



HAL
open science

Catchment dynamics and social response during flash floods: The potential of radar rainfall monitoring for warning procedures

Jean-Dominique Creutin, Marco Borga, Céline Lutoff, Anna Scolobig, Isabelle
Ruin, Laurence Creton-Cazanave

► To cite this version:

Jean-Dominique Creutin, Marco Borga, Céline Lutoff, Anna Scolobig, Isabelle Ruin, et al.. Catchment dynamics and social response during flash floods: The potential of radar rainfall monitoring for warning procedures. *Meteorological Applications*, 2009, 16, pp.115-125. <10.1002/met.128>. <halshs-00355543>

HAL Id: halshs-00355543

<https://shs.hal.science/halshs-00355543v1>

Submitted on 23 Oct 2025

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons CC BY 4.0 - Attribution - International License

Catchment dynamics and social response during flash floods: the potential of radar rainfall monitoring for warning procedures

Jean Dominique Creutin,^{a,*} Marco Borga,^b Céline Lutoff,^{a,e} Anna Scolobig,^c Isabelle Ruin^d and L. Créton-Cazanave^e

^a *Laboratoire d'Etude des Transferts en Hydrologie et Environnement – LTHE (CNRS-UMR 5564, UJF, INPG, IRD) Rue de la Piscine 1023–1025, Grenoble, France*

^b *Department of Land and Agroforest Environment, University of Padova, Agripolis, via dell'Università, 16, Legnaro IT-35020, Italy*

^c *Istituto di Sociologia Internazionale di Gorizia, via Mazzini 13-34170, Gorizia, Italy*

^d *National Center for Atmospheric Research (NCAR-ISSE), Boulder, USA*

^e *PACTE, Université Joseph Fourier, Grenoble, France*

ABSTRACT: The objective of this paper is to examine how current techniques for flash-flood monitoring and forecasting can meet the needs of the population at risk to evaluate the flood severity and anticipate its danger. To this end, the social response time for different social actions in the course of two well studied flash flood events which occurred in France and Italy is identified. The event management activities are broadly characterized into three types according to their main objective (information, organisation and protection). The activities are also classified into three other types according to the scale and nature of the human group involved (individuals, communities and institutions). The conclusions reached relate to (1) the characterisation of the social responses according to watershed scale and to the information available, and (2) to the appropriateness of the existing surveillance and forecasting tools to support the social responses. Results suggest that representing the dynamics of the social response with just one number representing the average time for warning a population is an oversimplification. It appears that the social response time exhibits a parallel with the hydrological response time, by diminishing in time with decreasing size of the relevant watershed. A second result is that the human groups have different capabilities of anticipation, apparently based on the nature of information they use. Comparing watershed response times and social response times shows clearly that at scales of less than 100 km², a number of actions were taken with response times comparable to the catchment response time. The implications for adapting the warning processes to social scales (individual or organisational scales) are considerable. At small scales, and for the implied anticipation times, the reliable and high-resolution description of the actual rainfall field becomes the major source of information for decision-making processes such as deciding between evacuations or advising to stay home. This points to the need to improve the accuracy and quality control of real time radar rainfall data, especially for extreme flash flood-generating storms. Copyright © 2009 Royal Meteorological Society

KEY WORDS flash food warning; weather radar; social response

Received 23 November 2008; Revised 5 January 2009; Accepted 8 January 2009

1. Introduction

The term 'flash flood' identifies a rapid hydrological response, with water levels reaching a peak within less than one hour to a few hours after the onset of the generating rain event (Creutin and Borga, 2003; Collier, 2007; Younis *et al.*, 2008). The time dimension of the flash flood response is linked, on the one hand, to the size of the concerned catchments, which is generally less than a few hundred square kilometres and, on the other to the activation of surface runoff that becomes the prevailing transfer process. Fast surface runoff mainly results from

the combination of intense rainfall with steep slopes and/or saturated soils. It also results from anthropogenic forcing such as land use modification, urbanization and fire-induced alteration of the natural drainage system.

As regards the implementation of risk management measures, the increasing speed of response of a cascade of medium to very small size nested river catchments has two consequences. Firstly, people are exposed to hazard individually or in small groups and in a diffused manner in space (Montz and Grunfest, 2002; Drobot and Parker, 2007). The more we go to smaller scales, the less they are protected by traditional structural defences which are too expensive to build. Ruin *et al.* (2008) show that, during the September 2002 storm in the Gard region, almost half of the casualties occurred on watersheds of *ca* 10 km² and impacted drivers on ill-protected secondary roads

* Correspondence to: Jean Dominique Creutin, Laboratoire d'Etude des Transferts en Hydrologie et Environnement – LTHE (CNRS-UMR 5564, UJF, INPG, IRD) Rue de la Piscine 1023–1025, Grenoble, France. E-mail: jean-dominique.creutin@inpg.fr

and also campers. In such circumstances, the only way to protect people is to warn them to move to safer areas *via* secured routes. Secondly, this rather complex type of evacuation must be organised before a deadline, which becomes progressively shorter when considering smaller catchments. Thus, the warning procedure that converts perceived or forecast signals into hazard evaluation and action (Créton-Cazanave *et al.*, 2009), must be completed with as short a delay as possible after the onset of the storm (Montz and Grunfest, 2002).

The current paradigm for flood hazard monitoring and forecasting relies on the relationship between the social response time and the catchment response time. When the social response time is shorter than the catchment response time, purely hydrological-hydraulic models may provide the forecast at the required lead time. On the contrary, when the social response time is larger than the catchment response time, the planning of the event management measures requires the use of forecast rainfall fields such as from Numerical Weather Prediction (NWP) models (Siccardi *et al.*, 2005). Since the catchment response time gradually varies with the size of the catchment, both space and time considerations govern the appropriateness of the monitoring and forecasting strategies.

After exploring the relationship between watershed dynamics and the observed social responses in two well-studied flash flood events, this paper examines how the current techniques available for flash-flood monitoring and forecasting can meet the needs of the population at risk to evaluate the flood severity and anticipate its danger. To this end, the chronology of different social actions in the course of the events is identified and well known space-time characteristics of catchment responses employed.

The paper is organised as follows. Section 2 describes the event selection procedure as well as the choice of descriptive parameters, for both the geophysical and human aspects. Section 3 quantifies catchment response time under flash flood forcing. Section 4 introduces the characterisation of social response, defining the type of activity and the size of the human groups concerned. Section 5 reviews the current monitoring and forecasting methods that are appropriate to the range of scales considered. The conclusions are reported in Section 6, where the need to adapt the warning process to social scales (individual or organisational scales), by obtaining more real time information about rainfall accumulations, is emphasized.

2. Data set used

The data set used combines the geophysical and human data that were collected in the framework of recent European research projects (FLOODsite and HYDRATE). These data are somewhat heterogeneous, mainly as a result of the various difficulties encountered when observing both geophysical and social processes during extreme

events. In this section the event selection procedure and the selected descriptive parameters employed are outlined.

2.1. Event selection

The selection procedure used is guided by two stages of screening. The first stage consists of identifying within Europe a number of 'remarkable' flash flood events that caused casualties as well as damage. These events were then checked to ensure that they resulted from a storm that has, for some rainfall durations, a return period of 50 years or more. The second stage of screening is to ensure that the available social observations are precise enough to locate and describe the human actions and decisions during the event.

The above procedure led, at the first stage, to selection of a set of 20 notable events that were used for the basic understanding of flash-flood dynamics at a range of scales. At the second stage, two events were selected for which interviews have been conducted to document human and organisational responses.

The first storm occurred in the Gard region in France in September 2002 (Delrieu *et al.*, 2005). This event was one of the most violent observed in this region during the last few centuries (Huet *et al.*, 2003). Rainfall accumulations of more than 500 mm in 36 h covered a significant area (*ca* 5000 km²) giving rise to multiple individual reactions of the tributaries of the rivers Vidourle, Gard and Cèze across a wide range of scales.

The second storm affected the watershed of the Fella River, in the Eastern Italian Alps, where on 29 August 2003, a Mesoscale Convective System (MCS) impacted a 1500 km² wide area for almost 12 h, causing loss of life and substantial disruption of the local economy, with damage valued at close to 1 billion Euro (Borga *et al.*, 2007). The storm total precipitation peak was up to 400 mm and the event rainfall maxima were characterised by return periods in the range of 500–1000 years for 3–12 h durations (Norbiato *et al.*, 2007). The flood response in the upper Fella exceeded all the historical records, with unit peak discharges in the order of 20 m³ s⁻¹ km⁻² for catchment areas up to 10 km².

2.2. Geophysical parameters

The geophysical description of the selected flash-flood events is based on a small number of simple and verifiable hydrological parameters that characterise the time and space scales of the event.

It is now well known that flash flood events are difficult to observe reliably because they develop at space and time scales that conventional measurement networks of rainfall and river discharges are not able to sample effectively (Creutin and Borga, 2003). Rainfall accumulations for each event were carefully evaluated by using both raingauge and bucket data. More detailed rainfall estimates in space and time were obtained by adjusting radar observations to account for the physics of the radar

sensing and incorporating the above rainfall accumulation data in the adjustment procedure (Borga *et al.*, 2002). Discharge data were obtained by combining streamgauge measurements when available and reliable, post-event surveys and model simulations, to obtain indirect peak discharge estimates together with eyewitness accounts to estimate the timing of the peak discharges (e.g. Borga *et al.*, 2007 and Marchi *et al.*, 2008).

Given these observations, the concept of lag time was used to characterise the dynamics of the basins of interest. In this study, the lag time was defined as the duration between the time of the centroid of the generating temporal rainfall sequence and the time of the discharge peak. Note that the centroid of rainfall amounts was used, instead of the more physically sound centroid of the excess rainfall (Morin *et al.*, 2002), due to the difficulty of reconstructing the excess rainfall sequence for each event.

2.3. Human organisation parameters

The human responses to the two flood events resulting after the second stage of selection are listed in Appendix A (Table A.I, A.II, A.III, A.IV). The data set is divided into a series of cases corresponding to the occurrence of a storm event on a particular watershed. For instance, the 2002 Gard event was split in to three distinct cases: the case of the Gard River itself that covers *ca.* 2500 km², the case of the Vidourle River (an adjacent river of *ca.* 600 km²) and the case of the Valliguières River (a tributary of the Gard River of *ca.* 100 km²). This distinction was useful to examine the different types of documented human responses as a function of catchment area size. For the 2003 event that occurred in the Fella region (Italy), given the lesser scale of the storm, only one case is considered.

Each case is associated with a documented sequence of human actions that are positioned in time and space and which are described in enough detail to be attributed to a type of activity and to the type of human group involved. The position of a given action in time is measured relative to the time of the flow peak in the catchment concerned. It can thus be considered an anticipation time with respect to the peak of danger if, as a first guess, a direct linear relationship between the water flow and the danger is assumed. The position in space is measured by the size of the watershed, assuming that watersheds of the same size will provide comparable conditions across the considered region.

Human data gathering included different but complementary strategies and techniques. For both events, existing data from secondary sources, such as municipal and provincial archives, logbooks from rescue brigades, as well as reports from experts (such as Huet *et al.*, 2003 for the Gard event; PC-FVG, 2004 for the Fella event) were used.

To supplement this information different types of interviews were also used. For the Fella case 14 semi-structured interviews were conducted with members of

relevant institutions, such as local authorities, civil servants, community leaders, politicians, scientific and technical experts and members of the local fire brigade corps. In addition, a semi-structured questionnaire survey of 100 residents was used which included some open-ended questions about residents' behaviours during the event (De Marchi *et al.*, 2007, for a description of the research design). For the Gard flood, 30 in-depth field interviews were conducted 8 months afterwards, asking people to explain how they experienced the event, with their own words and scale of time. For example, a witness on the Valliguières River watershed reported the following: *'Our Sunday went as usual until 1000 or 1030 in the evening. Then we saw some water entering the basement. A friend came to help us evacuating packs containing bright new furniture for our kitchen we stored there. My wife injured herself helping us to evacuate the packs. When my friend left I told him as a joke that if we were flooded tonight, we will come to him. [...] I worried. I tried to call the fire brigade in order to evacuate my wife but the road was flooded. One hour after, we decided to leave our home with our child'*. This example concerns a small group of people (a family). Four distinct activities have been identified in this interview and appear as elementary actions in Table A.III associated with the following types of activities and social scales: (1) identifying water inside the house (information, individual); (2) evacuating goods (protection, individual); (3) requesting help (organisation, individual); (4) evacuating people (protection, individual). The evacuation of the family has been set at 0030 local time (2230 UTC), assuming that it took them one hour to evacuate the goods from the basement and to request help.

3. Rainfall field variability and catchment dynamics

It is well established that atmospheric convection producing flash flood events is either isolated or organised in a mesoscale convective system (MCS) (See for instance Ricard *et al.*, 2007 about the 2002 event). Embedding convective cells with their own life cycle, MCSs produce rainfall fields that are highly variable in space and time. The rainfall variability stimulates the nonlinear dynamics of stream flow generation over a wide range of scales (Menabde and Sivapalan, 2001; Dodov and Foufoula-Georgiou, 2005, among others). In turn, significant differences can be observed between the flood dynamics of elementary tributaries compared to the dynamics of the global catchment. The example given in Figure 1 illustrates the response of the Fella River (Italy) in August 2003 at three different spatial scales (0.65 km², 24 km² and 165 km²). To assist in comparison, the Figure displays specific discharges, i.e. takes the ratio between the discharge values and the catchment area. The response time changes markedly through spatial scales, ranging from less than 1 hour (*ca.* 40 min.) over the basin of 0.65 km² to 5 h over the basin of 165 km². Moreover, this example confirms that the different response

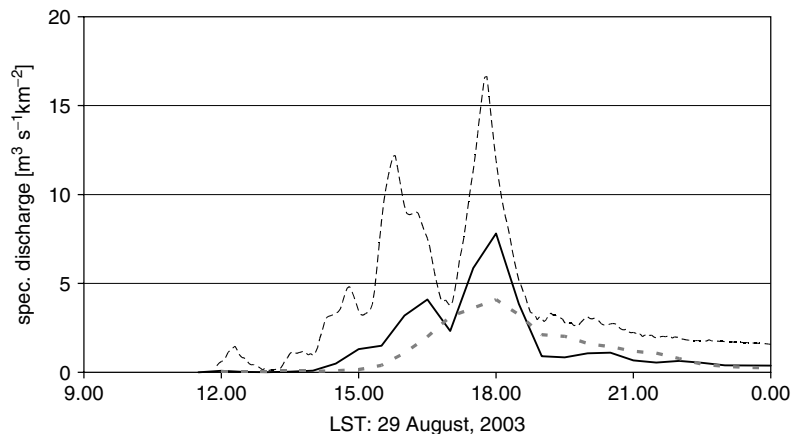


Figure 1. Catchment dynamics during the 29 August, 2003 event at three spatial scales: the Cucco basin (0.65 km²) (---) the Uqua River at Ugovizza (24 km²) (—) and the Fella River at Pontebba (165 km²) (- · -).

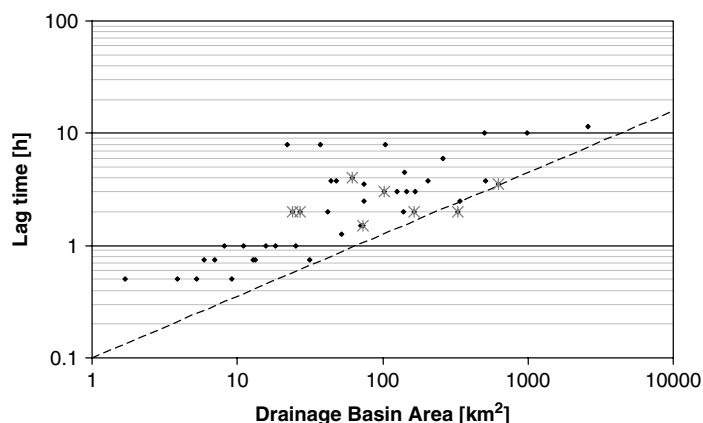


Figure 2. Lag time (in h) *versus* drainage area (in km²) for the selected events. The model representing the lower envelope is drawn in dashed line. Gard-2002 and Fella-2003 events are marked with stars.

timescales are observable within the same flash flood event which produces extreme values at all scales. Similar embedded responses have been observed for other flash flood events (Delrieu *et al.*, 2005).

Bearing in mind these general hydrometeorological considerations and seeking to understand how the watershed dynamics might impact human responses, we used a classical space *versus* time representation of the response time of a series of variously sized watersheds from the 20 flash flood events selected during the first stage of the study (See Orlanski, 1975 in meteorology and Blöschl and Sivapalan, 1995 in hydrology for examples of use of comparable graphs) was used. Figure 2 shows the lag time *versus* the watershed area for the set of flash-flood events, which occurred in Austria, France, Greece, Italia, Romania, Slovakia, Spain and the United Kingdom (Borga *et al.*, 2008). This graph clearly shows a lower limit to watershed response time, which increases as a power function of the watershed size:

$$t = 0.1A^{0.55} \quad (1)$$

with the lag time t , in h and the watershed area A , in km².

The line chosen to show this lag-time limit is close to that reported by previous studies (Sivapalan *et al.*, 2002; Berne *et al.*, 2004) and has an exponent close to 0.5, which would be expected if the water velocity was constant over the considered range of scales. The dispersion of the points above this limit reflects the degree of resonance between the strength, size, duration and position of the generating storms and the size and position of the watersheds.

As far as the two events specifically selected for the social response study are concerned (the two events are identified as Gard-2002 and Fella-2003, hereinafter) and Fella, 2003), their position in Figure 2 shows that they are representative of the set of events, with some points being rather extreme in term of speed of response.

4. Characteristics of the social response

As mentioned in Section 2, Tables A.I, A.II, A.III and A.IV describe the chronology of four cases of flash-floods. Each reported action is qualified by the nature of the actors at the origin (initiator) and at the end (receptor),

by the type of activity concerned (one of information, organisation or protection) and by the type of human group concerned (one of individual, communities or institutional).

In previous work, it was observed that social actions for protecting goods or persons are preceded by a phase of assessment of the situation (Créton-Cazanave, 2008). Three types of actions were distinguished: information, organisation and protection. These apply to all the actors, from forecasters to inhabitants and to all social group sizes. The information phase covers the collection of data and its crosschecking with other data or actors to assess its quality and relevance. It is the first activity of the warning cycle. Organisations synthesise and transform the above information before initiating a structured response such as mobilisation of human forces or the implementation of a pre-established defence plans. Chronological and logical organisation takes account of the available information and prepares the protection phase which ends the cycle. Protection involves efficient actions in terms of safety such as preventive evacuation of people or goods as well as rescue missions.

Human actions are also classified in to three types

according to the size of the groups concerned. Individuals, communities and institutions are distinguished. 'Individual' concerns just one person and/or a small social entity (a family, for instance). 'Community' pertains to small groups of people, which may be more or less organised, to deal with emergencies. Neighbourhood groups, voluntary associations, but also the population of a school or a company as well as the population of small geographic entities such as villages are included in this category. 'Institution' includes the public organisations such as police or civil protection as well as the national administration, its local representatives and technical operators like meteorological offices and water management departments.

Figure 3 displays the information contained in Tables A.I, A.II, A.III and A.IV according to the size of the relevant watershed and to the type of action (Figure 3a) as well as to the type of group of actors (Figure 3b). Examination of the different types of activities in Figure 3a supports the relevance of the logical cycle: information-organisation-protection. Even though the information gathering and analysis generally takes place among the

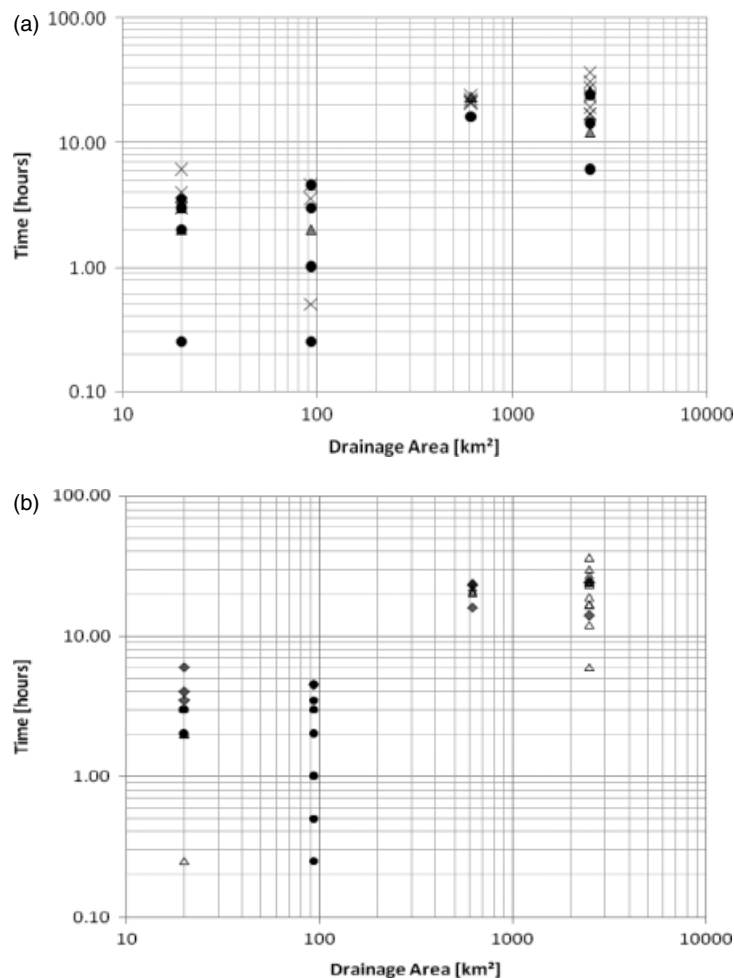


Figure 3. Representation of 43 elementary human actions in a logarithmic plot of their anticipation time (i.e. time of action before the flow peak) versus the area of the watershed where they occurred. Three types of actions (a) × Information, ▲ Organization, ● Protection; as well as three types of sizes of human groups (b) ● Individual, ◆ Communities, △ Institutional, are distinguished by the shape of each point representing an elementary action.

first activities (except in one case), it is first noticeable that organisation and protection intervene at different stages in the sequences for the four cases. Different explanations can be given. An evolving flood situation generally demands successive waves of reaction cycles. Missing information in the dataset makes the documentation of these basic cycles incomplete. Nevertheless, it is noticed that complete cycles are present at all scales, confirming that this generic decomposition pertains to all sizes of human groups and is useful at all scales. It is also noticeable that no action is reported after the time of the peak. This is related, in a sense by definition, to the fact that selection of actions on risk prevention, rather than risk relief, was concentrated on. However, given the time needed for these different types of response to be effective, it must be realized that some cycles can potentially fail to work correctly when the reaction of the watersheds to rain comes before the full implementation of the social response.

Examining the social scale of the activities in Figure 3(b), assists in the analysis of the spatial dimension of the social response. Firstly, the characteristic reaction time of the different human groups decreases markedly with reducing size. The institutional reaction time develops around 30–36 h before the flow peak (Table A.I). The community reaction appears to be organised in 7 h and starting from 23 h to 6 h before the peak (according to Table A.II). The individual reactions appear to be much shorter and starting a few hours before the peak.

Secondly, the size of the watersheds seems to be associated with the size of the reacting human groups. Most of the actions conducted by institutions apply mainly to the largest watersheds (Gard and Vidourle) while, on the smaller ones, communities and individuals take charge of the response. The dominance of institutional activities on large watersheds masks community and individual actions at those scales that are under-sampled in the dataset. For example, institutional actions certainly have effects on small scales through the broadcast of information but there was little indication in interviews of individuals and communities that they made use of such information. On the other hand, it is interesting to consider the cases where the individual response dominates. In the isolated locations that are not well covered by the institutional response, individuals have to protect themselves on their own. For example, in the Fella river case study some residents undertook an autonomous evacuation, saving their lives and those of their neighbours. This decision was made as a result of monitoring the level of the streams and possible points of obstruction. In this phase the village was almost isolated due to the obstruction of nearby roads caused by debris flows and institutional intervention was not possible.

A third point is that human groups have different abilities to anticipate flooding based on the nature of information to which they have access. The information available at institutional scale comes mostly from meteorological and water services. In the cases studied here, even when the meteorological information is distributed early, at the

smallest scales people appear to rely on their own monitoring of the water levels. In these cases, reliability of the sources of information plays a crucial role. In both the Italian and the French cases, the local voluntary fire brigade groups are considered the main safety agency by the residents, possibly due to their local attachment, their deep knowledge of the territory, and their training in facing such emergencies. Besides, the hydrological evidence of the flood seems to be necessary for individuals and communities to react. As shown in a parallel study (Créton-Cazanave, 2008) the current meteorological information needs to be adapted at a smaller scale to be used directly by communities and individuals.

In summary, the social response is reasonably well described by a generic cycle: information-organisation-prevention across different group sizes. These groups have rather different characteristic temporal behaviours as regards both their anticipation and response.

5. Adequateness of monitoring and forecasting techniques at different scales

Having defined, on one hand, the time and space characteristics of the hydrometeorological response (Figure 2) and, on the other, the characteristic times of different types of social responses (Figure 3), these elements can be combined in order to appreciate the relevance of existing monitoring and forecasting tools.

Figure 4 combines, into the same space-time graph used for Figure 3, the lag time limit of Figure 2, indicating the relationship between the lower limit of catchment lag time and the corresponding catchment area ($t = 0.1A^{0.55}$). In order to account, at least qualitatively, for the minimum duration of the rainfall event generating the catchment response, the function $t = 2 (0.1A^{0.55})$ has been drawn. The shaded transition area obtained divides the time and space scale domain into two areas. Above the shaded area, the meteorological generation of the rain field is the dominant process. At such space scales and anticipation times, the risk precursors are meteorological factors. Below the transition area, runoff propagation is the dominant process and the relevant risk precursors are hydrological factors. The time scale of Figure 4 is an anticipation time with respect to the peak discharge. This figure can thus be used to examine the type of action according to the anticipation time and the catchment lag time.

Figure 4 globally shows that the position of human responses with respect to the flood dynamics is rather homogeneous through a range of scales. Except for the Valliguières case (93 km²) the distribution patterns of human actions relative to the flood dynamics are similar. They cover a time range equal to 2 to 4 times the reaction time of the catchment and they rarely go beyond the rain peak (i.e. below the lag-time line). As a consequence, most part of the reported human actions develop at periods dominated by the meteorological processes. In that respect additional comments can be made.

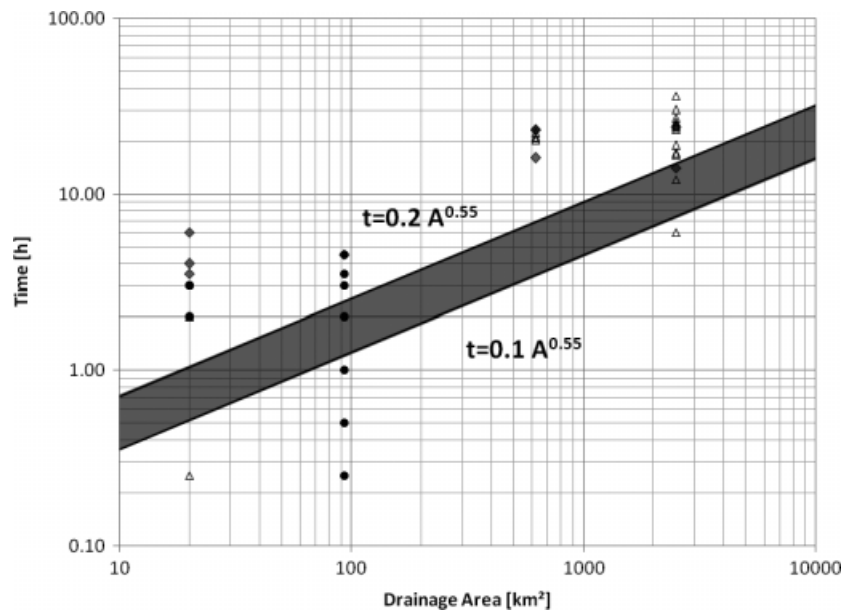


Figure 4. Representation of 43 elementary human actions in a logarithmic plot of their anticipation time *versus* the area of the watershed where they occurred. Three levels of organisation of the actors are distinguished by the different dot shapes: ● Individual, ◆ Communities, △ Institutional. The lower line of the shaded area represents the relationship between the catchment lag-time and its drainage area. The upper line is $\text{Log}(2)$ above the lower line and qualitatively indicates the characteristic duration of the generating rain event.

The anticipation at the broader scales relies on the use of NWP models for rainfall forecasting and on the generation of relevant flooding scenarios that are summarised in the official broadcast of the meteorological services. It is noted that the largest spatial scale explored in this study is still relatively modest (2500 km^2) compared to the typical areas targeted by NWP. At the smaller scales the anticipation time is much shorter (4 or 6 h) and the question is raised about the type of information used. Examination of the responses at a scale of less than 100 km^2 reveals that several organisation and protection actions occurred just before the peak time, and generally at anticipation times less than the catchment response. It is difficult to evaluate how these actions were triggered; however, as reported above, in general it was the rising water levels in the neighbouring rivers, rather than the information received from outside, that triggered the individual and community actions. Of course, some of the evacuations were organised at these short anticipation times proving that the reactivity of communities and individuals is well adapted. Other actions, which are equally important, included the decision to stay home and to avoid moving. This implies that the information required at these time scales, and for these anticipation times, is a reliable and high-resolution description of the actual rainfall field and of its likely impact on the hydrologic response at very short times. For example, organising the evacuations requires knowledge of how the potential routes can be hit by inundation in the next half hour or less.

Flash flood forecasting tools relying on accurate radar monitoring of the precipitation field and pre-established hydrological scenarios linked to the soil-moisture status of the soils, such as the Flash Flood Guidance method (Georgakakos, 2004, 2006; Martina *et al.*, 2006; Norbiato

et al., 2008), may provide enough information for warning at these space and time scales. Such real time analysis of radar rainfall accumulations allows forecast lead times that are at least equal to the response time of the watersheds and potentially allows handling of basin sizes that match the radar resolution. A key advantage of these methods is that they allow the forecaster to ingest local precipitation information easily and to update warnings without the need to run complex hydrometeorological forecasting chains (Norbiato *et al.*, 2008).

6. Conclusions and future research

This paper compares watershed dynamics under flash flood forcing to observed social responses for two well studied flash flood events, with the objective of identifying whether the current techniques available for flash-flood monitoring and forecasting can meet the requirements of populations to evaluate the severity of floods and anticipate their danger. To this end, the social response time for different social actions in the course of the floods are identified, and compared to the relevant catchment response time.

In the same way that the response time of a watershed is linked to its size, it is assumed that the characteristic time of the above defined warning procedure depends on the number of people concerned and on the level of information available about the hazardous phenomenon.

Event management activities are broadly characterized in to three types according to their main objective (information, organisation and protection). The activities were also characterised into three types according to the scale of human organisation involved (individuals, communities and institutions). This simplified schematisation of

the human response was necessary because of the lack of structured observations. Two main parameters are used to characterize the timescale of social actions in regard to the storm and flood dynamics: the anticipation time and the reaction time.

The conclusions pertain to (1) the characterisation of the social responses according to watershed scale and to the information available, and to (2) the appropriateness of the existing surveillance and forecasting tools to support the social responses identified above.

It is observed that the spatial scale seems to determine the size of the reacting human groups, and that there is a link between the spatial scale and the social response time. Most of the actions conducted by institutions apply to the largest watersheds while on the smaller ones communities and individuals are primarily in charge of the response. The institutional reactions develop as early as 30 h before the event when community reactions appear to be concentrated to *ca* 6 h and individual reactions in even less time. This suggests that representing the dynamics of the social response with just one number representing the average time for warning a population is an oversimplification. In practice the social response exhibits a parallel with the hydrological response time, by diminishing in time with decreasing the size of the considered watershed.

Secondly, it is observed that human groups have different capabilities of anticipation apparently based on the nature of information they use. The information available at institutional scale comes mostly from meteorological services, whereas at smaller scales, even when the meteorological information is provided in a timely fashion, people act on other types of data, primarily monitoring the level of water. This suggests that, even though at small scales, actions are characterised by shorter response times than at larger scales, worthwhile decisions may be taken with considerable delay with respect to the onset of the precipitation.

These results were confirmed when comparing, on the same graph, watershed response times and social response times. This showed clearly that at scales less than 100 km², a number of actions were taken with response times comparable to the catchment response time. The implications for adapting the warning processes to social scales (individual or organisational scales) are considerable. At small scales and for the implied anticipation times, the reliable and high-resolution description

of the actual rainfall field becomes the major source of information for decision-making processes e.g. initiating evacuations or advising to stay put. Methods such as the Flash Flood Guidance (FFG) may provide enough information for warning at these space and time scales. Such real-time analysis of radar rainfall accumulations allows forecast lead times that are least equal to the response time of the watersheds and potentially allows handling of basin sizes that match the radar resolution. Clearly, this leads to the stressing of three major issues: (1) the need to continue to keep improving the accuracy and quality control of real time radar rainfall data, especially during extreme flash flood generating storms; (2) the need to provide access to more and more accurate real time information about rainfall accumulations during the decision making process, and, (3) the need to ensure widespread access to this information and to produce products which are readily understandable (such as the FFG) by people at risk.

There is clearly a need to confirm these results by means of further studies based on other events. The observation that a human society is to some extent structured in cascade, with space and time scales of response that are adapted to the disturbing atmospheric and hydrologic processes, may have a wide range of implications. One may deserve specific attention. The observation may provide a clearer view of the differences between social responses to natural hazards, distinguishing those hazards which are organised according to a natural spatial scale ordering (such as the flood hazard), from those hazards which are not (such as the wildfire hazard). The question of scales, so pervasive in the hydrological science, may be developed further by considering the social scales as well.

Acknowledgements

This work was supported by the European Community's Sixth Framework Programme through the grant to the budget of the Integrated Project FLOODsite, Contract GOCE-CT-2004-505420 and in part by the STREP Project *HYDRATE*, Contract GOCE 037024. The two last authors thank respectively the National Center for Atmospheric Research, sponsored by the National Science Foundation (U.S.A.) and the Région Rhône Alpes (France), that supports their post-doctoral and doctoral fellowships. We thank Bruna De Marchi for fruitful discussions and advice on the Italian case study.

Appendix AA.I Display of the Gard River case (France). Drainage area: 2500 km². Peak time: 1800 UTC 9 September 2002

Anticipation Time	Type of response	Initiator	Receptor	Type of activity	Social scale
36:00	Meteorological vigilance level 3 (orange): BRS1 n° 1	Météo France	Gard Department	Information	Institutional
29:56	Meteorological vigilance level 3 (orange): BRS n° 2	Météo France	Gard Department	Information	Institutional
27:00	Press release	Préfecture2	Medias and population	Information	Institutional
25:35	Request of heavy means (copters, army means, etc.)	Préfecture	National authorities	Organisation	Institutional
24:30	Opening of the cell of operational defence	SIDPC3		Organisation	Institutional
24:00	Warning and organization of the population's evacuation	Mayor of Collias (800 in h)	Population of Collias	Protection	Communities
23:53	Meteorological vigilance level 3 (orange): BRS n° 3	Météo France	Gard Department	Information	Institutional
23:05	Specialized bulletin (for operators) un-alarmed	Météo France	SIDPC	Information	Institutional
18:48	Météo France Vigilance level 3 (orange): BRS n° 4	Météo France	Gard Department	Information	Institutional
17:00	The threshold of warning fixed by the civil defence plan is attained	Préfecture	Mairie de Collias	Information	Institutional
16:33	Meteorological vigilance level 34 (red): BRS n° 4	Météo France	Gard Department	Information	Institutional
14:00	Preventive evacuation. 200 people refused to leave	Mayor of Comps (1500 in h)	Population of Comps	Protection	Communities
12:00	Launching of plan ORSEC	Préfecture	Gard Department	Organisation	Institutional
6:00	Rescue by helicopters of 150 people who refused to evacuate	Army	Population of Comps	Protection	Institutional

A.II Display of the Vidourle case (France). Drainage area: 620 km². Peak time: 1400 UTC 9 September 2002

Anticipation Time	Type of response	Initiator	Receptor	Type of activity	Social scale
23:15	Information concerning the start of the flooding	Mayor of Sommières (3700 in h)	Préfecture	Information	Communities
23:00	Help request	Mayor of Aujargues (700 in h)	SIDPC	Organisation	Communities
22:10	Vigilance thresholds of precipitations reached on the Vidourle catchment	SAC4	Préfecture	Information	Institutional
21:00	Proposal of warning on Vidourle (without previous warning)	SAC	Préfecture	Information	Institutional
20:50	Warning transmission (by phone)	SAC	SIDPC	Information	Institutional
20:11	Reception of warning message	SAC	Defence Ministry	Information	Institutional
16:00	Preventive evacuation of the population	Mayor of Quissac (2300 in h)	Quissac population	Protection	Communities

A.III Display of the Valliguières River case (France). Drainage area: 93 km². Peak time: 2330 UTC 8 September 2002

Anticipation Time	Type of response	Initiator	Receptor	Type of activity	Social scale
4:30	Self warning by inhabitants watching the level of the Gard river	Residents	Neighbours	Information	Individual
4:30	Rescue of people on the roof of their cars	Fire brigade	Residents	Protection	Communities
3:30	Watching water level	Residents		Information	Individual
3:00	Furniture evacuation	Residents		Protection	Individual
2:00	Help request for an injured person	Residents	Fire brigade	Organisation	Individual
1:00	Spontaneous evacuation of a couple with a child	Residents		Protection	Individual
0:30	Watching water level	Residents		Information	Individual
0:15	Furniture evacuation	Residents		Protection	Individual

A.IV Display of the Fella River case (Italy). Drainage area: 20 km². Peak time: 1700 UTC 29 August 2003

Anticipation Time	Type of response	Initiator	Receptor	Type of activity	Social scale
25:30	Alert (via Fax and SMS)	Regional civil protection	Local civil protection	Information	Institutional
6:00	Control and monitoring of the most endangered areas	Local fire brigades corps	Local authorities	Information	Communities
4:00	Warning (sirens)	Local fire brigades corps	Local authorities	Information	Communities
3:30	Protection for the most endangered houses (sandbags, water channels, etc.)	Local fire brigades corps	Residents	Protection	Communities
3:00	Local vigilance and organization	Residents		Organisation	Individual
3:00	Help brought to neighbours	Residents	Neighbours	Protection	Individual
3:00	Watching of water level	Residents		Information	Individual
3:00	Decision to stay at home and to avoid to move	Residents		Protection	Individual
3:00	Spontaneous individual evacuation	Residents		Protection	Individual
3:00	Went to control house	Residents		Information	Individual
2:00	Road closed to the traffic	Provincial civil protection and prefect		Organisation	Institutional
2:00	Help and support request	National Interior Ministry	Foreign civil protection (Austria, Slovenia, city of Bamberg)	Organisation	Institutional
1:00	Autonomous evacuation	Residents		Protection	Individual
0:15	Compulsory evacuation	Provincial civil protection, mayor, residents		Protection	Institutional

References

- Berne A, Delrieu G, Creutin JD, Obled C. 2004. Temporal and spatial resolution of rainfall measurements required for urban hydrology. *Journal of Hydrology* **299**: 166–179.
- Blöschl G, Sivapalan M. 1995. Scale issues in hydrological modelling: a review. *Hydrological Processes* **9**: 251–290.
- Borga M, Boscolo P, Zanon F, Sangati M. 2007. Hydrometeorological analysis of the August 29, 2003 flash flood in the eastern Italian Alps. *Journal of Hydrometeorology* **8**(5): 1049–1067.
- Borga M, Gaume E, Creutin JD, Marchi L. 2008. Surveying flash flood response: gauging the ungauged extremes. *Hydrological Processes* **22**(18): 3883–3885.
- Borga M, Tonelli F, Moore RJ, Andrieu H. 2002. Long-term assessment of bias adjustment in radar rainfall estimation. *Water Resources Research* **38**(11): 1226, DOI:10.1029/2001WR000555.
- Collier C. 2007. Flash flood forecasting: What are the limits of predictability? *Quarterly Journal of the Royal Meteorological Society* **133**: 622A, 3–23.
- Créton-Cazanave L. 2008. Warning! What makes a meteo signal relevant along a flash-floods warning process? *8th EMS Annual Meeting, 7th European Conference on Applied Climatology 29 September–3 October 2008, Amsterdam*.
- Créton-Cazanave L, Lutoff C, Soubeyran O. 2009. Alerte aux crues rapides : de l'utilité d'une nouvelle approche. *Colloque 'Vulnérabilités sociétales, risques et environnement : comprendre et évaluer'*, May 2008, L'Harmattan, in print.
- Creutin JD, Borga M. 2003. Radar hydrology modifies the monitoring of flash flood hazard. *Hydrological Processes* **17**(7): 1453–1456, DOI:10.1002/hyp.5122.
- De Marchi B, Scolobig A, Delli Zotti G, Del Zotto M. 2007. Risk construction and social vulnerability in an Italian Alpine Region. *Report T11-07-12 of FLOODsite Project*, <http://www.floodsite.net/html/publications2.asp?ALLdocs=on&Submit=View>.
- Delrieu G, Ducrocq V, Gaume E, Nicol J, Payrastra O, Yates E, Kirstetter PE, Andrieu H, Ayrat PA, Bouvier C, Creutin JD, Livet M, Anquetin S, Lang M, Neppel L, Obled C, Parent-du-Chatelet J, Saulnier GM, Walpersdorf A, Wobrock W. 2005. The catastrophic flash-flood event of 8–9 September 2002 in the Gard region, France: a first case study for the Cévennes-Vivarais Mediterranean Hydro-meteorological Observatory. *Journal of Hydrometeorology* **6**: 34–52.
- Dodov B, Foufoula-Georgiou E. 2005. Incorporating the spatio-temporal distribution of rainfall and basin geomorphology into nonlinear analyses of streamflow dynamics. *Advances in Water Resources* **28**: 711–728.
- Drobot S, Parker DJ. 2007. Advances and challenges in flash flood warnings. *Environmental Hazards* **7**: 173–178.
- Georgakakos KP. 2004. *Mitigating adverse hydrological impacts of storms on a global scale with high resolution, global flash flood guidance*, Abstracts Volume of International Conference on Storms/AMOS-MSNZ National Conference, 5–9 July. Australian Meteorological Society, Brisbane, Australia, 23–30.
- Georgakakos KP. 2006. Analytical results for operational flash flood guidance. *Journal of Hydrology* **317**(1–2): 81–103, DOI:10.1016/j.jhydrol.2005.05.009.
- Huet P, Martin X, Prime JL, Foin P, Laurain C, Cannard P. 2003. Retour d'expérience des Crues de Septembre 2002 dans les départements du Gard, de l'Hérault, du Vaucluse, des Bouches du Rhône, de l'Ardèche et de la Drôme. *Rapport d'expertise, Ministère de l'environnement*, 130.
- Marchi L, Cavalli M, Sangati M, Borga M. 2008. Hydrological controls and erosive response of a major debris flows triggered during a flash flood event. *Hydrological Processes* In print.
- Martina MLV, Todini E, Libralon A. 2006. A Bayesian decision approach to rainfall thresholds based flood warning. *Hydrology and Earth System Sciences* **10**: 413–426.
- Menabde M, Sivapalan M. 2001. Linking space–time variability of river runoff and rainfall fields: a dynamic approach. *Advances in Water Resources* **24**: 1001–1014.
- Montz BE, Grunfest E. 2002. Flash flood mitigation: recommendations for research and applications. *Environmental Hazards* **4**: 15–22.
- Morin E, Georgakakos KP, Shamir U, Garti R, Enzel Y. 2002. Objective, observations-based, automatic estimation of the catchment response timescale. *Water Resources Research* **38**(10): 1212, DOI:10.1029/2001WR000808.
- Norbiato D, Borga M, Degli Esposti S, Gaume E, Anquetin S. 2008. Flash flood warning based on rainfall depth-duration thresholds and soil moisture conditions: An assessment for gauged and ungauged basins. *Journal of Hydrology* **362**(3–4): 274–290.
- Norbiato D, Borga M, Sangati M, Zanon F. 2007. Regional frequency analysis of extreme precipitation in the eastern Italian Alps and the August 29, 2003 flash flood. *Journal of Hydrology* **345**(3–4): 149–166.
- Orlanski I. 1975. A rational subdivision of scales for atmospheric processes. *Bulletin of the American Meteorological Society* **56**(5): 527–530.
- PC FVG – Protezione Civile della Regione Autonoma Friuli Venezia Giulia. 2004. *Alluvione 29 agosto 2003: Stato degli interventi*. IV Commissione Protezione Civile.
- Ricard D, Ducrocq V, Bresson R, Auger L. 2007. Mesoscale environment associated with mediterranean heavy precipitating events. *12th Conference on Mesoscale Processes*, 7.
- Ruin I, Creutin JD, Anquetin S, Lutoff C. 2008. Human exposure to flash-floods – relation between flood parameters and human vulnerability during a storm of September 2002 in Southern France. *Journal of Hydrology* **361**(1–2): 199–213.
- Siccardi F, Boni G, Ferraris L, Rudari R. 2005. A hydrometeorological approach for probabilistic flood forecast. *Journal of Geophysical Research* **110**: D05101, DOI:10.1029/2004JD005314.
- Sivapalan M, Jothityangkoon C, Menabde M. 2002. Linearity and nonlinearity of basin response as a function of scale: Discussion of alternative definitions. *Water Resources Research* **38**(2): 1012, DOI:10.1029/2001WR000482.
- Younis J, Anquetin S, Thielen J. 2008. The benefit of high-resolution operational weather forecasts for flash-flood warning. *Hydrology and Earth System Sciences and Discussion* **5**: 345–377.