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Human vulnerability to flash floods: Addressing physical exposure and behavioural questions

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ABSTRACT: Flash floods surprise people in the midst of their daily activities because they are sudden. They, particularly strike people traveling. For each catastrophe, up to half of the deaths are road users. Hydrometeorological research allows longer prediction lead-times and reduced uncertainty. However, social vulnerability remains an outstanding focus. Experts call for a comprehensive integration of social and natural sciences to improve the understanding of public responses and target loss reduction. A first step in the direction indicated is to better understand the hydrometeorological circumstances of the resulting accidents as well as the behavior of the population during the crisis. The catastrophic September 2002 flash floods in Southern France took 23 human lives in 16 distinct sub catchments. Based on this experience, the authors combine analysis of the physical and human response to Mediterranean storms by using both the results of hydrometeorological simulations and qualitative research tools as interviews of flood victims.

1 INTRODUCTION

Flash floods are floods characterized by their suddenness, fast and violent movement, rarity, small scale but high level of damage (Gruntfest and Handmer, 2001). They are particularly difficult to forecast accurately and leave very little lead-time for warnings. Flash floods can surprise people who are in the midst of their daily activities, with particularly serious impacts when people travel across roads vulnerable to flooding. Studies (Staes et al., 1994; Gruntfest, E.C. and Handmer, 2001; Jonkman and Kelman, 2005; Kundzewicz and Kundzewicz, 2005; Bourque et al., 2006) show that a large number of disaster deaths occurred on the road among motorists. Inappropriate and dangerous behaviours have often been suspected (Coates, 1999; Gruntfest, 1977; Gruntfest and Ripps, 2000; Ruin and Lutoff, 2004).

The Languedoc-Roussillon region (France), especially prone to flash flooding, has suffered about seventy fatal floods over the last 600 years, causing around one thousand deaths (Antoine et al., 2001). In the last fifty years, 40% of these fatal accidents were vehicle related. The 8th and 9th of September 2002 a storm produced more than 600 mm of rainfall in less than 24 hours and triggered a series of flash floods on the Gard River basin in the south of France (Delrieu et al. 2005). This catastrophic event took 23 human lives in 16 distinct sub catchments. In order to understand what make motorists especially vulnerable the authors investigate the hydrometeorological circumstances of the resulting accidents as well as the behaviour of the population during the crisis.

After details concerning i) the methodology of the vulnerability and hydro-meteorological analysis, ii) the description of the event and its local dynamics in the locations where the behavioural survey took place, the authors examine human exposure and adaptive capacity over scales as a critical problem affecting flood risk.

2 METHODOLOGY AND DATA SET

2.1 *Human vulnerability data collection*

In terms of vulnerability two types of data were collected for this study. The first type concerns information about the 2002 flash flood victims and the spatio-temporal circumstances of their death. The second involves the set of activities that were undertaken by some of the flooded area residents during the crisis period.

In the first case data were collected by combining different sources. The victim list was first established from a review of the newspapers following the event, which means that only short-term flood mortality is explored. The precise location and time of the accidents as well as the gender, the age and the activity of the victims were obtained later on from municipality services where the accidents happened and were officially registered; and from the detailed post-flood reports when available from the rescue services.

The collection of this kind of data is faced with many difficulties. Not only the information is held by many different services but also it isn't usually collected in the purpose of doing research, meaning that no standard data grid is in use. Apart from this first aspect, the accuracy of the information depends on the presence of witnesses able to describe the circumstances of the accidents. In many cases the exact time and/or place of the accident has not been registered and the data corresponds to the location and time at which the victims have been reported missing or their bodies were found. In summary, the location has been precisely documented for 19 fatal accidents over 23 and a reliable time of the accident is only known for 13 of them.

The second set of data telling us about the spatio-temporal activities of the residents of the flooded area is a result of a qualitative survey conducted 6 months after the September 2002 event. In order to better understand individual responses and especially travel patterns in the context of flash flooding, we interviewed 30 inhabitants in Remoulins, Comps and Saint Hilaire d'Ozilhan, 3 small municipalities that were partly flooded during the 2002 episode. They are all included in the same large watershed of the Gard river but are located at the outlet of sub-catchments of very different sizes. We used face-to-face in-depth interviews to learn what people actually did and what was the purpose of their actions since the Meteo France orange vigilance (watch) was issued for this event. The schedule of their activities was then compared with the dynamics of the hydro-meteorological and social responses (community warnings and response).

2.2 *Hydro-meteorological information*

The meteorological and hydrological data used in this study is collected and analysed in the framework of the "Cévennes-Vivarais Mediterranean Hydrometeorological Observatory" (OHM-CV). This natural observatory is a research initiative to understand intense Mediterranean storms that lead to devastating flash floods. Within a window of 160 x 200 km^2, the OHM-CV obtains data from;

– Three weather radars of Météo-France located about 100 to 150 km apart in Nîmes, Bollène and Sembadel;
– A network of 400 daily rain gages and 160 hourly rain gages; and
– 45 water level stations.

Rainfall information is readily available at the time and space resolution needed for this study from the radar data archive. Radar data has been processed in order to eliminate most part of known sources of errors (Delrieu et al., 2004) and to correct electronic calibration using rain gage information. At the end, the radar observation is provided on a regular 1x1 km^2 grid at a 5 minutes time step.

River discharge information is more critical to obtain as most of the fatal accidents occurred on very small basins of around 10 km^2. In fact, available density of water level stations only covers catchments greater than several hundreds of km^2 in area. And unfortunately hydrological post-event investigations carried out during the months following the event only focused on catchments of about 100 km^2. To get an order of magnitude of peak discharges and of the timing of the flow, the authors implemented a physically based hydrological model developed within the LIQUID hydrological modeling platform (Viallet et al., 2006). The model was built for the whole Cévennes—Vivarais region and was run without any parameter calibration (Ruin *et al.*, 2008).

3 THE SEPTEMBER 2002 EVENT

3.1 *Overview of the event*

In September 2002 the storm entirely covered the Gard River basin (approximately 2500 km^2, Fig. 1 for its location) and part of the neighboring watersheds of the Cèze and the Vidourle rivers.

The weather situation was typical of flash-flood generation in the Mediterranean (Nuissier et al., 2007). In the warm sector of a perturbation several convective aggregates circulated over the Gulf of Lion during the night of the 7th of September. The 8th at noon, one of these aggregates moving northward stabilized over the hilly region drained by the Gard River. This aggregate developed into a well organized V-shaped Mesoscale Convective System (MCS) that remained quasi-stationary for 28 hours. Constantly fed in humidity by a flux of moist air coming Northward

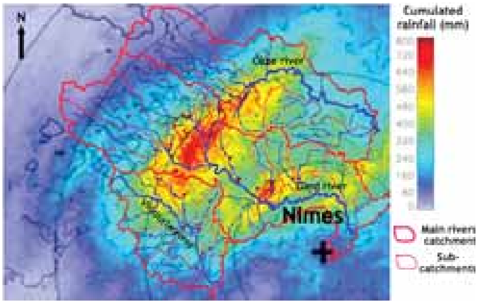

Figure 1. Cumulated rainfall for the September 8–9 Gard event estimated from calibrated data from Nîmes radar (Gaume et al., 2003).

from the sea, the MCS oscillated between the Rhône River and the Cévennes Mountain Ridge in three phases producing each approximately 200 mm of rain accumulation over significant areas. The total rainfall accumulation exceeded 200, 400 and 600 mm over, respectively, 5500, 1600 and 170 km² (figure 1).

As described Delrieu et al. (2005), the evolution of the storm is organized in three phases, each of which produced approximately 200 mm of rain. Phase I lasted from September, 8th at 08UTC to 22UTC, Phase II from September 8th at 22UTC to September 9th at 04UTC and, Phase III from September 9th at 04UTC to 12UTC. Each phase triggered fast responses in small catchments depending on the location of the rainfall. During each phase, fatal accidents occurred.

From a climatological point of view, this storm is among the three most intense events that occurred in the South of France during the last fifty years. A previous event on the Gard basin occurred in September 1958 killing 37 people. The areas exceeding the thresholds 200 and 400 mm were respectively 2800 and 30 km². More recently, a storm occurred on 12–13th November 1999 on the neighbouring basin of the Aude River and was responsible for 35 casualties. It exceeded the thresholds 200 and 400 mm over respectively 4000 and 1800 km².

The storm triggered both violent flash-floods on many small tributaries located all over the Gard and the Cèze basins and the most important flood ever recorded on the main stream of the Gard River. In term of river flow dynamics, small tributaries reacted in two or three peaks whereas the major river had only one peak. Post-event investigation allowed estimating peak discharges of 17 watersheds of sizes from 10 to 100 km^2. Inside the isoline 600 mm of rain, most of these estimated peaks indicate specific discharges of more than 5 m^{3}s^{-1} km^{-2}, with some of them over 20 m^{3}s^{-1} km^{-2}. These are the most important values ever reported for watersheds of similar areas in France (Delrieu et al., 2005). The 10 years return period discharge for such catchments is about 2 m^{3}s^{-1} km^{-2} in this region.

As a consequence of the floods 297 municipalities, covering 4925 km^2 were devastated. The event took 23 human lives, 15 of them in the sole Gard catchment. The location of the accidents and the responsible watersheds is given in figure 2. The victims were killed more often outside (13 victims among which 5 motorists, 5 campers and 3 pedestrians) than at home (10 victims including 5 persons killed by the break of a Rhône River dike at Aramon (not represented in figure 2). Table 1 summarizes the circumstances of the accidents. According to the report of rescue services, 18000 phone calls were registered in three days including 10000 for the day of September 9th. About 600 ground vehicles rescued 2940 persons. 40 of these rescue vehicles were lost and 200 were damaged. 1260 persons were winched by 20 helicopters.

The event started on a Sunday night when less people is on the roads compared to weekdays. Considering simply that more than 200 school buses transporting 4000 children circulate on weekdays in this sector gives an indication that the consequences could have been worse at a different time of the week.

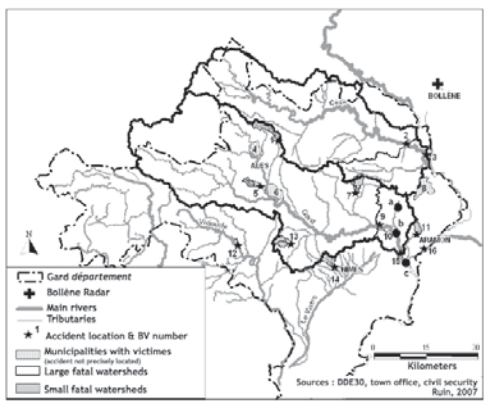

Figure 2. Map of the Gard area where most of the fatalities occurred in September 2002. The two main catchments, Gard and Cèze basin, are delineated with the thick black lines. The catchments responsible for the fatalities are numbered from 1 to 16. When they are clearly identified, their perimeter is delineated by a black solid line and the surface area is shaded in grey. The municipality perimeter (shaded in light grey) is represented when the accurate location and cause of the casualty is unknown (no 4, 6, 8 and 10). Catchment 16 is the Rhône River basin itself since the 5 fatalities in the city of Aramon are due to a dike break. The black dots show the location of Saint Hilaire d'Ozilhan (a), Remoulins (b) and Comps (c) (Ruin et al., 2008).

Table 1. Summary of the circumstances of the fatal accidents that occurred during the September 2002 flash flood episode. The basins are ranked according to the known or suspected time of the accident. They are accordingly related either to a phase of the storm or to the riverine response of the Cèze and the Gard rivers to the total storm (Ruin et al., 2008).

	Municipaly where casualties happened	Gender	Age	Deaths circumstances	Date of the accident	Deaths location LIII	Stream name	Catchment N º
Phase I	Domazan	F	46	driver outside	Reported missing on 09/08 10:00 pm	785,9 ; 3183,4	Briancon	11
	Fons	M	52	driver outside	08/09 11:00 pm	749,2 ; 3180,7	Running water	13
	St Laurent les Arbes	F	46	pedestrian outside	Reported missing on 09/08 8:00 – 10:00 pm	No data	Nizon	8
Phase II	St Christol les Alès	M	55	driver outside	09/09 6:00 am	740,18 ; 3197,625	Gardon	5
	St Quentin la Poterie	M	62	driver outside	Body found 09/09 7:30am	767,9 ; 3195,8	Alzon	7
Phase III	Quissac	F	52	inside house HLRW	09/09 9:00 am	733,4 ; 3180,3	Garonnette	12
	Rousson	M	42	campers late evacuation	Bodies found 9/09 11:56 am	745,37 ; 3211	Avène	1
		Child	2					
		Child	6					
	Nimes	M	70	driver inside	9/09/2006 1:00 pm ou 4:00 pm (journal)	761,8 ; 3174	Cadereau d'Alès	14
Riverine response	Aramon	F	84	inside house HLRW	dike break on 9/09 9:50 pm	788,2 ; 3179,4	Rhöne dike break	16
		F	54					
		F	67					
		F	75					
		M	77					
	Vers Pont du Gard	F	71	inside house HLRW	09/09 5:00 pm	775 ; 3186,3	Gardon	9
	Bagnols/Cèze	M	84	inside house HLWR	10/09 7:30 am	783 ; 3210,1	Cèze	2
	Montfrin	M	72	inside house	Body found 09/10 9:00 am	781 ; 3177,9	Gardon?	15
	Chuscian	M	74	campers late evacuation	Death certificate 10/03 6:40 pm	788.97 ; 3207	Cèze	3
		M	34		Body found 09/13 5:46 pm			
?	Vezenobres	M	52	inside house, indirect cause	No data	No data	No data	6
	St Martin de Valgualgues	M	35	pedestrian outside (animal rescue)	No data	No data	Running water?	4
	Remoulins	M	?	pedestrian outside (animal rescue)	Reported missing on 09/09	No data	Gardon	10

The event happened in September when much less tourists are on holidays in the region than in the summer. The region welcomes 4.5 millions of tourists per year and there are many campsites close to rivers. Campers confirmed to be very vulnerable with a tribute of 5 victims at a period where most of the camps are empty.

3.2 *The event dynamics in the context of Remoulins, Comps and Saint Hilaire d'Ozilhan*

The 3 municipalities where the survey took place were all differently affected by the event. First of all, because of their locations and the related watershed sizes, residents were faced with different event dynamics (figure 2). The village of Saint Hilaire d'Ozilhan located the most upstream has the smallest catchment area. It was therefore affected by important runoff since the beginning of the rainfall event. The town of Remoulins downstream, located at the confluence of 2 watersheds of very different size one of less than an hundred km^2 of area whereas the Gard river basin is 1,855 km^2, was flooded successively by two peak flows. Finally, Comps is a village protected by dikes that haven't been submerged since their construction in 1927. Unfortunately during this event, the village was flooded by the combined action of the Gard and the Rhone peak flows that overtopped the dike. Secondly, in terms of warnings the 3 municipalities also experienced different situations, ranging from no local warnings at all in Saint Hilaire d'Ozilhan to preventive evacuation orders in Comps.

In terms of dynamic, Saint Hilaire d'Ozilhan and Remoulins respectively located upstream and downstream of the small basin of La Valliguière were flooded as soon as Sunday 8th in the evening during phase I of the rain event. During that phase, this catchment received a total amount rainfall of 100 mm. As a consequence, torrential runoff went through the village of Saint Hilaire Sunday in the evening and during the night. Only residual runoff was still punctually occurring on Monday. This case perfectly illustrates flash flood response for which warnings are really difficult or even impossible to achieve. Indeed the inhabitants didn't receive any local alerts besides the orange vigilance of Météo France warning for dangerous rainfall at the *département* scale. In Remoulins, in response to La Valliguière flooding Sunday evening, numerous emergency calls reported motorists trapped in their vehicle. Many people were rescued and roads were submerged for several hours.

Still in Remoulins but in reaction to rainfall phase I, II and III, the Gard river progressively rise during the night. It started to overflow the old part of the town next to his bed on Monday morning and carry on rising until his peak at 6 pm. Since the beginning of the afternoon, emergency services started to rescue people trapped on the roof of their car. In this case only the old town inhabitants got to auto-alert themselves by surveying the water rise. No official warnings were issued at the municipality level even if this peak flow was highly predictable.

In Comps downstream, the Gard river flooding only started Monday evening and lasted until Tuesday morning. Because the municipal authorities thought the dike was weak, they ordered the village evacuation as soon as they were informed that the doors of the Rhône dam upstream had been opened. They realized that there was a risk that the Gard river would flow back because of the Rhône peak flow. The evacuation order was passed by local officials going door-to-door to overcome the lack of sirens because of electricity break down. The evacuation took place between 6:30pm and 8pm, but about 200 inhabitants refused to leave their home. The Gard river overtopped the dike around 8:30pm. The peak flow finally occurred at 3am and submerged the lowest part of the village with 3 meters of water. Among the 200 persons that decided to stay home, 150 had to be rescued by helicopter around 2pm.

4 VULNERABILITY OVER SCALES

4.1 *Human exposure over scales*

In order to better understand human exposure to flash floods, we looked at two parameters that appear to be especially relevant in flash flood events. These are space and time scales. In fact, these two dimensions are linked together and used both in meteorology and hydrology to characterize atmospheric objects and stream responses. For instance, Orlanski (1975) proposed "A rational subdivision of scale for atmospheric processes" that simply related "typical" scales in space (extension surface) and time (life time) for a series of atmospheric objects (figure 3).

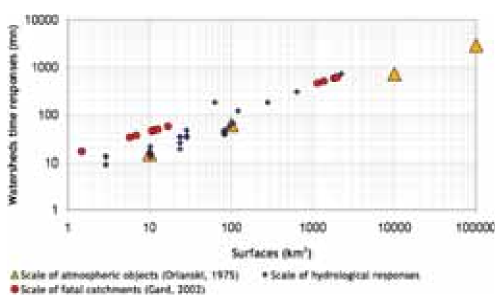

Figure 3. Estimated response time in function of the drainage area for the fatal catchments based on the regression law relationship obtained from historical data (Diamonds).

Basically, elementary convective cells (10 to 100 km^2 surface/1 hour duration) are organised in clusters named Mesoscale Convective Systems (1000 to 10000 km^2/10 hours to 1 day duration). In response to these atmospheric objects, river networks react over a wide range of "corresponding" scales, meaning that the time needed to concentrate the rain waters in the river is of the same order of magnitude than the life time of the triggering meteorological objects (figure 3). The relationship, linking in orders of magnitude the characteristic space and time scales of basins, makes it possible to relate the rapidity of response to basin scale.

By using this quantitative framework for the sizes of the 16 basins where 19 accidents occurred in 2002 but also the circumstances of these accidents and the personal traits of the victims, we were able to distinguish two type of exposure (figure 3).

On the first hand 7 basins with surface areas of less than 20 km^2 and characteristic response times of less than 1 hour are related to 9 to 11 deaths (if taking into account small watersheds where the location of the accident is inaccurate). Victims were a priori in good health condition with an average age of 43 years, and were mostly men (6/9). The casualties happened out in the open, all except one in home being pedestrians, drivers or campers. The only person struck at home was mentally handicapped and was killed trying to escape from her home. The reaction of these small tributaries is related to the local dynamics of individual convective cells and thus is spread all over the area covered by the storm in accordance with the different storm phases.

On the other hand 5 watersheds larger than 1000 km^2 with characteristic response times of around 10 hours are responsible for the death of 11 persons of 76 years old in average. 8 persons died by drowning in their home including 5 fatalities due to levee break and 3 others by being imprudent (campers trying to get a closer view of the flood, people trying to save their pets). The response of these large basins is related to the occurrence of all the MCS that were centered unfortunately on the Gard Basin. The statistical significance of the available sample may be questioned, but it seems that on basin areas in the range of a few hundreds of km^2 the risk has been lower.

During the September 2002 flood, rapid flood response threatened people in two ways. At the onset of the storm (Phase I), several victims were trapped before the official issue of the maximum level of flood warning by the meteorological services, issued at 01:37 September 9th, and before any form of crisis management could start. As shown in figure 4 representing the chronology of the event and the 5 vehicle-related accidents versus cumulated peak discharges, 2 deaths happened because of a sudden rise of water flow during the orange vigilance (watch).

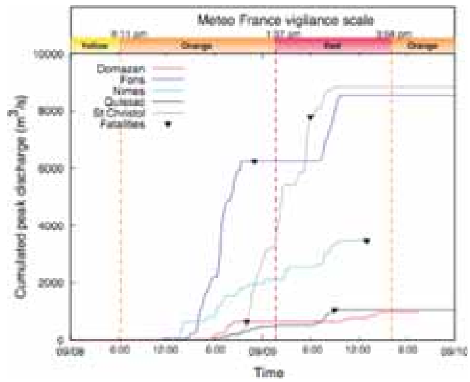

Figure 4. Chronology of the 5 vehicle-related fatalities. Comparison of the hour of the accident with the cumulated peak discharge in the concerned watersheds and the timing of Météo France warnings.

This initial rapid response is in close agreement with what is expected from flash floods. The short time lag between the rainfall occurrence and the peak discharge (short response time) is particularly dangerous because of the inability to warn and prepare the community.

During the course of the storm (Phases II and III), the rapid local reaction of very small catchments kept surprising people, almost exclusively trapped out in the open, even though the dangerousness of the situation was more evident than during Phase I: eg after the issue of red warning (maximum level) by the authorities and in view of the persistent bad weather. Figure 4 shows that 3 vehicle-related fatalities occurred during that period. This kind of "delayed" suddenness is contrary the intuitive understanding of a flash flood. For some time after the onset of the storm, many small tributaries remain dangerous because their water level can rise dramatically at very short notice (some witnesses speak about a "sudden wave" or a "water front") if a convective cell imbedded in the MCS hit them.

4.2 *Adaptive capacity over scales*

We propose to analyze here individual reactions in function of the catchment size and the dynamic its response.

In Saint Hilaire and Remoulins, 7 inhabitants out of the 20 interviewed, had to cope in phase I with the fast response of the small tributary of the Gard river. As it happened Sunday evening most of them were home when the flood hit them. During the flooding, 2 persons chose to walk closer to the stream to get a better view of the situation and 2 others chose to keep on doing their normal activity like driving their car to work or to go to the restaurant. The ones who traveled by car were both faced with flooded roads and both carried on their trip to their destination sometimes by changing their itinerary. Those people were in their mid forties and were long-established residents of the area. This flash flood response only provoked one spontaneous evacuation from a couple with a baby that was afraid to be trapped in their ground-floor house.

Concerning the behaviours associated with the riverine response, we can base our reflection on the interview of 20 inhabitants of Remoulins and Comps and 3 other inhabitants of Saint Hilaire that also faced the Gard river flooding during their travels. All the behaviors associated with this late peak flow (slower response of bigger watershed) occurred on Monday after Meteo France issued at the *département* scale a red vigilance warning for extreme and dangerous rainfall. In that case, many people travelled. 7 persons walked closer to the river to monitor the water rise. This reaction mainly concerned long-established residents that were living next to the river. 12 others (5 from Remoulins, 5 from Comps and 2 from St Hilaire) maintained their usual activities that day, mainly to commute or to take their children back and forth from school. Only one travelled for leisure purpose. Among this 12, 9 drove their car including 6 that faced what we may call "dangerous conditions". In fact, they either drove through flooded roads or over bridges that were submerged to the deck. One person of our pool was finally rescued by helicopter from the roof of his vehicle (as well as the driver of the car).

This behavioural analysis by watershed size shows that individuals keep on being surprised in their daily activity independently of the speed of hydrological response. Most of them maintain their normal activity during the crisis and especially their usual travel patterns corresponding to professional and family constraints. As expected, we observed this kind of behaviours next to small tributary with fast response; but surprisingly, also in the case of larger rivers with slower response. What seems to have much more influence on people's behavior is when the event takes place during the day or week. If it starts before their planned activities (at night or in the early morning) they have more chance to be stuck at home and not to be surprised during their travel. As we have seen in this case study, less people were surprised out of their home on Sunday evening that on Monday morning, a working week day.

5 CONCLUSION

This investigation stresses the specificity of small catchments, which appear to be the more dangerous. It also shows the need for a deeper thinking of post-event investigations and analyses. Usually these analyses further our knowledge within the discipline studied and provide evaluations upon which various types of mitigation and loss reducing practices can be based. Trans-disciplinary contributions are still rare and they tend to be focused temporally, spatially, or institutionally. This contribution to linking social sciences and geophysics constitutes one step in what Morss et al (2005) call the "end to end to end" process that also shows what may be the benefit of expanding those discipline-specific boundaries. To conclude our paper we would like to report a new initiative called DELUGE (Disasters Evolving Lessons Using Global Experience) that wish to widen existing interdisciplinary and international efforts in substantive and sustainable ways in order to assist practitioners and researchers to reduce losses from short-fuse flood events. This initiative launched by Eve Gruntfest Focuses on post-event field studies for floods to maximize interactions between social scientists, hydrologists and meteorologists. It aims at discussing and proposing new guidelines on post-event investigations for use by integrated teams of physical scientists, social scientists, and practitioners.

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