Relations between streamflow indices, rainfall characteristics and catchment physical descriptors for flash flood events

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Abstract Flash flood is a very intense and quick hydrologic response of a catchment to rainfall. This phenomenon has a high spatial-temporal variability as the generating storm often hits small catchments (few km²). Given the small spatial-temporal scales and high variability of flash floods, their prediction remains a hard exercise as the necessary data are often scarce. This study investigates the potential of hydrologic indices at different scales to improve understanding of flash floods dynamics and characterize catchment response in a model independent approach. These hydrologic indices gather information on hydrograph shape or catchment dynamic for instance and are useful to examine catchment signature in function of their size. Results show that for middle-size (>100 km²) catchments response shape can be correlated to storm cell position within the catchment contrarily to smaller catchments. In a multi-scale point of view, regional characteristics about catchment geomorphology or rainfall field statistics should provide useful insight to find pertinent hydrologic response indices. The combined use of these indices with a physically-based distributed modelling could facilitate calibration on ungauged catchments.

Key words flash flood; hydrologic indice; ungauged catchment

INTRODUCTION

The stream hydrograph is a spatial and temporal integration of all the water input, storage and transfer processes within a catchment. Thus the shape and magnitude of the hydrograph potentially yields a wealth of information about catchment hydrological process.

Streamflow indices are calculated from the streamflow hydrograph data of a catchment (Shamir *et al.*, 2005); thus such indices as runoff ratio or time to peak flow are catchment specific: they contain the unique signature of the catchment behaviour. Indices derived from hydrograph shape are also called dynamic response characteristics.

Numerous streamflow hydrograph indices are introduced in the literature. Olden & Poff (2003) address a review of 171 currently available hydrologic indices using stream flow records from 420 sites from across the continental USA. They examine patterns of redundancy in hydrologic indices with principal component analysis (PCA) and conclude that the statistical framework provided can be helpful for the selection of hydrologic indices in hydro-ecological studies. Chinnayakanahalli *et al.* (2005) examined possible links between various hydrologic indices from Olden & Poff (2003) and physical characteristics of catchments to predict hydrologic flow regimes for biological assessment in ungauged basins.

Of particular interest for hydrological modellers are studies like Farmer *et al.* (2003) who use “water balance signatures”, which are derived from streamflow records at three different temporal time scales to evaluate the model complexity that is required to reproduce these signatures. Morin *et al.* (2001) propose a peak density measure and a conceptual basin response time scale that is defined as the time to aggregate the precipitation so that the hyetograph and hydrograph are of comparable shape. An objective measure of shape similarity is provided by Morin & Konstantine (2002) with the Rising Limb Density and the Declining Limb Density (RLD, DLD) index calculated for the aggregated hyetograph and the hydrograph.

This paper presents the study at the regional scale of model independent dynamic response characteristics in the case of flash floods. Several physical descriptors are derived from available catchment physiographic data and rainfall field maps. We calculate dynamic response characteristic correlations to physical characteristics of catchments and rainfall fields. The objective here is to improve understanding of the flash flood generating mechanisms by linking dynamic flow indices to physical descriptors in a model independent approach.

The study site is first presented, and then the chosen hydrologic indices are listed: descriptors of physiographic catchment characteristics, descriptors of dynamic response characteristics and descriptors of rainfall characteristics. Finally, correlations between dynamic response characteristics and the other indices are calculated.

STUDY SITE AND DATASET

A set of seven small to medium size (45–619 km^2) gauged catchments located in the Cévennes-Vivarais region was selected for this study (Fig. 1). These catchments are characterized by a strong topographic gradient, and high spatial variability in their litho-pedology and soil cover and occupation. None of the catchment streamflows used here are significantly affected by abstractions or other alterations. All of them are hit by highly variable thunderstorms generating flash floods.

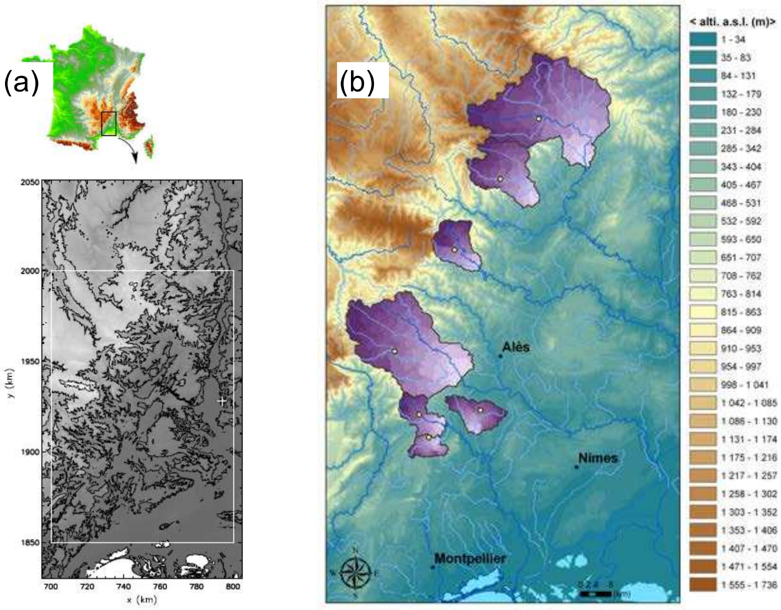

Fig. 1 (a) OHMCV (Observatoire Hydrométéorologique Cévennes Vivarais) pilot site and topography. The white lines delineate rainfall data spatial extend (source (Berne *et al.*, 2009)). (b) Flowpath distances for the seven catchments of interest, yellow dots are the basin centroids in terms of flowpaths. Main rivers and towns are plotted.

We constituted a set of 51 events, occurring during the last decade, by selecting more than eight events for each of the seven catchments. Event hydrograph data, at five minute time-steps, are considered from the beginning of the storm to the end of the rapid recession.

Synoptic events can show some spatial coherence (Merz & Blöschl, 2003); this is the case of few events of the dataset used in the current study, and consequently few points can be statistically dependent. One of the main obstacles to flash flood prediction is the lack of data (Gaume & Borga, 2008; Gaume *et al.*, 2009) so these points have still been considered in this study. However, a better dataset in terms of statistical independence, location and more contrasting catchment characteristics is being collected for a larger area of the French Mediterranean region. Note that most of the events considered here are convective and data are mainly statistically independent, so the method and results presented here are useful at the regional scale.

INDICES DESCRIPTION

Description of catchment characteristics

The variables for the catchments considered here are listed in Table 1.

Table 1 Descriptors of physical characteristics.

Name	Units	Description	Ref
Slope	[–]	Global slope index	–
Kcomp	[–]	Compacity index (Gravelius constant)	–
Rcirc	[–]	Circularity index	–
Dmoy	m	Mean flowpath distance	–
elance	[–]	Horton index ($S / Lmax^2$)	(Wagener *et al.*, 2004)
DPSBAR	m/km	Index of watershed steepness	(Wagener *et al.*, 2004)
DPLBAR	km	Index describing watershed size and drainage path	(Wagener *et al.*, 2004)
APSBAR	[–]	Index representing dominant watershed slopes	(Wagener *et al.*, 2004)
APSVAR	[–]	Index of invariability of aspect of watershed slopes	(Wagener *et al.*, 2004)
tan(α)m	m/m	Mean topographic slope index	(Hjerdt *et al.*, 2004)
tan(α)s	m/m	Topographic slope index standard deviation	(Hjerdt *et al.*, 2004)

Table 2 Descriptors of dynamic response characteristics.

Name	Units	Description	Ref
RLD	h^{-1}	Rising limb density	(Morin *et al.*, 2002)
DLD	h^{-1}	Declining limb density	(Morin *et al.*, 2002)
HFDisch	[–]	High flow discharge (mean of the 99th percentile)	(Clausen & Bigs, 2000)
Hpcount	[–]	High pulse count (3 times median)	(Clausen & Bigs, 2000)
HPdur	h^{-1}	High pulse duration	(Clausen & Bigs, 2000)
Skew	[–]	Skewness (mean flows divided by median flows)	(Clausen & Bigs, 2000)
Cvar	[–]	Streamflow variability	(Clausen & Bigs, 2000)
Grise	$m^3/s/km^2$/jour	Mean rising limb gradient	(Clausen & Bigs, 2000)
Gdec	$m^3/s/km^2$/jour	Mean declining limb gradient	(Clausen & Bigs, 2000)
Vruiss	m^3	Coefficient of variation in streamflow	–
Vruispe	m^3/km^2	Flow volume / catchment area	–

Description of streamflow shape

Studies about flash floods and their generating storms (Le Lay & Saulnier, 2007; Castaings *et al.*, 2009), and technical breakthroughs lead to improved understanding of this physical phenomenon. Information might be extracted from the statistical characterization of catchment response behaviour during a flash flood where most of the surface and subsurface flow paths are active. Several shape descriptors derived from event hydrographs (Table 2) have been used in this study. The idea is to find simple relevant shape descriptors of the flash flood hydrographs.

Description of rainfall characteristics

We follow the intent of (Jakeman & Hornberger, 1993) and attempt to determine: "What reliable information may reside in concurrent observed precipitation-streamflow measurements for assessing the dynamic characteristic of catchment response?"

The area of interest for this study is the Cévennes-Vivarais region (Fig. 1) particularly hit by thunderstorms generating flash floods in the Cévennes foothills. We limit this preliminary study to the OHMCV hourly Kriged rainfall data where raingauge density is high. The OHMCV hourly rainfall data are gridded at 1-km resolution and hourly time-steps.

In the Mediterranean climatic zone, precipitation is highly variable, both in time and space, and this variability increases with elevation in mountainous regions (Moussa *et al.*, 2007). Spatial variability of rainfall was measured by Smith *et al.* (2004) who developed a general variability index and a location index. We calculate this variability index I_σ and the rainfall field location I_L with the Kriged rainfalls maps according to the methodology proposed by Smith *et al.* (2004). The flowpath distance for each cell and topographic characteristics are derived from a 50 m resolution DEM (IGN).

CORRELATIONS BETWEEN STREAMFLOW INDICES, CATCHMENT PHYSIOGRAPHIC DATA AND RAINFALL CHARACTERISTICS

In this section we relate hydrologic response characteristics both to rainfall characteristics and to observable physical catchment characteristics in order to build regional regression relationships. The behavioural information contained in these relations is model independent.

Single correlations are calculated for the 51 event set, i.e. over the seven different catchments (Table 3). For reasons of clarity, only correlation coefficients greater than 0.5 are indicated. Rainfall field characteristics such as intrastorm variability (Iσ) are correlated to dynamic response characteristics such as rising limb gradient (Grise) or declining limb gradient (Gdec). No significant correlations were found with Hu2 the daily wetness index from SIM platform (Habets *et al.*, 2008), I_L, Pente, Kcmp, Rcirc: so these do not appear in the table.

On the basis of these correlations, some streamflow indices can be explained in multiple regressions by physical descriptors (Fig. 2). For the seven catchments dataset, results show that the mean rising limb gradient (Grise) is correlated with intrastorm variability (Iσ) and the mean topographic index (tan(α)) with a r^2 of 0.61; the maximum specific discharge (Qpspe) is correlated with the total accumulated rainfall (Cumul) and intrastorm variability (Iσ) (r^2 = 0.72). Further investigation will include some other shape and frequency characteristics, peak descriptors or wavelet built indices.

Table 3 Single correlations between streamflow indices and physical descriptors for the full dataset.

	Cumul	Iσ	Vpluie	Dmoy	elance	Dpsbar	tan(α)	tan(α)s
Mean	0.73	0.77	0	0	0	0	0	0
Med	0.63	0	0	0	0	0	0	0
Std.dv	0.66	0.79	0	0	0	0	0	0
RLD	0	0	0	0	0.54	0	0	0.52
DLD	0	0	0	0	0	0	0	0
HFDis	0	0	0	0	0	–0.53	0	0
Hpcnt	0.70	0	0	0	0	0	0	0
HPdur	0	0	0	0	–0.53	0	0	0
Skew	0	0.57	0	0	0	–0.56	–0.55	0
Cvar	0	0	0	0	0.58	–0.56	0	0.51
Grise	0	0.59	0	0	0.52	0	0	0.55
Gdec	0.59	–0.70	0	0	0	0	0	0
Vruisp	0	0	0.63	0.56	–0.51	0	0	0
Qpoint	0.74	0.52	0	0	0	0	0	0
Qpspe	0.50	0.65	0.70	0	0	0	0	0

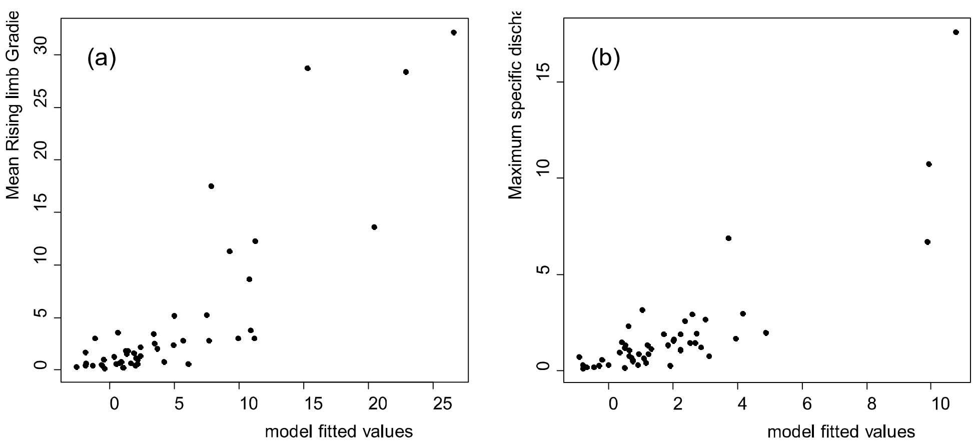

Fig. 2 Multiple regressions (gaussian family) for the full dataset. (a) Mean rising limb gradient estimated from intrastorm variability (Pvalue = 5.04e-05) and mean topographic index (Pvalue = 0.00034); r^2 = 0.61. (b) Maximum specific discharge estimated from total accumulated rainfall (Pvalue = 0.0047) and intrastorm variability (Pvalue = 7.98e09); r^2 = 0.72.

Table 4 Single correlations between streamflow indices and physical descriptors. (left) Set of four catchments (area < 100 km^2) (right) Set of three catchments (area > 100 km^2).

	area < 100 km^2							area > 100 km^2						
	Cumul	I_L	Iσ	Vpluie	Pente	Kcmp	Rcirc	Cumul	I_L	Iσ	Vpluie	Pente	Kcmp	Rcirc
Mean	0.81	0	0.83	0.61	0	0	0	0.62	0	0.73	0.53	0	0	0
Med	0.66	0	0.57	0.51	0	0	0	0.58	0	0	0	0	0	0
Std.dv	0.76	0	0.84	0.55	0	0	0	0.57	0	0.91	0.59	0	0	0
RLD	0	0	0	0	0	0	0	0.69	0	0	0	0	0	0
DLD	0	0	0	0	0	0	0	0.51	0	0	0	0	0	0
HFDis	0	0	0	0	0	0	0	0	–0.60	0.61	0	0	–0.56	0.56
Hpcnt	0.85	0	0.54	0.75	0	0	0	0.57	0	0	0	0	0	0
HPdur	0	0	0	0.51	0	0	0	0	0	0	0	0	0	0
Skew	0	0	0.58	0	0	0	0	0	–0.60	0.68	0	0	–0.54	0.54
Cvar	0	0	0	0	0	0	0	0	–0.50	0.61	0	–0.61	–0.66	0.66
Grise	0	0	0.63	0	0	0	0	0	0	0.94	0.51	0	0	0
Gdec	–0.71	0	–0.78	–0.53	0	0	0	0	0	–0.88	–0.53	0	0	0
Vruisp	0.86	0	0.53	0.86	0	0	0	0	0	0	0	0	0	0
Qpoint	0.88	0	0.71	0.77	0	0	0	0	0	0	0	0	0	0
Qpspe	0.80	0	0.73	0.68	0	0	0	0.51	0	0.89	0.70	0	0	0

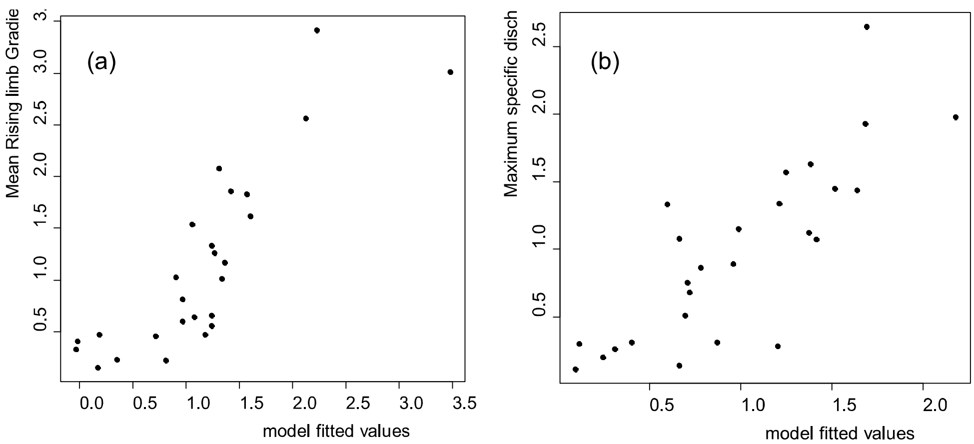

Fig. 3 Multiple regressions for set of 3 catchments (area > 100 km^2) (a) Mean rising limb gradient estimated from intrastorm variability (Pvalue= 1.29e-07) and rainfall location index (Pvalue= 0.023); r^2 = 0.72. (b) Maximum specific discharge estimated from total accumulated rainfall (Pvalue= 0.00097) and intrastorm variability (Pvalue= 0.0024); r^2 = 0.73.

Considering the previous correlations, the dataset has been split into two subsets: catchments with area smaller than 100 km^2 and the others (Table 4). We can see in the case of small catchments that cumulative rainfall intensity or rainfall volume are correlated with several streamflow indices, whereas in the case of middle-size catchments, location index (Iσ) and storm variability (I_L) play a greater role, as do hydrograph skewness and variability.

Indeed, for middle-size catchments, we can now correlate the mean rising limb gradient (Grise) with intrastorm variability (Iσ) and storm location index (I_L) with a r^2 = 0.72 (Fig. 3); whereas this regression gives no significant correlation (r^2 < 0.4 and bad P-values) for the small catchment set. This is due to a scale problem: indeed storm cells can be larger than small catchments and so location within a catchment loses importance. Moreover these small basins can have very contrasting responses depending on forcing variability and physiographic characteristic variability and often show a small dampening effect. That is why a large dataset is needed to study small catchments in the statistical framework we propose.

CONCLUSIONS

This study, for the case of flash floods events, tackles the problem of physical process description and catchment signature analysis through streamflow indices, physical descriptors and rainfall characteristics. The correlation between mean rising limb gradient, rainfall location and variability index, for middle-size catchments, is quite good contrary to the one for small catchments (<100 km^2). Knowing this threshold could be useful to study a catchment's dampening effect and response. We can also wonder which descriptors or parameters and which spatial averaging are representative of the processes and can explain catchment response dynamics. Moreover this approach gives a statistical framework to quantify catchment response dispersivity/similarity, and could allow scale analysis.

The study will be carried on with radar data at 5-min time-steps on more catchments and events to improve the hydrograph shape description and statistical independence. We hope to obtain strong regression relations between streamflow indices, physical descriptors and rainfall characteristics. Another explanatory variable may be the soil storage capacity derived from high resolution pedologic data. This could enable the elaboration of a model independent calibration methodology at the regional scale, and its application to ungauged catchments (Yadav *et al.*, 2007; Zhang *et al.*, 2008).

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