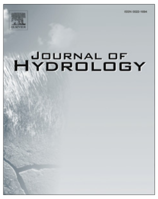
Journal of Hydrology 523 (2015) 1–13

Contents lists available at ScienceDirect

Journal of Hydrology

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



Organized variability of surface runoff responses across neighboring hillslopes in Iowa

Bo Chen [a,b,*], Witold F. Krajewski [b], Xiaobo Zhou [c], Matthew J. Helmers [c]

[a] State Key Laboratory of Earth Surface Processes and Resource Ecology, Haidian District, Beijing Normal University, Beijing, China
[b] IIHR-Hydroscience & Engineering, The University of Iowa, Iowa City, IA, USA
[c] Department of Agricultural and Biosystems Engineering, Iowa State University, Ames, IA, USA

ARTICLE INFO

Article history:
Received 8 August 2014
Received in revised form 3 November 2014
Accepted 17 January 2015
Available online 28 January 2015
This manuscript was handled by Konstantine P. Georgakakos, Editor-in-Chief, with the assistance of Ana P. Barros, Associate Editor

Keywords:
Variability
Distributed hydrologic model
Hillslope
Spatial pattern
Organization
Randomness

SUMMARY

Characterizing the spatial and temporal variability of small scale runoff responses is essential to distributed hydrologic modeling. To explore the variability of runoff responses, we analyzed surface runoff hydrographs from 12 neighboring hillslopes in central Iowa, USA that were observed for 72 runoff events over a four-year period. These agricultural experimental hillslopes receive various prairie filter strip treatments and drain areas ranging from 0.48 to 3.19 ha. The distances between them vary from tens of meters to about 3 km. We compared the hydrographs from the remaining 11 hillslopes to the hydrograph at the benchmark hillslope (i.e., hillslope B6 with no treatment). The results showed that: (1) for any individual event in which noticeable surface runoff occurred, the hydrographs from these hillslopes had similar shapes but different magnitudes; (2) for any paired hillslopes, the shape similarity persisted, but the scaling factor (the regression slope between two flow series) changed across events; and (3) for any runoff event, no simple relationship exists between the spatial variation of the scaling factor and the slope, slope length, area, and prairie strip width at the footslope of the hillslopes. Interestingly, we found that for 9 out of the 11 paired hillslopes, 40–70% of the temporal variation in the scaling factors can be explained by the antecedent wetness condition and the maximum hourly rain accumulation. These results suggest that the small-scale surface runoff responses are spatially variable but organized linearly, i.e., shape similarity (or linearity) in space is another feature of the small-scale runoff process. This phenomenon seems to result from the spatial vicinity and small-scale spatial variability of rainfall intensity and antecedent soil moisture.

1. Introduction

Variability in space and time is fundamental to the science and practice of hydrology. Three common approaches that can be used to study the variability of hydrologic responses are: (1) comparing the hydrologic responses to various atmospheric forcings observed at a fixed experimental watershed, which allows the examination of the temporal variability of hydrologic responses; (2) comparing the hydrologic responses observed at places with contrasting climates or physiographic conditions, i.e., investigating the space–time variability of hydrologic responses; and (3) comparing the hydrologic responses to similar atmospheric forcings observed at watersheds with spatial proximity, which facilitates the study of the spatial variability of hydrologic responses. It seems that, due to the relative ease with which we can measure at high temporal resolution for a long time period, many aspects of the temporal variability of hydrologic responses can be better understood. For example, by adopting the first method, the nonlinearity of hydrologic responses has been recognized. This widely accepted nonlinearity emphasizes the dynamical property of the rainfall–runoff relationship at a site, and it arises from the dependence of the storm response on antecedent conditions and rainfall inputs (e.g., Minshall, 1960; Grayson et al., 1997; Sivapalan et al., 2002; Zehe and Bloschl, 2004; Tromp-van Meerveld and McDonnell, 2006; Graham et al., 2010). Many applications of the second method, i.e., comparing the hydrologic responses observed at different places (e.g., Chapman and Falkenmark, 1989; Whitehead and Robinson, 1993; Jones, 2006), have demonstrated that the hydrologic processes at the hillslope scale are rich in complexity and heterogeneity. For example, different runoff generation mechanisms exist (Horton, 1933; Betson, 1964; Hewlett and Hibbert, 1967; Dunne and Black,

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* Corresponding author at: State Key Laboratory of Earth Surface Processes and Resource Ecology, Beijing Normal University, Haidian District, Beijing 100875, China. Tel./fax: +86 10 58808179.

E-mail address: bochen@bnu.edu.cn (B. Chen).

http://dx.doi.org/10.1016/j.jhydrol.2015.01.038
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1970; Weyman, 1970; Uchida et al., 2005; Scherrer et al., 2007; Kienzler and Naef, 2008a; de Araújo and González Piedra, 2009; Beven, 2012).

However, applying the third method in the field is rarely done due to the difficulties inherent in making comprehensive spatial measurements covering an area large enough and a period long enough to be hydrologically meaningful. One example of the implementation of the third method was conducted by Bachmair et al. (2012), who examined the effects of vegetation cover on the subsurface flow processes at neighboring hillslopes with similar slope, exposure, curvature, geologic, and pedologic properties but different vegetation cover. The third method has the potential to answer the question – what is the relationship between hydrologic responses that triggered by similar patterns of rainfall but that originate from different geographic vicinities? A good understanding of this issue would be particularly helpful for distributed hydrologic modeling for a specific region. Distributed hydrologic models attempt to represent hydrological variability by partitioning watersheds into multiple computational elements. Examples of such computational elements are the representative elementary watershed (REW) (e.g., Hubbert, 1957; Wood et al., 1988; Reggiani et al., 1998), hillslopes (e.g., Band, 1986; Yang et al., 2002; McGlynn and Seibert, 2003; Mantilla and Gupta, 2005) and regular grids (e.g., Liang et al., 1994; Arnold et al., 1998). However, the challenge remains in characterizing the spatial variability of the hydrologic response between elements (e.g., hillslopes). Applying the third method in the field, which would allow exploration of the organization (or pattern) of the spatial variability of hillslope hydrologic responses at the event scale (hours), is the first step in addressing this question.

In this study, we investigated the spatial variability of surface runoff responses at the event scale (~few hours), i.e., how runoff responses are related across multiple instrumented hillslopes. We used a unique data set of 5 min runoff records over 12 agricultural experimental hillslopes in central Iowa, USA. These hillslopes are clustered into three blocks, and the distances between the clusters are about 2 km. The hillslopes within each cluster are close to each other and drain areas ranging from 0.48 to 3.19 ha.

We used the inter-site comparison method. By pairing the hillslopes with a benchmark (reference) hillslope, we investigated the relationships of surface runoff processes at the event scale. We are concerned with both the similarity and dissimilarity of the hydrologic responses. Our comparison of neighboring hillslopes alleviates the common challenge of the inter-site comparison technique, i.e., its difficulty in differentiating whether the variability in hydrologic responses is caused by different underlying basin response mechanisms or variations in affecting factors that include but are not limited to rainfall forcings, soil properties, topology, and geology.

We adopted the lagged regression method, which is a well-established approach to describe and model the relationship between two time series and to quantify the association between the rainfall–runoff behaviors of paired hillslopes. In contrast to the commonly used runoff ratio, peak discharge, and total runoff volume-based inter-site comparison, the lagged regression technique provides information about the relationship between the hydrologic responses at paired hillslopes from the perspectives of both magnitude and shape.

In all, the large number and the spatial vicinity of these monitored hillslopes allow us to study the relationship between rainfall–runoff responses across hillslopes. We first evaluate the variability/similarity of the hydrographs of these neighboring hillslopes for individual runoff events and subsequently investigate how this variability/similarity in hydrologic responses from these hillslopes varies in space and time. Finally, we explore the factors that control the characteristics of the hydrologic variability/similarity between these hillslopes.

2. Study site and data

2.1. Site description

We use the data sample collected from three clusters of hillslopes that are designed and maintained by the ecohydrology research group at Iowa State University (Helmers et al., 2012; Hernandez-Santana et al., 2013). A total of twelve hillslopes (Basswood (B1–B6), Interim (I1–I3), and Orbweaver (O1–O3)) were selected in the Neal Smith National Wildlife Refuge in central Iowa (Fig. 1). Their sizes range from 0.48 to 3.19 ha. These hillslopes are distributed in three clusters and are monitored to evaluate the benefits, in terms of enhancing water quality, of integrating prairie filter strips (PFS) into row crop agriculture. They are majorly farmland and receive various treatments that are specified by the amounts and the planting positions of the PFSs (Table 1). The PFSs were seeded on 7 July 2007. Starting in spring 2007, a two-year, no-till corn–soybean rotation (soybeans in 2007) was grown over these hillslopes. The soil properties and agricultural management are similar over these hillslopes. Annual precipitation in the study area is about 900 mm, and the majority occurs from May through August. A detailed description of these hillslopes and the experiments can be found in Helmers et al. (2012).

2.2. Surface runoff and rainfall measurements

The surface runoff at the bottom of each hillslope was measured by a fiberglass H-flume (Fig. 2) at 5 min intervals dating back to 2007. Eight 0.61 m H-flumes and four 0.76 m H-flumes were installed according to the sizes of the hillslopes. Plywood wing walls (5 m at each side of a flume) were constructed at the bottom of each hillslope to guide surface runoff to the flumes (Helmers et al., 2012). These hillslopes are drained by poorly defined ephemeral channels. In order to avoid the extensive disturbance due to site equipment malfunction, we did not use the data observed in 2007. We analyze the hydrograph of specific discharges (have units of (L/T), i.e., the average contribution of drained areas to the outflow discharge) at the bottom of each hillslope. We use the rainfall data collected at a U.S. Climate Reference Network weather station that is maintained by the National Oceanic and Atmospheric Administration (NOAA), which is 1.1–3.3 km from the hillslopes. This distance is greater than the spatial scale of the variability of convective storms. The observational frequency is 5 min for rainfall that occurred from 2008 to 2011. Another nearby weather station operated by the National Weather Service, which is 1.3–3.6 km from the hillslopes, collects hourly rainfall data. Our comparison at the hourly time scale revealed that the rainfall data from these two stations are highly correlated with limited differences, which indicates relatively similar storm events over this small region. This is consistent with the analysis by Helmers et al. (2012).

2.3. Soil moisture data

Hourly soil moisture data were also collected from 2010 to 2011 at the same NOAA weather station (Fig. 2). Soil dielectric permittivity values are measured by the Hydra Probe soil water sensors that are installed in a vertical profile at depths 5 cm, 10 cm, 20 cm, 50 cm, and 100 cm and are then converted to volumetric soil moisture content using an empirical relationship (Seyfried et al., 2005). We calculated the depth-weighted soil moisture contents for the top 10, 20, and 50 cm layers at the weather station based on the point measurements. Prior to the runoff events investigated in this study, the maximum depth-weighted soil moisture content (m^3/m^3) for the top 10, 20, and 50 cm layers were 50%, 51%, and 54% and the minimums were 29%, 33%, and 37%, respectively.