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On the non-uniqueness of the hydro-geomorphic responses in a zero-order catchment with respect to soil moisture

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ABSTRACT

This study advances mechanistic interpretation of predictability challenges in hydro-geomorphology related to the role of soil moisture spatial variability. Using model formulations describing the physics of overland flow, variably saturated subsurface flow, and erosion and sediment transport, this study explores (1) why a basin with the same mean soil moisture can exhibit distinctly different spatial moisture distributions, (2) whether these varying distributions lead to non-unique hydro-geomorphic responses, and (3) what controls non-uniqueness in relation to the response type. Two sets of numerical experiments are carried out with two physically-based models, HYDRUS and tRIBS+VEGGIE+FEaST, and their outputs are analyzed with respect to pre-storm moisture state. The results demonstrate that distinct spatial moisture distributions for the same mean wetness arise because near-surface soil moisture dynamics exhibit different degrees of coupling with deeper-soil moisture and the process of subsurface drainage. The consequences of such variations are different depending on the type of hydrological response. Specifically, if the predominant runoff response is of infiltration excess type, the degree of non-uniqueness is related to the spatial distribution of near-surface moisture. If runoff is governed by subsurface stormflow, the extent of deep moisture contributing area and its "readiness to drain" determine the response characteristics. Because the processes of erosion and sediment transport superimpose additional controls over factors governing runoff generation and overland flow, non-uniqueness of the geomorphic response can be highly dampened or enhanced. The explanation is sediment composed by multi-size particles can alternate states of mobilization or surface shielding and the transient behavior is inherently intertwined with the availability of mobile particles. We conclude that complex nonlinear dynamics of hydro-geomorphic processes are inherent expressions of physical interactions. As complete knowledge of watershed properties, states, or forcings will always present the ultimate, if ever resolvable, challenge, deterministic predictability will remain handicapped. Coupling of uncertainty quantification methods and space-time physics-based approaches will need to evolve to facilitate mechanistic interpretations and informed practical applications.

1. Introduction

The superimposed responses of headwater catchments, such as zero-order basins, to a hydrometeorological event underlies the hydrological response characteristics of basins of higher orders (Beven, 1978; Troch et al., 2003; Tromp-van Meerveld and Weiler, 2008; Tsuboyama et al., 2000; Weiler and McDonnell, 2004). Inferences about the hydrological behavior made at smaller scales are therefore important for understanding the hydrologic response of larger watersheds that feature similar geomorphoclimatic conditions. A number of field experiments have offered interesting insights on the features of hydrologic response of zero-order basins in various geographic settings. For example, in their work in Hitachi Ohta Experimental Watershed, Japan, Sidle et al. (1995); 2000) contributed to the development of the concept of "threshold hydrological response" that has been the subject of many subsequent studies (e.g., Freer et al., 1997; James and Roulet, 2007; McDonnell et al., 1996; Spence and Woo, 2003; Weiler and McDonnell, 2007; Woods and Rowe, 1996), leading to useful

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conceptualizations (e.g., Hopp and McDonnell, 2009; Tromp-van Meerveld and McDonnell, 2006) and an increased interest in identifying, understanding, and quantifying the notion of hydrologic "connectivity" (e.g., Michaelides and Chappell, 2009). Other studies provided specific evidence that there is compartmentalization of different sources of water, e.g., highlighting that in watersheds with predominantly subsurface contributions, the chemical signature of event runoff can be quite different than that of rainfall and hillslope storage (Burns et al., 2001), and that event hydrographs are due to the prompt release of stored, "old" water (Benettin et al., 2015; Kirchner et al., 2001; Kirchner, 2003; Rinaldo et al., 2015). The identification of complexities in the hillslope/watershed hydrologic response has led to a search for a uniform platform for interpretation of space-time process interactions (McDonnell, 2013). While the large variability of vital hydrologic characteristics (surface topography, bedrock geometry, soil properties, and vegetative cover) has made generalizations of field experiments difficult, "virtual laboratories" (e.g., Camporese et al., 2014; Davison et al., 2015; Gan and Burges, 1990; Hilberts et al., 2007; Rahman et al., 2015; Weiler and McDonnell, 2004; Wood et al., 2005; Orlandini et al., 1996) have been important in testing hypotheses and development of new ideas that should be subsequently tested with experimentation in the field. Explorations of internal hydrologic, ecohydrologic, and geomorphic dynamics in various settings highlighted the principal and secondary effects in the simulated behaviors and their relations (e.g., Fatichi and Ivanov, 2014; Fatichi et al., 2015; Francipane et al., 2015; Hopp and McDonnell, 2009; Hopp et al., 2009; Kim and Ivanov, 2014, 2015; Kim et al., 2016; Mirus et al., 2009; Mirus and Loague, 2013; Paschalis et al., 2015). Importantly, the consensus of both empirical and modeling research has been that emerging complexity of hydro-geomorphic dynamics need to be explicitly linked to observable/quantifiable governing processes. Patterns, interdependencies, and time scales of relevant physical mechanisms should thus be appropriately determined. From a practical perspective, the enhancement as well as *limit identification* of predictive skill of operational models remain key issues (Blöschl and Zehe, 2005; Bronstert et al., 2011; Kumar, 2011).

Soil moisture is one of the fundamental hydrologic states, whose space-time variations mediate most of the observed complexities and nonlinearities of the physical behavior of watershed systems. In both field and modeling studies, antecedent moisture, specifically, its magnitude and distributions have been shown to exert a strong control on the short-term runoff response to rainfall (e.g., Brocca et al., 2008; Chen et al., 2013; Kampf, 2011; Neumann et al., 2010; Noto et al., 2008; Shen et al., 2013; Zehe and Blöschl, 2004). Thus, intensive field campaigns have been dedicated to measuring spatial distributions of near-surface moisture and its relation to the integrated runoff response of a hillslope or catchment (e.g., Blume et al., 2009; Brocca et al., 2007; Wilson et al., 2004). However, mechanistic relations between soil moisture spatial distributions (especially for deep-profile water) and runoff response are not always readily evident from field measurements alone. Results from multiple locations have suggested that finer-scale organization of moisture within a hillslope or catchment, and not simply the mean, can affect the nature of the hydrologic response. For example, several studies have highlighted "preferred moisture states" (partitioned according to existence or absence of lateral subsurface exchange) that can be associated with distinct event responses to rainfall (e.g., Grayson et al., 1997; Montgomery and Dietrich, 1995; Sidle et al., 1995). Comparing soil moisture measurements in several catchment locations to event runoff, Zehe et al. (2010) found that wetness levels in the lower part of a hillslope were more important than the overall catchment wetness in determining event runoff, suggesting that moisture spatial organization can have a distinct effect on the hydrologic response.

The studies of Ivanov et al. (2010) and Fatichi et al. (2015) numerically addressed aspects of soil moisture spatial variability in a hypothetical zero-order basin, as affected by topography and vegetation. Ivanov et al. (2010) argued for the existence of the "attractor space" for domain soil moisture states, i.e., a set of spatial patterns (in relation to the mean basin wetness) that characterized majority of soil moisture spatial distributions exhibited by the domain. They also identified and illustrated hysteresis of spatial variability of depth-integrated soil moisture with respect to the mean catchment wetness. Fatichi et al. (2015) combined an analytical approach and modeling to demonstrate the contributions and interactions of biotic and abiotic factors in determining the soil moisture spatial variability. In both studies, key reasons leading to the multiple moisture distributions were the imposed conditions of shallow soil over regular bedrock replicating surface topography. The explanation was that (1) while some storms lead to infiltration fronts that arrest at shallow depths and, ultimately, are depleted by the evapotranspiration process, (2) for certain wetting conditions, the high conductivity soil column allows for percolation of event moisture down to the impervious bottom, resulting in the saturated (or nearly-saturated) conditions that lead to efficient subsurface lateral exchange. These conclusions highlighted a nontrivial dependency of the catchment hydrological dynamics on "hydraulic connectivity" between soil mantle shallow and deep moisture, implying that both first- and higher-order moment properties of soil water spatial distribution may control runoff response. Neither Ivanov et al. (2010) nor Fatichi et al. (2015) considered how the hydrologic response can be affected by the observed hysteresis in soil moisture spatial variability. A mechanistic attribution of the emerging non-uniqueness of runoff response thus remains to be explored.

Runoff is the main surface transport agent for a variety of admixtures, from chemicals to soil particulate matter. Complex physical dynamics arising in rainfall-runoff transformation thus must be characteristic of these other transport related processes and, likely, additionally superimposed by the features of the transient behavior of these admixtures. For example, a non-unique behavior in the geomorphic response (sediment loss and yield) had been observed at the plot and watershed scales (Boix-Fayos et al., 2006; Nearing et al., 2007; Smith and Wischmeier, 1965). The studies of Kim and Ivanov (2014) and Kim et al. (2016) demonstrated that potential clues to the non-uniqueness of sediment loss with respect to runoff can be elucidated by analyzing antecedent conditions of soil particle distributions: a preceding rainfall event can result in a deposited soil layer that can exhibit two conflicting roles; it can both increase and decrease soil erosion of the following event for the *same magnitude and timing* of overland flow. However, how spatial variations of watershed antecedent "hydraulic connectivity" can impact soil loss has not yet been explored.

This study advances the thread of research on why hydro-geomorphic variability caused by boundary conditions, domain properties, or variation of internal states really matters and can lead to response properties that are difficult, if ever possible, to address using a deterministic mindset. We aim to demonstrate why hydro-geomorphic response is inherently non-unique with respect to the essential hydrologic state, soil moisture. We also highlight that first-principle physics of variably saturated flow and sediment transport with spatial interactions can lead to complex nonlinear dynamics that are consistent with observed behaviors in experimental basins. Specifically, we investigate the effect of pre-storm (antecedent) soil moisture spatial distributions (three-dimensional – 3D) on the hydro-geomorphic response – the drainage outflow, overland flow, and sediment transport from a zero-order catchment.

The study builds on the hypotheses that (1) a domain with the same mean soil moisture can have distinctly different spatial