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The relative role of hillslope and river network routing in the hydrologic response to spatially variable rainfall fields

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ABSTRACT

This paper introduces a new methodology and a rainfall spatial organisation index to examine the relative role of hillslope and channel residence times in the analysis of the significance of spatial rainfall representation in catchment flood response modelling. The relationship between the flood response, the hillslope and channel residence time representation and the spatial organisation of the rainfall fields is obtained by extending the 'spatial moments of catchment rainfall' statistics (Zoccatelli et al., 2011) to the hillslope system. The flood prediction error generated by assuming spatially uniform rainfall is related to the spatial organisation of the rainfall fields by means of the scaled spatial moment of order one for the channel network and the hillslope system. The methodology provides a basis for a more general consideration of the relationship between the flood response dependence to spatial rainfall organisation and catchment size. The methodology is illustrated based on data from five extreme flash floods occurred in various European regions in the period 2002–2007. Discharge data are available either from streamgauges or from post-flood surveys for 27 catchments, ranging in size between 36 and 982 km^2. High space–time resolution radar rainfall fields are also available for the analyses. These data are used to implement a distributed hydrological model simulating the runoff generation by infiltration excess and explicitly representing the surface flow paths across both the hillslopes and the river network. The hydrological model is alternatively forced with spatially-distributed and spatially-uniform rainfall input, to analyse the factors controlling the sensitivity of the model output to the spatial rainfall data. Our results show that the spatial variability of the rainfall can influence the flash-flood hydrographs for catchments as small as 50 km^2, and that the dependence of flood hydrograph shape to spatial rainfall variability cannot be treated as scale dependent relative to the size of the catchment.

The rainfall index can be exploited as similarity index for classifying catchments and flood events according to the hillslopes/channel residence times and to provide guidance on the space and time resolution of the rainfall monitoring system required to predict the flood response.

1. Introduction

Runoff propagation processes along hillslopes and flow dynamics along the river network combine to shape the hydrologic response of a basin (D'Odorico and Rigon, 2003; Giannoni et al., 2003; Naden, 1992; Robinson et al., 1995; Saco and Kumar, 2004; Snell and Sivapalan, 1994; Viglione et al., 2010; Yen and Lee, 1997). The relative contribution of hillslope processes and network geomorphology to the catchment's hydrologic response has been investigated by several researchers (Saco and Kumar, 2004; Viglione et al., 2010). A general result is that the relative role and mutual interactions of hillslope and channel network transport change substantially with catchment size (Beven and Wood, 1993; Di Lazzaro, 2009; Kirkby, 1976; Robinson et al., 1995; Saco and Kumar, 2002). In small catchments, the time delay to rainfall forcing tends to be dominated by the routing of surface and subsurface flow on the hillslopes, whereas in large catchments the flow routing through the river network controls the hydrograph shape (Beven and Wood, 1993; Botter and Rinaldo, 2003).

Less attention has been devoted to examine to what extent the relative role of hillslope and river network processes affects the sensitivity of the flood response to rainfall spatial variability. Some hypotheses have been put forward to identify the mechanisms through which rainfall spatial variability may affect catchment response, with an emphasis on hydrologic partitioning

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processes (Anquetin et al., 2010; Brath and Montanari, 2003; Gabellani et al., 2007; Shah et al., 1996; Winchell et al., 1998). Several works have focused on the relation between the spatial rainfall organisation and the heterogeneities embedded in the basin geomorphic structure, mostly by examining the rainfall variability relative to a distance metric imposed by the drainage network (Lobligeois et al., 2014; Smith et al., 2005, 2002; Zhang et al., 2001). Nicótina et al. (2008) focused on the effects of transport processes along the hillslopes and the channel network as a key element to clarify the extent of the possible influence of rainfall spatial variability on the hydrologic response. They used a geomorphological model of the runoff response and analysed the distribution of travel times, showing that the sensitivity of the hydrologic response to rainfall distribution increases with decreasing hillslope residence time. By considering relatively large storm events, they found that rainfall spatial variability does not significantly influence the flood response for basin areas up to about 3500 km^2. These results confirm earlier results by a number of studies (Andreassian et al., 2001; Beven and Hornberger, 1982; Naden, 1992; Obled et al., 1994; Smith et al., 2004a,b), which were carried out in relatively small to medium-size catchments where the catchment response is expected to be dominated by the hillslope response. However, these results are at odds with other empirical findings which show that the rainfall spatial variability can play a major role in flood modelling even at the scale of a small basin (Faurès et al., 1995; Michaelides and Wainwright, 2002; Michaud and Sorooshian, 1994; Schuurmans and Bierkens, 2007), hence implying that the sensitivity to spatial rainfall variability cannot be treated as scale dependent relative to the size of the catchment. There is therefore a need for a more general approach, which is able to characterise the relative role of the hillslope and river network routing in the hydrologic response to spatially variable rainfall fields.

A number of papers have focused on the interaction between rainfall spatial organisation and flow distance, i.e. the distance along the runoff flow path from a given point to the outlet, to predict the impact of spatial and temporal variability of precipitation on the flood hydrograph (Emmanuel et al., 2012a,b; Smith et al., 2002; Viglione et al., 2010; Woods and Sivapalan, 1999; Zhang et al., 2001). Based on these works, Zoccatelli et al. (2011) proposed a series of statistics, termed 'spatial moments of catchment rainfall', which are able to isolate the effect of rainfall spatial variability on mean and variance of runoff time. These authors reported large impacts of rainfall spatial variability on hydrologic response for catchments as small as 50 km^2. In the development of the 'spatial moments of catchment rainfall', Zoccatelli et al. (2011) disregarded the differentiation between hillslopes and channel network contribution to the total runoff travel time. However, for most river basins the contribution of hillslopes to the total residence time is relevant to the proper representation of the basin response (D'Odorico and Rigon, 2003; Nicótina et al., 2008; Rinaldo et al., 1995). The correct description of hillslope contribution is even more important in the small to medium catchments (less than 1000 km^2), which are more frequently impacted by flash floods (Yakir and Morin, 2011).

In this work, we aim to identify how large the hillslope residence time has to be relative to the channel residence time, to smooth out the effects of a certain degree of spatial rainfall organisation – quantified by the spatial first moment of catchment rainfall – on the flood hydrograph. This objective is achieved by extending the concept of 'spatial moments of catchment rainfall' by incorporating both hillslope and channel contributions to the travel time in the moment formulations. This formulation leads to an index of spatial rainfall organisation which is used to gain insight into the relative role of the hillslope and channel residence time. This approach provides a basis for a more general consideration of the relationship between the flood response sensitivity to spatial rainfall organisation and catchment size.

The role of the hillslope residence time in damping the rainfall spatial variability is illustrated by analysing five extreme flash floods occurred in various European regions in the period 2002–2007. The size of the study catchments ranges between 36 and 982 km^2. These events are characterised by high intensity and large space–time variability of rainfall, which have a strong effect on the flood response even at small spatial basin size. Extended spatial moments are evaluated by exploiting high resolution, carefully controlled, radar rainfall fields. Results obtained by means of the extended spatial moments are compared with those provided by using a spatially distributed hydrological model of the flood response. The model is alternatively forced with spatially-distributed and spatially-uniform rainfall input, to analyse the factors controlling the sensitivity of the model output to the spatial rainfall data and to assess the relevance of the results obtained by using the index of spatial rainfall organisation.

2. Spatial moments of catchment rainfall: extension to the hillslope processes

'Spatial moments of catchment rainfall' (Zoccatelli et al., 2011, referred to as Z2011 hereinafter) provide a description of the spatial rainfall organisation at a certain time t as a function of the rainfall field $r(x, y, t)$ value at any position (x, y) within a catchment, and of the flow distance $d(x, y)$ to the catchment outlet measured along the flow path. Similar statistics have been introduced in previous works by Smith et al. (2002) and Smith et al. (2005) to describe the rainfall spatial variability from the perspective of a distance metric imposed by the drainage network. In Z2011 the spatial moments of catchment rainfall have been defined under the assumption of flood routing with constant flow velocity, in both space and time.

In this section, the spatial moments are extended to include the hillslope processes. The runoff transport is described by using two different time invariant values of velocity, v_h and v_c, characterising the hillslope and the channel system, respectively. This assumption has been used in a number of flood modelling works (Marchi et al., 2010; Nicótina et al., 2008; Zanon et al., 2010, among the others). Evaluation of simulation results reported in these works supports the assumption that models of the hydrologic response employing basin-constant channel celerity explain observed travel time distributions, at least for high flows conditions as observed in Pilgrim (1976). The invariant hillslope celerity assumption is more conceptual in nature (Botter and Rinaldo, 2003). In fact, great variability in hillslope transport properties is expected, particularly when it is driven by local topographic gradients as subsurface runoff through partially saturated areas and in the presence of preferential flow paths (Beven and Wood, 1983; Dunne, 1978).

The term $d_h(x, y)$ identifies here the distance from any point in the basin to the channel network following the steepest descent path, while $d_c(x, y)$ identifies the length of the subsequent drainage path through the streams down to the watershed outlet. Then, the following definitions are provided for the spatial moments of catchment rainfall of order n for the channel ($p_{n,c}(t)$) and hillslope systems ($p_{n,h}(t)$) at time t, respectively:

$$
\begin{aligned}
p_{n,c}(t) &= A^{-1}\int_A r(x,y,t)d_c(x,y)^n\,dA \\
p_{n,h}(t) &= A^{-1}\int_A r(x,y,t)d_h(x,y)^n\,dA
\end{aligned}
\qquad (1)
$$

where A indicates the catchment area. It is easy to verify that the *zero*-th order spatial moment along hillslope and channel flow