Journal of Hydrology (2008) **362**, 260–273

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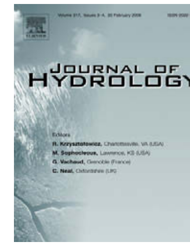

Correlation between channel and hillslope lengths and its effects on the hydrologic response

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Received 8 November 2007; received in revised form 12 June 2008; accepted 31 August 2008

KEYWORDS
Hydrologic response;
Geomorphology;
Kinematic dispersion;
Hillslopes;
Channel network

Summary In the geomorphologic approach based on width functions, the instantaneous response function (IRF) is completely determined once the distributions of hillslope and channel lengths in addition to flow parameters are assigned. The relative contributions of hillslopes and channels to the variance of the travel times have been analyzed in the literature, and three different variance-producing mechanisms, namely geomorphologic, kinematic and hydrodynamic have been identified. In this study the width function approach is employed to investigate a dispersive mechanism of geomorphologic and kinematic nature, due to the existence of a relevant correlation between hillslope and channel lengths distributions. The effects of this correlation on the variance of the IRF were neglected in previous works, assuming that the two distributions are uncorrelated. Here several basins of different size in the central Apennines (Italy) have been studied, finding that both positive and negative values of correlation can occur, their absolute values being seldom negligible. The sign of the correlation is related to the distribution of slopes within the basin, thus appearing to be influenced by typical morphologic signatures such as the presence of canyons or alluvial valleys. In particular, basins with large flat areas located near the outlet generally show negative values of correlation and are consequently more prone to produce peaked flow hydrographs. Finally an analytical expression is proposed to investigate the size of the catchments whose hydrologic response can be considerably affected by the hillslope–channel correlation.
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Introduction

The hydrologic response of a basin is the result of different dynamic processes that combine and interact with one another producing runoff. The shape and the overall variance of the generated flow hydrograph can be quite dissimilar from that of the generating rainfall event, hinting that variance-producing sources are embedded in the mechanisms of the rainfall–runoff transformation. Early field studies showed that processes taking place, respectively, in the hillslopes and in the channel network are characterized by

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doi:10.1016/j.jhydrol.2008.08.022

distinct time scales of transport (Emmet, 1978), suggesting that the velocities of the overland and subsurface flow and of the channel streamflow can differ by orders of magnitude. This has long been recognized as a primary source of the overall variance of the hydrograph.

Some of these mechanisms and their relative role on the total variance of the basin response function have been systematically addressed within the context of the Geomorphological Instantaneous Unit Hydrograph theory, introduced by Rodriguez-Iturbe and Valdes (1979a, b) and later extended and formalized by Rinaldo and Rodriguez-Iturbe (1996) among others. The GIUH provides a coherent framework to express the dependence of the hydrologic response from the geomorphic signatures of the basin. The underlying assumption of the GIUH theory (the equivalence between the Instantaneous Unit Hydrograph and the probability density function of the travel times from any point of the basin) led to a renewed interest in the use of the geomorphologic width function, already defined by Shreve (1969) to concisely represent the network structure of a basin (Kirkby, 1976). The width function $W(x)$, which gives the number of links located at a flow distance x from the outlet, was first employed by Mesa and Mifflin (1986) as a weight function to express the channel network response to an instantaneous rainfall input. Their pioneering work emphasizes the importance of network geometry in defining the basin unit hydrograph, even at very small scale. However, the authors underline the need to combine a detailed model of fast and slow hillslope response to reproduce recorded runoff, hinting that the role of hillslopes is primary.

The issue of the relative contribution of hillslope processes and network geomorphology to the hydrologic response of natural catchments has been investigated by Robinson et al. (1995) over a range of catchment sizes, using geomorphology based models of runoff routing. In their work hillslope and network processes are assumed entirely independent. Total catchment dispersion coefficient, measuring the total variance in time of the hydrologic response, was quantified up to catchment size of 1000 km^2, concluding that the dispersion originated by network response becomes largely predominant as a threshold of about 10 km^2 is exceeded.

This threshold was revised by recent works that invite to pay a growing attention to the role of hillslopes in defining the overall shape of the response function, even for very large basins. Rinaldo et al. (1995) highlighted that the typical skewness observed in the shape of natural hydrographs is a dynamic effect resulting from the delay introduced by hillslope transport processes. Recently Botter and Rinaldo (2003) showed that mean residence times within the hillslopes can be compared to mean travel times within the network even for basins exceeding 1000 km^2 in size. They conclude that this result is further enforced if second moment of the residence time distribution is analyzed.

In order to quantify the role of the different mechanisms generating the variance of travel times, specific dispersion coefficients were introduced, each one straightforwardly accounting for a different dispersive effect.

The role of heterogeneities in the stream network was highlighted with the introduction of the concept of geomorphological dispersion (Rinaldo et al., 1991), a channel-borne dispersive effect which addresses to the fraction of spreading of the arrival times deriving from the difference of path lengths. Moreover, if a travel time distribution accounting for dispersive processes is adopted, the portion of variance induced by nonidentical travel times of particles injected simultaneously at the upstream origin of an individual reach is measured through a suitable hydrodynamic dispersion coefficient.

Relative roles of hydrodynamic and geomorphologic dispersion were established by Rinaldo et al. (1991) showing that the contribution to residence times variance induced by geomorphological heterogeneities within the channels is at least one order of magnitude higher than hydrodynamic dispersion, exact results being analytically obtained for Hortonian networks. Even adopting high values of the hydrodynamic coefficient, in the range of acceptable Peclet numbers for natural basins, the effect of hydrodynamic dispersion appears to be negligible (see also Botter and Rinaldo, 2003).

Recently Saco and Kumar (2002a,b) proposed an analytical approach taking into account spatial variations of velocity within channels of different orders with respect to the Strahler ordering scheme. They refer to this mechanism, that introduces another dispersive effect in the travel time distribution, as kinematic dispersion, since it is generated by the spatial heterogeneity of convective processes. Neglecting this effect leads to an underestimation of the time to peak and of the duration of the hydrograph, while peak discharge is overestimated. Nevertheless, the actual impact of the downstream velocity increase on the basic moments of the travel times distribution was quantified by Botter and Rinaldo (2003), concluding that, even for quite unrealistic increase of channel velocities, this effect appears to be of less relevance.

Using the link-based approach given by the width function, Saco and Kumar (2004) extended their previous work accounting for dispersive mechanisms induced by hillslope dynamics. They found that rescaling the width function with distinct hillslopes and network velocities (but neglecting the variation of velocity within the channelized part of the basin) produces a hillslope-borne dispersion of kinematic origin that can reinforce or counteract geomorphological dispersion. Their results confirm anyway that, as hillslope velocity becomes smaller enough if compared with channel velocity, the variance, duration and peak discharge of the generated hydrograph are strongly affected by the distribution of hillslope lengths.

Following the same width function approach of Saco and Kumar (2004), this paper investigates the effects of an additional dispersive mechanism of geomorphologic and kinematic nature, directly related to the existence of a significant correlation between hillslope and channel lengths distributions in natural basins. This type of correlation was not taken into account in previous works. However, it can strongly affect the shape of basin's hydrographs and should be considered in rainfall—runoff models based on the metric analysis of the drainage network.

The existence of the correlation between hillslope and channel lengths is embedded in some well-known geomorphological evidences involving the concept of drainage density which is defined as

$$D_d = \frac{\sum l_c}{A} \tag{1}$$

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