Journal of Hydrology 518 (2014) 194–205

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

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

Marco Borga [a,*], Markus Stoffel [b,c], Lorenzo Marchi [d], Francesco Marra [f], Matthias Jakob [e]

[a] Department of Land, Environment, Agriculture and Forestry, University of Padova, Padova, Italy
[b] Institute for Environmental Sciences, University of Geneva, Geneva, Switzerland
[c] Laboratory of Dendrogeomorphology (dendrolab.ch), Institute of Geological Sciences, University of Berne, Berne, Switzerland
[d] National Research Council of Italy, Research Institute for Geo-Hydrological Protection, Padova, Italy
[e] BGC Engineering, Vancouver, Canada
[f] Department of Geography, Hebrew University of Jerusalem, Israel

ARTICLE INFO

Article history:
Available online 23 May 2014

Keywords:
Flash flood
Debris flows
Early warning systems
Flood risk management
Climate change
Hydrogeomorphology

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

---

* Corresponding author. Address: Department of Land, Environment, Agriculture and Forestry, University of Padova, AGRIPOLIS, via dell'Università, 16, Legnaro (PD) IT-35020, Italy. Tel.: +39 049 8272681; fax: +39 049 8272686.

E-mail addresses: marco.borga@unipd.it (M. Borga), markus.stoffel@unige.ch, markus.stoffel@dendrolab.ch (M. Stoffel), lorenzo.marchi@irpi.cnr.it (L. Marchi), marra.francesco@mail.huji.ac.il (F. Marra), mjakob@bgcengineering.ca (M. Jakob).

http://dx.doi.org/10.1016/j.jhydrol.2014.05.022
0022-1694/© 2014 Elsevier B.V. All rights reserved.

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):