Journal of Hydrology 418–419 (2012) 90–109

Contents lists available at ScienceDirect

Journal of Hydrology

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

Comparative diagnostic analysis of runoff generation processes in Oklahoma DMIP2 basins: The Blue River and the Illinois River

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ARTICLE INFO

Article history:
Available online 12 August 2010
This manuscript was handled by Konstantine P. Georgakakos, Editor-in-Chief, with the assistance of Michael Bryan Smith, Associate Editor

Keywords:
Comparative hydrology
Diagnostics
Signatures
Runoff generation
Spatio-temperal pattern

SUMMARY

This paper presents the results of a comparative diagnostic study of runoff generation processes in two test basins in Oklahoma: The Blue River at Blue and the Illinois River near Tahlequah. This study involves analysis of signatures of spatio-temporal runoff variability, extracted from both observed rainfall–runoff data and from predictions of a distributed, physically based rainfall–runoff model. Analysis of observed data in both basins indicates that event runoff coefficients are systematically higher in the wet season than in the dry season. Model predictions indicate that the transition from high to low runoff coefficients in the Blue River basin is linked to variations of water table depth and surface soil moisture, contributing to a seasonal switching of surface runoff generation mechanisms, from saturation excess to infiltration excess. In the Illinois River basin, however, due to more permeable soils, infiltration excess runoff occurs rarely. The differences in intra-annual patterns of runoff coefficients and runoff generation mechanisms can be partly explained by the seasonality of climate forcing and water table position. Despite the significant differences of runoff generation mechanisms between the two basins, spatial analysis of the model results reveals that in both watersheds, but especially so in the more humid Illinois River basin, saturation excess runoff and subsurface stormflow coexist in competition throughout the year. This competition is quantitatively shown to be controlled by the relative magnitudes of the saturated hydraulic conductivity of the soils and the topographic slope. In addition, the spatial variabilities of runoff generation processes also impact the spatial scaling behavior of runoff ratios, indicating the existence of a threshold watershed size beyond which the variability is averaged out.

Published by Elsevier B.V.

1. Introduction

Improved understanding of the hydrological functioning of catchments has become the primary focus of recent hydrologic studies, especially in the context of "predictions in ungauged basins". One approach to generating this understanding is through inter-comparisons of hydrological responses of catchments located in different hydro-climatic regions (Sivapalan et al., 2003). Some recent examples of comparative hydrologic studies include Atkinson et al. (2003), Farmer et al. (2003), Smith et al. (2004), Yang et al. (2007), van Werkhoven et al. (2008), Samuel et al. (2008), Oudin et al. (2008), Breuer et al. (2009), Kling and Nachtnebel (2009) and De Aráujo and Piedra (2009). Collectively, these studies and others help define and contribute to the emerging discipline of comparative hydrology, envisioned by Falkenmark and Chapman (1989).

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0022-1694/$ - see front matter Published by Elsevier B.V.
doi:10.1016/j.jhydrol.2010.08.005

Comparative hydrological studies can take many forms. Firstly, they may involve comparative analyses of observed data, including from field studies in experimental catchments, through comparison of key signatures of hydrologic variability extracted from the data. For example, Yang et al. (2007) carried out extensive comparative analysis of the inter-annual variability of annual water balance based on long time series of rainfall, radiation and runoff from 108 non-humid catchments in China. De Araujo and Piedra (2009) carried out a comparative data-based study of two small tropical watersheds to understand the relative impacts of climate and landscape factors on the similarity and differences in their rainfall-runoff behavior.

Secondly, they may involve comparative studies where rainfall-runoff data in just one catchment is used to perform model inter-comparison studies, with a view to generating insights into catchment functioning through comparisons of model performances. For example, Kling and Nachtnebel (2009) present a comparative case study of two conceptual water balance models using different spatio-temporal discretizations in a large mountainous catchment in southern Austria. Breuer et al. (2009) presented the results of the LUCHEM project, which was aimed at assessing the impact of land use change on water balance through the use of ensemble modeling.

Finally, the comparative studies may adopt an approach where a single model is applied to a number of catchments in different hydro-climatic regions with a view to learning from differences in catchment responses, and to exploring their physical basis through diagnostic studies with the chosen model. Atkinson et al. (2003) carried out a comparative modeling analysis of four small catchments located in a relatively moderate climate in New Zealand and found that streamflow responses of drier catchments are more sensitive to soil properties (e.g., field capacity) than in wetter catchments. In a recent study, Samuel et al. (2008) used a common conceptual model to explore interactions between climate variability and landscape factors that control water balance variability in three diverse regions of Australia: Perth (temperate with distinct dry summers); Newcastle (temperate with no distinct dry season); and Darwin (tropical, affected by monsoons). In a recent study, Ivanov et al. (2004) applied a distributed hydrologic model based on the triangulated irregular network (TIN) approach to several basins in Oklahoma and Kansas region. As a demonstration of the value of fully-distributed models for hydrological forecasting, they presented spatio-temporal variabilities of runoff generation rates, evaporative flux, water table etc., and related these variabilities to landscape characteristics such as topography and soils.

The work presented in this paper falls in the last of these categories, and is a contribution to the ‘‘distributed model inter-comparison project’’, or DMIP, organized by the National Oceanic and Atmospheric Administration (NOAA), l National Weather Service. The first phase of DMIP project, or DMIP1, was completed in 2004 (Smith et al., 2004), and represented a broad comparison of a number of distributed models, amongst themselves, and comparison against a lumped model, in terms of their ability to predict basin outflow hydrographs of the type crucial for flood forecasting. Recently, the second phase of the DMIP project, or DMIP2, has been completed with an expanded set of questions, together with extensions to more complex catchments (Smith et al., in press). The work presented in this paper is focused on addressing one of the key scientific questions addressed by the DMIP2 project, as outlined in Smith et al. (in press), namely, ‘‘the nature of spatial variability of rainfall and basin physiographic features, and the effects of their variability on runoff generation processes’’. Our work is complimentary to the distributed modeling work carried out by Ivanov et al. (2004) on some DMIP study catchments.

Whereas the comparative studies reviewed in the sections above generated valuable insights into the effects of climatic conditions and landscape properties on the total runoff response, much less effort has been devoted to comparative analyses with respect to runoff generation mechanisms. Globally, it is generally acknowledged that infiltration excess (Hortonian) overland flow, saturation excess (Dunne) overland flow and subsurface stormflow are the three mechanisms contributing to runoff generation, the relative dominance of each being controlled by climatic conditions and landscape properties (Horton, 1935; Dunne, 1978). In a recent study, Yokoo et al. (2008) found that a switch from subsurface stormflow to surface runoff dominance occurs under a unique combination of soil type and topographic slope, which itself is affected by the relative seasonality of precipitation and potential evaporation. Vivoni et al. (2007) used a fully distributed hydrological model, with spatially uniform rainfall events, to show that the nonlinearity of the runoff generation mechanisms is strongly related to the storm characteristics and the antecedent soil wetness. Moreover, they reported the scaling behavior of event runoff coefficients. In an earlier study, Reggiani et al. (2000) used several dimensionless similarity variables, derived from watershed-scale conservation equations, to examine the climate, soil and topographic controls on annual water balance partitioning, i.e., the partitioning of rainfall into evaporation, subsurface runoff and surface runoff. The studies by Yokoo et al. (2008) and Reggiani et al. (2000), nevertheless, involved the use of hypothetical watersheds in a lumped manner. In contrast to these previous studies, the present work will go further to explore, through model diagnostic analyses, the effects of climate, soil and topography on the spatial–temporal variability of runoff generation mechanisms in actual watersheds. The work of Vivoni et al. (2007) focused on event scale dynamics, and our work will mainly focus on long-term variation of runoff response, i.e., annual and seasonal.

This paper will present results of a comparative diagnostic analysis of two catchments in Oklahoma with the use of THREW, a semi-distributed, physically based model that is based on the REW approach (Reggiani et al., 1998, 1999; Tian, 2006; Tian et al., 2007). The two chosen study catchments belong to the DMIP2 project (Smith et al., in press). Although the two catchments are located in the same State, there are differences in climate, soils, vegetation, topography, and underlying regional groundwater systems. The comparative analyses will explore how these differences, and any similarities, manifest themselves in differences and similarities in runoff generation responses of the two catchments. The diagnostic analyses presented will utilize key signatures of runoff variability extracted from data and from simulations with the model, in order to gain insights into the functioning of the watersheds, which may be the key to evaluating the performance and physical realism of the model. Examples of signatures that have been used in previous work include the cross-covariance structure between rainfall and runoff time series (Vogel and Sankarasubramanian, 2003), streamflow recession curves (Rupp and Selker, 2006), mean monthly variation of runoff (i.e., regime curve) and the flow duration curve (Farmer et al., 2003; Wagener et al., 2007). In this paper we will use one of these signatures, i.e., the regime curve, and will also introduce others, such as intra-annual and spatial variability of runoff generation mechanisms and event-scale runoff coefficients, to gain more insights into the unique features of each of the two catchments' responses. Benefiting from the fact that THREW is a spatially distributed physically based model the paper will especially focus on spatial patterns of runoff generation responses, including the breakdown into different runoff generation mechanisms, and the interacting roles of climate, soils and topography that govern the relative dominance of each of these mechanisms.

The remainder of this paper is organized into five sections, as follows. Section 2 introduces the study catchments and the data used in this study. Section 3 describes the methods adopted to conduct the investigation, including essential details of the THREW model, and the extraction of characteristic signatures of runoff variability. Section 4 presents a comparative analysis of the temporal variability of runoff responses within the two basins and their process controls. Section 5 examines the spatial variability of runoff responses within and between the two basins, and explores their underlying physical causes. Finally, Section 6 will present a summary of the main results, and a discussion of the implication of these results for further improvement of the model as well as their possible validation through detailed field observations.

2. Study areas and data collection

2.1. Study areas

The two study basins are a subset of a number of study basins of the Distributed Model Inter-comparison Project – Phase 2 (DMIP2) (Smith et al., in press). The Blue River basin is located in Blue in

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