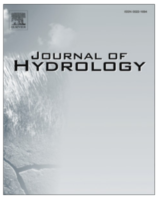
Journal of Hydrology 514 (2014) 313–327

Contents lists available at ScienceDirect

Journal of Hydrology

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



On the effects of small scale space–time variability of rainfall on basin flood response

Athanasios Paschalis [a,b,*], Simone Fatichi [a], Peter Molnar [a], Stefan Rimkus [a], Paolo Burlando [a]

[a] *Institute of Environmental Engineering, ETH Zurich, Switzerland*
[b] *Nicholas School of the Environment, Duke University, USA*

ARTICLE INFO

Article history:
Received 21 November 2013
Received in revised form 29 March 2014
Accepted 7 April 2014
Available online 16 April 2014
This manuscript was handled by Konstantine P. Georgakakos, Editor-in-Chief

Keywords:
Flood response
Hydrological modeling
Stochastic rainfall modeling, STREAP

SUMMARY

The spatio-temporal variability of rainfall, especially at fine temporal and spatial scales can significantly affect flood generation, leading to a large variability in the flood response and uncertainty in its prediction. In this study we quantify the impact of rainfall spatial and temporal structure on the catchment hydrological response based on a numerical experiment. Rainfall ensembles generated using a state-of-the-art space–time stochastic model are used as input into a distributed process-based hydrological model. The sensitivity of the hydrograph to several structural characteristics of storm rainfall for three soil moisture initial conditions is numerically assessed at the basin outlet of an Alpine catchment in central Switzerland. The results highlight that the flood response is strongly affected by the temporal correlation of rainfall and to a lesser extent by its spatial variability. Initial soil moisture conditions play a paramount role in mediating the response. We identify the underlying mechanistic explanations in terms of runoff generation and connectivity of saturated areas that determine the sensitivity of flood response to the spatio-temporal variability of rainfall. We show that the element that mostly influences both the flood peak and the time of peak occurrence is the clustering of saturated areas in the catchment which leads to local enhanced runoff.

1. Introduction

An important question in hydrology is how the spatial and temporal structure of precipitation affects the flood response of river basins. This problem is generally very complex, especially in areas prone to flash floods and/or where orography plays a dominant role in shaping the runoff response to rainfall, such as in steep mountainous catchments. Understanding the dependence of discharge on the spatio-temporal structure of precipitation events can be of major importance in operational hydrology for several reasons, e.g. in the design of precipitation monitoring networks, flood protection measures, flood forecasting, etc.

Various studies have focused on analyzing the effects of rainfall variability on runoff, sometimes yielding controversial results that highlight the complex nature of the problem (e.g. Krajewski et al., 1991; Shah et al., 1996b,a; Booij, 2002; Gabellani et al., 2007; Gires et al., 2012; Mandapaka et al., 2009; Nicotina et al., 2008; Nikolopoulos et al., 2011). The majority of previous studies was based on numerical experiments in which precipitation, either from observations or generated through stochastic models, was used to force hydrological models of different complexity.

Given the inherent importance of uncertainty, a large amount of literature used stochastic rainfall generators to create precipitation inputs for hydrological models used to transform rainfall into runoff (e.g. Krajewski et al., 1991; Shah et al., 1996b,a; Booij, 2002; Gabellani et al., 2007; Gires et al., 2012; Mandapaka et al., 2009). Such an approach has three major advantages, (i) the key statistical properties of the rainfall structure can be controlled since they depend on the parameters and type of stochastic model employed; (ii) the use of a stochastic model allows to generate ensembles of rainfall inputs which lead to a straightforward investigation of the process variability and uncertainty and (iii) the use of stochastic models allows for long-term simulations, which have been found a very important aspect for a correct prediction of flood risk statistics (e.g. Grimaldi et al., 2012). As a drawback, using a stochastic model to generate rainfall makes any result and assessment strongly dependent on the model structure, assumptions, and most important, performance. Stochastic rainfall models of different complexity are available from Poisson cluster models (Krajewski et al., 1991) to multiplicative random cascades (Gires et al., 2012). However, the skill of these models in correctly reproducing

---

* Corresponding author at: Nicholas School of the Environment, Duke University, USA. Tel.: +1 (919) 613 8068.

E-mail addresses: paschalis@ifu.baug.ethz.ch, athanasios.paschalis@duke.edu (A. Paschalis).

http://dx.doi.org/10.1016/j.jhydrol.2014.04.014
0022-1694/© 2014 Elsevier B.V. All rights reserved.

several spatial and temporal statistical properties of precipitation has been challenged (e.g. Paschalis et al., 2013). For instance, Poisson cluster models have been found to underestimate the small scale variability of rainfall in space and time (Paschalis, 2013,; Olsson and Burlando, 2002), while the multiplicative random cascades, when they are simulated in a discrete form, generate rather unrealistic spatial rainfall patterns (e.g. Deidda, 2000; Kang and Ramírez, 2010; Gires et al., 2012; Paschalis, 2013).

An alternative to the use of stochastic rainfall models is the direct use of measured rainfall (e.g. Obled et al., 1994; Nicotina et al., 2008; Nikolopoulos et al., 2011). Despite, the clear advantage of using the "true" rainfall structure, such an approach has at least two shortcomings. First, accurate high resolution observations in space and time are needed. Remote sensing and especially weather radars provide only a partial solution because of the well-known uncertainties and limitations of precipitation radar measurements (Berne and Krajewski, 2012). Second, the estimation of uncertainty is far from straightforward due to the limited amount of available data for a given area.

Independently of whether the rainfall fields are generated through stochastic models or observed, the skill and physical realism of the hydrological model used in the analysis of basin response is equally important. The hydrological models that have been used in this type of studies strongly differ with regard to their degree of complexity. Early attempts (e.g. Krajewski et al., 1991) were based on simplified, conceptual, modeling approaches (de Lima and Singh, 2002), while more recent studies (e.g. Nikolopoulos et al., 2011) are based on process-based hydrological models explicitly designed to simulate the physical controls on the catchment hydrology. This evolution follows the development in the hydrological modeling literature, from purely conceptual approaches (e.g., Kitanidis and Bras, 1980) to semi-empirical (Lindström et al., 1997), physically-based models (e.g., Kollet and Maxwell, 2006, 2008; Ivanov et al., 2004; Rigon et al., 2006; Shen and Phanikumar, 2010), and up to models that describe the complex interactions between biotic and abiotic factors (Ivanov et al., 2008; Fatichi et al., 2012a,b). This path has been primarily driven by an advancement in our physical understanding of various hydrological processes and feedbacks and in the continuous increase of computational resources.

Numerical experiments using the approaches described above raised crucial questions and provided some answers on how the spatio-temporal structure of rainfall can affect basin hydrological response. For instance, previous investigations focused on how the observation density (sampling resolution) of rainfall can affect the simulated streamflow in the river network (Krajewski et al., 1991; Shah et al., 1996b,a; Booij, 2002), on the role of storm kinematics (e.g., storm advection) (de Lima and Singh, 2002; Singh, 1997), as well as on the sensitivity of the generated hydrograph to rainfall variability as a function of the catchment size (Nikolopoulos et al., 2011; Nicotina et al., 2008). The emerging findings from those studies were: (a) the paramount role of spatial and temporal resolution of the precipitation input for the correct estimation of flood response (Krajewski et al., 1991; Shah et al., 1996b; Nikolopoulos et al., 2011; Nicotina et al., 2008); (b) the importance of the hydrological process representation in the different models (Krajewski et al., 1991; Booij, 2002); (c) the strong control exerted by the initial soil moisture conditions on flood generation (e.g. Shah et al., 1996a); and (d) the dependence of those effects on catchment size (Nikolopoulos et al., 2011; Nicotina et al., 2008). It is our opinion that in order to scrutinize such results, a study which designs a numerical experiment to analyze in a systematic way most of these aspects is warranted.

In this study we quantify the importance of various characteristics of the spatial and temporal structure of a rainfall event (spatio-temporal correlation, advection, spatial variability, peak intensity) in the generation of a flood for different initial conditions of soil moisture. This experiment makes use of two numerical tools. A detailed stochastic space–time model of rainfall (STREAP) (Paschalis et al., 2013), and a computationally efficient hydrological model (TOPKAPI-ETH) that operates at high temporal and spatial resolutions (Fatichi et al., 2013). Using these two tools we investigate the event scale hydrological response of the Kleine Emme river basin to rainfall events with different space–time variability. The Kleine Emme basin is an area particularly prone to floods and can be regarded as a representative catchment of the alpine region in Switzerland.

With comparison to previous research this study introduces two major novelties. The first novelty concerns the realism of the numerical tools used for generating the stochastic ensembles of rainfall inputs and hydrological response, as well as by the number of explicitly analyzed properties that are used to describe the rainfall fields. The space–time stochastic rainfall generator has the unique capability of reproducing in detail all the essential statistical characteristics of the structure of rainfall. The hydrological model provides a simulation of the processes that lead to runoff generation at the sub-hillslope spatial scales. Both tools combined together allow us to expand previous knowledge on the effect of the spatio-temporal structure of rainfall in flood generation and to provide a mechanistic interpretation of the results which was not possible in previous studies with more simplified numerical tools. Further, the assumptions embedded in simpler stochastic rainfall generators may have led to erroneous precipitation input and misleading results in the flood generation.

The second novelty is that our approach allows for a direct assessment of the uncertainty induced by the random variability of rainfall events because we use stochastic ensembles of rainfall inputs that represent equiprobable scenarios. In this way, we assess the uncertainty of the basin hydrological response to stochastic rainfall variability. This also represents a considerable and important novelty with comparison to the previous studies which were based on rainfall observations only.

2. Methods

The numerical experiment we constructed allows us to investigate the effects of different spatial and temporal statistical properties of rainfall in the generated hydrographs, similar to previous studies (Krajewski et al., 1991; Shah et al., 1996b,a). Using the stochastic rainfall model STREAP we generated ensembles of space–time rainfall events with prescribed statistical features, which were subsequently used as input to the distributed hydrological model TOPKAPI-ETH to evaluate their impacts on streamflow (Fig. 1).

2.1. Stochastic rainfall modeling

In this analysis we used the space–time stochastic precipitation model STREAP, which is a new modeling tool for the generation of high resolution ($\sim$1 km^2; $\sim$5 min) rainfall fields that outperforms commonly used models (Paschalis, 2013; Paschalis et al., 2013). The scope of the model is to reproduce the rainfall structure as captured by weather radars while also providing a good reproduction of rainfall amounts. A very important feature of the STREAP model is its realism in simulating rainfall fields. In contrast to existing space time rainfall models (e.g., space–time Neymann–Scott Rectangular Pulse model, discrete Multiplicative Random Cascades), STREAP is capable of representing adequately spatial and temporal rainfall statistics at the β-mesoscale and at the same time it consistently preserves the small scale spatial rainfall structures and temporal correlations captured by weather radars. Only a