Distributed hydrologic and hydraulic modelling with radar rainfall input: Reconstruction of the 8–9 September 2002 catastrophic flood event in the Gard region, France

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A B S T R A C T

On 8–9 September 2002, an extreme rainfall event caused by a stationary mesoscale convective system (MCS) occurred in the Gard region, France. Distributed hydrologic and hydraulic modelling has been carried out to assess and compare the various sources of data collected operationally and during the post-event field surveys. Distributed hydrological modelling was performed with n-TOPMODELs and assessed for ungauged basins with the discharge estimates of the post-event surveys. A careful examination of the occurrence in time and space of the flash floods over the head watersheds indicates that flooding was controlled by the trajectory of the convective part of the MCS. Stationarity of the MCS over the Gardon watershed (1858 km² at Remoulins) for 28 h was responsible for the exceptional magnitude of the flood at this scale. The flood dynamics were characterized by an extensive inundation of the Gardonnencque plain upstream of the Gardon Gorges resulting in a significant peak flow reduction downstream. One-dimensional unsteady-flow hydraulic modelling was found to be required to reproduce these dynamics. Hydraulic modelling also proved to be potentially useful for the critical analysis and extrapolation of operational discharge rating curves.

1. Introduction

Continuing the work of previous studies of extreme hydrologic events [14,2,17,7,5], this article is devoted to the 8–9 September 2002 catastrophic flood event that occurred in the Gard region (France). This event resulted in 24 casualties and economic damage evaluated at 1.2 billion euros [9]. The meteorological situation and a preliminary analysis of the hydrologic datasets collected by the research teams of the Cévennes–Vivarais Mediterranean Hydrometeorological Observatory (the French acronym OHMCV will be used hereafter) have already been presented in [5]. The present contribution is aimed at describing the distributed hydrologic and hydraulic modelling carried out to assess and compare the various sources of data collected operationally and during the OHMCV intense post-event field campaign (IPEC).

The region of interest and the datasets available are described in Section 2. This includes the quantitative precipitation estimation (QPE) from the OHMCV radar and raingauge datasets. The n-TOPMODELs distributed hydrologic model [11], the CARIMA hydraulic model of SOGREAH Consultants [4] and the modelling strategy are described in Section 3. Section 4 is dedicated to the assessment of the hydrologic response over the head tributaries of the Gardon watershed thanks to the operational and IPEC discharge estimates. Section 5 presents the reconstruction of the flood with the hydraulic model for the downstream part of the Gardon watershed. In addition, the potential of hydraulic modelling for critical analysis of operational discharge rating curves is illustrated. The main scientific and practical outcomes of this work are summarized in Section 6.

2. Study area and datasets

2.1. The region of interest

Three watersheds were particularly affected by the Gard 2002 event, namely the Vidourle (830 km² at Sommières), Gardon (1858 km² at Remoulins) and Cèze (1110 km² at Bagnols-sur-Cèze) watersheds (Fig. 1). The last two rivers are right bank tributaries of the Rhône river while the first flows into the
Mediterranean Sea. The rivers originate in the Cévennes mountains, a medium-elevation range culminating at Mount Lozère (1699 m asl). In terms of geology (Fig. 2), this ridge corresponds to the primary era geological formations of the French Massif Central and is mainly composed of granite, schist, gneiss and sandstone. This region exhibits a rather homogeneous landscape with heaths and pine forests on the crest while the steep slopes are covered with chestnut and oak forests. The rivers and roads present a high degree of tortuosity in this upstream area. Further downstream, the three rivers cross the Gard plains which are based on secondary geological formations with a stratigraphical series ranging from Jurassic (west) to Cretaceous (east). Close to the Cévennes mountains, this secondary series is interrupted by a network of NE–SW faults which delineate the Alès graben, a 1500-m graben filled with tertiary sediments from the Oligocene. The central part of the Gardon river plain, called the Gardonnenque, is filled with quaternary sediments from the Holocene. The rivers then cross Cretaceous limestone. Such massive formations forced the rivers to create deep canyons (e.g. the Gardon and Cèze gorges but also the famous Ardèche gorges northward of the affected regions). These limestone formations present a high degree of karstification. Downstream, the secondary formations are covered with the quaternary sediments of the Rhône river. The Gard plains have an elevation range of 20–200 m asl, with moderately sloping hills and a landscape principally composed of garrigue, orchards and vineyards. The region is largely rural with scattered habitations in the mountains, small villages often located close to the rivers and a few medium-sized cities like Nîmes (140,000 inhabitants) and Alès (42,000). Green tourism has grown over recent decades in this region, making the management of flash-flood risks a growing concern for local and regional authorities.

2.2. Quantitative precipitation estimation (QPE)

The Gard 2002 rain event was caused by a mesoscale convective system (MCS) that remained almost stationary for about 28 h from 0800 UTC 8/09/2002 to 1200 UTC 9/09/2002. Although intense rain events are relatively frequent in this Mediterranean region [10], this one was particularly extreme and remarkable by its spatial extent and magnitude (Fig. 3). The radar and raingauge networks used in the present study include the Bollène S-Band weather radar of the French radar network and 152 raingauge stations (including 82 stations providing hourly time series) over the region of 100 × 100 km² displayed in Fig. 3. The raingauge data were collected by OHMCV from various operational services (Météo-France, Service de Prévision des Crues du Grand Delta, Electricité de France) and critically analyzed. The event occurred in a region of good visibility for the Bollène radar: it affected mostly the Gard plains and was located within the 100-km radar range. The radar was operated with an experimental
volume-scanning protocol made of 8 plan position indicators (PPI) every 5 min.

The datasets collected during the Bollène 2002 experiment made it possible to develop an adaptive and regionalized radar data processing system extensively described in [6]. Here are the main steps of this physically-based radar processing.

1. A pre-processing step includes a radar calibration stability check, using external reference targets (derived from ground clutter here), and characterization of the radar detection domain. This characterization consists in determining dry-weather noise and screening effects for all the elevation angles using a digitized terrain model.

2. A second step is dedicated to dynamic identification during the course of the rain event. An algorithm based on a pulse-to-pulse reflectivity variability criterion is firstly implemented for selective clutter identification. The vertical profiles of reflectivity (VPR) are then identified with pre-conditioning of the reflectivity data using a rain typing method based on algorithms found in the literature [18,15].

3. Rainfall at ground level is estimated by a weighted average of the corrected reflectivities aloft and rain-typed $Z-R$ relationships. In [6], the NEXRAD $Z-R$ relationships were used with $Z = 300R^{1.4}$ for convective rainfall and $Z = 200R^{1.6}$ for non-convective rainfall.

The radar QPE map obtained at the event time scale with this procedure and this parameterization is displayed in Fig. 3a. Fig. 4a and b presents the scatterplots of the radar versus raingauge QPEs at event and hourly time steps respectively. Values of three assessment criteria (mean relative error defined as $(G-C)/C$, determination coefficient and Nash efficiency) are listed in Table 1 for various estimation and reference datasets. Radar performance appears to be very good (Nash efficiency of 0.87 and 0.79 at event and hourly time steps respectively) considering that (i) the radar QPEs are obtained independently with respect to raingauge data and (ii) the $Z-R$ relationships were not adapted to the Mediterranean climatology. There is a significant bias with a mean relative error of 12.5% at the event time step. The scatterplot (Fig. 4a) indicates in particular that a conditional bias exists with a systematic underestimation of rain amounts greater than 400 mm. The scatter is naturally greater at the hourly time step and some outliers can be detected in Fig. 4b. Note that part of such scatter can be attributed to the point-area representativeness of the raingauge measurements [3].

The Ordinary Kriging technique (e.g. [19]) was used to produce the QPE maps of the entire (hourly and daily stations) and hourly raingauge networks (Fig. 3b and d respectively). An isotropic variogram with a 50-km decorrelation distance has been considered at the event time step while a 25-km decorrelation distance has been used to process the 1-hour rainfall maps required for the hydrological modelling. The daily network can be considered very dense (1 raingauge every 8 km on the average) and the hourly raingauge network moderately dense (1 raingauge every 11 km on the average), referring to the rainfall decorrelation distances mentioned just above for the two time steps. Note however that the OHMCV hourly raingauge network is one of the densest networks in France due to the vulnerability of the region to extreme rain events. The fourth line of Table 1 lists the criteria values for the comparison of the Kriged values from the daily network with the measured rain amounts of the hourly raingauge network. Such results confirm the high consistency of the raingauge measurements at the event time step. However, the lack of raingauges in the centre of the domain of interest makes the rainfall volume rather uncertain in this area.

Radar–raingauge merging is the only practical solution to cope with the problems raised above for the two measurement systems considered separately. Several refined techniques are available for this purpose [19]. However, we chose to simply optimize a single $Z-R$ relationship by exploring the $Z-R$ coefficient space using the Nash coefficient between radar and raingauge estimates as the crite-
rion to be maximized. A detailed discussion of such an optimization technique is beyond the scope of the present paper. We took care to test the dependence of the results on the accumulation time step and on the optimization criterion (bias, scatter, Nash coefficient). Note that the optimized parameters may compensate for various error sources (mainly radar calibration uncertainty in the present case) and lack physical significance. We finally chose \( Z = 325R^{1.35} \) as the optimal relationship among a set of equifinal \( Z-R \) relationships.

The assessment criteria listed in Table 1 indicate a significant improvement of the Nash coefficient at the event time step (0.92 instead of 0.87) related mostly to the reduction of the bias, especially for the highest rain amounts. At the hourly time step, the improvement remains limited with a slight increase of the determination and Nash coefficients. The conditional bias is reduced at the cost of an inversion of the overall bias (MRE = -7.2\%). Therefore, the most significant improvement achieved by the \( Z-R \) relationship optimization is the bias reduction at the event time step, particularly important given that an accurate estimation of the rainfall volumes is critical for hydrologic modelling. We will consider two rainfall QPEs below, i.e. the radar QPE with the optimized \( Z-R \) relationship and the hourly raingauge Kriged rainfall (see Fig. 4c and d for the corresponding maps at the event time step).

Besides the previous considerations concerning the quantitative precipitation estimation, it is worth recalling [5] that the 8–9 September 2002 rain event presented a marked space–time structure with three distinct phases:

(i) Phase 1 (0800 UTC – 2200 UTC 8/09/2002): The MCS formed over the Gard plains with a southwest–northeast orientation and remained stationary producing rain amounts of typically 200–300 mm in 6–10 h over the Vidourle and downstream Gardon watersheds.

(ii) Phase 2 (2200 UTC 8/09/2002 – 0400 UTC 9/09/2002): The MCS pivoted progressively to a south–north direction and moved towards the upper part of the Gardon and Cèze watersheds. It became stationary at the limit of the Cévennes mountains and produced the same typical rain amounts there.

(iii) Phase 3 (0400 UTC – 1200 UTC 9/09/2002): During the morning of 9/09/2002, a cold front passed and swept the MCS out of the region. High rainfall intensities were observed as a result of the interactions of the cold front with the MCS. Due to the fast displacement of the cold front, total rain amounts were limited to about 100 mm during this phase, with a rather uniform spatial distribution. Note that the terrain was fully saturated at that time and that the cold front moved from upstream to downstream over the river network.

2.3. Hydrological datasets

The modelling exercise presented in this article is restricted to the Gardon watershed. A more detailed hydrographical map of this watershed and the available hydrological datasets are shown in Fig. 5. Eight operational stream gauges out of a total of eleven were...
considered to be usable in this study. Unfortunately, this excludes the Russian station, a station critically located at the entrance of the Gardon gorges. As an inherent feature of such extreme events, the water levels and discharges reached unprecedented values, damaging some gauges and making the stage–discharge conversion with the available operational rating curves highly uncertain for the others.

An intense post-event field campaign (IPEC) was conducted for the Gard 2002 event by several research teams associated with the OHMCV [5]. Basically, the procedure aimed at estimating maximum discharges by means of high water marks for the head watersheds in the affected areas. It also consisted of interviewing witnesses to document the chronology and dynamics of the flood i.e. time and duration of the flooding for particular levels (e.g. full-bank and peak levels). A detailed presentation of the IPEC methodology is given in [8]. The locations of the 49 IPEC discharge estimates for the Gardon watershed are shown in Fig. 5. Several estimates were made for each single watershed to test the consistency and increase the reliability of such rough discharge estimates. Fig. 6 presents the specific discharges as a function of the

Table 1
QPE assessment: the criteria (MRE: mean relative error; $R^2$: determination coefficient; Nash criterion) are calculated for the event and hourly rain amounts for 1-km² meshes containing a raingauge. Various estimation and reference datasets are considered.

<table>
<thead>
<tr>
<th>Compared variables</th>
<th>Time step</th>
<th>MRE (%)</th>
<th>$R^2$</th>
<th>Nash criterion</th>
<th>Number of pairs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimation</td>
<td>Reference</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radar with unoptimized Z–R relationships hourly and daily raingauges</td>
<td>Event</td>
<td>12.6</td>
<td>0.92</td>
<td>0.87</td>
<td>152</td>
</tr>
<tr>
<td>Radar with optimized Z–R relationship hourly and daily raingauges</td>
<td>Event</td>
<td>-2.0</td>
<td>0.95</td>
<td>0.92</td>
<td>152</td>
</tr>
<tr>
<td>Radar with unoptimized Z–R relationships hourly raingauges</td>
<td>Event</td>
<td>12.5</td>
<td>0.91</td>
<td>0.87</td>
<td>82</td>
</tr>
<tr>
<td>Radar with optimized Z–R relationships hourly raingauges</td>
<td>Event</td>
<td>8.5</td>
<td>0.80</td>
<td>0.79</td>
<td>2740</td>
</tr>
<tr>
<td>Daily raingauge Kriging hourly raingauges</td>
<td>Event</td>
<td>-1.7</td>
<td>0.93</td>
<td>0.92</td>
<td>82</td>
</tr>
<tr>
<td>Radar with optimized Z–R relationship hourly raingauges</td>
<td>Event</td>
<td>-3.5</td>
<td>0.92</td>
<td>0.92</td>
<td>82</td>
</tr>
<tr>
<td>Radar with optimized Z–R relationship hourly raingauges</td>
<td>Event</td>
<td>-7.2</td>
<td>0.81</td>
<td>0.81</td>
<td>2740</td>
</tr>
</tbody>
</table>

Fig. 4. QPE assessment: scatterplots of the radar versus raingauge estimates at the event (a and c) and hourly (b and d) time steps. The top graphs correspond to radar QPE obtained with the NEXRAD Z–R relationships while radar QPE on the bottom graphs are obtained with a single Z–R relationship optimized for the considered event using the raingauge dataset.
watershed area by grouping the IPEC and operational discharge estimates. This graph illustrates the exceptional magnitude of this event with specific discharges reaching 40 m$^3$ s$^{-1}$ km$^{-2}$ for watersheds of less than 10 km$^2$ and ranging between 3 and 6 m$^3$ s$^{-1}$ km$^{-2}$ for the watersheds greater than 200 km$^2$. For comparison, note that the 10-year (return period) specific discharge is about 2–3 m$^3$ s$^{-1}$ km$^{-2}$ for 100 km$^2$ watersheds in this region. Fig. 6 also illustrates the very significant added information provided by the IPEC compared to the operational discharge observation system for characterization of the hydrologic response of the head tributaries.

The inundated areas are also mapped in Fig. 5. They were estimated from an extensive set of high water marks collected by the operational services after the event. This map shows two severely affected areas with (1) the downstream part of the watershed from Remoulins to the Rhône confluence and (2) the Gardonnenque plain upstream of the Gardon Gorges. The gorges clearly played a major role in controlling the Gard 2002 flood resulting in an impressive inundation of the Gardonnenque plain.

3. Modelling strategy

Due to the significant observation and modelling uncertainties for such extreme events, a methodology based on robust model parameterization and multi-variable assessment was defined. It is described in this section after a brief presentation of the hydrologic and hydraulic models used.

3.1. Description of the hydrologic and hydraulic models

n-TOPMODELs [11] belongs to the TOPMODEL family [1]. This model predicts sub-surface lateral flow and subsequent saturation excess overland flow. Such hydrologic processes were found to be relevant to reproduce the flash-flood genesis in the French Mediterranean region [12,16,11]. The model uses a hydrologic similarity concept to effectively determine the distribution of the soil water content over the watershed at any time during a flood event. The model requires only three parameters to describe runoff production: (i) the hydraulic conductivity at the surface ($K$); (ii) the exponential rate of decline of the hydraulic conductivity in the soil profile ($m$) and (iii) the initial storage deficit in the root zone storage ($SR_{max}$). The originality of n-TOPMODELs mainly lies in the discretization of the watershed into hydrologic meshes of roughly the same size with the possibility of choosing the mesh size and considering the specific (distributed) rainfall input and parameters for each mesh. A geomorphological transfer function is used to sum up the calculated water fluxes for each hydrological mesh and estimate the discharge at any point of the hydrographic network. This function requires two additional parameters: (i) the average river flow velocity ($V_r$) and (ii) the average hillslope flow velocity ($V_h$).

CARIMA is a 1D hydraulic model developed by SOGREAH Consultants to model unsteady flow in rivers. The reader is referred to [4] for a comprehensive description of the modelling techniques and numerical methods used. CARIMA solves the full Barré de Saint Venant equations for the river and accounts as such for the backwater effects generated by topographical singularities and hydraulic works. Overflows are modelled with inundation cells using simplified flow equations. Given initial and boundary conditions, the model predicts the water level and discharge for each river.
node point and the discharge between each pair of inundation cells.

3.2. Overview of the model implementation and assessment strategy

As mentioned above, two distributed rainfall inputs were considered for the hydrological model implementation: (1) radar rain fields with the optimized Z–R relationship, (2) hourly raingauge rain fields derived from Ordinary Kriging. Owing to the typical rainfall–runoff dynamics in the region of interest, we chose to consider 50-km² hydrological meshes using a simulation time step of 30 min for the hydrological model implementation with the radar QPE products. We had to use the hourly time step for the raingauge Kriged QPE products.

The parameters of the hydrological model were calibrated with the single Ners stream gauge just downstream of the Gardon d’Anduze and Gardon d’Alès confluence. This point drains an area of 1090 km² and thus divides the Gardon watershed into roughly two equal parts. The Ners station is considered to be relatively reliable in terms of the stage–discharge relationship and worked satisfactorily during the Gard 2002 event. Homogeneity of the hydrologic and hydraulic parameters upstream was assumed. Considering the time delay between the operational hydrographs of Corbès and Ners, a \( V_r \) parameter value was adjusted for the mountainous part (\( V_r = 2 \text{ m s}^{-1} \)) of the watershed. The hillslope flow velocity \( V_h \) is not a very sensitive parameter due to the short hillslope average length: it was arbitrarily set to \( V_h = V_r / 10 \). The hydrologic parameters \( K_s \), \( m \) and \( SR_{\text{max}} \) were first adjusted for the two distributed rainfall inputs and compared with a parameterization already available from a previous study [20]. Due to the results obtained, a single parameterization was finally selected for the model implementation (Section 4.1). The operational and IPEC maximum discharge estimates were then used to assess hydrologic model performance (Section 4.2). In addition, several sensitivity tests to the hydrologic parameterization were performed to try to improve the simulation results for some specific parts of the Gardon watershed (Section 4.2).

The influence of the Gardon gorges on the Gard 2002 flood (Fig. 5) was one motivation for implementing a hydraulic model for the reconstruction of the flood dynamics in the downstream part of the watershed. A further motivation was related to the necessary improvement of the operational rating curves for high and extreme flood events. The modelled stream extends from the confluence of the Gardon d’Anduze and Gardon d’Alès watersheds, just upstream of Ners, down to the Gardon–Rhône confluence. Detailed topography describing the river cross-sections and the hydraulic works (bridges, sills, etc.) were provided by the Service de Prévision des crues du Grand Delta and the Syndicat Mixte d’Aménagement des Gardons. In the absence of specific topographical data, 1:25,000 maps were used to model the Gardon gorges. The definition of the inundation cells of the 1D hydraulic model was performed using a SOGREAH 2D model of the Gardonnenque inundation plain upstream of the Gardon gorges.

In terms of parameterization, recent non-overflowing cases were considered to determine the roughness coefficients of the river bed using the transfer times in the Ners–Russan and Russan–Remoulines streams. The inundation cells were specified only by their modelled geometrical characteristics. The overall agreement of the hydraulic simulation was then assessed by comparing the simulated and observed high water levels. In addition, since no discharge information was used in the previous steps for the hydrologic and hydraulic model implementations (with the exception of the Ners station), the simulated stage and discharge time series can be compared in gauged sections with the operational rating curves. Such an analysis is unfortunately restricted to the Remoulines stream gauge due to the non-availability of the Russian station for the Gard 2002 case. The hydraulic modelling results are presented in Section 5.

4. Distributed hydrologic response over the head tributaries

4.1. Parameterization of the hydrologic model

Table 2 lists the optimal parameters obtained for the Ners stream gauge. CAL0 is a parameterization obtained in a previous study [20] with raingauge rainfall inputs and the Ners discharge time series by grouping three events posterior to the Gard 2002 event (1–3/12/2003, 4–5/11/2004, 5–9/09/2005). CAL1 and CAL2 are the two parameterizations obtained specifically for the Gard 2002 case using the radar and raingauge rainfall inputs respectively. As a known result, the adjusted TOPMODEL parameters lack physical significance (e.g. \( K_s \) values of 50–60 m h⁻¹). The \( SR_{\text{max}} \) value is adjusted to reproduce the rising of the discharge at the beginning of the event. This parameter is particularly sensitive to the initial moisture state of the watershed which was dry given that antecedent precipitation was basically null for the upstream part of the watershed. The last column in Table 2 gives the Nash coefficient obtained between simulated and observed discharges.

Table 2
Calibration of n-TOPMODELs for the Ners stream gauge. CAL0 corresponds to the optimal parameterization obtained in a previous study by combining three events. The input rainfall was derived from the raingauge network. CAL1 and CAL2 correspond to the optimal parameterization obtained in the present study for the Gard 2002 case alone with the radar rainfall (with optimized Z–R relationship) and the hourly raingauge rainfall respectively.

<table>
<thead>
<tr>
<th></th>
<th>( K_s ) (m h⁻¹)</th>
<th>( m ) (m⁻¹)</th>
<th>( SR_{\text{max}} ) (m)</th>
<th>( V_r ) (m s⁻¹)</th>
<th>( V_h ) (m s⁻¹)</th>
<th>Nash efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAL0</td>
<td>60</td>
<td>0.04</td>
<td>0.05</td>
<td>2.0</td>
<td>0.2</td>
<td>0.970</td>
</tr>
<tr>
<td>CAL1</td>
<td>40</td>
<td>0.06</td>
<td>0.05</td>
<td>2.0</td>
<td>0.2</td>
<td>0.982</td>
</tr>
<tr>
<td>CAL2</td>
<td>40</td>
<td>0.054</td>
<td>0.05</td>
<td>2.0</td>
<td>0.2</td>
<td>0.969</td>
</tr>
</tbody>
</table>

Table 3
Parameterizations of n-TOPMODELs.

<table>
<thead>
<tr>
<th></th>
<th>( K_s ) (m h⁻¹)</th>
<th>( m ) (m⁻¹)</th>
<th>( SR_{\text{max}} ) (m)</th>
<th>( V_r ) (m s⁻¹)</th>
<th>( V_h ) (m s⁻¹)</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIM1</td>
<td>40</td>
<td>0.06</td>
<td>0.05</td>
<td>2.0</td>
<td>0.2</td>
<td>Upstream Ners</td>
</tr>
<tr>
<td>SIM2</td>
<td>40</td>
<td>0.06</td>
<td>0.05</td>
<td>1.6</td>
<td>0.16</td>
<td>Downstream Ners</td>
</tr>
<tr>
<td>SIM3</td>
<td>40</td>
<td>0.03</td>
<td>0.05</td>
<td>2.0</td>
<td>0.2</td>
<td>Upstream Ners</td>
</tr>
<tr>
<td>SIM4</td>
<td>40</td>
<td>0.03</td>
<td>0.02</td>
<td>1.6</td>
<td>0.16</td>
<td>Downstream Ners</td>
</tr>
</tbody>
</table>
for the Ners station. Implementations of the model for the two sets of parameters CAL1 and CAL2 (with radar and raingauge rainfall inputs respectively) did not produce significant differences in the results. We therefore restrict the following presentation of the simulation results to the SIM1 parameterization (see Table 3) derived from the CAL1 optimization.

4.2. Assessment of the hydrologic response

As mentioned in Section 2.3, 8 operational stream gauges and 49 IPEC maximum discharge estimates are available for the hydrologic response assessment. Fig. 7 displays the results for a number of selected watersheds. The Corbès (point 2 in Fig. 7) watershed is

Fig. 7. Distributed hydrologic responses over the Gardon watershed. The thick hydrographs and the horizontal bars correspond to operational and IPEC discharge observations, respectively. The IPEC maximum discharge estimates are plotted with a ±20% error bar. The n-TOPMODELS simulations obtained with the reference parameterization (SIM1) are plotted as continuous grey line and dotted grey line for the radar and raingauge rainfall inputs, respectively. The discharge scale is adapted for each single example. See Table 4 for complementary figures regarding the watershed areas, rainfall amounts and runoff coefficients.
representative of the mountainous part of the Gardon watershed; the Avène (3) and the Droude (5) watersheds are representative of the tertiary sediments of the Alès graben; the Braune (1), Bourdic (6) and Alzon d’Uzès (7) are representative of the downstream part of the Gard watershed with both karstified limestone and quaternary sediments. Also displayed are the results obtained over the Gardon river itself at Ners (4) and Remoulins (8). The n-TOPMODEL simulations results are compared with the operational discharge estimates when available (cases 2, 4 and 8) and with the IPEC maximum discharge estimates (represented with a ±20% error bar in Fig. 7) for the other cases. Both types of discharge estimations are highly uncertain for this extreme event and should be considered with care. Table 4 gives provides complementary data including the area, total rainfall, runoff and the simulated and observed runoff coefficients for these catchments.

The reference simulation (parameterization SIM1, Table 3) provides results that are relatively consistent with the discharge observations for the upstream watersheds (e.g. points 2, 3, 5) and downstream of Russan (e.g. point 7). There is however a rather systematic mismatch between simulations and observations for the central part of the watershed (illustrated in Fig. 7 with graphs 1 and 7). The runoff coefficients (Table 4) range between 0.4 and 0.65 with a significant dependence on the rainfall amounts. Two additional parameterizations (SIM2 and SIM3; Table 3) were tested to try to increase the hydrological response of the model in the central part of the Gardon watershed. The results are displayed for the Braune and Bourdic watersheds in Fig. 8. The SIM2 simulation performed with a decrease of the m parameter (equivalent to a reduction of the soil depth) suggests that the watersheds were fully saturated at the time of the second flood peak if the model assumptions are assumed to hold for these watersheds. The first peak is significantly enhanced compared to SIM1 and reaches the level of the second peak for the two watersheds. Further lowering of the m values would further increase the first peak but such flood dynamics are not consistent with witnessed accounts: the two peaks were reported to be equivalent or the second one to be slightly higher than the first. SIM3, with a decrease of the SRmax parameter (representing an initially wetter watershed), generates earlier hydrologic responses and no significant differences for the two discharge peaks. The runoff coefficients take on values of about 0.7 and 0.8 for SIM2 and SIM3 respectively, which is significantly higher than the SIM1 simulations and the observations (Table 4). Two factors may be invoked to explain the discrepancies between the hydrological simulations and the IPEC estimates in this part of the Gardon watershed: (1) the rainfall is underestimated; (2) n-TOPMODELS is not structurally able to simulate the response of these watersheds that may be influenced in a complex manner by the karstic groundwater compartment.

Looking again at Fig. 7, the hydrologic simulations (although imperfect) combined with the operational and IPEC observations provide valuable insight on the relationship between the space–time variability of rainfall and the flash-flood dynamics. For instance, the Braune watershed (point 1) experienced two rain peaks during the rainfall phases 1 and 3 as defined in [5] and Section 2.2. These rain peaks generated two distinct flash-floods separated by a time lapse of about 12 h. This example is also representative of the behaviour of the left-bank tributaries of the Vidourle watershed (not shown here). The Corbès, Avène and Gardon at Ners hydrographs present a first peak immediately followed by a second and much higher peak as the signature of rainfall phase 2 and phase 3 which followed each other immediately in that region. The Droude, Bourdic and Alzon received significant rain amounts during the three phases. Their hydrologic responses are characterized by an increasing time lapse between the peaks as long as the cold front of phase 3 moved to the east. Note that the major hydrological inputs into the Gardon stream are almost synchronous with the peak at Ners (the maximum delay between the inputs at Ners and the downstream tributaries is about 2 h) while the Gardon flood peaks 7 h later at Remoulins. The simulations performed with the radar rainfall inputs are usually closer to the observations than those made with the raingauge rainfall inputs, especially for the two-peak flash floods that occurred in the downstream watershed.

<table>
<thead>
<tr>
<th>Watershed/Area</th>
<th>Rainfall (mm)</th>
<th>Runoff (mm)</th>
<th>Runoff coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Braune</td>
<td>Case 1</td>
<td>336</td>
<td>170</td>
</tr>
<tr>
<td>38 km²</td>
<td>Case 2</td>
<td>460</td>
<td>241</td>
</tr>
<tr>
<td>Corbès</td>
<td>Case 1</td>
<td>360</td>
<td>148</td>
</tr>
<tr>
<td>202 km²</td>
<td>Case 2</td>
<td>325</td>
<td>122</td>
</tr>
<tr>
<td>Avène</td>
<td>Case 1</td>
<td>515</td>
<td>286</td>
</tr>
<tr>
<td>55 km²</td>
<td>Case 2</td>
<td>565</td>
<td>370</td>
</tr>
<tr>
<td>Ners</td>
<td>Case 1</td>
<td>356</td>
<td>192</td>
</tr>
<tr>
<td>1093 km²</td>
<td>Case 2</td>
<td>353</td>
<td>188</td>
</tr>
<tr>
<td>Droude</td>
<td>Case 1</td>
<td>503</td>
<td>331</td>
</tr>
<tr>
<td>99 km²</td>
<td>Case 2</td>
<td>533</td>
<td>368</td>
</tr>
<tr>
<td>Bourdic</td>
<td>Case 1</td>
<td>371</td>
<td>195</td>
</tr>
<tr>
<td>39 km²</td>
<td>Case 2</td>
<td>438</td>
<td>270</td>
</tr>
<tr>
<td>Alzon</td>
<td>Case 1</td>
<td>324</td>
<td>165</td>
</tr>
<tr>
<td>180 km²</td>
<td>Case 2</td>
<td>446</td>
<td>291</td>
</tr>
<tr>
<td>Remoulins</td>
<td>Case 1</td>
<td>353</td>
<td>195</td>
</tr>
<tr>
<td>1856 km²</td>
<td>Case 2</td>
<td>392</td>
<td>232</td>
</tr>
<tr>
<td></td>
<td>Case 3</td>
<td>392</td>
<td>229</td>
</tr>
</tbody>
</table>

Case 1: raingauge rainfall/n-TOPMODELS simulation.
Case 2: radar rainfall/n-TOPMODELS simulation.
Case 3: radar rainfall/observed discharge.

**Table 4** Summary of the characteristics of the reference hydrological simulations (SIM1 parameterization; Table 3) for the eight watersheds considered in Fig. 7 in terms of area, rainfall and runoff amounts, and runoff coefficients.
A precise assessment of the relative performance of the radar and raingauge network is however beyond the scope of the present article. Such results depend of course on the network density and configuration. To be fully objective, the radar estimates should also be obtained independently from the raingauge network: this not the case here since the $Z-R$ relationship adjustment was performed with the raingauge network. However, note once again that the OHMCV hourly raingauge network is particularly dense compared to standard networks. Therefore, the observed superiority of radar estimates for the description of the hydrologic response over the head tributaries for this extreme event is a promising result.

For the Remoulins hydrographs (point 8 in Fig. 7), there are significant differences between the SIM1 simulations with radar and raingauge rainfall inputs in the first part of the flood. The radar rainfall simulation is more in phase with the discharge observations but there is a significant overestimation. Both simulations converge for the main peak which is strongly overestimated and presents a much faster decay compared with the discharge estimates derived from the observations. The Gardonnenque plains and the Gardons gorges clearly played a major role in controlling the flood dynamics. Note that the SIM2 and SIM3 parameterizations tend to further increase the discharge in the first part of the flood, a result not consistent with the observations (not shown here for the sake of conciseness) which tends to confirms the structural deficiency of the hydrological model for the downstream part of the Gardon watershed. Although imperfect, we will therefore restrict the following analyses to the hydrological simulations performed with the SIM1 parameterization.

5. Flood hydraulic reconstruction for the Gardon watershed

5.1. Sensitivity with respect to hydraulic parameterization

In this sub-section, we consider the n-TOPMODELs simulations based on the radar QPEs and the SIM1 parameterization as the distributed discharge upstream conditions for the hydraulic model. For the global assessment of hydraulic model performance, Fig. 9 presents the 1D river profile between Ners and the Rhône confluence together with the observed and modelled high water levels. In addition, Fig. 10 provides a local assessment with the results obtained in terms of stage and discharge at the operational stream gauge of Remoulins downstream of the Gardon gorges.

Regarding the hydraulic parameterization, recent non-overflowing cases were considered to determine the roughness coefficients of the river bed using the transfer times in the Ners–Russan and Russan–Remoulins streams. Initially, the storage capacity between the Alzon–Gardon confluence and Remoulins (see Fig. 5) was neglected. These conditions correspond to the PAR1 parameterization (Table 5). Note in Fig. 9 the exceptional water stages reached by the flood in the Gardon gorges (16–18 m) and downstream (about 10 m), a further indication of the exceptional magnitude of the event. Two abrupt head losses can be noted in the Gorges. They are due to bridges, in particular the famous Pont-du-Gard Roman bridge (52 km; head loss of about 5 m) which resisted this huge flood. Note the simulated high water level agrees well with the observations downstream of the Gorges. There is a slight overestimation of about 1 m in the Gardon Gorges.

Fig. 9. High water levels in meters above sea level during the Gard 2002 event between Ners and the Rhône confluence. The two simulations resulting from the PAR1 (dotted line) and the PAR2 (continuous line) parameterizations are compared with the observations (+).

Fig. 10. Simulated and observed water level (a) and discharge (b) time series at Remoulins: influence of the hydraulic parameterization (see Section 5.1 for comments).
Table 5
Parameterization of the hydraulic model.

<table>
<thead>
<tr>
<th>Strickler coefficient</th>
<th>Ners–Russan</th>
<th>Gardon gorges</th>
<th>Remoulins–Rhône confluence</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAR1 River bed</td>
<td>$K_s = 20$</td>
<td>$K_s = 20$</td>
<td>$K_s = 20$</td>
</tr>
<tr>
<td>Flood plain</td>
<td>$K_s = 15$</td>
<td>$K_s = 15$</td>
<td>$K_s = 15$</td>
</tr>
<tr>
<td>PAR2 River bed</td>
<td>$K_s = 15$</td>
<td>$K_s = 15$</td>
<td>$K_s = 20$</td>
</tr>
<tr>
<td>Flood plain</td>
<td>$K_s = 15$</td>
<td>$K_s = 15$</td>
<td>$K_s = 15$</td>
</tr>
<tr>
<td>PAR3</td>
<td>Identical to PAR2 in terms of roughness coefficients, includes inundation cells between the Gardon–Alzon confluence and Remoulins.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

During such extreme events. Fig. 9 indicates that the maximum time advance of the flood peak of about 2 h. A detailed investigation of the reported timing of the flood along the stream between Russan and Remoulins confirms the fact that the PAR1 simulation leads to too early responses. As a first trial to improve the timing simulation, an increase of the roughness in the Gardonnenque plains and the Gardon Gorges (decrease of the Strickler coefficients; see Table 5) was tested with the PAR2 parameterization. Intuitively, the necessity for such a roughness adjustment could be justified by increased turbulence and sediment transport effects during such extreme events. Fig. 9 indicates that the maximum water level is slightly higher in the Gardonnenque plain with, in particular, satisfactory water level estimation at the entrance of the Gardon Gorges at Russan. In terms of water levels at Remoulins, there is a reduction of the overestimation (1.2 m) but the peak time advance is not significantly reduced. However, the PAR2 simulation timing was found to be perfect at the Gardon–Alzon confluence. This motivated a further series of tests of the Alzon contribution and an improved representation of the overflow storage capacity between the Gardon–Alzon confluence and Remoulins. The first option did not improve the results while the second one (PAR3 parameterization; Fig. 10a) was efficient in reproducing the observed flood timing and magnitude in terms of the high water level at Remoulins.

Fig. 10b displays the results obtained in terms of discharge at Remoulins. In addition to the three hydraulic simulations discussed above, the discharge time series estimated from the observed stage time series using the rating curve of Compagnie Nationale du Rhône (CNR) is displayed as well as the SIM1 n-TOPMODELs hydrological simulation. Two striking results can be discussed:

1. Comparison of the n-TOPMODELs and the hydraulic simulations makes it possible to estimate the flood peak reduction due to the Gardonnenque plain and the Gardon gorges from about 9700 m$^3$ s$^{-1}$ to 5200–6500 m$^3$ s$^{-1}$ (that is by a factor of between 0.54 and 0.67).

2. There is an important mismatch between the simulated and the rating-curve estimated discharges for the flood peak while the simulated and observed stages are in rather good agreement. The apparently consistent discharge estimations in the first part of the flood are actually misleading since there is an offset of about 1 m between the simulated and observed stages. This led us to carry out an in-depth analysis of the CNR rating curve (Figs. 11 and 12). Note that the Remoulins river bed geometry is complex and subject to drastic changes during floods. Several weirs and bridges create complex convergence and divergence effects and head losses that are clearly poorly represented by a 1D hydraulic model. In addition, stream gaugings are available only for low to medium floods due to the inherent limitations of conventional gauging techniques during major floods. For the Remoulins stream gauge, the maximum gauged discharge is equal to 1300 m$^3$ s$^{-1}$. For the Gard 2002 case, the maximum discharge was estimated by CNR to be equal to 6700 m$^3$ s$^{-1}$ ± 10% (note that the slightly lower value of 6500 m$^3$ s$^{-1}$ shown in Fig. 10b results from an hourly-averaged water level while the maximum reported discharge occurred over a shorter time period). A hydraulic-based extrapolation was performed to re-establish the rating curve above the maximum gauged discharges by considering the maximum discharge – water level pair estimated during the Gard 2002 case. Although based on the same topographical datasets, the rating curve resulting from the PAR3 hydraulic simulation differs notably from the CNR rating curve as can be seen in Fig. 11. Although it is difficult to draw firm conclusions, the hydrologic–hydraulic simulation performed suggests that the maximum discharge of the Gard 2002 case may have been significantly overestimated by the analyses carried out following the event.

5.2. Sensitivity with respect to rainfall

To test the importance of the description of the rainfall spatial variability at the scale of the Gardon watershed in Remoulins...
(1858 km²), three simulations were performed with the same hydrologic (SIM1) and hydraulic (PAR3) parameterizations. They differ by the rainfall inputs: (1) distributed radar QPE (50 km²; 30 min); (2) distributed raingauge QPE (50 km²; 1 h); uniform radar QPE (1858 km²; 30 min). Both the distributed raingauge QPE and the uniform radar QPE clearly fail to reproduce the flood dynamics and notably the first part of the flood. For the distributed raingauge QPE, this is clearly due to rainfall underestimation in the central part of the Gardon watershed during rainfall phase 1 related to the lack of raingauges in that area. As a result of the homogeneous spatial distribution of the rainfall volumes, the uniform radar QPE produces a rather symmetrical hydrological response with a significant peak flow reduction compared to the distributed radar QPE. In spite of its remaining shortcomings, we are inclined to consider the distributed radar QPE simulation as the most realistic owing to the unrepresented hydrologic processes related to the karst influence in the downstream part of the Gardon watershed and to the Remoulins rating curve problems described in Section 5.1.

6. Conclusions

The main results of this modelling exercise can be summarized as follows:

A careful examination of the occurrence in time and space of the flash floods over the head watersheds indicates that such events were controlled by the trajectory of the convective part of the MCS: Gard plains during phase 1, border of the Cévennes mountain ridge during phase 2 and cold front passage during phase 3 that produced additional flash floods over the downstream Gardon trib-

utaries synchronous with the flood over the entire watershed. The complexity of such rainfall dynamics illustrates the critical utility of radar imagery for flash-flood risk assessment at the regional scale owing to the typical densities of existing raingauge networks. Regarding the flood genesis over the Gardon watershed (1858 km² at Remoulins), MCS stationarity over the watershed for 28 h is the main factor explaining the exceptional magnitude of the flood at this scale. A good spatial description of rainfall was also shown to be essential to reproduce the watershed response at the scale of the Gardon watershed.

Distributed hydrological modelling with a very basic parameterization (calibrated with a single stream gauge and assumed to be uniform in space) proved to be relatively efficient in simulating the spatial hydrologic response in the upstream part of the Gardon watershed. This result confirms both that (1) the n-TOPMODEL concepts are relevant in that region and (2) for the rather dry initial conditions of the Gard 2002 event, rainfall was the dominant source of variability [11]. The peak discharge estimates made during the OHMVC post-event surveys pointed out an underestimation of the distributed hydrologic simulation in the central part of the Gardon watersheds. Two additional simulations with adapted soil and initial moisture parameters in the central part of the Gardon watershed were subsequently produced. This attempt to improve the consistency between the n-TOPMODEL simulations and the IPEC estimates was however unsuccessful, most likely due to a structural deficiency in the hydrological model regarding its representation of the karstic groundwater contribution.

The flood dynamics were characterized by an extensive inundation of the Gardonnenc plain upstream of the Gardon Gorges resulting in a very significant peak flow reduction downstream. This geomorphological factor clearly mitigated the impact of the unfavourable space–time distribution of rainfall during phase 3 (passage of the cold front from upstream to downstream of the fully saturated watershed). The 1D unsteady-flow hydraulic modelling was shown to be essential to reproduce the watershed response at the Gardon watershed outlet. Compared with parameterizations derived for non-overflowing cases, it was necessary to increase the roughness of the river beds and to refine the overflow storage description to improve the timing consistency between the simulations and the observations downstream of the Gardon Gorges. Finally, the proposed hydraulic modelling methodology was shown to be potentially useful for the critical analysis and extrapolation of the operational rating curves.

In conclusion, although marked by strong observational, structural and parametric uncertainties, this model reconstruction of an extreme hydrological event provides, in the end, a rather clear picture of the convolution of the space–time structure of rainfall with the geomorphological characteristics of the affected regions. All the observations (radar, post-event surveys) and modelling tools (hydrologic and hydraulic models) provided valuable information for this integrated analysis. Highly distributed observations of flooding rivers (magnitude and timing) would probably be the most valuable information to add to obtain a better reconstruction of such extreme hydrologic events. The modelling of groundwater dynamics and interactions with sub-surface flows in karstic geographical settings remains a challenging perspective.

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References