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## Inter-disciplinary post-event surveys to disentangle hazard from vulnerability in the impacts of Mediterranean flash-flood events

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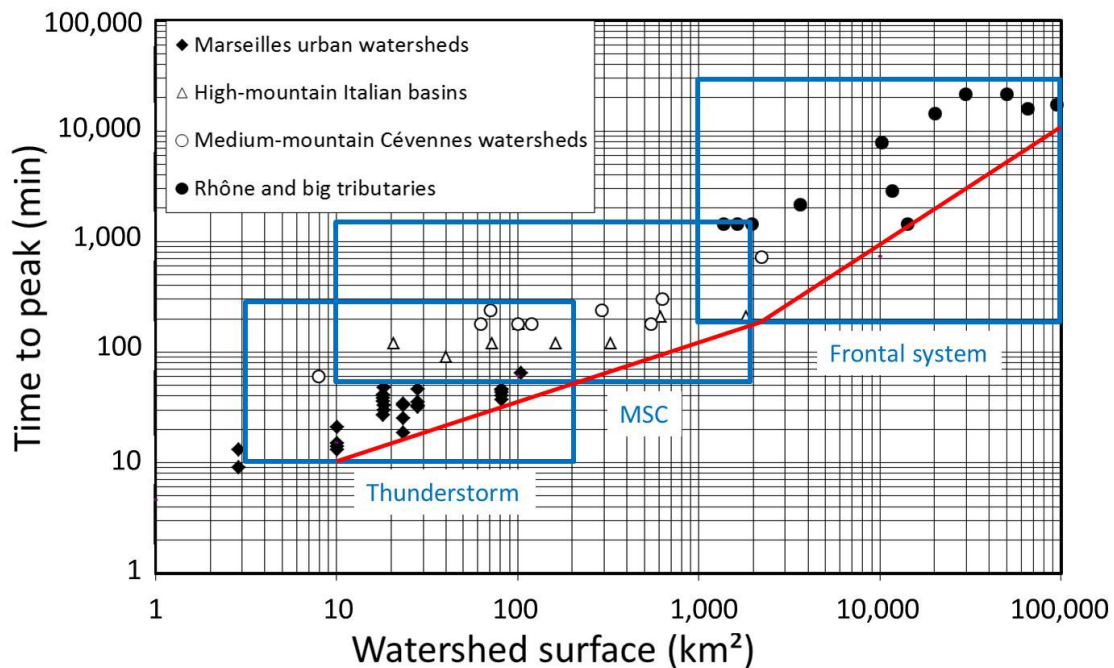
### A matter of space and time scales

Heavy precipitation events (HPE) and flash floods (FF) are common phenomena over the Mediterranean region. The peculiar topography and geographical location of this area make it especially favorable to the occurrence of intense events. The Mediterranean Sea acts as a vast heat and moisture reservoir from which baroclinic atmospheric systems pump part of their energy. The steep orography surrounding the Mediterranean Sea favors lifting of the low-level unstable air and initiation of condensation processes. Although they occur in well-known synoptic conditions, these intense rainfall events result from complex interactions between the atmosphere, the sea and continental surfaces. Mesoscale processes (orographic forcing, but also deflection and convergence of air masses, formation of cold pools and down-valley flows, etc.) lead to a variety of convective systems ranging from orographic rainfall events, thunderstorms to the most dangerous stationary mesoscale convective systems (MCS) (Bresson et al. 2012). Despite recent progress due to the assimilation of mesoscale meteorological data in highly resolved numerical weather prediction models, the predictability of thunderstorms and MCSs remains quite low both in terms of intensity and localization.

Moreover, the morphology of the Mediterranean basin with its numerous small and steep river catchments and increasing urbanization of the coastal zones trigger very rapid hydrologic responses. The subsequent FFs are very dangerous for the exposed populations. A clear link exists between the hydrologic response (Fig. 1) and the size of a watershed subject to a HPE. Typical times to peak can be as short as 10 min for urban watersheds of 10 km<sup>2</sup>, and as short as 1-2 hours for natural basins extending from some tens to some hundreds of km<sup>2</sup> in mountainous settings. The time to peak spans a range of about one order of magnitude for a given watershed surface, showing that the hydrological responses also depend on other factors, such as topography, geology, land use, storm intensity and initial soil moisture. There is also a relationship between the space-time scales of the generating rainfall events (Fig. 1) and the hydrologic response. This supports the concept of “scale resonance”, e.g., a thunderstorm is likely to generate FF events over urban basins of some tens of km<sup>2</sup> while a stationary MCS is required to produce FFs and floods over watersheds of 100-2,000 km<sup>2</sup>. Regional floods (e.g. Rhône River floods) are associated with frontal systems with much larger spatial extension and temporal duration.

Regarding the coping capacity of the exposed societies, the concept of “timeliness of flood anticipation” was proposed by Creutin et al. (2013) to describe how a sequence of anticipatory actions (known as the IOP sequence, for Information, Organization, Protection) is synchronized with the development of the flood. The situation is particularly tense in the Mediterranean context due to the limited predictability of rainfall and the rapid hydrological responses. Exposed individuals may experience a wide range of hazard conditions with different timeframes, depending on the size of the upstream watershed on which they are located. The most critical situations are likely to occur at the

finest spatial scales. Ruin et al. (2008) demonstrated that the majority of casualties that occurred during the 2002 Gard event in France happened in watersheds of less than 50 km<sup>2</sup>.



*Figure 1 Hydrological response of Mediterranean and Alpine basins expressed in terms of the time to peak (delay between the hyetograph centroid and the flood peak) as a function of the surface area of the watershed. The red lines define the envelope curve of the shortest times to peak, critical information for warning and crisis management. The blue rectangles show typical space-time scales of the generating rain events.*

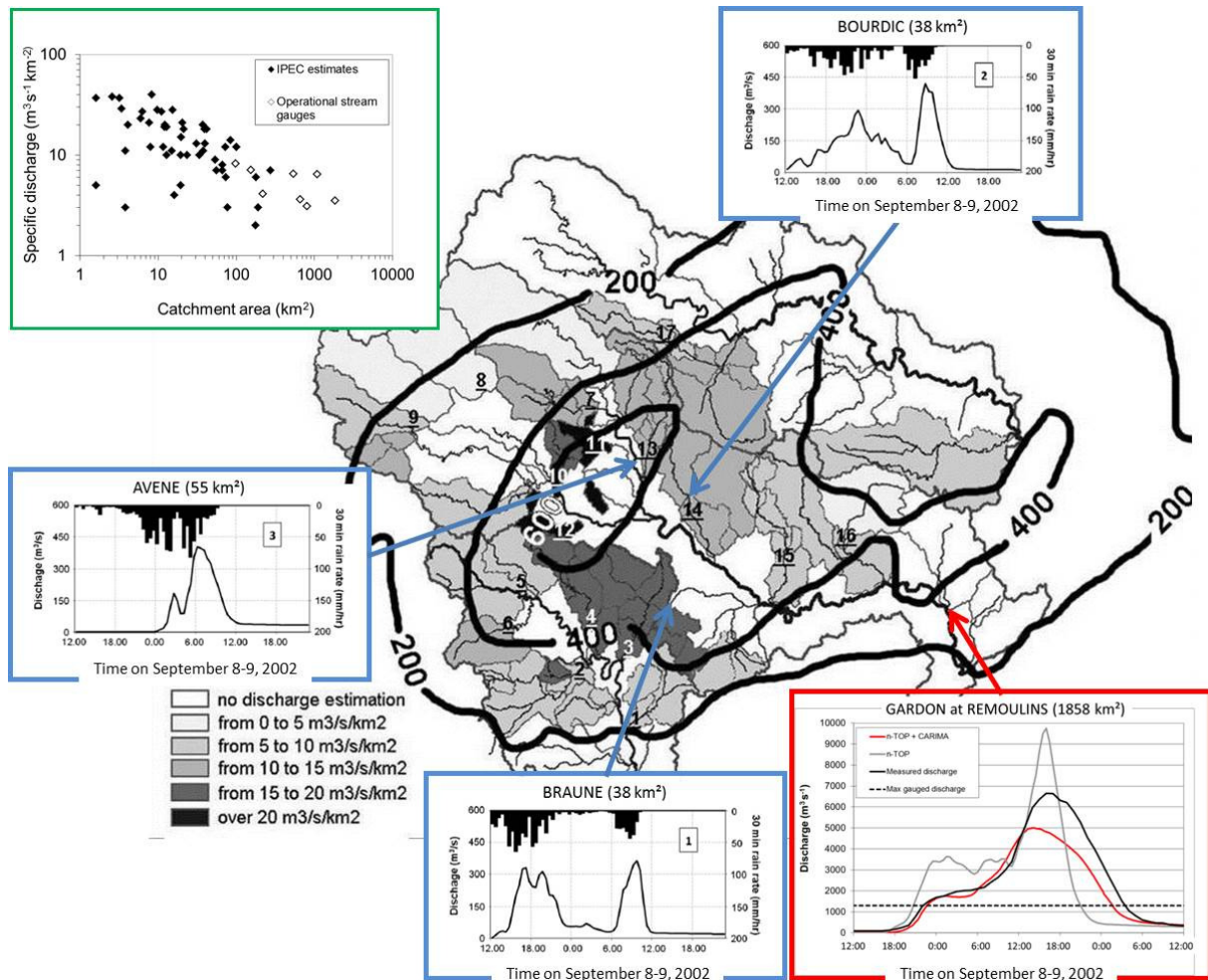
As a detailed complement to the regional analyses proposed by Gaume et al. (2016), subchapter 1.3.4), in the following sections we provide illustrative results obtained from inter-disciplinary post-event surveys (PES) aimed at understanding the complexity of both the hydrological responses to HPE and the behavior of the exposed populations during such sudden crises. So far research on hydrological and social systems has proceeded in "separate boxes" without many contacts between research disciplines (Parker et al. 2012). The consequence is that neither the physical nor the social sciences have acquired a comprehensive overview that would enable improvement of event response. We believe that the PES approach is needed to disentangle the respective contributions of hazard and human vulnerability to the impacts of flash-flood events, notably the causes and dynamics of casualties.

### Complexity of the hydrologic response to extreme precipitation events

The recent development of weather radar networks opens new perspectives for the characterization of the space-time variability of the generating rainfall events. Weather radars provide rainfall estimates at appropriate resolutions, typically (1 km<sup>2</sup>, 5 min). However, rain gauge data remain a critical source of information to constrain radar data processing algorithms and/or to validate the radar estimations. Bouilloud et al. (2010) proposed a pragmatic method for dealing with two main physical errors of radar, namely those due to the interactions between radar waves and the relief and those due to the vertical structure of the rain systems. Geostatistical methods proved to be optimal for merging corrected radar data and rain gauge data (Delrieu et al. 2014) by removing the bias of radar estimates while retaining their enhanced perception of the spatial variability of rainfall.

Hydrological PESs aim to collect three types of data (Gaume and Borga 2008; Marchi et al. 2009):

- (i) Peak discharge estimates over ungauged upstream basins; this is done by performing cross section surveys (cross section and energy slope estimation using flood marks) complemented by clues of flow velocities (e.g., video recordings, water super-elevations in front of obstacles, etc.).
- (ii) Indicators of the time sequence of the flood (time of peak(s), dynamics of the flood rise and recession). For ungauged sections, this information is obtained from eyewitness accounts.
- (iii) Indicators of sediment transfer processes (erosion and deposition in the river beds, mud or debris flows) as an indication of the runoff processes, flow energy and velocity. This is particularly relevant in high mountain settings (Borga et al. 2014; Rinaldi et al. 2016) where such processes create specific risks and affect both the landscapes (soil conservation) and the rivers (channel instability, reservoir filling, etc.).



*Figure 2* Illustration of the hydrological response complexity of the Gard event in France on September 8-9, 2002. The map shows the rainfall isohyets (contours of 200, 400, and 600 mm of rain) superimposed on the river network of the affected area. The sub-watersheds are colored as a function of the maximum specific discharges estimated during the PES. The green insert shows the maximum specific discharges estimated during the PES for ungauged catchments as well as those derived from operational gauging stations as a function of the surface area of the watershed. The blue inserts give 3 examples of the response of small upstream watersheds. The red insert shows the hydrologic/hydraulic response at the outlet of the Gardon watershed at Remoulins.

Figure 2 illustrates the results of the PES realized after the disastrous flood event that affected the Gard region on September 8-9, 2002 (Delrieu et al. 2005; Bonnifait et al. 2009). This disaster (24 casualties, 1.2 billion euros) was due to an MCS system that remained stationary for 28 hours and

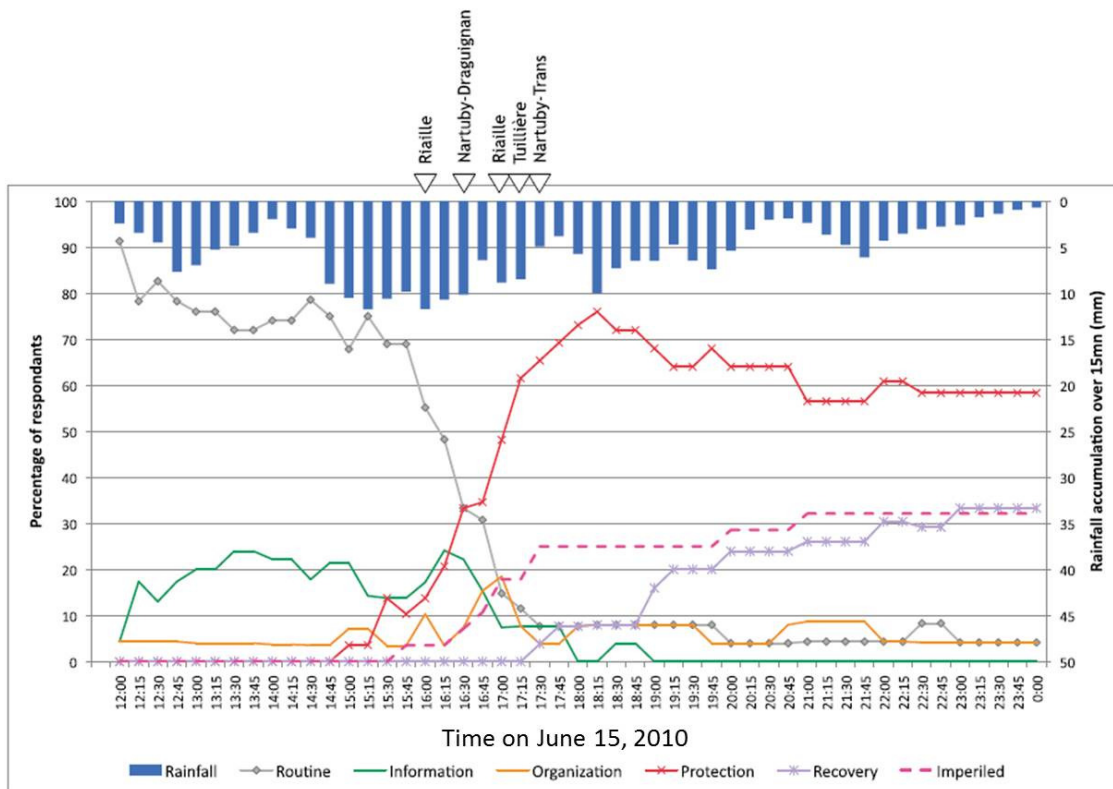
produced more than 200 mm rain over an area of 5,500 km<sup>2</sup>, and which locally reached more than 700 mm. The green insert in Fig. 2 shows the added value obtained from the PES in terms of documenting the peak discharges for ungauged basins (< 100 km<sup>2</sup>). The specific peak discharges reached extreme values (40 m<sup>3</sup>s<sup>-1</sup>km<sup>-2</sup>) at the smallest spatial scales investigated (1-10 km<sup>2</sup>). The blue insert give three examples of rainfall-runoff time series for upstream ungauged watersheds. The hydrographs were produced with a hydrological model constrained by the estimated PES discharges and checked with the reconstructed time sequences obtained from the PES. Note that different rainfall-runoff scenarios can be observed locally with single and double peak discharges, fully explained by the displacement of the MCS during the event. At the outlet of one of the main rivers (red insert), the distributed hydrological model was too reactive; coupling with a 1D hydraulic model was necessary to represent the control exerted by the Gardon Gorges. The latter resulted in major flooding of the upstream plain, thereby protecting the city of Remoulins from an even more disastrous flood, an interesting example of geomorphological control on medium-scale flood. The hydraulic model also showed that the operational rating curve of the gauging station available prior to the event largely overestimated the discharges, an example of the marked uncertainties affecting flood discharges even in gauged stations. Other factors that determine the hydrological response are the initial soil moisture status and the geology (Vannier et al. 2016). Frequently advocated factors such as deforestation, poor river bed maintenance and even urbanization are likely to play a marginal role in the case of heavy rainfall events when the storage capacity of the soils is fully saturated.

### How do individuals cope with flash floods?

The social PES aims to collect behavioral, temporal and spatial information related to changes in the environmental conditions and activities in which people are involved prior to and during the crisis. Its objective is to document how individuals switch from routine activities to emergency coping behaviors. It is structured around a chronological guideline with which interviewees are invited to recall what they perceived from their environment, what actions they undertook, and with whom they interacted in different places and while moving in between places. The survey campaign starts by interviewing the contact persons identified during the hydrological PES. These people are also asked to recruit other interviewees with whom they were in contact directly or indirectly at various stages of the event. This snowball sampling technique makes it possible to collect diversified and complementary information.

This approach was first used after the June 15, 2010 FF event in the Var region, France (Ruin et al. 2014) which was responsible for the deaths of 26 people. Data collection efforts concentrated on three municipalities located on the Nartuby River. Figure 3 shows the proportion of interviewees as a function of the type of activity over time, together with rainfall intensity and the times of peak flood in the corresponding watersheds.

This social PES allowed us to identify some possible causes of the individual responses. The possible conflicts of priority between routine and exceptional circumstances explained the difficulty in switching from daily activities to responding to warnings. The difficulty in making sense of environmental cues in the case of insufficient official warning also emerged as a possible cause of delay in individual responses. Because FF environmental conditions vary tremendously across space in very short periods of time, it is often difficult for those who are affected to fully grasp the situation in which they find themselves or to imagine the variability of the threat moving across space. The study also revealed a form of the individual's self-organization and the emergence of helpful social interactions that may involve different types of social ties. Finally, this case study confirmed the role of contextual factors (Parker et al. 2009): the timing of the hydro-meteorological event, its severity, and experience of the flood appear to be essential in the ability of individuals to make sense of the situation and to adapt their activities.



*Figure 3* Changes in behavioral responses of the social PES respondents during the FF event on June 15, 2010 in Draguignan, France, in terms of routine activity, awareness of the crisis through information, organization, protection and recovery actions. The cumulative percentage of imperiled people during the event is also shown. Note the rapid drop in routine, information, and organization curves to the profit of the protection curve between 15:30 and 17:30 which corresponds to the danger outburst (peak flows, generalized surface runoff). The orange vigilance warning launched by Météo France the preceding day and the TV news at midday reached a limited proportion of respondents (20%).

## Conclusions

As a complement to regional analyses (Gaume et al. 2016, **subchapter** 1.3.4), we believe such interdisciplinary post-event surveys are indispensable for the mitigation of FF events in the Mediterranean because they allow a better understanding of the causative hydrological processes and the subsequent social responses in different climatological and social contexts around the Mediterranean Sea. Due to their heavy death toll, the focus has so far been on short-term crisis management with the aim of increasing people's preparedness through education, and improving the efficiency of warning and alert systems. Obviously, long-term management of this type of natural hazard also involves socio-economic considerations related to land-planning and controlled urbanization, a particularly difficult topic in the context of the increasing human pressure and the expected climate change in the Mediterranean region.

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