at the site. We then present a series of virtual experiments designed to probe the controls on the threshold response. We show that the threshold behavior is due to a combination of environmental (storm spacing and potential evapotranspiration) and geologic (bedrock permeability and bedrock topography) factors. The predicted precipitation–discharge threshold subsumes the complexity of plot-scale soil water response. We then demonstrate its use for prediction of whole-catchment storm discharge at other first order catchments at Maimai and the HJ Andrews Experimental Forest in Oregon.

Introduction

Hillslope hydrology still lacks the compact organization of empirical data and observations of hydrological response to precipitation events that might facilitate extrapolation to and prediction of hillslope behavior in different places. Hillslope hydrology models based on our current small scale theories emphasize the explicit resolution of more and more of the unknown and unknowable heterogeneities of landscape properties and the resulting process complexities (McDonnell et al., 2007). While the utility of a search for macroscale laws was enunciated over 20 years ago (Dooge, 1986), few studies have been able to even observe macroscale behavior given the enormous logistical challenge for characterizing whole-hillslope response. The heterogeneity in hillslope soil, bedrock, and topographic conditions and complexity of the spatial and temporal rainfall and throughfall input are still extraordinarily difficult to quantify and include in macroscale descriptions of hillslope and catchment behavior.

Graham et al. (this issue) presented a new macroscale perceptual model of subsurface flow processes at the well studied Maimai experimental watershed (McGlynn et al., 2002). This work was based on whole-hillslope excavation of subsurface flow paths and detailed hillslope scale irrigation aimed at identifying the dominant subsurface flow pathways and the role of bedrock topography and bedrock permeability on hillslope scale hydrological processes. The complexities of hillslope response and heterogeneity of the hillslope site at Maimai could be summarized by three key process statements: (1) A connected preferential flow network located at the soil/bedrock interface dominates lateral water and solute transport (with very high flow and transport velocities ranging from 6 to 21 m/h). (2) The bedrock surface controls the subsurface flow routing (where the filling of small depressions along the bedrock surface results in threshold lateral subsurface flow). (3) Vertical loss to the permeable bedrock is large (up to 35% of the precipitation input) delaying lateral flow initiation and reducing lateral flow volumes.

Here we take the perceptual model of hillslope behavior developed by Graham et al. (this issue) and apply the dominant processes modeling concept of Grayson and Blöschl (2000) to construct, test and use a macroscale rainfall–runoff model for the Maimai hillslope. Within the dominant processes philosophy, only

* Corresponding author. Address: The Pennsylvania State University, Department of Crop and Soil Sciences, 116 Agricultural Sciences and Industry Building, University Park, PA 16802-3504, USA. Tel.: +1 814 867 3074; fax: +1 814 863 7043.
E-mail address: cbg12@psu.edu (C.B. Graham).

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doi:10.1016/j.jhydrol.2010.03.008

the dominant flow processes, in this case the three listed above are incorporated into model structure. This philosophy is motivated by the difficulty in identifying and quantifying the myriad complex and heterogeneous hydrological processes at a given site. Our dominant processes approach is also motivated by the finding that only a small number of processes may dominate lateral subsurface flow and transport at the hillslope scale. We translate the hydrological processes identified at Maimai into a simple, low dimensional conceptual mathematical model. This follows similar model development work at Maimai and elsewhere (Seibert and McDonnell, 2002; Son and Sivapalan, 2007; Weiler and McDonnell, 2007). In this way the experimentalist works directly with the modeler, both in the experimental design to determine the dominant flow processes, and in model design to accurately implement the experimental findings.

We evaluate our new model using a multiple objective criteria framework (Gupta et al., 1998) incorporating extensive hydrometric and tracer data available from at Maimai site. We then use this new model as a learning tool to shed new light on whole-hillslope threshold responses to storm rainfall. Analysis of long term data records of flow at several field sites around the world has shown that such hillslope threshold response (i.e. the precipitation threshold before significant lateral subsurface flow is initiated) is a fundamental constitutive relation in hydrology (Buttle et al., 2004; Mosley, 1979; Peters et al., 1995; Weiler et al., 2006; Whipkey, 1965). While this threshold behavior is a potential macroscale descriptor of hillslope response to storm precipitation, the dominant controls on the magnitude of the threshold are not well known. While catchment geologic factors (e.g. soil depth, bedrock permeability, etc. (Tromp-van Meerveld and McDonnell, 2006b; Uchida et al., 2005)) and catchment environmental factors (e.g. antecedent moisture conditions (Tani, 1997; Tromp-van Meerveld and McDonnell, 2006a)) have been proposed as possible controls, the relative importance of each remains unclear and unresolved.

Two specific hypotheses have been previously proposed to explain the threshold relationship between rainfall and resulting subsurface stormflow: (1) fill and spill, and (2) pre-storm soil moisture deficit. In the fill and spill hypothesis, subsurface storage at the base of the soil profile must be filled (often in saturated patches) to connect the upslope areas with the base of the hillslope (Spence and Woo, 2002; Tromp-van Meerveld and McDonnell, 2006b). Accordingly, the permeability of the bedrock and the volume of subsurface storage that must be filled are the primary controls on the initiation of lateral subsurface flow. Alternatively, the pre-storm soil moisture deficit hypothesis (Tani, 1997; Tromp-van Meerveld and McDonnell, 2006b) suggests that filling of the moisture deficit in the soil profile is a prerequisite for lateral subsurface flow. This hypothesis is supported by an apparent change in the threshold under different antecedent moisture conditions. While both factors may operate in concert with one another, the relative influence of fill and spill and soil moisture deficit factors on the threshold response to precipitation has not been tested to date—largely because of the extremely small sample size of experimental hillslopes and limited range of climate and geology conditions explored to date.

Here we develop and then use our new model to test alternative hypotheses of controls on the threshold response to precipitation for diverse climate and geology. We use our model as a learning tool to explore how subsurface processes represented in our model structure may link to those properties that can be extracted from a long terms data record, such as the threshold for initiation of storm runoff, and the relationship between the excess precipitation and runoff. The new understanding of the controls of the threshold relationship is then tested on a number of different first order catchments at Maimai and at the HJ Andrews Experimental Forest in Oregon, USA. We use readily available data for storm spacing, evaporative demands and storm size extracted from the long term record at these sites to demonstrate how the complexity of catchment response to precipitation can be collapsed to the threshold metric to allow for simple macroscale model prediction of catchment discharge.

Study site and model development

Site physical and process description

We use the experimental work of Graham et al. (this issue) at the Maimai Experimental Catchments as the basis for model development and the virtual experiments aimed at understanding the controls on thresholds. The Maimai Experimental Catchments, South Island, New Zealand, have been a site of continuing hydrological research for over 30 years (see review in McGlynn et al. (2002)). While isotopic work has shown that the majority of hillslope discharge and streamflow at Maimai is pre-event water stored for weeks to months (McDonnell, 1990; Mosley, 1979; Pearce et al., 1986; Sklash et al., 1986), tracer experiments have demonstrated the ability of the hillslopes to rapidly transmit quantities of applied water at high velocities over long distances (Brammer, 1996; Mosley, 1979, 1982). Graham et al. (this issue) showed that lateral preferential flow is confined to the soil bedrock interface where flow velocities are very high (up to 21 m/h), routed by the bedrock topography. Filling subsurface storage in topographic pools upon the bedrock surface is a prerequisite for downslope connection and significant lateral subsurface flow. Once storage is filled, preferential flow paths seen on the bedrock surface have been shown to be connected upslope for distances up to 8 m, and appear to be stationary in time and space (Graham et al., this issue). The bedrock, while previously considered effectively impermeable (McDonnell, 1990; Mosley, 1979), was shown to be semi-perveous, with bedrock hydraulic conductivity on the order of 1–3 mm/h, leading to the potential of substantial fluxes of water and nutrients through the bedrock (Graham et al., this issue). Overland flow has not been observed at this site except in limited areas near the stream channel. Vertical preferential flow from the soil surface to depth during rainfall events has been hypothesized to occur in vertical cracks seen throughout the catchment dissecting the soil profile (Graham et al., this issue; McDonnell, 1990). Mixing of old and new water is thought to occur in both the soil column as well as in transient groundwater that forms at the soil bedrock interface, leading low amounts of new water observed in trench discharge and streamflow (Pearce et al., 1986; Sklash et al., 1986).

Description of the numerical model

The numerical model (called MaiModel) was built to incorporate the dominant processes that control subsurface flow at the Maimai hillslope as described by Graham et al. (this issue). Key components of MaiModel are

- Preferential flow pathways are connected, and located at the soil bedrock interface.
- Lateral subsurface travel velocities are high.
- Subsurface storage on the bedrock surface is explicitly designated.
- The bedrock is permeable.

In general terms, MaiModel consists of two reservoir types, soil storage and bedrock pool storage, which are fully distributed across the model domain (Fig. 1). Two bulk reservoirs are included for system losses of evapotranspiration and bedrock leakage. Water is transmitted vertically from the soil surface, through the