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Hydrogeomorphic response to extreme rainfall in headwater systems: Flash floods and debris flows

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SUMMARY

Flash floods and debris flows develop at space and time scales that conventional observation systems for rainfall, streamflow and sediment discharge are not able to monitor. Consequently, the atmospheric, hydrological and geomorphic controls on these hydrogeomorphic processes are poorly understood, leading to highly uncertain warning and risk management. On the other hand, remote sensing of precipitation and numerical weather predictions have become the basis of several flood forecasting systems, enabling increasingly accurate detection of hazardous events. The objective of this paper is to provide a review on current European and international research on early warning systems for flash floods and debris flows. We expand upon these themes by identifying: (a) the state of the art; (b) knowledge gaps; and (c) suggested research directions to advance warning capabilities for extreme hydrogeomorphic processes. We also suggest three areas in which advancements in science will have immediate and important practical consequence, namely development of rainfall estimation and nowcasting schemes suited to the specific space–time scales, consolidating physical, engineering and social datasets of flash floods and debris-flows, integration of methods for multiple hydrogeomorphic hazard warning.

1. Introduction

Extreme rainstorms in headwater catchments may trigger liquid floods, debris floods or debris flows. The type of process triggered depends on several characteristics, including the hydrologic, geomorphometric and geotechnical features of the slopes, the source materials and the availability of sediments, and the frequency-magnitude characteristics of the precipitation event. The understanding of the hydro-geomorphic response of the slope and channel systems to various types of extreme rainfalls is key to identifying the impacts of land use and climatic changes and to predict long-term landform evolution (Schumm, 1977; Harvey, 2007). In the long standing debate of which event magnitudes are more significant in long-term river channel and landscape evolution, i.e., frequent moderate-size runoff events or extreme hydro-climatic events (Lane et al., 2007), much less is known about the latter (Grodek et al., 2012). These issues are central to the development of hydrogeomorphology, i.e. the interdisciplinary science that focuses on the interaction of hydrologic processes with landforms and the interaction of geomorphic processes with surface and subsurface water (Sidle and Onda, 2004).

The type, magnitude and intensity of the hydro-geomorphic response may affect hazard and risk in the downstream channel system and the associated fans and floodplains (Jakob et al., 2006; Marchi et al., 2009). In this paper, the attention is given primarily to events triggered by intense convection, such as flash floods and debris flows. The occurrence of these events is of concern in natural hazards sciences due to the relevance of flash floods and debris flows in terms of both the number of people affected globally and the proportion of fatalities for individual events. Jonkman (2005) gave a global perspective on the 176,000 + people killed in freshwater flooding for the period 1975–2002. He reported that flash floods are characterized by the highest average

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mortality event. Although flash floods generally affect a limited number of persons when compared with other types of floods, they can be considered as the most deadly type of flood (Doocy et al., 2013). According to Barredo (2007), flash floods in Europe caused 2764 fatalities over the period 1950–2005, i.e., 49 casualties per year on average. Similar values of flash flood-related fatalities are reported for the United States (U.S.) by Ashley and Ashley (2008). Analysis of debris flow-related fatalities and damages is more difficult, because the impact data are usually reported in combination either with information on landslide or flood damage. Analysis of a global data set of fatalities from non-seismically triggered landslides (Petley, 2012) shows that 2620 fatal landslides were recorded worldwide in the period 2004–2010, causing a total of 32,322 recorded fatalities. Examination of a catalogue of landslides and debris flows compiled by Salvati et al. (2010) for Italy revealed that in the 59-year period 1950–2008 most of the 2204 landslides that have resulted in at least 4103 fatalities in Italy, were rainfall-induced shallow landslides or debris flows.

Evidence of increasing high-intensity precipitation at regional (Trenberth et al., 2007) and global scales (Beniston, 2009; Giorgi et al., 2011) supports the view that the global hydrological cycle is intensifying as a result of global warming and the associated increasing water vapor content and energy in the atmosphere. Consequently, in many areas, the flash flood and debris-flow hazard is expected to increase in severity, through the impacts of global change on climate, severe weather in the form of heavy rains and river discharge conditions (Kleinen and Petschel-Held, 2007; Beniston et al., 2011). Together with an increase in population and infrastructure densification in some affected areas, this will result in higher life and economic loss potential from hydrogeomorphic hazards.

The high risk potential of flash floods and debris flows is related to the spatial dispersion of the potentially affected areas and to their rapid occurrence, with very short lead times between the generating storm and the ensuing flood and sediment response. As opposed to large river floods, such short lead times often do not allow to warn the affected communities in a timely manner and to establish effective event risk management procedures (Creutin et al., 2013). The quantification of downstream risk from extreme hydrogeomorphic processes in headwater basins is complex as well and requires an integrated approach that recognizes the triggering processes as well as secondary hydrogeomorphic effects. Some challenges include (i) the difficulties to rely solely on traditional physical flood protection such as dikes, groins and bank protection; (ii) the integration of multi-hazard and interconnected hazards of hillslope processes and downstream fluvial geomorphic and hydrological processes, and (iii) the difficulties in developing disaster preparedness and response strategies (Kuhlicke et al., 2011). In all types of preparedness and response strategies, the activities of early warning play a key role. As such, early warning systems (EWS), specifically developed to generate and disseminate timely and meaningful warning information for event risk management, represent an essential part of an effective natural hazards preparedness tool (UNISDR, 2009; European Commission, 2007). To be effective and complete, an early warning system needs to comprise four interacting elements, namely: (i) risk knowledge, (ii) monitoring and warning service, (iii) dissemination and communication and (iv) response capability. In this paper, we will focus mostly on the first two elements. Given the limited spatial and temporal scale of occurrence of the involved physical processes, EWS for flash floods and debris flows are based on very short-range forecasts of up to 6 h. These short-term forecasts are termed 'nowcasts' (Collier, 2007) in the following sections.

For joint flash flood and debris flow risk management, it is crucial to account for the multi-hazard nature and chrono-sequential interconnectivity of the entire spectrum of hydrogeomorphic processes. This may cause hazard amplification, for instance by inducing drastic channel changes during flood events which can significantly affect flood wave celerity, peak discharge, local channel hydraulics, bank instability, avulsions and inundation in ways that cannot be accounted for or predicted using conventional hydraulic analyses (Worni et al., 2014b). However, existing EWS are generally designed with a focus on specific individual processes (Neuhold et al., 2009). Hence a need has emerged to develop a multi-hazard risk management system able to integrate simultaneous and chrono-sequential hydrogeomorphic processes.

In the following sections we explore selected key areas for ongoing and future research efforts on nowcasting and forecasting of flash floods and debris flows. We expand upon these themes by identifying: (a) the state of the art; (b) knowledge gaps; and (c) suggested research directions to advance forecasting capabilities for extreme hydrogeomorphic processes. We also suggest three areas in which advancements in science will have immediate and important practical consequence, namely (i) development of rainfall estimation and nowcasting schemes suited to the specific space–time scales, (ii) consolidating physical, engineering and social datasets of flash floods and debris-flows, and (iii) integration of methods for multiple-hydrogeomorphic hazard warning.

2. Forecasting of flash floods and debris flows

Due to the short lead times, the accuracy of any early warning for flash floods and debris flows depends to a high degree upon the quality of the monitoring and forecasting of precipitation (Collier, 2007; Alfieri et al., 2012a; Quintero et al., 2012; Liechti et al., 2013). The uncertainties affecting the estimation and nowcasting of intense precipitation and of the ensuing hydrogeomorphic response are tied to the relevant temporal and spatial scales of the physical phenomena that are being monitored or forecasted. The review of the systems available for the forecasting of flash floods and debris flows thus begins with the identification of the spatial and temporal scales of the physical processes under investigation as they relate to elements at risk.

2.1. Processes and space–time scales

2.1.1. Flash floods

Flash floods are usually the consequence of short, high-intensity rainfalls mainly of spatially confined convective origin and often orographically enhanced (Gaume et al., 2009). Other flash flood types exist in the form of landslide dam-, man-made dam-, or glacial lake outbreaks (e.g., Worni et al., 2014a), but those are typically designated by their specific name and are not considered here. As a consequence of the limited duration of flash-flood triggering storms, the area of the impacted catchment is relatively small. Marchi et al. (2010), analyzing data from 25 major flash floods in Europe, reported that impacted catchment area was generally less than 1000 km^2. The delay between the rainfall forcing and the flash flood response is linked to the size of the affected catchments and to the activation of surface runoff which becomes the prevailing runoff transfer process. Surface runoff may be due to different generating processes, such as infiltration excess and saturation excess, as a combination of intense rainfall, soil moisture regime and soil hydraulic properties which in turn depend strongly on the dominant soil and land use types.

The relationship between catchment size and rate of stage increase (i.e., the flood response time) is central to flood forecasting. A useful metric for the quantification of this relationship is represented by the time lag, i.e. the period between the barycenter of the rainfall input and the flood peak. Creutin et al. (2013) identified the following envelope power law relationship defining the lower limit of the time lag (Fig. 1):

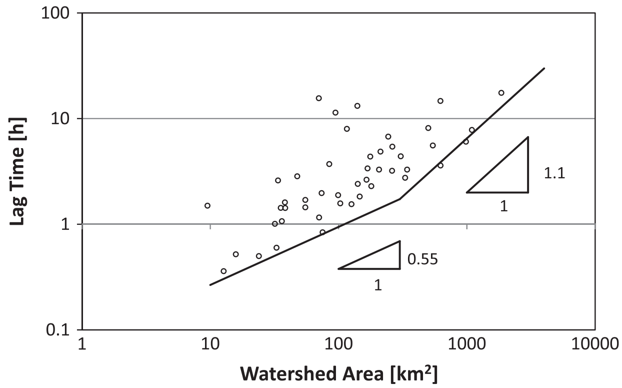

Fig. 1. Lag time versus watershed area for flash floods. As discussed in the text, the envelope lines mark the bottom limit of the watershed response time. Redrafted from Creutin et al. (2013).

$$T_L = 0.08 \cdot A^{0.55} \quad \text{for } A \leqslant 350\ \text{km}^2 \tag{1}$$

$$T_L = 0.0032 \cdot A^{1.10} \quad \text{for } A > 350\ \text{km}^2 \tag{2}$$

where T_L is the time lag (hours) and A is the basin area (km^2). Fig. 1 shows that for catchment sizes up to 100 km^2, which accounts for a significant share of flash flood casualties (up to half of the cases for the events examined by Creutin et al., 2013), the limit response time is less or equal to 1 h, thereby emphasizing the urgency of timely warning. The median response time reported by Creutin et al. (2013) for the ensemble of the studied events is 6 h. This confirms the widespread use of this time scale to qualify the flash flood response time (Gruntfest and Huber, 1991; Georgakakos, 2006).

Marchi et al. (2010) reported that steepness represents a distinctive morphological features of flash flood catchments even though flash floods have been observed in more gentle terrain as well (Rossa et al., 2010). Relief is important since it may affect flash flood occurrence in specific catchments by the combination of two main mechanisms, namely (i) orographically enhanced precipitation and convection anchoring, as well as (ii) rapid concentration of streamflow in a defined channel network. Given the association of large runoff and steep topography, it is not surprising that flash floods are also responsible for significant erosion and sediment transport, and may lead to debris flows where channels are steep enough and abundant sediment available for entrainment.

The flash flood distinctive spatial and temporal scales of occurrence qualify, together with the intensive nature of the involved hydro-meteorological processes, the differences with respect to the more widespread riverine floods. On one hand, the conventional hydro-meteorological monitoring networks (rain-gauges and stream gauges) are usually unable to sample flash floods effectively. Marchi et al. (2010) showed that only around 20% of the major flash flood events considered in their study for catchments less than 100 km^2 were gauged by a stream gauge section. This means that flash floods are typically under-represented in streamflow data archives. Hydrological models used to predict flash floods generally cannot be calibrated by using streamflow observations at forecast points. Moreover, lack of real-time streamflow data implies that the potential of discharge data assimilation systems for the updating of real-time flood forecasting models is severely limited under flash flood conditions. Similar considerations apply to the raingauge-based monitoring of flash flood-triggering storms, showing that errors in rainfall estimates cannot average out at the smaller spatial and temporal scales associated to flash floods (Zoccatelli et al., 2010, 2011). Collectively, these factors imply that predictive uncertainties tend to be greater for flash floods than for riverine floods.

2.1.2. Debris flows

Debris flows are defined as rapidly flowing gravity-driven mixtures of roughly equal parts of sediment and water in which a broad distribution of grain size, commonly including gravel and boulders, is well mixed vertically (Iverson, 2005). They differ from surging water floods in which sediment is held in suspension almost exclusively by fluid mechanical forces. Turbulence is suppressed through largely laminar flow due to the higher sediment concentration. At the opposite extreme, they differ from dry rock avalanches where grains interact almost exclusively through solid-contact phenomena (Iverson et al., 1997). Strong interactions of the solid and liquid constituents are an essential element of the mechanics of debris flows. Conditions favoring debris flow initiation include steep hillslope and channel slopes, abundant noncohesive channel and bank sediments, and sufficient water to maintain the sediment–water ratio required for debris-flow transport (e.g., Costa, 1984). Initiation mechanisms can be broadly grouped into flows originating from landslide initiation, or from the entrainment of sediment by flowing water in a channel or in coalescing rills and gullies (e.g., Iverson et al. 1997). The relative importance of these initiation mechanisms varies regionally depending on basin morphology, surficial geology, local climate and meteorology.

While debris flows initiate in typically small catchments of a few square kilometers (exceptions are large lahars or debris flows triggered by outbreak floods; Worni et al., 2014b), sediment transport and deposition processes may impact larger catchments. The time intervals from the occurrence of precipitation to the triggering of debris flows may vary significantly depending on rainstorm characteristics, antecedent moisture conditions and morphometry of the affected watersheds. Once initiated, debris flows develop rapidly entraining sediment along their transport zone which, combined with high flow velocities and associated high impact forces and the small spatial scale, render this type of landslide hazard particularly dangerous.

Intense rainfalls that characterize flash floods in headwater systems are also typical triggers for debris flows. However, debris flows may also occur in association with less intense but more prolonged precipitation events as well as outbreak floods from the rupture of landslide, ice, moraine and even beaver dams.

2.2. Types of geomorphic responses

The recognition of sediment transport type is a basic step towards the classification of catchments into those being primarily prone to water flood or debris flows. A well-established approach to this problem is based on the analysis of the relationships between morphometric characteristics of drainage basins and the type of flow process. The recognition of flow processes, with the basic separation of debris flows from water floods, can be performed through the analysis of historical documents or, more commonly, from geomorphic and sedimentological field evidence. The approach developed by Jackson et al. (1987) in the Canadian Rocky Mountains, which differentiates debris-flow catchments from "fluvial" (water floods) catchments by integrating fan slope with basin ruggedness, proved successful in other geographical regions, such as the European Alps (Marchi et al., 1993; Marchi and Brochot, 2000) and the Southern Alps of New Zealand (De Scally and Owens, 2004) (Fig. 2). In these studies, catchment ruggedness has been expressed by the Melton index, computed as the ratio of catchment relief to the square root of catchment area. Other studies differentiate debris-flow prone catchment from water flood catchments through statistical procedures, such as discriminant analysis and logistic regression (Crosta and Frattini, 2004; Santos Alonso, 2011; Bertrand et al., 2013). Bertrand et al. (2013) have applied linear discriminant analysis and logistic regression to a

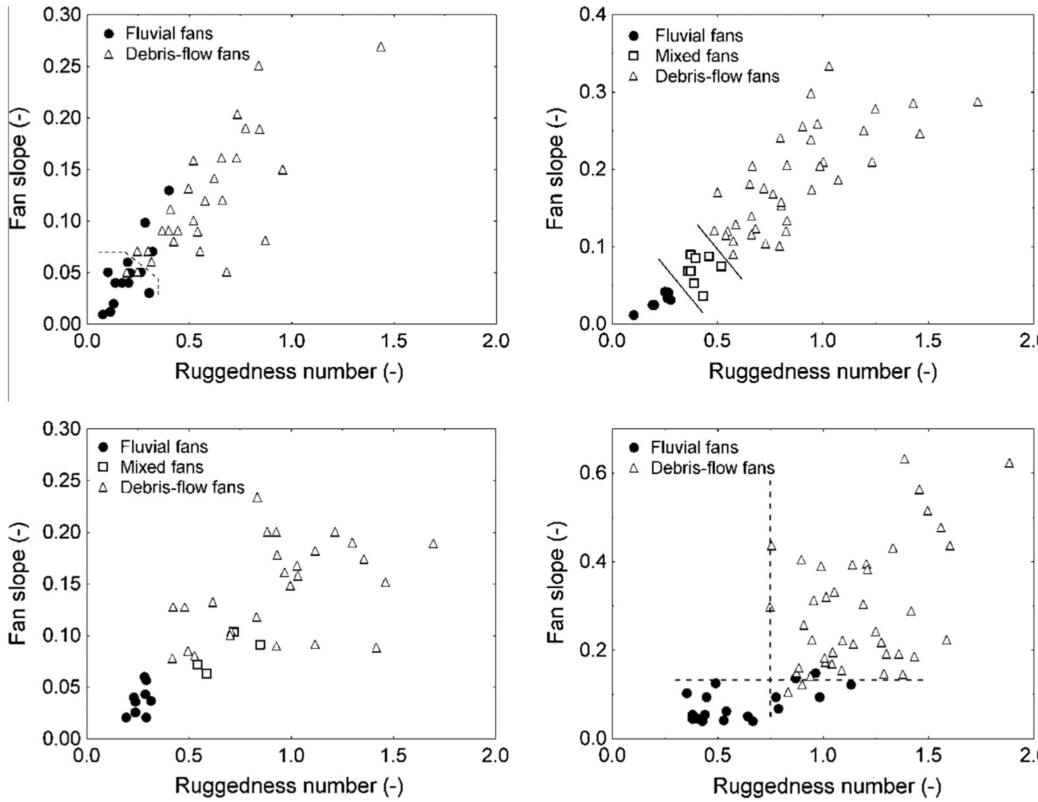

Fig. 2. Differentiation of debris-flow fans from fluvial (bedload) fan in plots of basin ruggedness versus fan slope in various geographical regions: (a) Canadian Rocky Mountains (Jackson et al., 1987), (b) Eastern Italian Alps (Marchi et al., 1993), (c) French Alps (Marchi and Brochot, 2000), (d) New Zealand (De Scally and Owens, 2004).

large database of 620 fluvial and debris-flow catchments and fans compiled from the literature and have derived robust morphometric thresholds for discriminating the type of flow response.

The identification of morphometric thresholds that discriminate debris-flow catchments from water floods catchments often outlines an intermediate area in which the catchments cannot be ascribed clearly to either process and are likely subject to both. Some studies refer to this intermediate class as "mixed" (Marchi et al., 1993), implying the possible occurrence of the continuum from floods to debris flows, whereas other studies suggest that only debris floods (Wilford et al., 2004; Mayer et al., 2010) take place. Scheidl and Rickenmann (2010) underline that different processes, encompassing fluvial sediment transport, debris flood and debris flow, may occur in some catchments during the same rainstorm, making classification particularly difficult.

Limitations in the use of simple morphometric variables for classifying catchments based on the type of flow processes are recognized and discussed by the same authors that developed and proposed these methods (e.g. Jackson et al., 1987; Marchi et al., 1993). In the framework of the joint study of debris flows and flash floods, a drawback of these methods is that the static assessment of debris flow and flash flood catchments depicts the spatial occurrence of these processes separately and does not provide information on their spatial or temporal interactions that are known to occur but which are rarely directly observed.

2.3. Rainfall estimation and nowcasting

The large spatial and temporal variability of precipitation in orographically complex landscapes typical of flash floods and debris flows makes monitoring and nowcasting of rainfall very difficult. Such large variability requires monitoring systems capable of measuring rainfall with high spatial and temporal resolutions. Rain-gauge networks are typically not dense enough to reproduce such high spatial variability. Even in the European Alps, with a comparatively dense rain-gauge network, typical spacing between stations is 10 km, whereas the precipitation distribution varies at scales below 10 km (e.g. Smith et al., 2003; Panziera et al., 2011). For the case of debris flows, characterized by smaller spatial and temporal scales, the sampling problem is even more severe, with rain-gauges that are often located in the valley floor and debris-flow initiation occurring at higher elevations (e.g., Stoffel et al., 2011, 2014). Marra et al. (2014) developed weather radar estimates of rainfall for a number of debris-flow triggering storms occurred in the Upper Adige river basin in Italy (Eastern Alps). Rainfall maps for three events are reported in Fig. 3, together with the locations of the debris flows, showing how the raingauge network is systematically unable to cover the high-accumulation rainfall portions of the events. The rain-gauge network in this region has a mean station spacing of 8 km, with larger values in the mountainous areas. The inconsistency between the spatial density of the rainfall sampling and the space–time variability of the triggering precipitation leads to high uncertainty in the estimation of the gauge-based rain intensity and amounts for debris-flow triggering events.

A potential solution to the observational limitations posed by raingauges, lies on remote-sensing observations, and more specifically on weather radar rainfall estimates. Weather radar offers technology capable of providing extensive measurements of rainfall in real time from a single location over wide areas, at space and time resolution which enable effective monitoring of flash floods and debris flows. For the case of flash floods, this is shown schematically in Fig. 4, which reports typical monitoring scales of weather radar systems and raingauge networks together with the time and space scales of a number of flash flood generating storms observed in Europe since 2000. On the other hand, weather radar

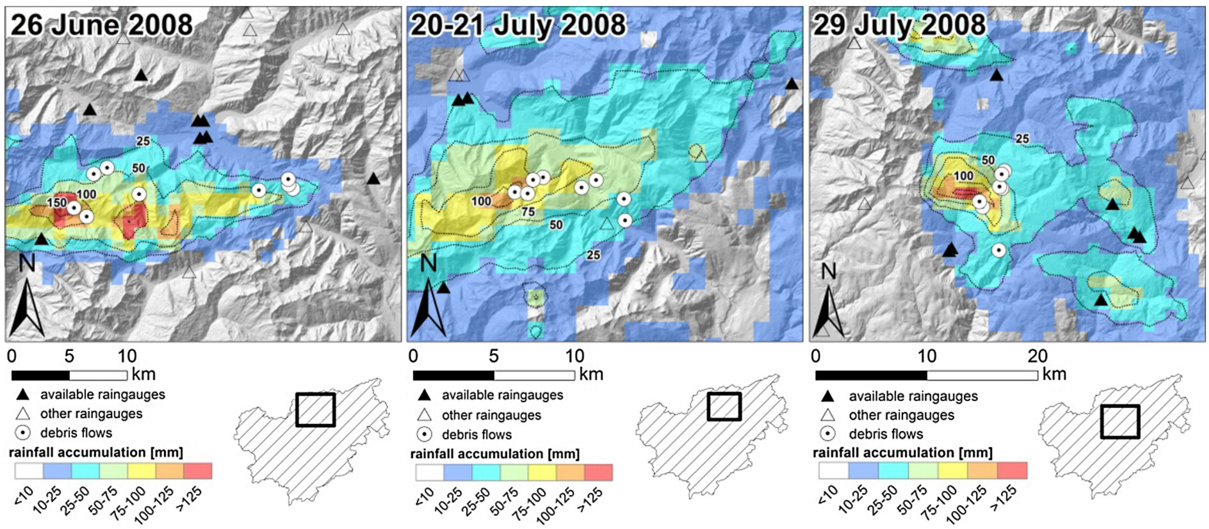

Fig. 3. Maps of radar-derived rainfall accumulation for three debris flow triggering rainfall events occurred over the Upper Adige River basin in Italy (insert) during 2008. Dotted circles represent the location of triggered debris flows, black triangles the location of raingauges.

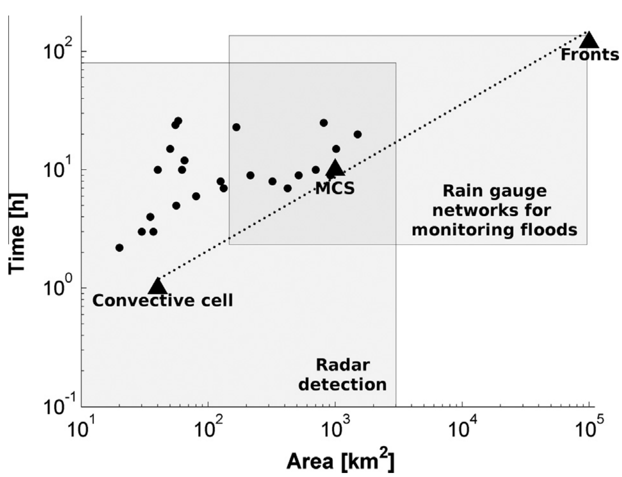

Fig. 4. Schematic of flash-flood space-time scale versus monitoring capabilities of weather radar and raingauge networks. Dots represent time and space scales of a number of flash flood generating storms observed in Europe since 20,000. Scales of convective cells, Mesoscale Convective Systems (MCS) and fronts are taken from Orlanski (1975). Redrafted from Borga et al. (2008).

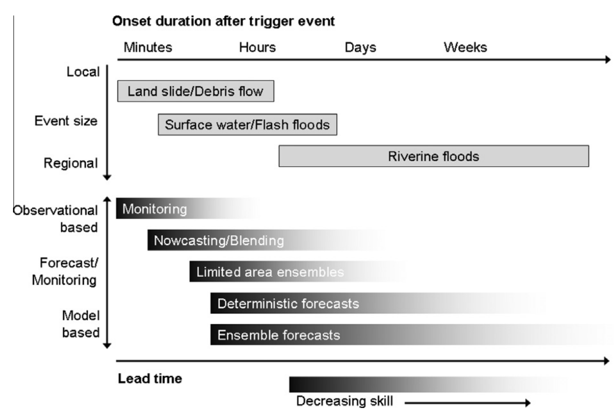

Fig. 5. Space-time scales of debris flows, flash floods and riverine floods and meteorological products for monitoring and forecasting (redrafted from Alfieri et al., 2012a).

applications for the monitoring of debris flows triggering rainfall are still limited, mainly due to observation problems in the typical mountain context (Marra et al., 2014).

A number of methods are available for rainfall nowcasting and forecasting at the scales of interest for debris flows and flash floods. These methods range from weather radar-based nowcasting to use of ensemble limited area Numerical Weather Prediction (NWP) models (Collier, 2007; Alfieri et al., 2012a,b). Fig. 5 (top panel) reports the typical space–time scales of debris flows, flash floods and conventional floods, as described in the previous section. The bottom panel in Fig. 5 shows how these scales correspond to specific forecasting/nowcasting methods, with an estimate of their skill to predict forecast lead time. Quantitative information on the main available products used as meteorological input for operational EWS is shown in Table 1, together with references to some key examples. Examination of Fig. 5 shows that flash floods and debris flows are characterized by space-temporal scales challenging the resolution of most available NWP. Besides, fine resolution NWP have wide uncertainty ranges, so results from deterministic estimates often lead to poor performance. Rainfall nowcasting therefore plays a central role in debris flow/flash flood forecasting, albeit with short lead times and large uncertainties (Collier, 2007). To extend the lead times made available by pure nowcasting, Rossa et al. (2010) tested a hydro-meteorological forecasting chain that assimilates radar rainfall data into the NWP model COSMO-2 prior to processing the forecast data with a hydrological model. This allows the main convective systems to be introduced into the model state, which enhances the timing and localization of precipitation forecasts. This method improved discharge forecasts up to a lead time of three hours.

2.4. Flash floods and debris flows forecasting: the role of threshold-based methods

When dealing with intense, localised and short living events such as flash floods and debris flows, early warning systems frequently rely on detection indicators, rather than quantitative discharge/level forecasting. Methods relying on rainfall thresholds and assessment of local soil moisture status for flash flood and debris-flows forecasting have a long tradition in hydrology and geomorphology (Zehe and Sivapalan, 2009). These methods aim to replicate the natural threshold behavior of intermittent phenomena whose related state variables and fluxes switch from zero to non-zero values over a short time or space increment (Zehe and

Table 1
Quantitative precipitation nowcasts and forecast products and technical details (redrafted from Alfieri et al., 2012a).

Product type	Spatial extent	Resolution		Forecast range	References
		Space	Time		
Radar nowcasting	~10.000–50.000 km^2	1–4 km	5–60 min	1–6 h	Turner et al. (2004) and Berenguer et al. (2005)
Ensemble radar nowcasting	~10.000–50.000 km^2	1–4 km	5–60 min	1–6 h	Germann et al. (2009) Panziera et al. (2011)
Radar-NWP blending	Regional	~2 km	15–60 min	~6 h	Bowler et al. (2006) and Rossa et al. (2010)
Limited area NWP	Regional-continental	2–25 km	1–6 h	1–3 days	Rotach et al. (2009)
Ensemble limited-area NWP	Regional-continental	4–25 km	3–6 h	1–5 days	Rotach et al. (2009)

Sivapalan, 2009). Threshold-based warning methods are particularly helpful when the triggering of the processes is controlled by poorly known meteorological characteristics and local factors, such as soil moisture and sediment availability. These methods may be incorporated into diagnostic systems aiming at a broad indication on the spatial distribution of the localized flash flood/debris flow potential within a relatively large area. Once the monitored or nowcasted precipitation is provided, these systems may be used for early identification of the areas where the triggering threshold will be likely exceeded (examples are reported by the DRIHM EU Project, http://www.drihm.eu/).

2.4.1. Flash floods

Among the simplest threshold-based approaches for flash flood forecasts are those aimed at detecting extreme weather conditions by using indices based purely on meteorological variables, such as upstream accumulated precipitation depth (e.g., Lalaurette, 2003; Golding, 2009; Hurford et al., 2012; Silvestro et al., 2012). Results reported by Alfieri and Thielen (2012) show that this approach represents in some cases a good tradeoff between low complexity and good skill, and is often justified by the large uncertainty spread of the ensemble weather predictions, which outweigh that of other hydrological processes not considered. However, results reported by Norbiato et al. (2008) have shown that in humid climates accounting for soil moisture initial conditions is key to evaluate the flash flood potential of storms, particularly in the fringe of the flood/no flood threshold. Owing to this reason, a number of methods are conditional on the soil moisture regime and are specified with reference to threshold flood peaks at the outlet of the considered catchment, as in the Flash Flood Guidance (FFG) system (Mogil et al., 1978; Borga et al., 2011) or in the Bayesian method proposed by Martina et al. (2006). A number of European research projects, such as FLOODSite (www.floodsite.net/), HYDRATE (www.hydrate.tesaf.unipd.it), and IMPRINTS (www.imprints-fp7.eu), aimed at assessing the advantage for using combined rainfall-soil moisture threshold approached in the case of flash floods (Borga et al., 2011; Cabello et al., 2011).

The FFG exemplifies the threshold-based method for flash floods (Gourley et al., 2012) and represents the depth of rain of a given duration, taken as uniform in space and time in a specific watershed, necessary to cause threshold flooding at the outlet of the watershed. A 2-yr return flow value, often corresponding to the bankfull discharge, is generally used as the threshold peak value. This rainfall depth is computed by running a hydrological model in inverse mode, i.e. by solving iteratively the rainfall input required to obtain the known flood peak provided watershed scale soil moisture conditions. The FFG is compared to either observed or forecasted rainfall of the same duration and in the same watershed. If the nowcasted or forecasted rainfall depth is greater than the FFG, then flooding in the basin is considered likely. As such, the FFG is not a forecast quantity; rather, it is a diagnostic tool. The FFG technique does not predict flash flood timing or location; it is to be used together with monitored or nowcasted precipitation to identify areas where the flood threat may be imminent.

Systematic assessments of threshold-based methods for FFG are rarely reported, mainly due to the considerable difficulties in gathering accurate and systematic information on flash flood occurrence and magnitude. Norbiato et al. (2008) and Gourley et al. (2012) provide an assessment of FFG in Europe and the U.S., respectively. Norbiato et al. (2008) evaluated the FFG performance by means of categorical statistics, such as the critical success index (CSI, Schaefer, 1990) which goes from 0 to 1, the latter value being desirable. The authors reported an overall Critical Success Index equal to 0.43 for the basins where the hydrological model has been calibrated. However, CSI reduces to 0.28 for the ungauged basins, where the model parameters are transposed from parent basins. These results show how important is the sensitivity of flash flood forecasts to errors in uncalibrated, regionalised hydrological predictions. The impact of this sensitivity is reduced in approaches where the severity of the flood forecasts is evaluated with respect to flood frequencies based on model simulations instead than observations (Reed et al., 2007; Norbiato et al., 2009). These approaches have the potential to correct inherently for simulation model biases and to filter out a portion of the hydrological model prediction uncertainty by maintaining a relatively simple framework (Alfieri et al., 2014).

The simplified structure of the threshold-based approaches is beneficial for a number of reasons. They can be applied by non-technical stakeholders at local flood forecasting centres, hence increasing the preparedness of communities exposed to hydro-geomorphic risks (Blöschl, 2008). Moreover, diagnostic methods based on the rainfall thresholds and soil moisture indexes allow processing of local precipitation information and promote close collaboration between hydrologists and meteorologists by simplifying communication about the hydrological status of basins.

2.4.2. Debris flows

For debris flows, the initiation threshold identifies the rainfall, soil moisture, or hydrological conditions required for debris flow triggering (e.g., Crozier 1996; Guzzetti et al. 2008; Chleborad et al., 2008; Jakob et al. 2012b). Rainfall thresholds can be defined adopting physical (process-based, conceptual) or empirical (historical, statistical) approaches (Aleotti, 2004; Wieczorek and Glade 2005; Guzzetti et al. 2007; Schneuwly-Bollschweiler and Stoffel, 2012; and references therein). Most commonly, rainfall thresholds for debris-flow initiation take the form of a simple relationship linking rainfall duration to other measures of rainfall, including rainfall intensity or event-cumulated rainfall. Usually rainfall intensity-duration thresholds are minimum thresholds, i.e., they correspond to a low level above which the process may take place. Although a number of rainfall thresholds have been developed specifically for debris flows (e.g. Jibson, 1989; Wilson and Wieczorek, 1995; Deganutti et al., 2000; Jakob and Weatherly, 2003; Cannon and Gartner, 2005; Chen et al., 2011; Jakob et al., 2012b), often debris flows are pooled with rapid, rainfall-triggered shallow landslides. Starting from the pioneering work by Caine (1980), rainfall thresholds for shallow landslides and debris flows have been developed at local, regional and global scales; a review of the literature on rainfall thresholds for the initiation of landslides has been presented by Guzzetti et al. (2008). Fig. 6 reports mean rainfall intensity and duration for a global database of 2626 rainfall events that have resulted in shallow landslides and debris flows (Guzzetti et al., 2008).

Three broad categories can be identified for empirical thresholds: (1) thresholds that combine precipitation measurements obtained for specific rainfall events (Guzzetti et al., 2008), (2) thresholds that include the antecedent conditions (e.g., Terlien, 1998; Glade et al., 2000; Aleotti, 2004), and (3) other thresholds, including hydrological thresholds (e.g., Jakob and Weatherly, 2003). Equations for average rainfall intensity I over the rainstorm duration D are one of the most common forms for rainfall thresholds:

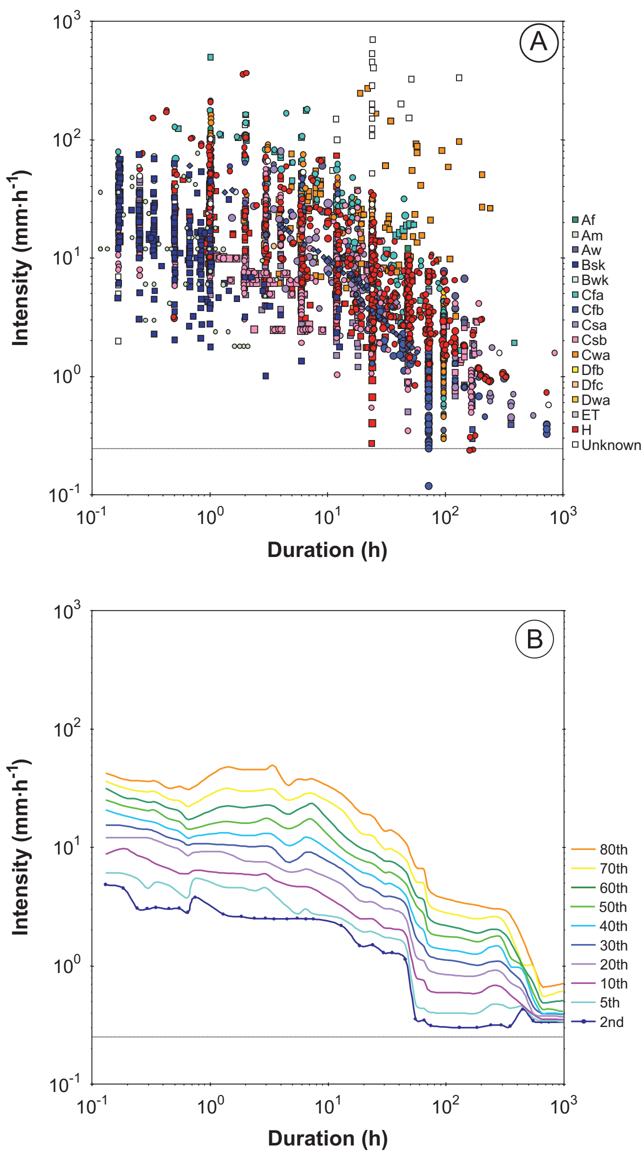

Fig. 6. Worldwide, rainfall intensity-duration conditions that have resulted in shallow landslides and debris flows. Upper plot (a) portrays raw intensity-duration data. Square: debris flow, dot: shallow failure, small symbol: single triggered landslide, large symbol: multiple triggered landslides; color shows climate (see Guzzetti et al., 2008, for climate classification), empty symbol: event for which climate is unknown, dashed line shows 0.25 mm h^{-1} rainfall intensity. Lower plot (b) portrays percentile estimates of rainfall intensity-duration conditions. Lines show, from bottom to top, 2nd, 5th, 10th, 20th, 30th, 40th, 50th, 60th, 70th, and 80th percentiles. Redrafted from Guzzetti et al. (2008).

$$I = \alpha D^{-\beta} \tag{3}$$

where α and β are calibration parameters. Methods used for establishing empirical rainfall thresholds can be practical, or based on rigorous statistical procedures (Guzzetti et al., 2007). Statistical methods, including the *frequentist* method proposed by Brunetti et al. (2010), permit the identification of rainfall thresholds in a coherent framework, and result in thresholds that are reproducible and for which measures of uncertainty are estimated (Peruccacci et al., 2012). Rainfall thresholds are used in debris-flow forecasting systems, especially for issuing alerts at regional scale. As for the case of flash floods, a problem in the operation of the debris flows thresholds is the occurrence of false positives (i.e., rainfall conditions that should have resulted in landslides that were not reported) and false negatives (i.e., rainfall conditions that should have not resulted in landslides that were reported) (Staley et al., 2013). When minimizing the fraction of misses, a false alarm rate around 40% is reported for threshold relationships in an Alpine region (Badoux et al., 2012). An excess of warnings that is not accompanied by landslide activity (false positives) is detrimental towards public acceptance of such warning systems (Staley et al., 2013), but unavoidable given the inherent uncertainties in the threshold-based forecasting of debris flow occurrence.

A recognized component of the uncertainty associated with the estimation and use of rainfall thresholds for debris flow forecasting is related to the large spatial and temporal variability of the precipitation. Surprisingly, although rainfall estimation uncertainty has been long recognized as an important factor in definition of the thresholds (Caine, 1980), studies investigating explicitly the effect on this estimation uncertainty of the thresholds are lacking. Based on data from the Eastern Italian Alps, Nikolopoulos et al. (2014) have shown that the rainfall estimation uncertainty translates into a systematic underestimation of the rainfall thresholds. These uncertainties have consequences in the operational use of the thresholds, leading to a step degradation of the performances of the rainfall threshold for identification of debris flows occurrence.

3. Selected science and data gaps and ways forward

The observations reported above show that monitoring and nowcasting of flash floods and debris flows depend on meso-scale storm monitoring and forecasting, and require real-time comparison of the nowcasted precipitation with thresholds variously specified either for flash floods or debris flows. In the following, we identify selected science and data gaps, and ways forwards, focusing on (i) intense rainfall estimation and nowcasting in complex orography; (ii) improved process understanding of hydrologic and geomorphic response to intense storm events; (iii) real-time identification of hazards due to concurrent flash floods and debris flows.

3.1. Rainfall estimation and nowcasting

Weather radars are designed to monitor precipitation over large areas with high space–time resolution and as such have a significant potential for monitoring and nowcasting highly localized storm events. However, using weather radars for precipitation measurements in mountainous regions is still a challenge, since ground clutter, beam shielding and large vertical variability strongly affect the accuracy of radar estimates and need to be treated properly if quantitative estimates of precipitation amounts are to be produced routinely (Berne and Krajewski, 2013). Improving the quality of the radar rainfall estimates is therefore a research and operational priority. An approach to achieve this objective is offered by the widespread deployment and use of polarimetric radar technologies, which are in principle capable to provide rain-rate estimates without rain-gauge calibration, and by networking many limited-range radars so that they mainly see the sub-cloud processes more closely related to surface rainfall (Berne and Krajewski, 2013). However, these networks are in the early stages of development. The only operating examples are the CASA network in Oklahoma (Junyent et al., 2010) and the X-NET network in Japan. Hydrologic and geomorphic applications are likely to emerge in coming years (Chandrasekar, personal communication). There is a need to extend the implementation of these networks to areas where flash floods and debris flows are more frequently observed, in order to assess the reduction of uncertainty due to increased accuracy and resolution in rainfall estimation.

Improving the quality of radar rainfall estimates should go in parallel with the provision of methods for the generation of ensembles based on uncertainty in radar observations (Rossa et al., 2011) Providing radar rainfall estimation errors will also permit the development of assimilation schemes into NWP for the cloud resolving scale, including nudging, 3- and 4- dimensional variational assimilation and the ensemble Kalman filter techniques.

Tools for precipitation nowcasting exploiting the orographic forcing and the increasing volumes of radar data archives have been recently developed based on use of the method of analogues (see for instance NORA, Nowcasting of Orographic Rainfall by means of Analogues, Panziera et al., 2011). The key idea in NORA is to retrieve from a data archive the situations most similar to the current observations in terms of mesoscale flows, air mass stability and rainfall patterns. Deterministic nowcasts are constructed by blending the natural evolution of these past situations with Eulerian persistence, while probabilistic forecasts are achieved by constructing an empirical probability density function from the ensemble members (Panziera et al., 2011). These nowcasting methods have the potential to increase the accuracy and availability of nowcasting at scales relevant for flash floods and debris flows risk management.

Ensemble forecasting is recognized as a major advancement in operational systems made possible by developments in numerical weather predictions (Alfieri et al., 2012b). It is largely applied in river flood early warning and increasingly in storm surge forecasting. We believe that ongoing improvements of small-scale ensemble products will be beneficial in flash flood and debris flow applications and for their integrated risk management, when co-occurrence risk is recognised.

Progress in flash flood and debris flows forecasts can be quantified if a verification system exists to provide feedback on the accuracy of the forecasts; however, no such a verification system do exist in Europe. Since these forecasts rely heavily on rainfall nowcasts, a data platform should be developed to enable an European scale system verification program with a focus on flash flood-triggering rainfall events. Given the local and regional rarity of these events, a storm data archive should be developed which collect detailed radar-based rainfall information about intense flash floods and debris flows.

3.2. Improved process understanding of hydrologic and geomorphic response to intense storm events

Lack of accurate estimates of precipitation forcing is not the only limitation to the accuracy of nowcasting and warning for flash floods and debris flows. By definition, hydrologic and geomorphic processes that are triggered by thresholds-exceeding precipitation input are locally rare and poorly observable events, even in well-instrumented experimental catchments. Moreover, data concerning the below-threshold behavior have a limited potential to improve the understanding of the processes involved in more extreme events and to enhance the predictive power of the forecasting models. Indeed, understanding and predicting drastic changes in hydrological and geomorphic functioning are among the greatest challenges in the hydro-geomorphic science as it requires extrapolations far beyond the range of commonly observed natural behavior (Zehe and Sivapalan, 2009).

3.2.1. Flash floods

The quality of flood forecasts largely depends on the availability of streamflow data for the calibration of the hydrological models (Wagener and Gupta, 2005). These data are generally unavailable at the scales and at the runoff process intensities that characterize flash floods. For riverine floods, a transfer of hydrologic information (e.g., model parameters, hydrologic indices, streamflow values) from neighboring gauged has been widely investigated in the last decades as a way to improve flood prediction in ungauged basins (Merz and Blöschl, 2004; Oudin et al., 2008). However, flash floods are poorly monitored even at the regional level, posing an effective barrier to the transfer of information. This shows the urgency of developing and consolidating flash flood archives (Borga et al., 2008; Gourley et al., 2013, 2014). Standard use of post-flood surveys is recommended to gather flood response data (flow types, flood peak magnitude and time, damages, social response) with the objective to advance understanding of the causative processes and improve assessment of both hazard and vulnerability aspects (Calianno et al., 2013; Ruin et al., 2014).

Indirect methods for flood peak estimation during post-flash flood surveys include the slope-area, contracted opening, flow-over-dam, or flow-through-culvert approaches (Gaume and Borga, 2008). In case those surveys are performed immediately after an event, the observations of traces left by water and sediments during floods will provide valuable information for the development of spatially detailed estimates of peak discharges along the stream network (Borga et al., 2008). This information is helpful for a better understanding of the role of rainfall accumulation, rainfall rates, soil and land use properties in runoff generation in ungauged basins as well as for flood events characterized by sharp gradients in runoff response properties. An improved understanding of these factors plays a key role in improving threshold-based methods for flash flood forecasting. Current methods, such as those based on FFG, show specific limitations in arid and urban settings. In these settings, flash-floods are thought to be more dependent on rainfall intensity than antecedent soil moisture. Infiltration excess type models attempting to deal explicitly with rainfall intensity are particularly sensitive to changes in spatial and temporal scales (Borga et al., 2011).

The standardization of methods and techniques for post-flood survey is also instrumental in creating a cohesive European archive of flash flood response data. Rainfall and stream response data from the flash flood archives could be utilized in verification of the methods for flash flood forecasts.

3.2.2. Debris flows

For debris flows, the key for predicting their timing and magnitude is not only the combination of hydro-climatic thresholds but an understanding and quantification of sediment sources and channel recharge mechanisms. For that, a differentiation between sediment supply-limited and supply-unlimited systems is of paramount importance (Bovis and Jakob, 1999) as is the consideration of channel recharge rates over time (Jakob et al. 2005). In absence of entrainable channel materials in supply-limited basins debris flows may not occur even during extreme rainfall. The amount and recharge of sediment into the channel system as well as the volume of expected point source landslides are key in understanding the timing and volume forecasting for debris flows, which in turn is key to the understanding geomorphic response on the fan and of higher order streams into which the debris flow may discharge. Furthermore, any prediction of debris flows in space or time need to account for the entire spectrum of debris-flow triggers. This may involve in-channel mobilization, single shallow landslides, multiple shallow landslides, landslide-dam, glacial, moraine dam, beaver dam and man-made dam outburst floods or transformation of large deep-seated landslides into debris flows. Recognition and quantification of these processes require detailed forensic analyses of past events (Guzzetti et al., 2012; Schneuwly-Bollschweiler and Stoffel, 2012).

Methods used to decipher the history of past events mainly include stratigraphic techniques as well as a series of dating techniques including radiocarbon, cosmogenic nuclide, or dendrogeomorphic dating (for details see Bollschweiler and Stoffel, 2010a; Stoffel and Corona, 2014). The latter has been demonstrated to be particularly useful on (partly) forested fans and cones, as it allows a rather detailed assessment of changes in temporal frequency (Stoffel and Beniston, 2006; Bollschweiler and Stoffel, 2010b), spread and reach of events (Stoffel and Bollschweiler, 2008), analysis of channel activity and avulsion (Bollschweiler et al., 2007, 2008). Under ideal conditions, dendrogeomorphic data can also be used for the establishment of reliable frequency-magnitude relations (Stoffel, 2010; Jakob et al., 2012a) and for the assessment of precipitation thresholds of past events (Stoffel et al., 2005, 2011; Schneuwly-Bollschweiler and Stoffel, 2012). Little is known presently on the entrainment rates of debris flows particularly in colluvial channels and on fans which are known to have produced large amounts of debris (Hungr et al. 2005; Lugon and Stoffel, 2010). This fan-entrainment potential has long been ignored in the scientific literature as it is a rare, but potentially an equally catastrophic process (Jakob et al. 1997; Stoffel and Huggel, 2012; Stoffel and Wilford, 2012). Last not least, the past may not always be a key to the future timing or magnitude behavior if land use changes, or higher order effects of climate change (changes in rainfall frequency, intensity and magnitude, changes in rain-on-snow events, changes in the distribution and stability of permafrost, changes in wildfire frequencies, or widespread insect infestations that lead to tree mortality) can drastically and lastingly alter the hydroclimatic, pedologic and geomorphic regimes.

Nevertheless, and despite the possible limitations mentioned above, the development of flash flood and debris-flow archives is key to establish verification systems with the potential to check the accuracy of flash flood and debris-flow warning techniques.

3.3. Concurrence of flash floods and debris flows and the need to account for multiple hazards

Extreme precipitation in headwater systems may trigger debris flows, flash floods and both. The coincidence of flash floods and debris flows is of particular concern, because it may amplify the hazard corresponding to the individual generative process taken in isolation. Indeed, the simultaneous occurrence of intense flooding, landslides and debris flows may trigger cascading or progressive events (e.g. Helbing, 2013). Landslides may block a river, forming a dam which then bursts, magnifying the already high flooding hazard. Landslides and debris flows may enhance the transfer of large woody debris from forest to streams, with large impact on infrastructure vulnerability (Mazzorana et al., 2012). Abnormal sediment transport may drastically alter the channel planform, with risk amplification in specific locations. In spite of the pervasive multi-hazard nature of the extreme hydro-geomorphic processes, the structure of the hazard is often assessed fragmentally, considering one aspect only. For example, existing EWS are generally designed with a focus on specific individual processes (Neuhold et al., 2009). Therefore a need has emerged to develop a multi-hazard approach which can tackle possible simultaneous and cascading hydro-geomorphic effects. This should take into consideration causes (such as geological structure, sediment availability, vegetation distribution and density) and the water–sediment connectivity between slopes, flood plains and channels (Arnaud-Fassetta and Fort, 2009; Cavalli et al., 2013).

A key driving processes linking debris flows and floods is the connectivity of debris flows with higher order streams (Cavalli et al., 2013). Very few studies have attempted to quantify how much debris is recruited from either direct discharge of debris flows into higher order streams or through bank erosion of truncated debris flow fans where they intersect with the higher order streams. Clearly this has important impacts on the sediment availability, rates of downstream aggradation or degradation and sudden sediment accumulations that may lead to avulsions in areas that had not previously been designated as flood plains.

4. Conclusions

This work gives an overview of early warning systems for flash floods and debris flows. Such systems may provide useful early information which enhances population preparedness, enables damage reduction to assets, and improves the set up of emergency and recovery procedures. Three main aspects are considered: development of rainfall estimation and nowcasting schemes suited to the specific space–time scales, consolidating physical, engineering and social datasets of flash floods and debris-flows, integration of methods for multiple-hydrogeomorphic hazard warning.

Due to local characteristics, the small spatial scale and the sudden nature, flash floods and debris flows are best managed by local authorities with effective involvement of people at risk. However, these events are also sufficiently infrequent in any given geographical area that it is difficult for the local forecasters and experts to develop an adequate experience base. Given the uncertainties affecting the currently-available relevant warnings, experience remains an essential element for issuing effective warning and implement preparedness strategies. The implications of these observations are twofold: there is urgent need to develop both (i) methods capable to constrain, quantify and communicate the uncertainties in EWS output (Pappenberger et al., 2013); and (ii) methodologies and tools to share experience, methods and results among different communities, organization and institutions which may be exposed to flash floods and debris flows.

These actions should be integrated to combine economy-centred and vulnerability-centred approaches to flood risk management (Blöschl et al., 2013). This will afford full exploitation of local expertise and enhance the value of regional monitoring and forecasting centers. Increased global interdependence underlines the necessity of cooperation, coordination and information exchange on EWS. Including EWS into policies and risk management plans, easily accessible and understandable warnings, and appropriate training ensures that those systems are properly integrated at all governmental levels. Stronger involvement of private and public stakeholders and additional information on hazard detection methods and performances are key factors to make people rely on warning systems and consequently benefit from them. This process requires more communication both to the public and within the scientific community as well.

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