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Georges-Marie Saulnier, Matthieu Le Lay. Sensitivity of flash flood simulations on the volume, the intensity and the localization of rainfall in the Cevennes-Vivarais region (France). *Water Resources Research*, 2009, 45, pp.W10425. halsde-00441431

HAL Id: halsde-00441431

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Sensitivity of flash-flood simulations on the volume, the intensity, and the localization of rainfall in the Cévennes-Vivarais region (France)

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Received 7 February 2008; revised 5 May 2009; accepted 29 July 2009; published 17 October 2009.

[1] This paper suggests a new method to investigate the signature of the spatial structure of the rainfall on flash-floods events. The rainfall structure is analyzed considering three of its characteristics: (1) the areal rainfall over the basins, (2) the rainfall intensity statistical distribution, and (3) the convective cells geographical localizations within the catchments. The analysis is done by performing hydrological simulations forced by uniform rainfall pattern, fully spatially distributed rainfall patterns, and spatially broken down rainfall patterns. Two contrasted severe flood events that occurred within the Cévennes-Vivarais region (France) are studied as applications using actual data. A distributed hydrological model-based approach was applied on 20 catchments ranging from 50 to 2240 km². For one event, the method suggested that the accurate geographical storm cell localization is needed to obtain accurate discharges simulations. For both events, the method allowed to show that the accurate areal rainfall estimation for each intermediate catchment was not of larger importance than an accurate sampling of the rainfall intensities spectrum.

Citation: Saulnier, G.-M., and M. Le Lay (2009), Sensitivity of flash-flood simulations on the volume, the intensity, and the localization of rainfall in the Cévennes-Vivarais region (France), *Water Resour. Res.*, 45, W10425, doi:10.1029/2008WR006906.

1. Introduction

[2] Several studies analyzed the effects of rainfall spatial variability on runoff hydrographs in various hydrological contexts. An accepted result is that the accurate estimation of the areal rainfall is first needed when simulating flash-floods. Indeed, some studies concluded that rainfall patterns have only a secondary effect on runoff hydrographs when using actual events [e.g., *Beven and Hornberger*, 1982; *Obled et al.*, 1994; *Schuermans and Bierkens*, 2007]. Conversely, some authors concluded that whatever the catchment size, the spatial structure of the rainfall fields may have a significant influence on floods. For these authors, distributed modeling should be used and taken into account for detailed sampling of the rainfall spatial variability [e.g., *Wilson et al.*, 1979; *Faurès et al.*, 1995; *Boyle et al.*, 2001; *Carpenter and Georgakakos*, 2006; *Le Lay and Saulnier*, 2007]. Working on “chimera” catchments forced by artificially enhanced rainfall heterogeneity, *Andréassian et al.* [2004] aimed at establishing a hierarchy of sources of heterogeneity. They concluded that if a source of information was to be privileged, then it should be the rainfall variability.

[3] Such contradictory results may be explained by the nature of runoff process: catchments with preponderant infiltration-excess runoff process being more sensitive to the statistical distribution of rainfall intensities—obviously

better sampled when using maps of rainfall instead of a single areal value—than catchments with preponderant saturation-excess runoff mechanism [*Obled et al.*, 1994; *Winchell et al.*, 1998; *Koren et al.*, 1999]. Signature of rainfall spatial variability also seems to be influenced by catchment scale and rainfall event magnitude [*Arnaud et al.*, 2002], as well as by antecedent moisture conditions [*Shah et al.*, 1996]. Most authors finally conclude that generalizations concerning the effects of rainfall variability on runoff generation cannot be made.

[4] This paper aims to contribute to these evaluations of the rainfall spatial variability impact on flash-flood genesis. However, the above cited studies rely on hydrological model simulations when forced either by areal rainfall or by spatial rainfall maps. Thus they do not distinguish the two types of information that are embedded in a single rainfall pattern: (1) the statistical distribution of the rainfall intensity values and (2) the geographical localization of the storm cells within the catchments. Inventing methods that distinguish the actual impact of these two different informations on floods generation may be useful. For example, it could help to rank efforts that still need to be done to improve meteorological models development. Indeed, high-resolution meteorological models proved improvements in convective simulations. However, Quantitative Precipitations Forecast evaluations (QPF) concludes that improvements are still needed to better forecast both storms cell localization and full spectrum of rainfall intensity values [*Ducrocq et al.*, 2002; *Bougeault*, 2003].

[5] In what follows, a method is suggested to independently rank these two types of information in terms of their significance in the runoff hydrographs genesis. Indeed, both

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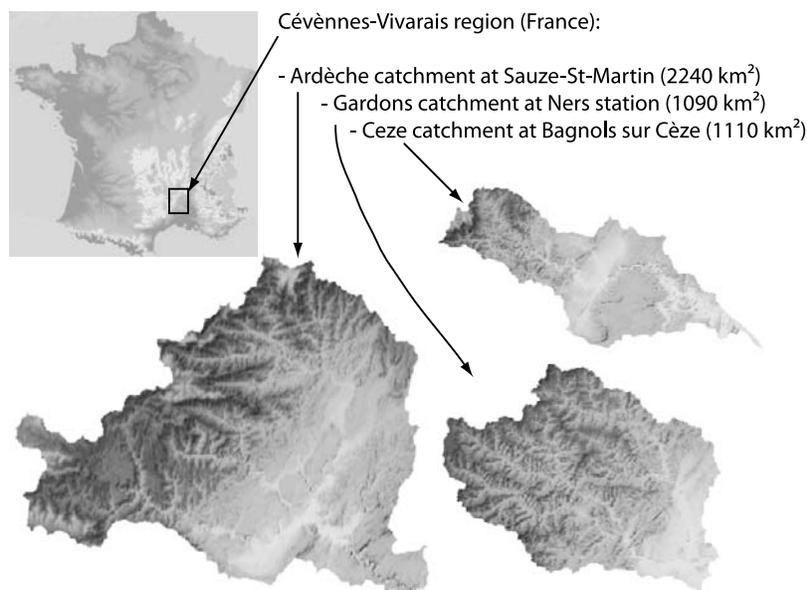


Figure 1. Location of the Cévennes-Vivarais window in France and of the three basins covered by the study.

are expected to influence the runoff generation differently [e.g., Syed *et al.*, 2003, for a data-based study]. Statistical distribution of rainfall intensities may affect the way the soil reacts and generate runoff volumes. Whereas the geographical localization of storm cells rather impacts the time delay to propagate these runoff volumes to the considered outlets.

[6] This study focuses on Cévennes-Vivarais region at the mesoscale (4500 km²), for 20 catchments ranging from 50 km² to 2240 km². For two major storm events, different simulations are performed with a spatially distributed hydrological model [see *Le Lay and Saulnier*, 2007] taking into account rainfall spatial variability, topography, and the spatial variability of soil and river hydrodynamic and hydraulic properties. Discharges sensitivity analyses were made on the 20 available gauged stations. In what follows, it will be shown how to take into account separately each of the three rainfall characteristics mentioned above.

2. Case Studies

[7] This paper focuses on two major flash-flood events that occurred on the Cévennes-Vivarais region: the 8–9 September 2002 and the 1–3 December 2003.

[8] On 8–9 September 2002 a heavy precipitation event was responsible for one of the most important floods ever recorded in the Cévennes-Vivarais region. It caused 24 casualties and economic damage estimated to 1.2 billion Euros. A detailed meteorological description of this event is provided by *Delrieu et al.* [2005]. On 1–3 December 2003 another rainfall event had a significantly different rainfall spatial variability. Although this was a smaller event, major flooding and 7 casualties occurred.

2.1. Geographical Region

[9] The Cévennes-Vivarais region is located southeast of the Massif Central in France (Figure 1). The relief is a southeasterly facing slope starting from the Mediterranean shore and the Rhône Valley. The altitude of the mountain

range varies from sea level to up to 1700 m over roughly 70 km. Particularly in the fall, this region experiences long-lasting rain events able to produce catastrophic floods over a wide range of river basin sizes (from 10 up to 10 000 km²).

[10] The hydrological survey of the Cévennes-Vivarais observatory covers the three main catchments studied in this paper which are the Gardons catchment at Ners station (1090 km²), the Cèze catchment at Bagnols-sur-Cèze station (1110 km²) and the Ardèche catchment at Sauze-Saint-Martin station (2240 km²). These three catchments are called “the river basins.”

2.2. Hydrometeorological Description

[11] In the Cévennes-Vivarais region, heavy precipitation are usually due to quasistationary mesoscale convective systems (MCS) whose several hours’ lifespan leads to high cumulative rainfall amounts.

[12] In the case of the 8–9 September 2002, the rain event lasted approximately 28 hours. It was particularly remarkable by its spatial extension, with rain amounts greater than 200 mm over 5500 km² in 24 hours. Heavy amounts primarily affected the Gardons River, with about 500 mm recorded in less than 9 hours at Anduze rain gauge. Indeed, the hydrological impacts were dramatic. In some catchments, the specific discharge rose to values of up to 3–4 m³.s⁻¹.km⁻² on catchments of several 100 km² and up to 7 m³.s⁻¹.km⁻² on catchments of several 10 km² [*Delrieu et al.*, 2005].

[13] During the 1–3 December 2003 rainfall event, the accumulated rainfall amounts were above 100 mm over a large part of the region. The area having received more than 150 mm was of about 25 000 km². The maximum rainfall accumulated over the 3-day period reached more than 300 mm. The precipitation fell over soil already moistened by previous heavy rainfall over the region since the beginning of the fall. In some catchments, the specific discharge rose to values of up to 2–3 m³.s⁻¹.km⁻² on catchments of several 10 km².

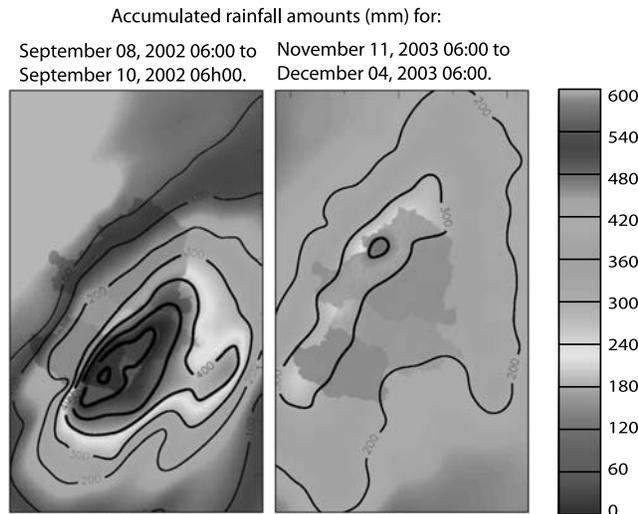


Figure 2. Accumulated rainfall amounts for (a) 8–9 September 2002 (48 h cumulative amount) and (b) 1–3 December 2003 (96 h cumulative amount).

[14] Figure 2 shows the accumulated rainfall amounts for the two events.

3. Material and Method

3.1. Available Data

[15] The 160 km \times 200 km Cévennes-Vivarais window synoptic hydro meteorological measurements network include 400 daily and 180 hourly rain gauges and 45 water level stations. For extreme storm events, some of these river gauges may malfunction or may be destroyed. Finally, 20 water level stations were chosen for this study, spread as follows: 8 gauges for the Ardèche river basin, 6 gauges for the Gardons river basin and 6 stations for the Cèze river basin. Following previous studies within these regions [Obled *et al.*, 1994; Lardet and Obled, 1994; Saulnier and Datin, 2004; Delrieu *et al.*, 2005; Chancibault *et al.*, 2006; Le Lay and Saulnier, 2007], the 180 hourly rainfall stations were mapped using the krigging technique [Creutin and Obled, 1982; Lebel *et al.*, 1987] after identification of the variogram function. The variogram statistically describes the spatial structure of the rain field. Previous exhaustive works on the rainfall climatology in these regions [Bois *et al.*, 1997] suggest that the rain fields may possess a significant anisotropy at the daily timescale. This was taken into account by krigging the rainfall stations data of all the available storm events with an anisotropic variogram. This variogram may be then considered as a climatologic variogram rather than an event-based variogram. The identified range values are 65 km in the north-northeast direction and 40 km in the orthogonal east-southeast direction [see Delrieu *et al.*, 2005, for more details] and was used for the two rainfall events studied in this paper.

3.2. Hydrological Simulation

3.2.1. Spatial Resolution

[16] Lebel *et al.* [1987] and Berne *et al.* [2004] showed that a maximal resolution of 70 km² should be enough to ensure an accurate spatial variability representation of the

krigged hourly rainfall fields on the studied region. In order to capture the whole spatial variability of rainfall fields, the spatial resolution was here chosen to be 30 km².

[17] The three river basins were then divided into 150 subcatchments of similar area equal to ≈ 30 km², using classical topographic treatment routines derived from the detailed 50 m DTM available for this study. Each of these subcatchments is called the “hydrological mesh.”

3.2.2. Processes Representation

[18] The catchment behavior is represented using one of the version of the well known TOPMODEL framework [Beven and Kirkby, 1979; Beven *et al.*, 1995]. Considerations for the choice of this hydrological model are given by Le Lay and Saulnier [2007].

[19] Basically, given some assumptions and approximations, TOPMODEL predicts the spatial distribution of the soil water content at each time step. That is a function of the spatial variability of an index of hydrological similarity and of the mean overall water storage (or storage deficit), based on the water balance estimated at each time step. The topographic variability within a particular catchment is then synthesized by a statistical empirical distribution function of this index of hydrological similarity.

[20] Greater details may be found in the works of Beven *et al.* [1995], Saulnier *et al.* [1997], or Saulnier and Datin [2004]. The version used in this paper is an event-based version, with four parameters: (1) an hydrodynamic soil characteristics set including the hydraulic soil conductivity at the surface (K_0 (m.s⁻¹)) and its exponential decrease with soil depth (m (m)), (2) the initial water content of the superficial soil layer at the beginning of the storm event ($SRMax$ (m)), and (3) the evapotranspiration losses rate ($Inter$ (m.s⁻¹)). Each of these parameters may change from one hydrological mesh to another.

[21] The TOPMODEL framework is then applied on each hydrological mesh, at an hourly time step, to estimate two discharge components: the soil subsurface exfiltration flows and the quick soil surface runoff.

3.2.3. Transfer Algorithm

[22] In order to estimate the cumulative discharge at any point of the river network of the 4500 km² studied region, a geomorphological approach was used to sum the calculated water fluxes for each hydrological mesh. Firstly, for each DTM pixel, distance to the closest river network is derived. Secondly, distance between any points in the river networks is also derived. These calculations are made once and for all prior to any hydrological simulations. Simple assumption on river propagation velocity and hillslope runoff velocity allow then to estimate the time delay between any DTM pixel and any river pixel [see Le Lay and Saulnier, 2007]. In order to decrease the number of calibrated parameters, as the hillslope runoff velocity is very difficult to measure, it was taken equal to 1/10 of the river velocity. This simplification is equivalent to say that runoff velocity on hillslope is one order lower than the velocity within the river network [Le Lay *et al.*, 2008]. Furthermore, as the hillslope lengths are typically of 1 km while the river network paths can reach a few 10 km this simplification has little effect on the hydrological discharges simulations.

[23] As the TOPMODEL framework provides a cumulative subsurface discharge, *i.e.* at the mesh scale, an isochrone transfer function was calculated for each hydrological mesh

Table 1. Parameter Values for the Three Largest Outlets of the Arèche, Ceze, and Gardons Rivers

River Basin	Inter (mm/h)	SRMax (m)	M (m)	Ko (m/h)	Velocity (m/s)
Ardèche	[0;0]	[0.03;0.06]	[0.01;0.055]	[10;100]	[1.4;2.0]
Ceze	[0;0]	[0.01;0.06]	[0.01;0.05]	[10;100]	[1.0;2.4]
Gardons	[0;0]	[0.01;0.04]	[0.03;0.07]	[50;120]	[2.0;3.0]

and was used to transfer this discharge to the outlet of each mesh [Beven *et al.*, 1995]. On the other hand, the model provides at the DTM grid cell scale the localization and the amount of surface runoff. At each time step, a transfer function is then calculated to propagate the surface runoff to the outlet of each hydrological mesh. Then, as the geographical localization of each hydrological mesh is known, both subsurface and surface discharges can be shifted in time to any considered outlet, gauged or not. However, this method does not take into account for the hydraulic diffusion within the river network and for the relation between average propagation celerity and river heights, which may be considered as acceptable for these flash-floods.

3.2.4. Model Calibration

[24] Maps of spatially variable parameters values were derived as described by *Le Lay and Saulnier* [2007] using distributed rainfall inputs [e.g., *Arnaud et al.*, 2002; *Zehe et al.*, 2005]. A Monte Carlo uniform sampling was used as a calibration procedure and the Nash efficiency [Nash and Sutcliffe, 1970] as objective function. The calibration of a distributed model is quite a challenge [Smith *et al.*, 2004]. When using automatic calibration numerical procedures, parameters often compensate for bias in the physics of the model and uncertainties in the data. Parameters values may be then significantly different from their “true” values. In order to avoid this bias as much as possible, *Le Lay and Saulnier* [2007] suggested the following method:

[25] 1. Lumped values of the 4 parameters and of the river velocity were calibrated on the three largest outlets of the three river basins using the spatially distributed rainfall.

[26] 2. Velocities within the river network were then allowed to vary in between each intermediate stations. These velocities were either calibrated either estimated by comparing the time-to-peak propagation in between two stations with no significant intermediate tributaries and/or significant changes in the river network characteristics (slopes, widths, etc.).

[27] 3. Hydrodynamics parameters for each hydrological mesh were finally allowed to vary around their lumped values. They were calibrated independently on the three largest outlets. Proceeding this way, there is no evidence that the retained parameter set is unique. It may then lead to uncertainties in the intermediate catchments simulations. On the other hand, it avoids to propagate bias due to discharges measures uncertainties (very large in these regions) as it would be the case if a more classical upstream-downstream calibration was followed. Nevertheless, the overall uncertainty of the model may be assessed and compared to the others simulations. This will be explained in the section “Results and Discussion.”

[28] Calibrating the model this way, a kind of sketch of the parameters and river velocity values is first drawn in step one. This sketch is step by step refined. Doing this, it is

hoped that the parameters of the model will less compensate for bias in the rainfall intensities and inconsistent time-to-peak estimations.

[29] The model was previously calibrated on 4 significant event storms [see *Vincendon et al.*, 2008]: 8–9 September 2002; 1–3 December 2003; 4–5 November 2004; 5–9 September 2005. These events were the only available that were equivalent in terms of rainfall elaboration procedure based on raingauges. Radar data were not fully reanalyzed and then not available for this study.

[30] Obviously, calibrated parameters may vary from one event to another. Nevertheless, these variations shown to be small. This is consistent with the relative homogeneity of the catchments characteristics in terms of topography, soils/vegetation cover and their impacts on infiltration capacities. Indeed, Table 1 indicates the range of the calibrated parameter values for each of the three river basins. It may be seen that these ranges do not vary significantly from one river basin to another. Those values are moreover similar to TOPMODEL parameters calibrated in previous studies in Mediterranean catchments [*Obled et al.*, 1994; *Lardet and Obled*, 1994; *Saulnier et al.*, 1997; *Saulnier and Datin*, 2004; *Chancibault et al.*, 2006].

[31] Therefore a single parameter set was chosen for all of the simulations described in this paper with no recalibration. The parameter set chosen is the one calibrated for the 8–9 September 2002 storm event. Indeed, this event is intensively studied in several papers [see, for example, *Delrieu et al.*, 2005; *Chancibault et al.*, 2006]. *Le Lay and Saulnier* [2007] showed that this model lead to reasonably fair or good simulations at the regional scale. Therefore once calibrated, the model may be considered as a likely physical description of the studied area. In *Le Lay and Saulnier* [2007], the authors tried to quantify the relative importance of several spatial variabilities on flash-flood generation within this region (topography, soils hydrodynamics properties, propagation velocities within the river network, spatial rainfall variability and spatial variability of initial soil water contents prior an event). They concluded that the spatial rainfall variability was of major importance to be able to perform correct hydrological simulations within this region. However, they did not explain how this rainfall variability was impacting the hydrological behavior of the catchments. This open question is studied in this paper.

[32] The analysis was driven by the following considerations.

3.2.5. Model Implementation

[33] First, the model is run using the full rainfall spatial variability. To do this the areal rainfall over each of the 30 km² is calculated at each time step. In what follows this simulation is referred to as “Distributed Rainfall simulation” (DR). This hydrological simulation benefits from the maximal available knowledge: the areal rainfall, the statistical distribution of rainfall intensity values spread around this areal rainfall and the accurate geographical localization of each rainfall cells within the catchment.

[34] The second simulation loses the benefit of knowing the localization of the storm cells. To do this, each hydrological mesh rainfall value is randomly affected to another hydrological mesh within the same river basin. All mesh area are close to 30 km² but still not necessarily exactly fits

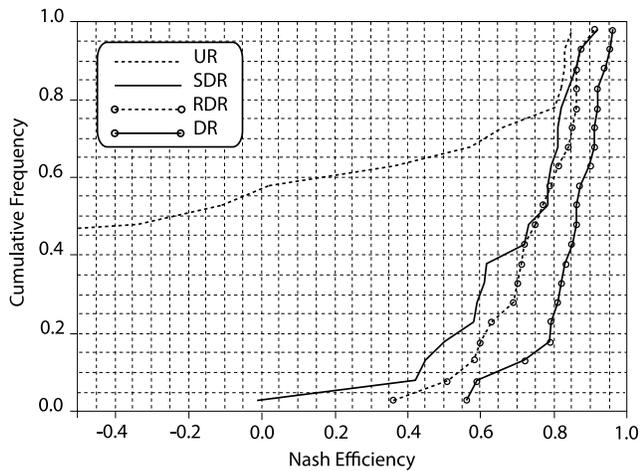


Figure 3. Cumulative distributions of regional model performances for the 8–9 September 2002 event and for the different rainfall inputs.

this value. This is clearly due to the irregular topographic contours of each mesh. In order to avoid a bias in the overall amount of rainfall for each of the three river basins, the rainfall value $R_{i,t}$ of each mesh i at each time step t is multiplied by a factor κ_i . This factor simply expresses as $\kappa_i = A_i/30$ where A_i (km²) is the area of the mesh i . The effect on the statistical distribution of the rainfall intensity values shown to be insignificant.

[35] Each randomly remixed rainfall field is then used as input to the hydrological model that computes the hydrographs at each gauged station. One hundred random redistributions were performed to reach robust median statistics presented below. This simulation is referred to as “Randomly Distributed Rainfall simulation” (*RDR*). In this simulation a bias occurs as the distances between the storm cells and the outlets are disorganized and as the convective rainfall intensity will overlay regions from different hydrodynamics properties. In terms of accuracy of the simulated discharges, the loss may be then compared to the *DR* simulation, thus making it possible to estimate the hydrological benefit of the pure knowledge of the geographical localization of the storm cells.

[36] Third, only the areal rainfalls of each of the three river basins are used for inputs to each hydrological mesh. This simulation, referred to as “Uniform Rainfall simulation” (*UR*), benefits from the knowledge of the overall amount of rainfall but loses the knowledge of the localization of the storm events and of the statistical distribution of the rainfall intensity values. *UR* simulations make use of the littlest amount of available rainfall informations. They should then lead to poor results. Nevertheless, these simulations are presented in this paper as some papers still discuss the advantage of using distributed rainfall simulations for flood forecasting [see, for example, *Cole and Moore, 2009; Smith et al., 2004; Moore et al., 2000*].

[37] One may say that the last simulation (“*UR*” simulation) is not fair. Indeed, by doing this some outlets within each of the three river basins will lose the knowledge of their own areal rainfall, contrary to the larger river basin outlets. To answer this, an intermediate simulation was also performed and added to the analysis. The areal rainfall of

each of the 20 gauged stations was calculated for each time step. Doing this, the areal rainfall of each of the gauged stations is correct but the localization of the storm cells within each of the upstream part of each gauged station is lost. This simulation is referred to as “Semi-Distributed Rainfall simulation” (*SDR*).

[38] The parameter values keep the same for each of these simulations as stated before. For each of these simulations the Nash efficiency is calculated for each of the 20 gauged stations. For the *RDR* simulation the median of the hundred Nash efficiencies was taken for each gauged station. The empirical cumulative distribution function of the 20 Nash efficiency values are then calculated and plotted as by *Le Lay and Saulnier [2007]*. These empirical cumulative distribution are built as follows: (1) the Nash efficiencies are ranked from smallest to largest, the smallest being denoted E_1 and the largest E_n with n the number of values (here $n = 20$); (2) the cumulative frequency p_i , i.e. the probability of a value being less than the i th smallest observation in the data set of n observations, is then calculated as $p_i = (i - 0.5)/n$ [*Maidment, 1993*]. This kind of statistical synthesis may be considered as well suited to display the overall accuracy of a distributed hydrological model when applied to a large region [*Habets et al., 2008; Vincendon et al., 2008*]. However, it loses the possibility to analyze the accuracy of the simulations outlet by outlet, which is not anyway the specific purpose of this study. Results are shown and discussed in the following section.

4. Results and Discussion

[39] Figures 3 and 4 show the empirical cumulative Nash efficiencies for the 20 gauged river stations for the two storm events and for the 4 rainfall scenarios. The more the distribution is shifted to the right, the better the model simulation is. *DR* distribution corresponds to the highest model likelihood as it takes into account the whole available rainfall information. If the simulations were perfect, all the Nash efficiencies would be equal to 1. The “perfect” simulations would then lead to an empirical cumulative efficiencies distribution equal to a vertical line in Figures 3 and 4, crossing the X axis at the 1.0 Nash value. The

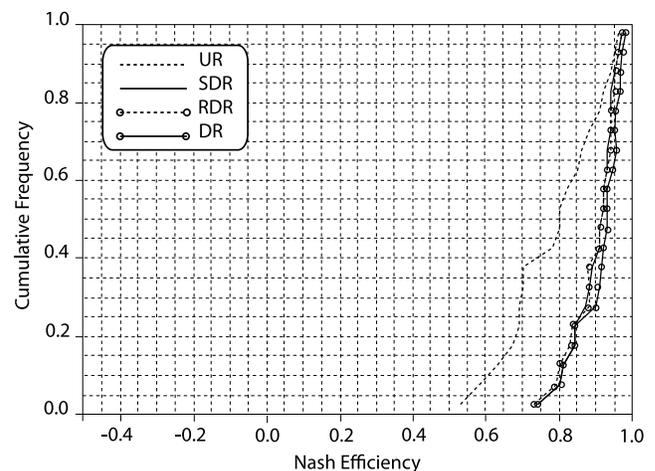


Figure 4. Cumulative distributions of regional model performances for the 1–3 December 2003 event and for the different rainfall inputs.

distance between this “ideal” distribution and the *DR* empirical distribution drawn on Figures 3 and 4 can then be seen as a qualitative indicator of the simulation errors due to both modeling and data uncertainties. *UR* distribution corresponds to the lowest model likelihood as it takes into account only the areal rainfall at the global outlets of the three river basins. In between, the other distributions and their relative shift from the *DR* distribution illustrate the relative impacts when losing such and such rainfall information.

4.1. 8–9 September 2002 Event

[40] Results for the 8–9 September 2002 event are shown on Figure 3 and suggest the following.

[41] 1. The spatial variability of rainfall has a strong signature on distributed hydrological response. Indeed, *DR*, *RDR* and *SDR* scenarios lead to significantly better results than *UR* scenario.

[42] 2. Losing the knowledge of the storm cells localization within catchments (*RDR* and *SDR* scenarios) leads to a significant decrease in hydrographs simulations compared to *DR* scenario.

[43] 3. *RDR* and *SDR* scenarios are close. One would expect larger differences between overall accuracy of the *RDR* and the *SDR* simulations than those observed on Figure 3. Indeed, in the *RDR* simulations, the mean areal rainfall upstream of intermediate stations are not necessarily preserved unlike in the *SDR* simulations. This is discussed deeper in section “Discussion.”

4.2. 1–3 December 2003 Event

[44] Figure 4 shows results obtained for the 1–3 December 2003 event. It is worth noting that this case study strongly differs from the first one. Four differences can be outlined:

[45] 1. Firstly, overall model performances are better, whatever the rainfall scenario, even when using the *UR* scenario.

[46] 2. Secondly, whatever the catchment size, the knowledge of its areal rainfall (*SDR* scenario) is enough to correctly simulate the hydrograph. Sampling the rainfall intensity values (*RDR* scenario) or measuring the accurate localization of the storm cells (*DR* scenario) only give little improvements.

[47] This is clearly a consequence of the relative homogeneity of the rainfall field, contrary to the 8–9 September 2002 event (see Figure 2).

4.3. Discussion

[48] The method suggested in this paper proved to be able to distinguish the role of the rainfall intensities statistical variability from the role of the rainfall geographical localization. For both events, no clear evidence was found to allow to rank the importance of an accurate sampling of the rainfall intensities values and of an accurate estimation of the areal rainfall of the subcatchments. The rainfall spatial pattern of the 8–9 September 2002 event was more contrasted than the 1–3 December 2003 event in terms of hydrological impacts (see Figures 3 and 4). However, the suggested approach allowed to show that the sampling of the rainfall intensity values was of same importance that the accurate knowledge of the areal rainfall of each intermediate catchments. This may be understood as the *SDR* simulations is in a way already a sample of the spatial

variability of the rainfall. However, this “coarse” sampling loses information compared to a fully distributed rainfall pattern (the smallest gauged catchment is about 50 km² and intermediate catchments sizes are typically about 100 km²). The method suggested in this paper allowed to observe that in the case of the particular events studied in this paper, the *SDR* simulations contains about the same amount of relevant informations than those contained in the *RDR* simulations.

[49] This may be seen as an interesting result as it is still often considered that sampling the accurate areal rainfall upstream intermediate catchments may be enough to conduct accurate hydrological simulations. In the same time, this does not necessary lead to conclude that a fully distributed hydrological is always needed and that lumped models should be necessary out of interests. Indeed, one may say that obtaining the areal rainfall on each subcatchments catches some parts of the spatial variability of the rainfall but may be not enough. This could may be compensated if a way was found in lumped hydrological models to analytically take into account for the variability of rainfall intensities. Indeed, the approach described here showed that the *SDR* and the *RDR* simulations were catching completely different informations embedded in a rainfall pattern but were quite of same relevancy for flood simulations. One may then wonder if their combination would lead to simulations as accurate as the *DR* simulations.

[50] The method suggested in this paper may be seen as general. However, some of the results may be seen as hydrologically specific to these catchments which are driven by saturation-excess runoff process rather than infiltration-excess process [Quinn *et al.*, 1991; Lardet and Obled, 1994; Cosandey, 1994; Cosandey *et al.*, 2005; Medici *et al.*, 2008]. In such catchments, the spatial dynamic extent and localization of the saturated areas are mainly controlled by catchment water balance rather than high intensity values. However, the accurate knowledge of the rainfall intensity values is still a valuable information (*RDR* simulation) as it allows to correctly simulate the part of the rainfall that will runoff on saturated areas. Also, the localization of the storm cells (*SDR* simulations) is important as it allows to avoid bias in time propagation estimations. Obviously, the *DR* simulations benefits of the entire informations needed to simulate the hydrological response as well as possible for any model given.

[51] Figure 5 shows some hydrographs simulated for the two events at two basin outlets (Gardons at Ners station and Ardèche at Saint Martin station). Both *SDR* and *DR* simulations are represented. Firstly, the 2003 event hydrographs illustrate the negligible impact of the rainfall spatial variability on the discharges such as explained above. Secondly, the hydrographs for the 2002 event illustrate how losing the fine scale rainfall spatial variability within the catchment may impact on both peak flow errors and timing errors. This in return suggests that errors are both induced by (1) runoff generation and (2) runoff localization. For this event, the Figure 6 shows the simulated relative soil water contents on the Ardèche basin during the peak flow, for the *DR* and *SDR* scenarios. With the latest, soil wetness is only controlled by landscape heterogeneities, such as topography and soil hydrodynamic characteristics [Le Lay and Saulnier, 2007]. With the *DR* scenario, the spatial variability of rainfall adds a significant control on the soil wetness and therefore on the runoff generation, as shown by

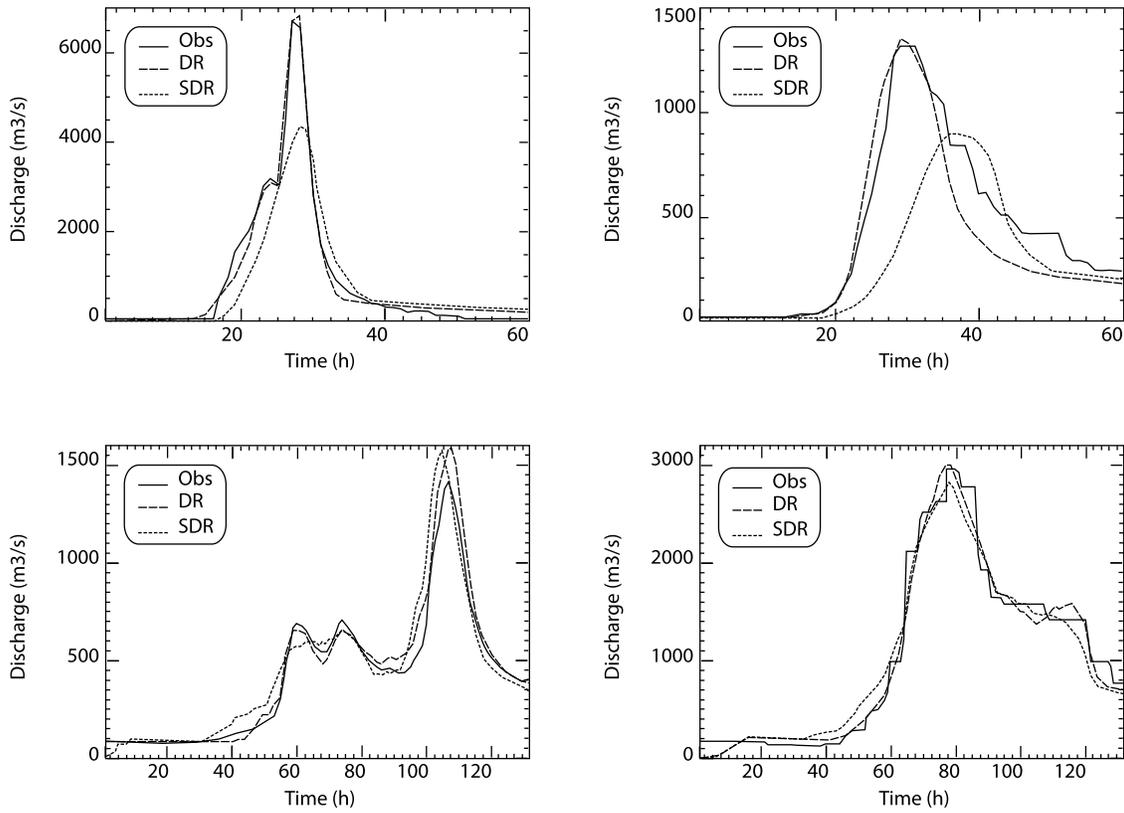


Figure 5. Discharge simulations for (top) the 8–9 September 2002 and (bottom) the 1–3 December 2003 event at two gauged stations. (left) Gardons at Ners and (right) Ardèche at Saint Martin and for the *SDR* and *DR* rainfall inputs.

the large differences in the upper and lower parts of the basin.

5. Conclusions

[52] The impacts of the rainfall space structure on flash-flood genesis were analyzed using an original approach. For a given event, the method suggested in this paper allow to distinguish between the role of the rainfall intensities statistical variability and the role of the geographical localization

of the storm events. The method is model-independent but is still time-consuming and then should be applied to numerically efficient hydrological models.

[53] By breaking down the spatial consistency of the rainfall patterns, the approach allows to quantify the single impact of the rainfall intensities variability on a flood event, while ensuring the correct areal amount of rainfall. By comparison with the fully distributed rainfall hydrological simulations one may assess the impact of the geographical storm cells localization.

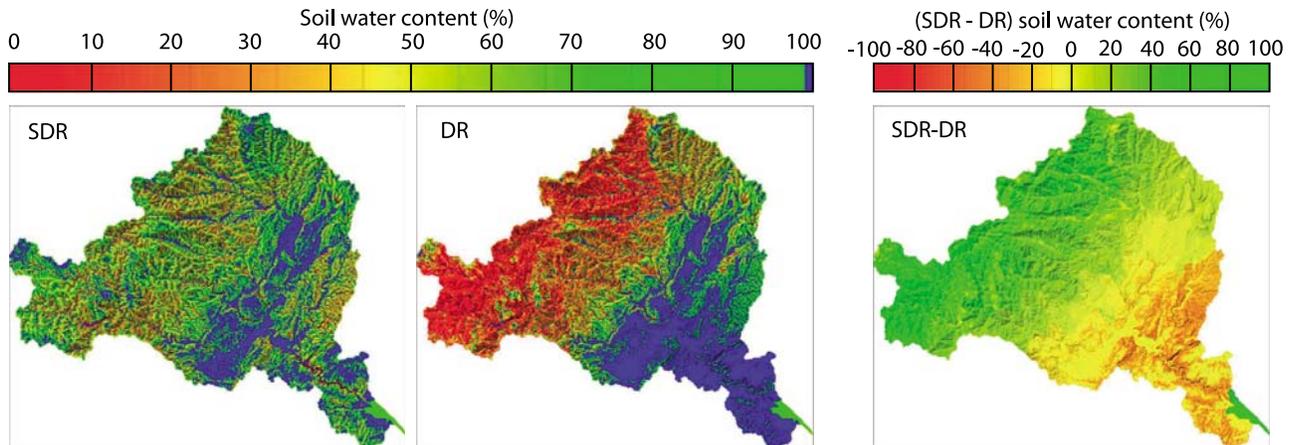


Figure 6. Simulated relative soil water contents (in percentage) on the Ardèche basin during the 8–9 September 2002 event peak flow for (left) the *SDR* and (middle) the *DR* scenarios. The figure on the right shows the differences between the *SDR* and the *DR* maps.

[54] When applied on three catchments of the Cévennes-Vivarais region (covering 4400 km²) for two particular severe event, results suggested that the accurate sampling of the rainfall intensities statistical variability may be of same importance that the knowledge of the areal rainfall of each intermediate catchments. For one particular event, the 8–9 September 2002 event it was found that the accurate geographical localization of the storm cells was needed to significantly improve the discharges simulations. On the contrary of the 1–3 December 2003 event where the spatial extent of the rainfall patterns did not show to be of major importance.

[55] Results of this method would lead to conclude that on this particular region, the full spectrum of the rainfall intensity should be accurately estimated when performing discharges simulations. This should be taken into account when forcing hydrological models with mesoscale meteorological models. Indeed, within the Cévennes-Vivarais region, the method suggested here was able to prove that the only knowledge of areal rainfall upstream intermediate catchments may not be of prior importance compared to a correct sampling of the rainfall intensities spectrum.

[56] **Acknowledgments.** This work was funded by the EC FP 6 Integrated Project PREVIEW (“PREvention, Information and Early Warning,” www.preview-risk.com): WP 4340 “Very Short Range Flash-Flood Laboratory”) and by the MEDUP project (www.cnrm.meteo.fr/medup, ANR-VMC French Program).

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