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Characterisation of selected extreme flash floods in Europe and implications for flood risk management

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SUMMARY

High-resolution data enabling identification and analysis of the hydrometeorological causative processes of flash floods have been collected and analysed for 25 extreme flash floods (60 drainage basins, ranging in area from 9.5 to 1856 km^2) across Europe. Most of the selected floods are located in a geographical belt crossing Europe from western Mediterranean (Catalunia and southwestern France) to Black Sea, covering northern Italy, Slovenia, Austria, Slovakia and Romania. Criteria for flood selection were high intensity of triggering rainfall and flood response and availability of high-resolution reliable data. Hydrometeorological data collected and collated for each event were checked by using a hydrological model. The derivation and analysis of summarising variables based on the data archive has made it possible to outline some characteristics of flash floods in various morphoclimatic regions of Europe. Peak discharge data for more than 50% of the studied watersheds derive from post-flood surveys in ungauged streams. This stresses both the significance of post-flood surveys in building and extending flash flood data bases, and the need to develop new methods for flash flood hazard assessment able to take into account data from post-event analysis. Examination of data shows a peculiar seasonality effect on flash flood occurrence, with events in the Mediterranean and Alpine–Mediterranean regions mostly occurring in autumn, whereas events in the inland Continental region commonly occur in summer, revealing different climatic forcing. Consistently with this seasonality effect, spatial extent and duration of the events is generally smaller for the Continental events with respect to those occurring in the Mediterranean region. Furthermore, the flash flood regime is generally more intense in the Mediterranean Region than in the Continental areas. The runoff coefficients of the studied flash floods are usually rather low (mean value: 0.35). Moderate differences in runoff coefficient are observed between the studied climatic regions, with higher values in the Mediterranean region. Antecedent saturation conditions have a significant impact on event runoff coefficients, showing the influence of initial soil moisture status even on extreme flash flood events and stressing the importance of accounting soil moisture for operational flash flood forecasting. The runoff response displays short lag times (mostly <6 h). The identified relations between watershed area, stream length and response time enable determination of a characteristic mean velocity of the flash flood process (at basin scales less than 350 km^2), defined as the ratio of characteristic length (mean river length) and time (response time or lag time), equal to 3 m s^{-1}. This is related to the celerity with which the flood wave moves through the catchment. The analysis of the response time provides information on the time resolution and the spatial density of the networks required for monitoring the storms that generate flash floods.

1. Introduction

The occurrence of flash flooding is of concern in hydrologic and natural hazards science due to the top ranking of such events among natural disasters in terms of both the number of people affected globally and the proportion of individual fatalities. According to Barredo (2007), 40% of the flood-related casualties occurred in Europe in the period 1950–2006 are due to flash floods. The potential for flash flood casualties and damages is also increasing in many regions due to the social and economic development bringing pressure on land use. Furthermore, evidence of increasing heavy precipitation at continental (Groisman et al., 2004) and global scales (Groisman et al., 2005) supports the view that the global hydrological cycle is intensifying as the planet warms (Huntington, 2006). As a consequence, the flash flood hazard is expected to

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increase in frequency and severity in many areas, through the impacts of global change on climate, storm–weather systems and river discharge conditions.

Flash floods are associated with short, high-intensity rainfalls, mainly of convective origin that occur locally. As such, flash flood usually impact basins less than 1000 km^2, with response times of a few hours or less. The time dimension of the flash flood response is linked, on one side, to the size of the concerned catchments, and on the other side, on the activation of surface runoff that becomes the prevailing transfer process. Surface runoff may be due to different generating processes, owing to the combination of intense rainfall, soil moisture and soil hydraulic properties. It may be also enhanced by land use modification, urbanization and fire-induced alteration. Analysis of flash flood processes is important because these events often reveal aspects of hydrological behaviour that either were unexpected on the basis of weaker responses or highlight anticipated but previously unobserved behaviour (Archer et al., 2007; Delrieu et al., 2005; Borga et al., 2007). Characterising the response of a catchment during flash flood events, thus, may provide new and valuable insight into the rate-limiting processes for extreme flood response and their dependency on catchment properties and flood severity. Moreover, local flood-producing processes are more amenable to analysis in the typical small-scale flash flood basins than in larger catchments where the regional combination of controls can be relatively more important (Merz and Blöschl, 2008).

The examination of flash flood regimes across Europe shows that space and time scales of flash floods change systematically when moving from Continental to Mediterranean regions, while seasonality shifts accordingly from summer to autumn months (Gaume et al., 2009). This has several hydrological implications, which need to be considered, for example, when examining potential effects of land use (urbanization, deforestation, afforestation) and climate change on flash flood occurrence.

Flash flood forecasting, warning and emergency management are, by their nature, suitable to cope with the characteristics of flash flood risk (Drobot and Parker, 2007; Collier, 2007). Specific difficulties with flash flood forecasting relate to the short lead times and to the need to provide local and distributed forecast (Norbiato et al., 2008). Attempts to characterise the flood response to short and intense storm events is therefore central in this context (Collier and Fox, 2003). However, investigating these aspects is difficult due to lack of systematic observational data for flash floods, encompassing data on the flood-generating rainfall at the required space and time detail and discharge data. Flash flood events are difficult to monitor because they develop at space and time scales that conventional measurement networks of rain and river discharges are not able to sample effectively (Gaume and Borga, 2008). Moreover, being flash floods relatively rare event at the local scale, these are difficult to observe in experimental catchments.

A better characterisation of flash floods in Europe over various time and spatial scales is sought in this work as an important aspect of climate and hydrologic science in general, and to improve flood risk management in particular. The aim of this research is threefold: (i) to summarise the data from an archive of selected extreme flash flood events occurred in Europe in the period from 1994 to 2007, together with background climatic and hydrological information, (ii) to characterise these events in terms of basins morphology, flood-generating rainfall, peak discharges, runoff coefficient and response time, and (iii) to use the insight gained with this analysis to identify implications for flash flood risk management.

The archive includes data from 25 major flash flood events occurred since 1994, with 20 events occurred since 2000. Data have been collected in several regions of Europe, even if without achieving a systematic coverage at continental scale. The hydrometeorological data include high-resolution rainfall patterns and flood hydrographs or peak discharges. Climatic information and data concerning morphology, land use and geology are also included in the database. Hydrologic and hydraulic models are used to check the consistency of the data and to enable the reconstruction of specific events for which only partial information is available.

The presentation of the paper will adopt the following outline. Section 2 summarises prior studies on flood and flash flood characterisation across Europe. The methodology adopted to develop the archive and basic statistics are reported in Section 3. Section 4 provides a characterisation of the events in terms of climate and basins morphology. Section 5 is devoted to the analysis of the flood-generating rainfall, peak discharges, runoff coefficient and response time. Finally, the implications for flash flood risk management are examined in Section 6, together with the conclusions from the study.

2. Prior studies on flash flood characterisation across Europe

Observational difficulties of flash floods, barriers in hydrometeorological data transfer (Viglione et al., in press) and lack of a comprehensive archive of flood events across Europe hinder the development of a coherent framework for analysis of flood climatology, hazard and vulnerability at the pan-European scale (Barredo, 2007). Among the few studies with a continental view, Barredo (2007) reports a catalogue of the major flood events from 1950 to 2006 in the European Union. In his study, Barredo characterised major floods in terms of casualties and direct damages. Twenty-three out of the 47 events listed in the catalogue are classified as flash floods, and are mainly localised in Italy, Spain and southern France. Flash flood events are also reported in Germany, Belgium and UK. In spite of the smaller areas impacted by these events, flash floods caused 2764 fatalities (i.e., 52 casualties per year in average), making 40% of the overall casualties reported in the study, largely exceeding river floods (18%), and being second only to storm-surge floods (42%). It is worth noting that fatalities due to storm–surge floods concentrate into three large events which occurred from 1953 to 1962 on coastal regions of northern Europe, whereas flash floods occurred over the whole considered period in a number of European regions.

Gaume et al. (2009) analysed date of occurrence and flood peak distribution of flash floods from an inventory of events that occurred in selected regions of Europe over a 60 years period (from 1946 to 2007). The archive collated data from both instrumented and ungauged basins. In contrast to Barredo (2007), the archive used by Gaume et al. (2009) includes a substantial number of events from central and eastern European countries. Gaume et al. (2009) noted a peculiar seasonality effect on flash flood occurrence, with events in the Mediterranean region (Italy, France and Catalonia) mostly occurring in the autumn months, whereas events in the inland Continental region (Romania, Austria and Slovakia) tend to occur in the summer months, revealing different climatic forcing. Consistently with this seasonality effect, spatial extent and duration of the events was smaller for the Continental events with respect to those occurring in the Mediterranean region. Finally, Gaume et al. (2009) outlined that the flash flood regime is generally more intense in the Mediterranean Region than in the Continental areas. The present work builds upon the investigation by Gaume et al. (2009), by examining more closely the control of watershed physiography and channel network geometry on flood response, and extending the analysis to the runoff coefficient and the response time. Because of the requirement of high-resolution data, in particular spatially-distributed rainfall, we used only a portion of the events considered by Gaume et al. (2009), and several cases,