Journal of Hydrology 393 (2010) 65–76

Contents lists available at ScienceDirect

Journal of Hydrology

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

# Hillslope threshold response to rainfall: (1) A field based forensic approach

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ARTICLE INFO

*Keywords:*
Hillslope hydrology
Runoff generation
Tracers
Destructive sampling
Preferential flow
Subsurface flow

SUMMARY

Hillslope threshold response to storm rainfall is poorly understood. Basic questions regarding the type, location, and flow dynamics of lateral, subsurface flow remain unanswered, even at our most intensively studied field sites. Here we apply a forensic approach where we combined irrigation and excavation experiments at the well studied Maimai hillslope to determine the typology and morphology of the primary lateral subsurface flowpaths, and the control of bedrock permeability and topography on these flowpaths. The experiments showed that downslope flow is concentrated at the soil bedrock interface, with flowpath locations controlled by small features in the bedrock topography. Lateral subsurface flow is characterized by high velocities, several orders of magnitude greater than predicted by Darcy's Law using measured hydraulic conductivities at the site. We found the bedrock to be moderately permeable, and showed that vertical percolation of water into the bedrock is a potentially large component of the hillslope water balance. Our results suggest that it is the properties of the bedrock (topography and permeability) that control subsurface flow at Maimai, and the soil profile plays a less significant role than previously thought. A companion paper incorporates these findings into a conceptual model of hydrological processes at the site to explore the generalities of whole-hillslope threshold response to storm rainfall.

## Introduction

Hillslopes are fundamental units of the hydrologic landscape and the main filter for water and solute transport from the atmosphere to the stream. In forested regions of the world, quick lateral subsurface stormflow (often called interflow or throughflow) is the primary mechanism for stormflow generation in headwater catchments (Hursh, 1944). Much of the progress in identifying the different manifestations of subsurface stormflow behaviors was made in the 1960s and 1970s (Hewlett and Hibbert, 1967; Mosley, 1979; Whipkey, 1965). More recent work has tempered community excitement about these discoveries by revealing the staggering complexity, heterogeneity and uniqueness of hillslope drainage systems (McDonnell et al., 2007) and the enormous range of scales of processes imposed by climate, geology and vegetation that control hillslope response (Sidle et al., 2007; Sivapalan, 2003; Zehe et al., 2007).

While determining slope-specific processes remains daunting, one common denominator in hillslope response to rainfall is the often-observed threshold relationship between total storm precipitation and lateral subsurface stormflow (Fig. 1). This threshold relationship is an emergent property at the hillslope scale – a property that subsumes much of the sub-grid complexity at the plot scale (e.g. Lehmann et al., 2007). While threshold relationships between storm rainfall and hillslope-scale runoff have been shown now in several environments around the world based on hillslope trenchflow recording (Buttle and McDonald, 2002; Hutchinson and Moore, 2000; Mosley, 1979; Spence and Woo, 2002; Tani, 1997; Uchida et al., 1999, 2005) the physical cause of these thresholds has been difficult to generalize given the challenge of making hillslope-scale measurements. Recently, (Tromp-van Meerveld and McDonnell, 2006b) proposed "fill and spill" as a conceptual framework to explain the whole-slope precipitation threshold for lateral subsurface stormflow. The fill and spill theory states that connectivity of patches of (transient) subsurface saturation (at the interface between the soil and an impeding layer) is a necessary pre-condition for significant hillslope-scale storm response. These isolated patches of subsurface saturation are located in topographic depressions in the impeding layer, and connection of these patches of (transient) saturation is controlled by both the topography and permeability of the impeding layer. The fill and spill theory was supported by observed patterns of transient water table development and lateral subsurface stormflow at Panola, and since

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doi:10.1016/j.jhydrol.2009.12.015

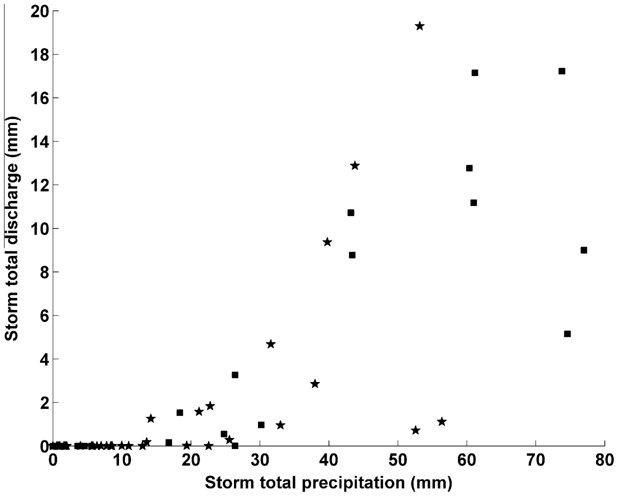

**Fig. 1.** Whole storm precipitation and hillslope discharge at instrumented Maimai hillslope. 150 days of monitoring included 125 storms (data from Woods and Rowe (1996) (stars) and Brammer (1996) (squares)).

then by model analysis in two and three dimensions (Hopp and McDonnell, 2009; Keim et al., 2006).

Despite the promise of fill and spill as a conceptual framework to explain whole-slope rainfall–runoff thresholds and emergent landscape behavior, physical measurement of the factors affecting fill and spill are rudimentary and poorly quantified at other sites. The mapping, measuring and quantifying the flow network activated during fill and spill and how these networks conspire with bedrock permeability has yet to be determined. Yet, this mapping and quantification is a critical research question in hillslope hydrology and essential for understanding whole-hillslope threshold processes and generalizing the fill and spill framework to other areas. However, such mapping and measurement is extremely difficult with current field techniques and approaches.

So how might we explore the mechanistic controls on hillslope threshold response to storm rainfall, explore further the fill and spill framework and develop a function that captures sub-grid scale variability into numerical macroscale behavior? Here we present a field-based experiment aimed at defining hillslope-scale internal controls on threshold response and whole hillslope emergent behavior via limited destructive sampling of a well-researched site. We follow in the tradition of soil science, where soil pits and excavations after tracer applications are a commonplace method for determining processes occurring at the soil pedon scale (Flury et al., 1995; Zehe and Flühler, 2001). Our work builds upon some destructive experimentation that has already been attempted in hillslope hydrology. Kitahara (1993) filled a network of macropores with plaster and removed the soil from surrounding the network, identifying the location and morphology of the preferential flow network. Additional pit scale irrigation and excavation experiments have been instrumental in revealing the structure and predominance of lateral and vertical preferential flow (Mosley, 1982; Noguchi et al., 2001; Weiler and Naef, 2003) but have been limited to the pedon scale and have not been attempted across a complete hillslope section. The only whole hillslope irrigation and excavation to date, by Anderson et al. (2009), has shown the power of such a destructive mapping approach and identified the subsurface flow network of a humid forested hillslope in British Colombia, Canada.

Here we show how destructive sampling at the hillslope scale can be especially useful at our well studied sites, where a history of observed field behaviors can be tested, *ex post facto*, using our forensic approach. Our research site is the Maimai Experimental Watershed on the South Island, New Zealand (see McGlynn et al. (2002) for review). Maimai was one of the early sites where lateral subsurface stormflow was mechanistically assessed (Mosley, 1979, 1982). More recently, studies at Maimai have chronicled the initiation of subsurface stormflow through soil pipes (McDonnell, 1990), the patterns of subsurface stormflow (Woods and Rowe, 1996) and solute transport (Brammer, 1996) at the slope base, the relative role of hillslope vs. riparian zones in runoff initiation (McGlynn and McDonnell, 2003a) and nutrient and solute transport (McGlynn and McDonnell, 2003b). While the recognition of rainfall thresholds for generating hillslope response at Maimai date back to the original work of Mosley (1979), the controls on this whole-hillslope response have been difficult to assess, even at this intensively studied site.

At Maimai, many key components of the fill and spill theory have not yet been resolved. Both the nature of the lateral subsurface flow network and the permeability of the bedrock are poorly understood. The characteristics of the lateral flow network have been extrapolated from observations made at trench faces and limited, small scale excavations ($<1\ m^2$) (Weiler and McDonnell, 2007) while the upslope form, connectivity, extent of the lateral flow network remains unknown. While the bedrock permeability has been estimated using a catchment scale water balance (O'Loughlin et al., 1978; Pearce and Rowe, 1979), no direct measurements have been made. We posit that hillslope scale excavations are a powerful field method to reveal the existence and extent of the lateral flow network and a way to expose the bedrock surface for permeability measurements.

This paper details a hillslope scale irrigation – excavation experiment designed to identify the dominant flow pathways and the role of bedrock topography and permeability at the hillslope scale. Our work tests three sets of multiple working hypotheses directed at the first order controls on the fill and spill theory stemming from previous work at Maimai and other steep, forested hillslopes:

1. How can we characterize the lateral subsurface flow?
1(a) Lateral subsurface storm flow is concentrated in the soil matrix and the preferential flow network is non existent or unimportant in generating flow at the hillslope scale (supported at the site by Sklash et al. (1986).
1(b) A lateral preferential flow network exists, consisting of disconnected soil pipes located in the soil profile (supported at the site by McDonnell (1990), elsewhere by Noguchi et al. (2001)).
1(c) A lateral preferential flow network exists, consisting of a connected network located at the soil/bedrock interface (supported at the site by Mosley (1979)).
2. How does the bedrock surface topography affect flow routing?
2(a) The bedrock surface plays an indirect role in flow routing (supported at the site by Woods and Rowe (1997)).
2(b) The bedrock surface determines flow routing (supported at the site by Freer et al. (1997) and McDonnell (1997), elsewhere by Freer et al. (2002)).
3. How does the permeability of the lower boundary affect flow processes?
3(a) The bedrock is effectively impermeable (supported at the site by McDonnell (1990), Mosley (1979), O'Loughlin et al. (1978), and Woods and Rowe (1996)).
3(b) The bedrock permeability is high enough to have a significant impact on flow processes (supported elsewhere by Onda et al. (2001), Tromp-van Meerveld et al. (2006) and Hopp and McDonnell (2009)).

## Site description

The experiments were performed at the Maimai Experimental Watershed, near Reefton, South Island, New Zealand (Fig. 2).