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Forensic analysis of flash flood response

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The last decade has witnessed the development of methodologies for the post-flood documentation of both hydrogeomorphological and social response to extreme precipitation. These investigations are particularly interesting for the case of flash floods, whose space–time scales make their observations by conventional hydrometeorological monitoring networks particularly challenging. Effective flash flood documentation requires post-flood survey strategies encompassing accurate radar estimation of rainfall, field and remote-sensing observations of the geomorphic processes, indirect reconstruction of peak discharges—as well eyewitness interviews. These latter can give valuable information on both flood dynamics and the related individual and collective responses. This study describes methods for post-flood surveys based on interdisciplinary collaborations between natural and social scientists. These surveys may help to better understand the links between hydrometeorological dynamics and geomorphic processes as well as the relationship between flood dynamics and behavioral response in the context of fast space–time changes of flooding conditions.

This article is categorized under:
Science of Water > Methods
Science of Water > Hydrological Processes

KEYWORDS

flash flood, flood risk, socio-hydrology, weather radar

1 | INTRODUCTION

A summer festival has been organized on Saturday (August 2, 2014) night at a beautiful open area close to the "Molinetto della Croda" ("The Peak's Watermill"), built in the 17th century along the Lierza Creek, a small stream flowing through a major wine-producing area in the Veneto Region (Italy). Almost 100 people have gathered there to dance and drink wine. Despite some rain, the festival runs smoothly until 8:15 p.m., when a heavy thunderstorm hits the Lierza basin upstream. Suddenly, the level of the stream starts rising quickly. In less than 30 min, the river bursts over its banks, turning the open area into a raging river as the waters carry away stands, vehicles, and people. Four men were swept away by the flood and died, 20 were injured. The festival had turned into a disaster.

After the catastrophe, heated discussions on the potential for flash flood warning and on the effects of recent land use change (from woodland to vineyard) on flood magnitude took place. Some people blamed the hay rolls floating with the flood for obstructing the channel and the lack of proper maintenance of the woody vegetation on the banks (allegedly responsible for the creation of wood dam-break surges). Others envisaged shallow landslides clogging the channel. However, no data were available to lead a scientific or technical discussion: the area impacted by the flood was very small (the Lierza basin at the Molinetto is 7.5 km^2 wide) and neither rain gauges nor stream gauges were available to quantitatively document rain depth and discharge during the flood.

Events of this type are occurring with an alarming frequency in Europe and elsewhere and are characterized by the highest average mortality, when compared with other types of floods (Doocy, Daniels, Murray, & Kirsch, 2013). Barredo (2007) reported that flash floods in Europe caused around 2,800 fatalities between 1950 and 2005, that is, 50 casualties per year on average.

As shown by the Lierza catastrophe, the high-risk potential of flash floods is related to their rapid occurrence and to the small and dispersed spatial extent of the impacted areas. Both characteristics limit the ability to issue timely flood warnings. The extremely short response time of flash floods is linked to the size of the affected catchments, which is generally less than a few 100 km^2 (Figure 1), and to the activation of rapid runoff processes, generally surface runoff, as the prevailing water transfer processes. Using the metric provided by lag time, that is, the duration between the time of the centroid of the generating rainfall sequence and the time of peak flow, and data from 26 major flash flood events in Europe, Figure 1 shows that the response time of most of the events is less than 10 hr. However, for catchments up to 100 km^2 size, which account for a significant share of flash flood casualties (Ruin, Creutin, Anquetin, & Lutoff, 2008), the limit response time is often less than 1 hr.

Marchi, Borga, Preciso, and Gaume (2010) showed that steepness represents a distinctive morphological feature of flash flood catchments. Indeed, topographic relief may enhance flash flood occurrence by promoting rapid concentration of streamflow. This results in high unit discharges and relevant geomorphic effects, inducing drastic channel changes during flood events which can significantly affect local channel hydraulics, bank instability, avulsions and inundation, hence causing hazard amplification (Ozturk et al., 2017).

The short response time of flash floods implies that impacted communities often do not have time to access rescue services. Often individuals and improvised groups manage to inform, organize and protect themselves on their own, in many cases without involvement of official risk managers (Creutin et al., 2013). Investigating the human and environmental circumstances experienced by individuals and groups in such crises is crucial to improve our knowledge about the link between environmental conditions, social settings, dynamic vulnerability, and behavioral response to floods (Ryan, 2018; Terti, Ruin, Anquetin, & Gourley, 2015). This is key information for improving individual and organizational preparedness and flash flood risk management.

As exemplified by the Lierza event, the small spatial and temporal scales of flash floods relative to the characteristics of the hydrological monitoring networks make these events particularly difficult to observe and predict (Marchi et al., 2010). In the last decade, the recognition of the poor observability of flash floods stimulated the development of focused monitoring methodology, which involves post-flood surveys of flood peaks and related geomorphic signatures, re-analyses of weather radar data, hydrological modeling and analysis of hydrogeomorphic processes (Amponsah et al., 2016; Bouilloud, Delrieu, Boudevillain, Borga, & Zanon, 2009; Calianno, Ruin, & Gourley, 2013). Such methodology, which provides information and knowledge for events where no direct systematic hydrometeorological data and observations are available, is termed here "flash flood forensic analysis" (Bronstert et al., 2018; Keating, Venkateswaran, Szoenyi, MacClune, & Mechler, 2016). This analysis borrows the term "forensics" from the field of criminal investigation, because it denotes a consistent approach to develop a full analysis of an event and its root causes (Keating et al., 2016). While enabling a systematic approach, flash flood forensic analysis provides a consistent approach which facilitates cross-event learning. In recent years, forensic analysis of flash floods has been extended to include analysis of social response (Scolobig, De Marchi, & Borga, 2012, among others), economic impacts (Laudan, Rözer, Sieg, Vogel, & Thieken, 2017 and references therein) and disaster risk management (Keating et al., 2016). In this context, a group of authors (Creutin et al., 2013; Lutoff, Creutin, Ruin, & Borga, 2016; Papagiannaki, Kotroni, Lagouvardos, Ruin, & Bezes, 2017; Ruin et al., 2014) advanced the integrated post-flood survey of behavioral response to floods. The approach focuses on the relation between flood dynamics and social response in the context of

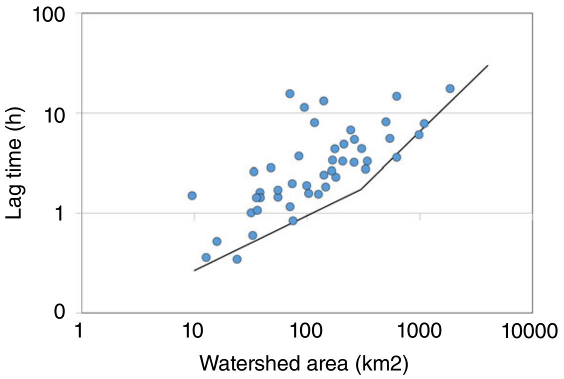

FIGURE 1 Lag time versus watershed area for major flash floods in Europe. (Reprinted with permission from Creutin et al. (2013). Copyright 2013 Elsevier)

fast space–time changes of flooding conditions. The integrated analysis of flood and social response may help to better understand the potential links between the hazard characteristics and their socioeconomic impacts and to explain behavioral responses with respect to hazard space–time features. This study illustrates forensic methods for the analysis of the hydromorphological and behavioral response to flash floods. The article is divided in two parts. The first part describes methods for post-flood survey of flash flood hydromorphological response. The second part is devoted to the post-flood survey of behavioral response to flash floods. A short conclusion reiterates the importance of flash flood forensic analysis to improve flash flood risk management and enhance awareness.

2 | FORENSIC ANALYSIS OF FLASH FLOOD HYDROMORPHOLOGICAL RESPONSE

The use of indirect hydraulic, geologic, and topographic observations for the analysis of floods when systematic hydrological records are lacking has a long scientific tradition in hydrology, dating back to the 19th century (Costa, 1987). In many cases, estimates based on indirect methods provide the foundation for developing databases of maximum floods, establishing regional peak discharge envelope curves and enhancing understanding of the impact of environmental changes on the flood regime (Bronstert et al., 2018; Gaume et al., 2009, 2010; Halbert, Nguyen, Payrastre, & Gaume, 2016). In the case of flash floods, observations of traces left by flood water and sediments during post-flood surveys provide an opportunity for developing spatially detailed estimates of peak discharges along the stream network (Figure 2) by using indirect methods. These methods are generally based on various solutions of the one-dimensional, gradually varied, steady-state flow equations for open channels (Jarrett, 1987; Lumbroso & Gaume, 2012), even though in some cases a more refined hydraulic modeling (non-stationary, two-dimensional or even three-dimensional) may be required (Bronstert et al., 2018). Among the possible sources of additional information for discharge estimation checking, pictures and movies taken by eyewitnesses and fixed cameras are now often available after major flood events (Gaume & Borga, 2008).

In general, post-flood investigations should start immediately after the event, before possible obliteration of field evidence from restoration work or subsequent floods. In particular, flagging of high-water marks, which could easily be removed or washed away by rain, should be performed as soon as possible. When the investigation is carried out to shed light on process dynamics, the survey should capture the whole spectrum of runoff response to rainfall: less intense responses within the flood-impacted region are in fact important to quantify the spatial variability of flash flood response. These surveys can be contrasted to the corresponding generating rainfall intensities and depths obtained by weather radar re-analyses, thus permitting identification of catchment properties controlling rate-limiting processes. Clearly, not all river sections are suitable for indirect peak discharge estimation. Nonetheless, Borga et al. (2008) showed that, provided that careful logistical planning and properly-staffed infrastructure is ensured, post-event surveys may deliver spatially consistent flood response analyses. At the same time, weather radar data need to be adequately treated and corrected in order to obtain accurate representations of precipitation in space and time (Berne & Krajewski, 2013). Identifying the geomorphic response that occurred during the event, through mapping of landslide/debris flow initiation and deposition areas, is important as well. This may help to exclude non-Newtonian flow processes from the analysis (e.g., hyperconcentrated flow and debris flows), hence avoiding incorrect peak

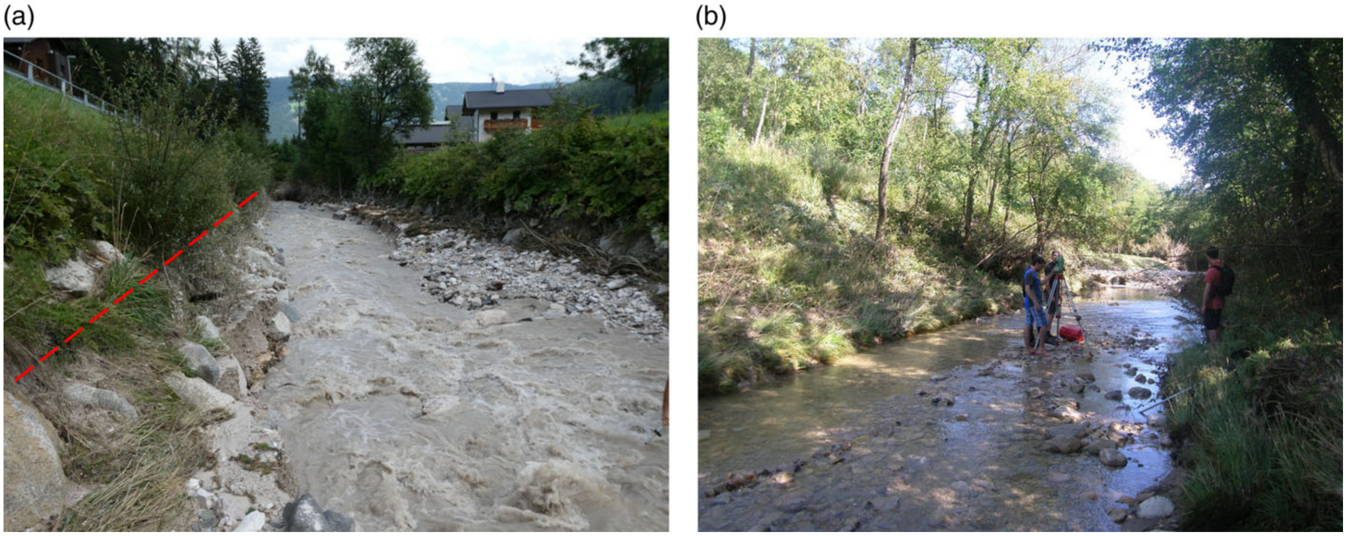

FIGURE 2 (a) Example of high-water marks. Vegetation eroded from the rocky bank shows the highest level reached by floodwater (red line). (b) Surveying the stream bed using a total station theodolite

discharge estimates. Similarly, channel changes that take place during the flood event may place considerable limitations on the reliability of indirect methods for flood peak estimation (Amponsah et al., 2016). For instance, scour and/or fill may occur after the high-water marks are left by the current. The effect is that the cross-section geometry surveyed after the flood is different from the one existing at the time of the peak. Since geomorphic impacts are typically more severe in sub-basins where runoff generation is more intense, these errors may have a considerable impact on the outcomes of post-flood surveys.

Amponsah et al. (2016) showed the advantages of contrasting spatially distributed model-based flood simulations with spatially detailed indirect peak flood estimates, taking the relevant uncertainties into account. Within this framework (Figure 3, where specific attention is placed on the evaluation of geomorphic dynamics), simulated flood hydrographs obtained using weather radar rainfall estimates are first compared to indirect peak discharge estimates, and, then, model-based analyses are carried out where modeled flood hydrographs are consistent with field-derived peak observations. The comparison between rainfall-runoff model simulations and indirect peak flow estimates may be used to remove erroneous field-derived estimates and isolate consistent hydrological simulations.

Figure 4 illustrates the comparison of indirect estimates of peak floods (with the related uncertainties) against simulated flood hydrographs for the 2014 flash flood in the Lierza basin. In this case, a simple spatially explicit flood model was calibrated based on data collected at the basin outlet and applied to three other surveyed channel sections. These analyses provide

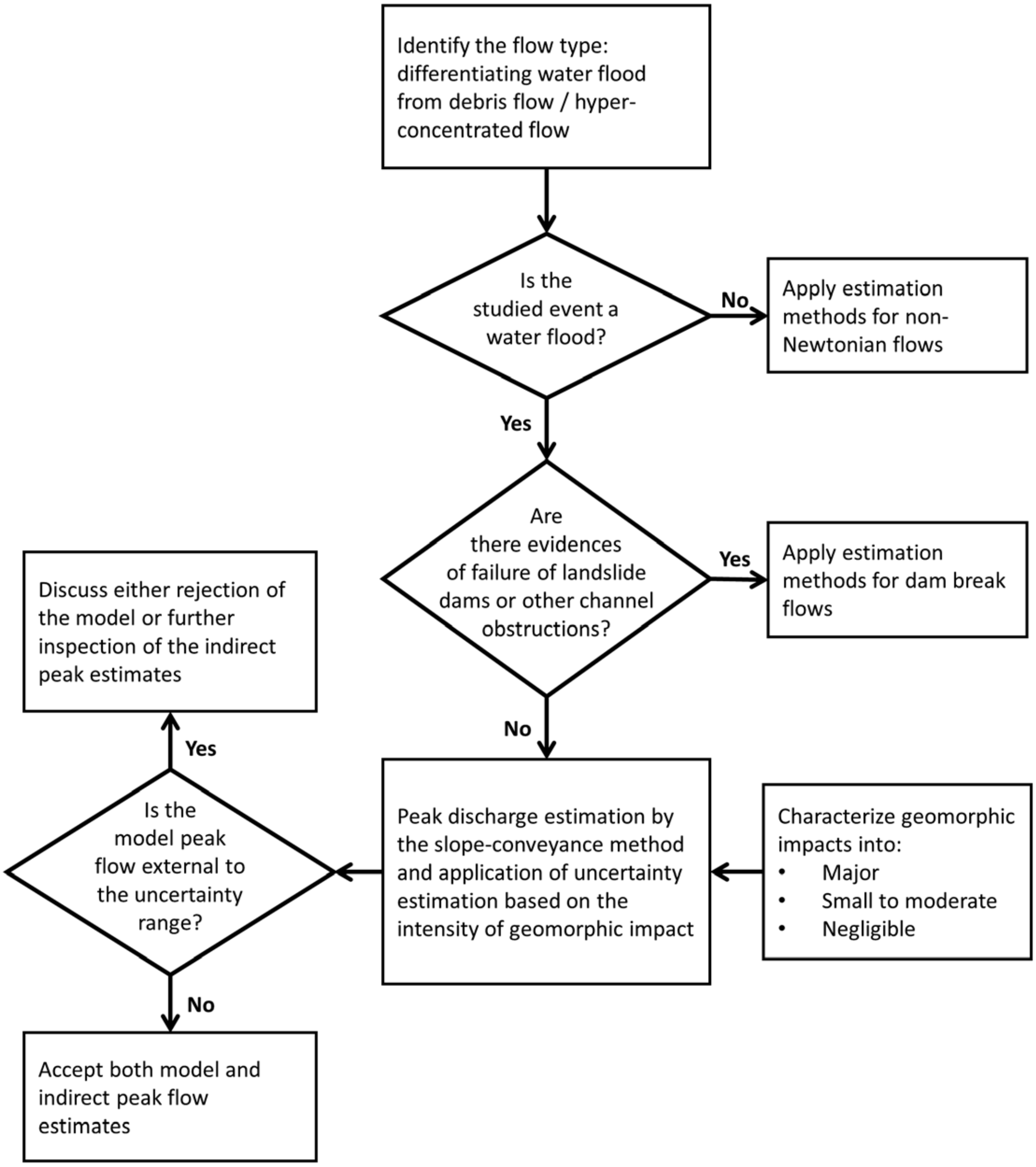

FIGURE 3 Flowchart for integrated use of indirect flood peak estimates and flood modeling: Indirect estimate of peak discharge, uncertainty assessment and comparison with model-based peak flows. (Reprinted with permission from Amponsah et al. (2016). Copyright 2016 American Meteorological Society)

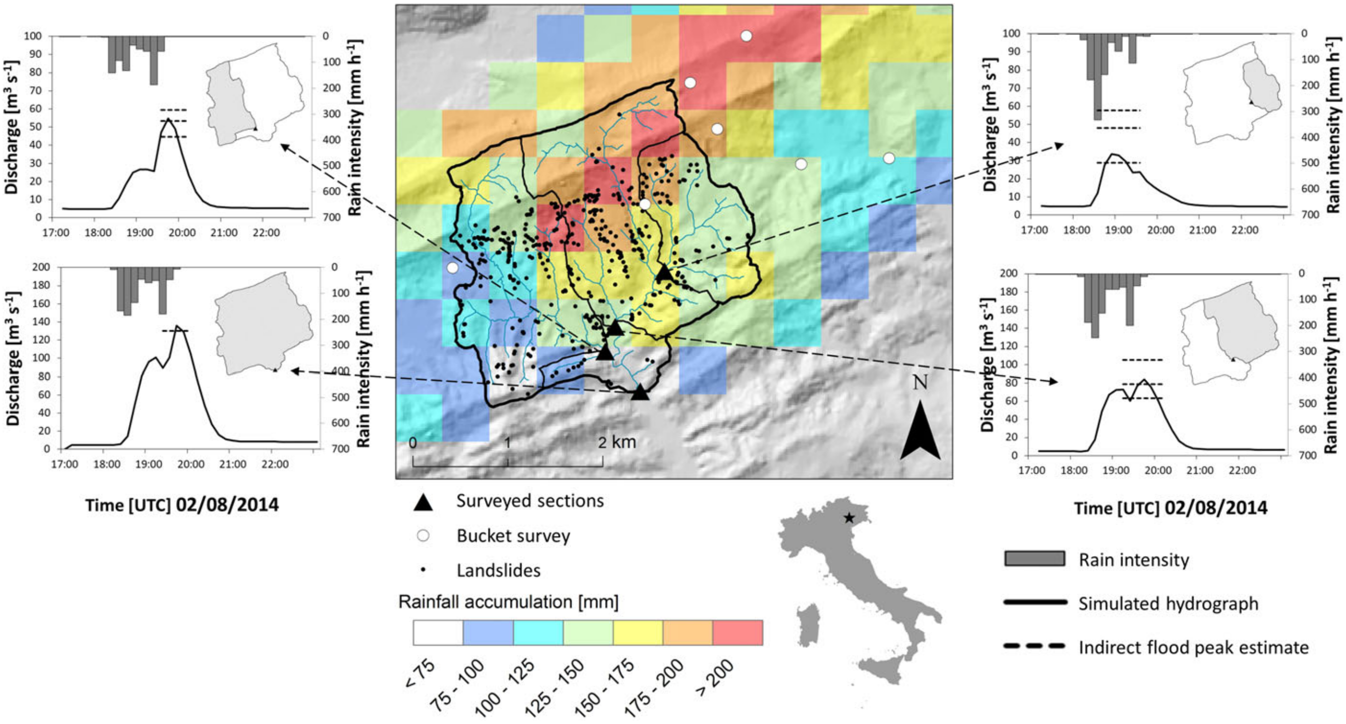

FIGURE 4 Comparison of indirect estimates of peak floods (and related uncertainties) with modeled flood hydrographs for the flash flood event of 2014 over the Lierza catchment

key insights on the role of land use on the runoff generation patterns and of shallow landslides (also reported in the figure) on flood propagation.

Channel changes—in terms of bed level and channel width—during floods are not just a "nuisance" affecting peak discharge estimation: in some river systems they may represent the most important hazard source. Indeed, channel aggradation, massive bank erosion, and slope destabilization by toe incision up to channel avulsions can seriously threaten buildings and infrastructure. Therefore, the forensic analysis has been extended to include possible factors governing the magnitude of geomorphic response, mostly addressing channel widening and bed level changes (Rinaldi et al., 2016). To this aim, the comparison of pre- and post-flood aerial imagery permits width ratio estimates, that is, the ratio between the channel width after and before the flood (Figure 5a,b). For such large floods, the width ratio can range from 1 (almost no channel widening, as it was in the Lierza case where the banks were probably very stable due to cohesive nature of its sediments) to about 10, and even more, as it was observed in recent flash floods occurred in the Apennines and Sardinia (Righini et al., 2017; Scorpio et al., 2018; Surian et al., 2016). More complex and uncertain is the determination of vertical changes, for which extensive field surveys, repeated topographic surveys (i.e., cross-sections) and/or high resolution, LiDAR-derived digital elevation models are required (Scorpio et al., 2018). Remarkably, the knowledge of peak water discharge variations along the channel network—thanks to the hydrological modeling mentioned above—enables the calculation of the peak unit stream power for different reaches, a hydraulic-related variable that explains about 50% of the variance observed in channel widening (Righini et al., 2017).

In forested catchments, mass wasting processes and wide bank erosions cause the input of massive large wood volumes into the channels during flash floods. Such wood material has the potential to obstruct critical channel sections such as bridges, thereby triggering or at least exacerbating inundation processes, as has occurred during many events in the last decades (see Comiti, Lucia, & Rickenmann, 2016). Again, a forensic approach aimed at investigating the origin of transported wood volumes (e.g., from hillslopes or from floodplains?) and at estimating its volumetric budget during events for the different portions of the channel network proved very effective (Lucía, Comiti, Borga, Cavalli, & Marchi, 2015; Steeb, Rickenmann, Badoux, Rickli, & Waldner, 2017).

Researchers have started leveraging social media and crowdsourcing to augment the availability and quality of data from post-flood surveys (Le Boursicaud, Penard, Hauet, Thollet, & Le Coz, 2016; Le Coz et al., 2016). The potential of such data will grow as the availability and pervasiveness of image-capturing devices such as smartphones, surveillance cameras, and unmanned aerial vehicles increases (Perks, Russell, & Large, 2016).

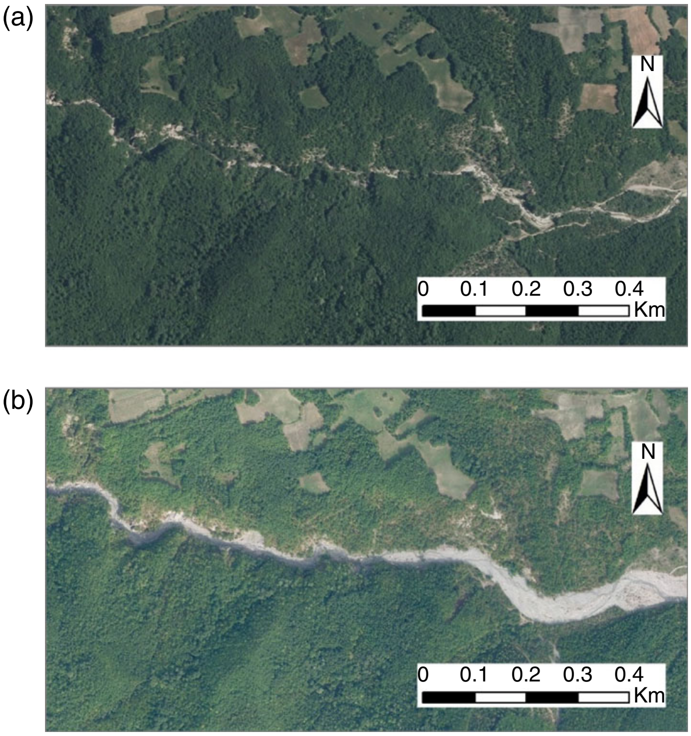

FIGURE 5 Analysis of geomorphic effects of large floods: The comparison of pre- (a) and post- (b) aerial flood photographs to determine the magnitude of channel widening. Images courtesy of Vittoria Scorpio

3 | FORENSIC ANALYSIS OF BEHAVIORAL RESPONSE TO FLASH FLOODS

Social scientists have a long history of documenting disasters and the associated response of people through the collection of post-event data (Drabek, 1999; Gruntfest, 1977; Kellens, Terpstra, & De Maeyer, 2013; Parker, Priest, & Tapsell, 2009; Quarantelli, 1997, 2003; Quarantelli & Dynes, 1977; Stallings, 1987; Walker et al., 2012, among others). Outputs from this field of research show that public warning and behavioral response are social processes that require multiple phases before protective action is put in place (Mileti, 1995; Parker et al., 2009, among others). These authors identified factors related to the characteristics of the hazard, the nature of the warning, the situational and personal characteristics of the receiver and sociocultural context as strong determinants of the behavioral response of those at risk. In rapidly evolving events like flash floods, the amount of time available to detect the threat and respond to it is so limited that protective actions often require dealing with contingent situations triggered by the rapid onset of dangerous circumstances amidst the ongoing rolling-on of normal routines and daily life (Ruin et al., 2008; Ruin, Creutin, Anquetin, Gruntfest, & Lutoff, 2009; Terti et al., 2015). Understanding how people actually detect potentially dangerous circumstances and manage to adapt their routine in time to cope with the speed of the hazard evolution remains a challenge. In a series of papers, a group of authors (Creutin et al., 2013; Lutoff et al., 2016; Ruin et al., 2014) presented a methodology to collect information needed for understanding individual human behavioral responses in their social and hydrological contexts. The main objective was to understand how floods interfere with the completion of a daily schedule and under what conditions people abandon their daily priorities to cope with risky changes in environmental circumstances. More specifically, Ruin et al. (2014) developed a method to establish a chronological guideline which permits the reconstruction of individual stories (sequence of actions in their respective context) from the viewpoint of people under pressure from dangerous flash flood circumstances. By considering the stories chronologically, it was possible to identify individual perceptions related to the evolution of environmental conditions, to social and conjectural circumstances and to the specific emotions aroused throughout the event, as well as the implemented protective measures (Ruin et al., 2014; Ruin, Lutoff, & Shabou, 2017, Durand & Ruin, 2018). The method integrates a spatial dimension to characterize the place of action, both in its spatial character (where the action takes place, accounting for the hydrometeorological context), as well as in its symbolic dimension (what this place represents for the person involved). From the symbolic point of view, the kind of place was qualified as fixed or mobile (house, work, vehicle, socialization arena, or shelter, etc.), on the assumption that decisions made in an emergency situation are partly influenced by the constraints and representations associated with these places. For example, cars, as well as houses (in the sense of "home") generally provide a feeling of well-being and safety that may sometimes be misleading in the advent of flash floods (Dubois & Moch, 2006).

The integrated natural-social post-flood investigation methodology presented in Ruin et al. (2014) serves as a basis for data collection and analyses allowing social and hydrometeorological scientists to characterize human response into action sequences localized at a given place (Ruin et al., 2014), as well as to formalize the "timeliness" of human actions with respect to flood dynamics and peaks of danger (Creutin et al., 2013; Lutoff et al., 2016). The "timeliness approach" is novel in that it does not simply measure behavior as an independent, dichotomous variable (action or not action) but rather links specific behaviors with hazard evolution in space and time. This allows the analysis of behavioral patterns not in isolation but rather relative to the nature of the physical threat that was actually present.

The collected data come from the interviews of about 30 witnesses for each event representing five different case studies in France and Italy (Creutin et al., 2013; Lutoff et al., 2016; Ruin et al., 2014). The collected data permit exploration of the multilevel resources of human response, showing how individuals and small groups of people emerge during crises to organize their own "unofficial" local protection. This also seems to confirm that people behave differently based on local conditions during flash flooding. Human actions adapt their pace to the hazardous environmental context, reaching a rushing pace as danger approaches.

The implications of these results for adapting warning processes to social scales are considerable and range from communication of uncertainty in hydrological forecast to understanding how different sources and nature of information (from direct environmental observations to social network communications) influence decision-making processes and adoption of protective measures in emergency situations. These understandings are a necessary first step toward the predictive analyses of coupled human–natural systems integrating interactions between social vulnerability and hazards dynamics.

Integrated natural–social post-event investigation methodologies have the potential to enhance our understanding of human–natural systems by combining the interactions between social vulnerability and hazards dynamics (Terti et al., 2015, Terti, Ruin, Anquetin, & Gourley, 2017). This will eventually enable forecasting of possible human impacts from flash floods (Terti et al., 2019; Shabou et al., 2017). To this aim, there is a need for progress in the collection of data on both the social and physical processes at different scales, even at very small ones. New tools could be used for this purpose, including analysis of social networks, which provide an impressive mass of information, temporally and spatially specified. For instance, Twitter messages are automatically screened and georeferenced in order to identify and locate flood events around the world (de Bruijn, de Moel, Jongman, Wagemaker, & Aerts, 2018).

As shown by Morss et al. (2017), social networks constitute interesting resources to learn about people's behavior in the face of dangerous and uncertain weather-related threats. As these technologies continue to grow in complexity and use, it is also of crucial importance to understand their impact and potential for modifying behavior, as well as to identify the often unidentified pitfalls in their analysis (Palen and Anderson, 2016).

4 | CONCLUSION

Forensic analysis of flash flood response may provide valuable insights for flash flood risk management. Peak flood data from post-flood surveys may be incorporated in statistical regional procedures to improve estimation of low-frequency floods at spatial scales which usually are not covered well by stream gauge networks. Ongoing research focuses on understanding how data generated by this observational methodology may be used to discriminate between various runoff generation hypotheses under flash flood conditions, hence improving flash flood forecasting and warning systems.

Data from integrated forensic analysis allows river managers to consider the integration of the individual's coping pace and hydrological responses into a holistic model of flood event dynamics. Such a model may eventually help to understand the role played by social and hydrological parameters and advance toward the prediction of high-impact flash floods. However, the value of post-flood integrated surveys is not limited to an improved scientific understanding of rare events. Forensic analyses proved to have a role in enhancing the quality of public debate in post-flood contexts, when attention is still turned to questions of disaster risk, reconstruction decisions are being made and disaster policies being revisited. Fundamental for flash flood forensic analysis are actionable recommendations, which allow for learning to be turned into action before the next disaster occurs.

A high return on investment represented by post-flood surveys will require additional effort to further develop this concept. Important opportunities are represented by the use of crowdsource information (photographs, movies, general information). Public or amateur participation in hydrological data gathering through citizen science is not novel (Paul et al., 2017), but the growth of digital technology and the organization of post-flood surveys provides researchers with new ways of engaging with the wider public. Crowdsource information may be effectively integrated within quantitative surveys, thereby leading to a more accurate analysis of the flood hydrogeomorphic response. At the same time, social media "big data" streams provide new sources of first-person data that can reveal new insights about the dynamic ways in which people evaluate and respond to approaching flash flood threats.

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CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

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