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Understanding the relative role of dispersion mechanisms across basin scales

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ABSTRACT

Different mechanisms are understood to represent the primary sources of the variance of travel time distribution in natural catchments. To quantify the fraction of variance introduced by each component, dispersion coefficients have been earlier defined in the framework of geomorphology-based rainfall-runoff models. In this paper we compare over a wide range of basin sizes and for a variety of runoff conditions the relative role of geomorphological dispersion, related to the heterogeneity of path lengths, and hillslope kinematic dispersion, generated by flow processes within the hillslopes. Unlike previous works, our approach does not focus on a specific study case; instead, we try to generalize results already obtained in previous literature stemming from the definition of a few significant parameters related to the metrics of the catchment and flow dynamics. We further extend this conceptual framework considering the effects of two additional variance-producing processes: the first covers the random variability of hillslope velocities (i.e. of travel times over hillslopes); the second deals with non-uniform production of runoff over the basin (specifically related to drainage density). Results are useful to clarify the role of hillslope kinematic dispersion and define under which conditions it counteracts or reinforces geomorphological dispersion. We show how its sign is ruled by the specific spatial distribution of hillslope lengths within the basin, as well as by flow conditions. Interestingly, while negative in a wide range of cases, kinematic dispersion is expected to become invariantly positive when the variability of hillslope velocity is large.

1. Introduction

Following the geomorphological interpretation of the basin response function [1], the time a drop of effective rainfall spends in a catchment – from the moment it is injected into the control volume to the time it crosses a control outlet – is suitable to be described as a random variable. Gupta et al. [2] showed that the response hydrograph to an instantaneous unit pulse of effective rain (IUH) and the probability density function (pdf) of travel times have a sound conceptual equivalence. The shape of this pdf defines how catchments release water in response to effective rainfall forcing [3], thus embedding spatial heterogeneity of geomorphology and flow dynamics [4]. In this simplified classical framework, travel times are considered time-invariant (i.e., they only depend on the location where rainfall is injected) and show inherent scatter which arises from a combination of metrics and flow conditions, both at the hillslope and river network scale. Further dispersive terms accounting for the dependence of the travel time from complex transport dynamics (see e.g. [5–10]) are not considered here.

We measure the overall spread of this distribution in terms of total hydrological dispersion coefficient (see e.g. [11–13]), with the underlying rationale that partial dispersion coefficients (each related to a single dispersive mechanism) may be individually computed and easily compared to the total, thus establishing their relative role.

Hydrological dispersion is acknowledged to be linked with some key features that rule the shape of runoff hydrograph, e.g. the time of runoff concentration [14], the magnitude of peak discharge [15,16], and the evolution in time of hydrograph recession limb [17]. Hence, understanding what controls dispersion in a catchment is crucial for the selection of relevant variables to consider in flood modeling [18,19].

Analytical quantification of variance-producing mechanisms has been introduced for the first time in the context of the geomorphologic theory of the hydrologic response by Rodriguez-Iturbe and Valdes [3]. Since then, different dispersive mechanisms have been formalized through specific dispersion coefficients, which can be broadly arranged in the following categories: (1) mechanisms that produce a spreading in the arrival times at the scale of the

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Nomenclature

$\langle\ \rangle$	expected value
$\tilde{D}$	dimensionless form of the dispersion coefficient D
Subscript g	denotes variables, parameters and functions for the non-uniform runoff production case
$CV(Z)$	variation coefficient of the random variable Z
D_G	geomorphological dispersion coefficient
D_{Gc}	channel geomorphological dispersion coefficient
D_K	kinematic dispersion coefficient
D_{Kc}	channel kinematic dispersion coefficient
D_{Kh}	hillslope kinematic dispersion coefficient
D_L	longitudinal dispersion coefficient
D_T	total dispersion coefficient
D_φ	productivity dispersion coefficient
$D_{\varphi G}$	geomorphological component of D_φ
$D_{\varphi K}$	kinematic component of D_φ
dd	drainage density
$F(z)$	cumulative distribution function of the random variable Z
$F(z, y)$	joint cumulative distribution function of the random variables (Z, Y)
$f(z)$	probability density function of the random variable Z
$f(z, y)$	joint probability density function of the random variables (Z, Y)
L	total path length
L_c	channel path length
L_h	hillslope path length
l_c	realization of L_c
l_h	realization of L_h
$\Pr(z)$	probability of the random variable Z
R	covariance matrix
T	catchment residence time
t	realization of T
U_h	random hillslope velocity
$\bar{u}$	equivalent velocity
u_c	channel velocity
u_h	hillslope velocity
ΔD_z	portion of the sampled space defined by a given rule
γ	ratio between the average value of the channel and hillslope lengths
$\rho(L_c, L_h)$ or ρ	Pearson correlation coefficient between the random variables L_c and L_h
θ	ratio between the channel and hillslope velocities or ratio between the channel velocity and the hillslope velocity average value
σ_Z^2	variance of the random variable Z
φ	weight proportional to runoff coefficient

individual channel, (2) dispersion that arises from the morphological heterogeneity of paths within a basin, (3) mechanisms that are originated by the heterogeneity of dynamic flow conditions and (4) dispersion that is generated from the spatial variability of runoff production.

The first mechanism is the only responsible for the variance of travel times when all travel paths are equal in length and show the same celerity. It is generally expressed through the hydrodynamic longitudinal dispersion coefficient D_L (see e.g. [12,20,21]). The second type of dispersion is related to the river network structure; it incorporates the idea that raindrops falling on different locations of a basin at the same time will not reach the outlet simultaneously. This effect is due to the heterogeneity of path lengths within the basin and is measured through the geomorphologic dispersion coefficient D_G, first introduced by Rinaldo et al. [21]; its value is, by definition, always positive. The original framework provided by Rinaldo et al. [21] compared the relative role of D_G and D_L making the simplification that travel times are only ruled by the shape of the channel network; they established that the contribution of D_L to the distribution of residence time could be considered negligible compared to D_G in a wide range of fluvial conditions. Further investigations by White et al. [22], which also included the role of flow frequency, broadly confirmed this analysis.

When the spatial variability of flow conditions is considered, a third mechanism of dispersion is introduced: the latter was coined kinematic dispersion D_K [23,24]. This dispersive term was first introduced considering variations of velocities in the channel network as function of stream order, and was addressed as channel-born kinematic dispersion D_{Kc}. Botter and Rinaldo [25] analyzed the relative importance of D_{Kc} and D_G, finding that even for the non-realistic case of channel velocity varying by an order of magnitude, its relative role compared to D_G remains subdued.

Later, active research focused on delay in time and dispersive effects introduced by the hillslope component; slower hillslope response generates an additional dispersion mechanism, which was termed hillslope kinematic dispersion D_{Kh} [26]. The relative importance of D_{Kh} and D_G has been studied by Saco and Kumar [12], Botter and Rinaldo [25], Fiori et al. [27], who extended the original quantification of the role of hillslopes in shaping the unit hydrograph [20,28,29]. While early work by Robinson et al. [30] concluded that the representation of hillslope response was crucial only for very small basins (i.e. smaller than 10 km^2), recent findings have deeply revised the extent of hillslope contribution: Botter and Rinaldo [25] highlight that the dominance of hillslope kinematic dispersion can occur in a wider range of basin scales, also exceeding the order of 1000 km^2. They also establish that the channel-based kinematic dispersion effects can be considered of minor importance compared to the role of hillslopes. Saco and Kumar [12] stress that the variance of the travel time distribution is enhanced by paths with long hillslopes, and it is therefore crucial to correctly incorporate the distribution of hillslope lengths in rainfall-runoff modeling.

Though a complete formalization through dispersion coefficients has been limited so far to hydrodynamic, geomorphological and kinematic components, additional dispersion mechanisms still inherent to the catchment itself have been clearly pointed out. Among them, some authors focused on the role of variable hillslope velocities on the moments of the travel time distribution [25,31], discussing the theoretical merits of this modeling assumption. In particular, Botter and Rinaldo [25] use hillslope velocities randomly sampled from exponential and log-normal distributions, showing that under the assumption of variable hillslope velocities the variance and the skewness of the travel time pdf are significantly larger compared to the deterministic case. Overall, their work underlines that the stochastic component further emphasizes the role of hillslopes as a variance-producing mechanism; however, their results are still limited to specific study cases.

Other authors indicated how the shape of the hydrologic response strongly depends on moisture conditions, and in particular on the degree of hillslope saturation, which in turn affects the extent of contributing areas. According to the study by D'Odorico and Rigon [4], when the basin is completely unsaturated total dispersion of the IUH is only composed by the geomorphological term and the hydrological response resembles the shape of the width function; for increasing saturated areas, hillslope kinematic contribution prevails. Di Lazzaro et al. [32] further investigated the role