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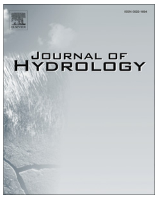

Rainfall organization control on the flood response of mild-slope basins

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SUMMARY

This study uses a long-term (8 years) dataset of radar-rainfall and runoff observations for the Tar River Basin in North Carolina, to explore the rainfall space–time organization control on the flood response of mild-slope (max slope <32 degrees) basins. We employ the concepts of "spatial moments of catchment rainfall" and "catchment scale storm velocity" to quantify the effect of spatial rainfall variability and basin geomorphology on flood response. A calibrated distributed hydrologic model is employed to assess the relevance of these statistics in describing the degree of spatial rainfall organization, which is important for runoff modeling. Furthermore, the Tar River Basin is divided into four nested sub-basins ranging from 1106 km^2 to 5654 km^2, in order to investigate the scale dependence of results. The rainfall spatio-temporal distribution represented in the analytical framework is shown to describe well the differences in hydrograph timing (less so in terms of magnitude of the simulated hydrographs) determined from forcing the hydrologic model with lumped vs. distributed rainfall. Specifically, the first moment exhibits a linear relationship with the difference in timing between lumped and distributed rainfall forcing. The analysis shows that the catchment scale storm velocity is scale dependent in terms of variability and rainfall dependent in terms of its value, assuming typically small values. Accordingly, the error in dispersion of simulated hydrographs between lumped and distributed rainfall forcing is relatively insensitive to the catchment scale storm velocity, which is attributed to the spatial variability of routing and hillslope velocities that is not accounted by the conceptual framework used in this study.

1. Introduction

The prediction of catchment flood response is one of the recurrent themes in hydrology (Nicótina et al., 2008; Smith et al., 2004; Woods and Sivapalan, 1999). A question asked is that, given certain catchment and precipitation characteristics, what are the dominant processes in flood response? In practical terms, operational flood and flash flood guidance systems are based on continuous hydrological models that provide catchment-scale soil moisture estimates representing the antecedent moisture conditions at spatial scales closer to the need of flash flood forecasting (Carpenter et al., 1999). Based on these antecedent moisture conditions, it is possible to provide an estimate of rainfall depth for a given duration that can lead to flooding without explicitly modeling the event dynamics (Georgakakos, 2005; Reed et al., 2004). At the ground of flood/flash flood guidance is the computation of the basin-average rainfall for a given duration that is necessary to cause flooding.

The fundamental problem facing flood modeling associated with flash flood guidance (FFG) is that small to medium size basins prone to flash floods are rarely gauged. Lack of runoff data strongly impact upon the flash flood predictive power, because data requirements to achieve accurate hydrological prediction increase with decreasing temporal and spatial scales of prediction (Merz and Blöschl, 2004). This is because at small spatial scales runoff tends to be more tightly linked to details of landscape structure, thereby exhibiting greater space-time variability and hampering parameter regionalization and scaling (Merz and Blöschl, 2004). At greater spatial scales, in contrast, much system heterogeneity is subsumed and averaged, thus often leading to simpler catchment response to precipitation forcing (Sivapalan et al., 2003). Owing to these reasons, forecasting of flash flood response relies on basin-average rainfall information and the parameterized response of the larger scale, parent basins. On the other hand, several past studies have indicated the basin flood response is sensitive to the spatial rainfall patterns (Lobligeois et al., 2013; Viglione et al., 2010a; de Lima and Singh, 2002; Naden, 1992; Wood et al., 1988; Wilson et al., 1979; Dawdy and Bergmann, 1969). Therefore, from the perspective of developing effective flood forecasting

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systems, it is important to develop a consistent framework to quantify the effects of space–time rainfall aggregations on the prediction accuracy of flood response for different basin and storm characteristics (Parajka et al., 2010; Zoccatelli et al., 2010; Saulnier and Le Lay, 2009; Norbiato et al., 2008; Borga et al., 2007; Merz and Blöschl, 2003).

An important feature frequently reported in hydrologic modeling studies is the catchment dampening effect, which is often interpreted as the property of the catchment to filter out specific space–time characteristics of the precipitation input in the flood response (Skøien and Blöschl, 2006; van De Giesen et al., 2000; van Loon and Keesman, 2000). Therefore, only a portion of rainfall space–time characteristics (e.g. spatial concentration in specific catchment regions and storm motion) will emerge to control the hydrograph shape (Skøien et al., 2003). As shown in a number of works (Smith et al., 2005, 2002; Woods and Sivapalan, 1999), the river network geometry plays an essential role in the structure of the catchment smoothing properties. Therefore a flow distance coordinate, i.e. the coordinate defined by the distance along the runoff flow path to the basin outlet, has been introduced with the aim of providing information on rainfall spatial organization relative to the basin network structure as represented by the routing time (Borga et al., 2007; Smith et al., 2005; Zhang et al., 2001). Similar works (Smith et al., 2005, 2002) have developed dimensionless normalized indicators based on the flow distance coordinate in terms of either routing time or length of flow path (e.g. normalized flow distance, normalized dispersion) and used them for quantifying the geomorphologic driven spatial rainfall patterns. Zanon et al. (2010) showed that the normalized time distances and normalized time dispersion of a severe storm event at four small size cascade basins (less than 150 km^2) with complex terrain structure had a value very close to one while similar results were also exhibited in Sangati et al. (2009). Sangati et al. (2009) additionally showed that the normalized time distance and dispersion have a considerable increase for basin sizes exceeding 500 km^2. Beside the normalized time distance and dispersion, the concept of rainfall movement has been developed to quantify theoretically and experimentally the combined effect between the rainfall space–time properties and basin geomorphology. Viglione et al. (2010b) applied the analytical framework developed in Viglione et al. (2010a) and concluded that due to the high spatial heterogeneity properties of short-rain event, the roles of movement component of flood inducing complex terrain storms can be important in runoff generation; and that for the more spatially uniform long-lasting rain events, the movement component is weak in influencing the hydrograph. Seo et al. (2012) on the other hand has shown that storm motion may have significant impact even for long-lasting precipitation events.

In a recent work, Zoccatelli et al. (2011) derived a statistic term named "catchment scale storm velocity", which accounts for the combined effects of total storm motion and temporal storm variability over catchment. The scale dependency of this statistic was further examined by Nikolopoulos et al. (in press) who showed strong nonlinearity and low value based on a single flash flood event. These studies on "catchment scale storm velocity" were focused on a limited number of short-living flood events occurring in small catchments. For this type of floods and basin sizes, differences between the assumptions in the method and the event characteristics are deemed to be small; therefore, the method may be applied to represent the effect of spatial rainfall aggregation on flood modeling. In this work, the method is applied on a large number of moderate storm intensity, long-lasting flood events occurring over large (greater than 1000 km^2) and mild-slope (max of slope less than 32° with mean at around 3°) catchments from the Tar River Basin in North Carolina. Our aim is to test the representation of "spatial moments of catchment rainfall" and "catchment scale storm velocity" reported in Zoccatelli et al. (2011) as potential metrics for quantifying the effect of rainfall organization and storm motion on the hydrologic response and to analyze the impact of some of its assumptions (e.g. uniform runoff routing velocity). In Section 2 we present the study area and data used in our analysis. Section 3 summarizes the analytical framework of Zoccatelli et al. (2011), while Section 4 presents the numerical experiments used to determine the two methods, and evaluates the correlations of those statistics to the hydrologic modeling error metrics. Conclusions and recommendations for further research are provided in Section 5.

2. Study area and data

2.1. Tar River Basin

The target area of this study is the Tar River Basin in North Carolina, USA. The Tar River originates in Person County as a freshwater spring and flows 225 km southeast to Washington, NC. The main stem of the upper river flows through Louisburg, Rocky Mount, Tarboro and Greenville and provides drinking water for these communities. Its major tributaries are Swift, Fishing and Tranters creeks and Cokey Swamp. The area within this basin is relatively undeveloped. Agriculture accounts for 33.6% of the land use while the rest includes mainly forests (29.6%), open water (19.7%), and wetlands (11.4%). Urban lands and scrub growth accounts for 5.2% of the land usage. Fig. 1 shows the location and elevation of the Tar River Basin. The basin is characterized by mild slopes (Table 1) and elevations ranging between 4 m a.s.l. (above sea level) close to the outlet on the southeast to about 225 m a.s.l. near the headwaters on the northwest. The study area was divided into four cascade basins namely B1, B2, B3, and B4 (shown in Fig. 1). Drainage areas for the four basins are approximately 1106, 2012, 2396, and 5654 km^2, respectively. Table 1 summarizes some basic statistics on local slope and flow length distribution, derived from available elevation dataset (10 feets) for each basin. Note that slope values reported corresponds to the steepest downhill descent for each point and flow length is equal to the distance, along the runoff flow path, from a given point to basin outlet.

2.2. Rainfall data

Rainfall information was based on the US National Weather Service (NWS) Multisensor Precipitation Estimation (MPE) rainfall product available at 4 km/hourly spatiotemporal resolution. MPE data are derived from a blend of automated and interactive procedures that combine information from satellite, the WSR-88D radar network and rain gauges (Fulton, 2002; Breidenbach and Bradberry, 2001). Hourly MPE data are available for the Southeast River Forecast Center (SERFC) region at HRAP (Hydrologic Rainfall Analysis Project) resolution since January 2002. The nominal size of an HRAP grid cell in the area is about 4 km (Reed and Maidment, 1999; Greene and Hudlow, 1982). A total of eight years of data (2002–2009) were analyzed for this work. Among the eight years, 2003 was the wettest, which had 1260 mm of annual basin-average rainfall, while the driest year of the study period was in 2007 with 831 mm of annual basin-average rainfall. Fig. 2 shows the eight-year average annual rainfall within the study area. A point to note is that the mean annual rainfall increases by 20% going from west (the headwaters of the basin) to east (basin outlet).

2.3. Flood events

The streamflow dataset used in this study consists of hourly streamguage measurements from US Geological Survey (USGS)