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Regionalization of subsurface stormflow parameters of hydrologic models: Up-scaling from physically based numerical simulations at hillslope scale

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SUMMARY

Subsurface stormflow is an important component of the rainfall-runoff response, especially in steep forested regions. However; its contribution is poorly represented in current generation of land surface hydrological models (LSMs) and catchment-scale rainfall-runoff models. The lack of physical basis of common parameterizations precludes *a priori* estimation (i.e. without calibration), which is a major drawback for prediction in ungauged basins, or for use in global models. This paper is aimed at deriving physically based parameterizations of the storage-discharge relationship relating to subsurface flow. These parameterizations are derived through a two-step up-scaling procedure: firstly, through simulations with a physically based (Darcian) subsurface flow model for idealized three dimensional rectangular hillslopes, accounting for within-hillslope random heterogeneity of soil hydraulic properties, and secondly, through subsequent up-scaling to the catchment scale by accounting for between-hillslope and within-catchment heterogeneity of topographic features (e.g., slope). These theoretical simulation results produced parameterizations of the storage-discharge relationship in terms of soil hydraulic properties, topographic slope and their heterogeneities, which were consistent with results of previous studies. Yet, regionalization of the resulting storage-discharge relations across 50 actual catchments in eastern United States, and a comparison of the regionalized results with equivalent empirical results obtained on the basis of analysis of observed streamflow recession curves, revealed a systematic inconsistency. It was found that the difference between the theoretical and empirically derived results could be explained, to first order, by climate in the form of climatic aridity index. This suggests a possible co-dependence of climate, soils, vegetation and topographic properties, and suggests that subsurface flow parameterization needed for ungauged locations must account for both the physics of flow in heterogeneous landscapes, and the co-dependence of soil and topographic properties with climate, including possibly the mediating role of vegetation.

1. Introduction

Due to high infiltration capacities of the soil, steep slopes, and the presence of macropores that enhance downslope water movement, subsurface stormflow is a dominant streamflow generation mechanism in steep forested regions of the world (McDonnell, 1990; Sidle et al., 2000; Fiori, 2012). However, its contribution is poorly represented in the current generation of land surface hydrological models (LSMs) and catchment-scale rainfall-runoff models. Most LSMs incorporate the role of the subsurface stormflow using various forms of parameterizations (Lee et al., 2005; Yeh and Eltahir, 2005; Huang and Liang, 2006; Huang et al., 2008). The lack of physical basis of most common parameterizations precludes *a priori* estimation (i.e. without calibration) and has provided the motivation for much research focused on the role of subsurface stormflow and groundwater dynamics on the simulation of land surface water and energy fluxes in climate models.

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Recent work by Hou et al. (2012) and Huang et al. (2013) has shown that water and energy flux predictions at the land surface with the CLM4 model were most sensitive to the subsurface runoff parameterizations (see also Niu et al., 2005, 2007). Most current LSMs do not fully account for the contribution of subsurface stormflow to total streamflow and parameters that represent subsurface stormflow are not physically based. For example, the ARNO formulation of subsurface flow (Todini, 1996), which is also embedded in the variable infiltration capacity (VIC) model (Liang et al., 1994), is empirically based and lacks physical grounds for establishing the associated parameters, which limits its extension to predict in ungauged catchments (e.g., Huang and Liang, 2006). On the other hand, most existing models of subsurface stormflow from hillslopes and small catchments are based on analytical solutions to the Boussinesq equation assuming equivalent representative values of catchment properties (e.g., Brutsaert and Nieber, 1977; Brutsaert and Lopez, 1998; Rupp and Selker, 2005, 2006). This critical review points to limitations of parameterizations of subsurface flow in current LSMs; the intention of this paper is to explore alternative approaches towards the improvement of subsurface flow parameterizations in both rainfall-runoff models and LSMs, including how to embed the effects of subsurface heterogeneity in a physically based manner.

This paper is the second of a two-part paper aimed at deriving physically based storage-discharge relations as parameterizations of subsurface stormflow, which can then be embedded in land surface models without the need to resolve the flows at smaller scales explicitly. We are looking for a catchment-scale parameterization of the form:

$$Q = aS^b \tag{1}$$

with parameters a and b that are meant to capture the net effects of the heterogeneity of soil and topographic properties. Along the way, the paper aims to (1) identify the most important landscape controls on the storage-discharge relationship and (2) use these to a develop simple prediction equation on the basis of measurable landscape characteristics that could be applied to ungauged basins on a regional basis.

One approach to developing such parameterizations is to infer these, using an inverse procedure, from catchment runoff measurements that already account for the net effects of natural variability of soil and topographic properties. It is straightforward to show that the parameters a and b of the storage-discharge relationship can be related to the parameters α and β associated with the recession slope curves (see also Ye et al., 2014):

$$\alpha = a^{1/b}b \tag{2b}$$

$$\beta = 2 - 1/b \tag{2c}$$

where the parameters α and β govern the shape of the recession-slope curve extracted from observed streamflow records. The recession-slope curve, defined by Brutsaert and Nieber (1977), describes the slope of the recession curve after cessation of rainfall, $-dQ/dt$, as a function of discharge Q, in terms of a power-function, as follows:

$$\frac{dQ}{dt} = -\alpha Q^{\beta} \tag{3}$$

In an accompanying paper, Ye et al. (2014) adopted an empirical analysis approach that capitalized on the use of recession-slope curves to derive the storage-discharge relationship. However, runoff measurements are limited to a few locations, and due to the high spatial variability of the factors that contribute to subsurface stormflow, some of which are not easy to measure, it is not straightforward to extrapolate such empirical relationships from gauged locations to ungauged ones. An alternative approach to developing these parameterizations is to use numerical simulation approaches with the use of detailed physically based hydrological models that account for known or assumed forms of spatial variability of soil and topographic properties (Robinson and Sivapalan, 1995; Duffy, 1996; Viney and Sivapalan, 2004; Lee et al., 2005). The present study falls in this latter area and builds on considerable prior research activity.

A recent study by Fiori and Russo (2007) used a three dimensional numerical model to study flow in heterogeneous hillslopes and found that discharge in the presence of heterogeneous soils is always larger than for homogeneous media with equivalent properties. Harman and Sivapalan (2009b) investigated flow through heterogeneous hillslopes and showed that the presence of heterogeneity produced responses fundamentally different from hillslopes with homogeneous soils. The role of topographic variability in controlling subsurface responses at the hillslope scale has also received increased attention in recent times (Freer et al., 1997; Troch et al., 2002, 2003; Bogaart and Troch, 2006; Fujimoto et al., 2008) since it has a considerable impact not only on the short-term dynamics of streamflow and spatial patterns of soil moisture, but in the long term it also impacts the spatial patterns of soil and vegetation properties (Bachmair and Weiler, 2012).

The present study is different from previous research in several respects: (i) it aims to derive physically based parameterizations of subsurface stormflow at the catchment scale, accounting for the effects of heterogeneity of both soil hydraulic properties and topographic slope; (ii) the two-stage up-scaling procedure adopted here (from point to hillslope, and from hillslope to catchment scales) is implemented in a comparative manner in 50 actual catchments; (iii) the parameters of the derived power-law storage-discharge relationships (a and b) are converted to (α and β) and then regionalized through derivation of multiple regression relationships with landscape soil and topographic properties, and these are then compared against corresponding expressions derived through empirical recession curve analyses on the same 50 catchments (Ye et al., 2014). In other words, the two studies approach the problem of subsurface flow parameterization from both bottom-up (this study) and top-down (Ye et al., 2014) perspectives.

2. Up-scaling methodology and data resources

The goal of this study is to derive catchment-scale closure relations in the form of storage-discharge relations at steady state that account for the net effects of spatial heterogeneity of landscape characteristics (i.e. soil hydraulic properties and topographic slope). The heterogeneity of landscape properties can be highly complex, multi-scale, and much of it (relating to the soils) unknown. For the purpose of this study we simplify the heterogeneity, without loss of generality, by considering two kinds of spatial heterogeneities: (i) within-hillslope soil heterogeneity (both random and deterministic), while topographic slope is assumed to remain uniform within the hillslope, and (ii) between-hillslope heterogeneity of topographic slope, whereas the nature of soil heterogeneity is assumed to be the same (and repeated) between hillslopes. In other words, the building blocks of the up-scaling analysis will be the population of hillslopes that constitute a catchment; for simplicity, the hillslopes will be assumed to be planar and rectangular.

Given the nature of spatial heterogeneity assumed above, the proposed work involves a two-step up-scaling procedure: (i) from the point (or local) scale to the hillslope scale, to account for within-hillslope soil heterogeneity, maintaining constancy of