Journal of Hydrology 519 (2014) 670–682

Contents lists available at ScienceDirect

Journal of Hydrology

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

Regionalization of subsurface stormflow parameters of hydrologic models: Derivation from regional analysis of streamflow recession curves

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ARTICLE INFO

Article history:
Received 1 October 2013
Received in revised form 23 June 2014
Accepted 12 July 2014
Available online 21 July 2014
This manuscript was handled by Konstantine P. Georgakakos, Editor-in-Chief, with the assistance of Yu Zhang, Associate Editor

Keywords:
Subsurface flow
Closure relations
Storage–discharge relationship
Recession–slope curve
Statistical methods

SUMMARY

Subsurface stormflow is an important component of the rainfall–runoff response, especially in steep terrain. Its contribution to total runoff is, however, poorly represented in the current generation of land surface models. The lack of physical basis of these common parameterizations precludes *a priori* estimation of the stormflow (i.e. without calibration), which is a major drawback for prediction in ungauged basins, or for use in global land surface models. This paper is aimed at deriving regionalized parameterizations of the storage–discharge relationship relating to subsurface stormflow from a top–down empirical data analysis of streamflow recession curves extracted from 50 eastern United States catchments. Detailed regression analyses were performed between parameters of the empirical storage–discharge relationships and the controlling climate, soil and topographic characteristics. The regression analyses performed on empirical recession curves at catchment scale indicated that the coefficient of the power-law form storage–discharge relationship is closely related to the catchment hydrologic characteristics, which is consistent with the hydraulic theory derived mainly at the hillslope scale. As for the exponent, besides the role of field scale soil hydraulic properties as suggested by hydraulic theory, it is found to be more strongly affected by climate (aridity) at the catchment scale. At a fundamental level these results point to the need for more detailed exploration of the co-dependence of soil, vegetation and topography with climate.

1. Introduction

Land surface processes are an integral part of the Earth system. By regulating surface moisture and heat fluxes, land surface processes can provide important feedbacks to climate and influence the regional and global hydrologic cycle (e.g., Koster et al., 2004; Seneviratne et al., 2010). To improve predictions of future climate, it is crucial to understand and constrain uncertainty stemming from parameterizations used in land surface models (LSMs). Recently Hou et al. (2012) and Huang et al. (2013) used an uncertainty quantification framework to assess hydrologic parameter uncertainties in Version 4 of the Community Land Model (CLM4) (Lawrence et al., 2011). Applying their framework to 13 flux towers and 20 catchments across the US spanning a wide range of climate and landscape characteristics, they found that the simulated land surface water and energy fluxes as well as runoff showed the largest sensitivity to parameters related to subsurface runoff generation (Niu et al., 2005, 2007). This highlights the need to improve subsurface runoff generation schemes in LSMs at the hillslope scale.

As shown by several previous studies, subsurface runoff generation can be parameterized using storage–discharge relationships of a power law form, which can capture the asymmetric response of subsurface hydrologic processes to floods and droughts (e.g., Eltahir and Yeh, 1999; Liang et al., 2003). Such parameterizations, including the TOPMODEL approach (Beven and Kirkby, 1979; Beven et al., 1984; Beven, 1997) included in CLM4 and the ARNO model (Francini and Pacciani, 1991; Todini, 1996), are now widely

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http://dx.doi.org/10.1016/j.jhydrol.2014.07.017
0022-1694/

used in LSMs (e.g., Liang et al., 1994; Huang and Liang, 2006; Warrach et al., 2002; Niu et al., 2005, 2007; Oleson et al., 2010, 2013; Ringeval et al., 2012), although each approach still suffers from limitations and can be further improved. Recent reviews on the advantages and disadvantages of these parameterizations can be found in Huang and Liang (2006), Huang et al. (2008), and Li et al. (2011). A particular challenge in applying these parameterizations in Earth system models is the limited availability of naturalized streamflow data for calibrating model parameters globally, and reducing the dependence of parameterizations on calibrations is a key requirement. This is the first of a two-part paper (the other being Ali et al., 2014) that aims towards developing improved parameterizations of shallow subsurface flow for land surface models such as CLM4, expressed in terms of the power-law form of a lumped storage–discharge relationship:

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

where Q is subsurface flow and S is saturated subsurface storage. To be consistent with recession curves observed at the catchment outlet, Q and S are also defined at the catchment scale with Q as the aggregated subsurface flow and S as the average storage for the whole catchment. As a result, a and b are parameters that represent the aggregated effects of land surface heterogeneity (i.e., of both soil hydraulic properties and topography) at the catchment scale. Ideally, for subsurface flow to be predicted using Eq. (1) without calibration (e.g., in ungauged basins or landscapes), the parameters a and b must be estimated *a priori* on the basis of measurable landscape characteristics. Such a parameterization of the subsurface flow must capture the effects of soil and landscape properties in a simple way, accounting for the effects of spatial heterogeneity without the need to resolve flows at smaller scales explicitly. This is the motivation for the work behind this paper. We have approached this estimation problem from two alternative perspectives: (i) empirical (top–down), and (ii) theoretical (bottom–up).

The theoretical (or bottom–up) approach (see accompanying paper by Ali et al., 2014) involves the use of numerical simulations that help to derive closure relations through application of detailed, distributed physically based hydrological models using appropriate boundary conditions and assumed forms of spatial variability of soil and topographic properties (Robinson and Sivapalan, 1995; Viney and Sivapalan, 2004). We categorize the spatial heterogeneities entering the problem here as (i) within hillslope, where the heterogeneity is assumed to relate to soil only, and topography is taken to be constant, and (ii) between hillslopes, where the heterogeneity arising from topography is explicitly resolved, while the effects of within-hillslope heterogeneity of soil properties is parameterized from (i). The theoretical approach of Ali et al. (2014) is based on Richards equation based simulations at the hillslope scale, parameterizing the effects of within-hillslope heterogeneity and their subsequent up-scaling to the catchment scale, incorporating the effects of topographic variability between hillslopes.

The empirical (or top–down) approach (the subject of this paper) involves (i) making inferences of the storage–discharge relationships, and associated parameters a and b, directly at the catchment scale on the basis of analysis of observed streamflow recession curves in a large number of catchments, followed by (ii) multiple regression analyses of the estimated recession parameters a and b against measurable climatic and landscape (soils and topography) characteristics.

The streamflow recession curve (Brutsaert and Nieber, 1977) is one of the most widely used catchment runoff signatures, and provides insights into the subsurface flow generation processes (Tague and Grant, 2004). By measuring how river flow recedes at the end of a storm event, it can reveal the internal hydrologic dynamics at catchment scale as a holistic measure of the catchment's drainage characteristics (Troch et al., 2013). Many studies have been conducted to interpret the recession flow based on hydraulic groundwater theory, such as the Boussinesq equation (Troch et al., 2013). For convenience, the recession behavior of the catchment is often expressed in terms of the so-called recession–slope curve, the relationship between the rate of decline rate of flow ($-dQ/dt$) and Q:

$$-\frac{dQ}{dt} = \alpha Q^{\beta} \tag{2}$$

Note that the parameters α and exponent β may vary with time during the year due to the effect of seasonality of evaporation loss (Wittenberg and Sivapalan, 1999; Shaw and Riha, 2012), which can be minimized by focusing on periods when evaporation is minimal (e.g., winter) or by explicitly accounting for the evaporation loss. Provided this is done, it can then be deemed a unique signature of the catchment response. The coefficient α and exponent β can be directly estimated from observed recession curves by curve fitting, and reflect the net effects of the population of hillslopes (of various sizes and shapes) and the soils that constitute the catchment.

Considerable work has been carried out to derive analytical solutions to the Boussinesq equation governing saturated subsurface drainage from an unconfined homogeneous aquifer into the river below to aid the deciphering of the physical meaning and controls of both recession parameters α and β. Several studies have explored the effects of catchment-scale heterogeneity on the shape of the recession curves. These theoretical studies suggest that the shapes of the recession curves are strongly affected by soil hydraulic conductivity and its vertical and horizontal (downslope) heterogeneity (Rupp and Selker, 2005, 2006a,b; Troch et al., 2008; Harman et al., 2009). Landscape geomorphologic features too can contribute to the shape of the recession curves (Biswal and Marani, 2010; Harman et al., 2009; Lyon and Troch, 2010). However, due to the many simplifying assumptions and lack of data, most of the pioneering studies in this area have been largely theoretical, and only a few went further and validated the equations derived on the basis of the recession curves in real catchments (Harman et al., 2009; Lyon and Troch, 2010).

The storage–discharge relationship that we are interested in can be derived from the recession–slope curve in a straightforward manner by utilizing the relationship that exists between parameters a and b of the storage–discharge relationship and the parameters α and β of the recession–slope curve. From Eqs. (1) and (2), we obtain the derivative of storage (S):

$$\frac{dS}{dt} = \frac{d}{dt}\left\{\left(\frac{Q}{a}\right)^{1/b}\right\} = \frac{Q^{1/b-1}}{ba^{1/b}}\frac{dQ}{dt} = -\frac{\alpha}{ba^{1/b}}Q^{1/b-1+\beta} \tag{3}$$

When the impact of evaporation is negligible, $dS/dt = -Q$, and combining this with Eq. (3) yields:

$$a = [\alpha(2-\beta)]^{1/(2-\beta)} \tag{4a}$$

$$b = \frac{1}{2-\beta} \tag{4b}$$

In this study, we explore the nature of the storage–discharge relationship and its controls through empirical analysis of the recession curve data from hundreds of catchments across the continental United States, and their connection to measureable catchment characteristics such as topography, soil properties, and other geomorphologic features.

The theoretical (or bottom–up) approach will follow in the second paper of the series (Ali et al., 2014), which can yield results that are physically consistent, but their applicability in actual catchments is hampered by our inability to fully characterize the