

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

L. Marchi^{a,*}, M. Borga^b, E. Preciso^a, E. Gaume^c

^a CNR IRPI, Padova, Italy

^b Department of Land and Agroforest Environment, University of Padova, Legnaro, Italy

^c Laboratoire Central des Ponts et Chaussées, Bouguenais, France

ARTICLE INFO

Keywords:

Flash flood
Runoff coefficient
Antecedent soil moisture
Lag time
Climatic regions
Flood risk management

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 km²) 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 km²), 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.

© 2010 Elsevier B.V. All rights reserved.

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. Accord-

ing 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

* Corresponding author. Tel.: +39 0498295825.

E-mail address: lorenzo.marchi@irpi.cnr.it (L. Marchi).

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 km², 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 high-light 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 achiev-

ing 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,

especially from the Mediterranean region, were not included in this study.

Parajka et al. (in press) analysed the differences in the long-term regimes of extreme precipitation and floods across the Alpine–Carpathian range (from France to Romania) using seasonality indices and atmospheric circulation patterns to understand the main flood-producing processes. The analysis was supported by cluster analyses to identify areas of similar flood processes, both in terms of precipitation forcing and catchment processes. The results allowed to isolate regions of similar flood generation processes including southerly versus westerly circulation patterns, effects of soil moisture seasonality due to evaporation and effects of soil moisture seasonality due to snow melt.

3. Data collection methodology

The aim of the data collection methodology was threefold: (i) to identify extreme flash flood events representative of different hydroclimatic European regions, (ii) to collect high-resolution data enabling the characterisation of the flood response for each event (in terms of response time and runoff coefficient), initial soil moisture status and climate, and (iii) to collect data for the characterisation of the morphological properties of the catchments, land use, soil properties and geology. These requirements led to focus on events with a high-resolution data coverage, and in particular with the availability of weather radar observations permitting rainfall estimation with fine spatial and temporal resolution and of discharge data from streamgauge stations and/or post-flood analysis (Borga et al., 2008; Marchi et al., 2009). As a consequence, attention was focused on events occurred since mid 1990s in European regions covered by weather radar systems. The preliminary identification of flash floods benefited from the collection of primary data on flash floods described by Gaume et al. (2009). The three steps of the methodology used for the set up of the archive are described in the following sections.

3.1. Events selection and severity

A definition of flash flood event was required as a working principle to develop the archive and select the events. Initially, the definition of flash flood event was based on the duration of the causative rainfall, the size of the catchment impacted by the flood and the severity of the event. Consistently with the rules adopted by Gaume et al. (2009), duration of the storm event was limited to 34 h and maximum size of the catchment area was set to 1000 km². As a follow up, these rules were slightly relaxed to include one event with a larger catchment size (Gard flood in France, 2002, with a maximum basin area of 1856 km²).

Severity of storm precipitation and flood response was a further requisite for event selection. The criterion adopted and met by all selected events is that the return period of the flood-generating rainfall exceeds 50 years at least for some rainfall duration. The selection of the 50-year recurrence interval as a threshold for event selection ensures consistency of the study archive with earlier archives of extreme rainfall events (Hershfield, 1961; Schumacher and Johnson, 2006). Rainfall was preferred to peak discharge for assessing flash flood severity because of the difficulties in providing estimates of flood peak return period in many ungauged basins. In many cases, the events were extraordinary in terms of severity. Either rainfall or peak discharge return period exceeded 500 years (and sometimes 1000 years) for the events of Fella (Italy, 2003) (Norbiato et al., 2007), Valency (UK, 2004) (Roca and Davison, 2010), Kamp (Austria, 2002) (Gutknecht et al., 2002), Mala Svinka (Slovakia, 1998) (Gaume et al., in press), Aude (France, 1999) (Gaume et al., in press) and Gard (France, 2002) (Gaume et al., in press). The point rainfall amount recorded by one rain gauge for

the Weisseritz river event (Germany, 2002) represents the new all time record for the whole territory of Germany for a daily duration (James et al., 2004).

For twelve out of 25 studied flash floods, discharge data were available at more than one cross-section, and for some of these several internal watersheds could be analysed. We retained all these data but for a few events for which a disproportionately high number of internal data were available. To avoid over-representing these floods in the analysis, we removed those cases where catchment properties and catchment responses were notably similar each other. As a general rule, the number of retained nested catchments is proportional to the size of the largest catchment area impacted by the flood (A_{max}). One basin was retained for events with A_{max} up to 100 km², and more basins were added for the events in which this threshold (or multiples of 100) was exceeded. The maximum number of watersheds retained for each flood (n_{max}) thus corresponds to the ratio $A_{max}/100$ rounded to the upper integer:

$$n_{max} = \left\lceil \frac{A_{max}}{100} \right\rceil \quad (1)$$

A few exceptions were applied to include in the sample watersheds with good quality hydrometeorological data and representative of particular morphoclimatic conditions. The criterion described above was not applied to contiguous, non-nested, catchments.

The final catalogue reports data from 25 flash flood events, including 60 catchments in ten European countries (Table 1). Some of the events were investigated in earlier studies (Table 1); results from these analyses and modelling efforts were taken into account during this study. Fig. 1 shows the location of the flash floods on a European map of Köppen–Geiger climate classification (Peel et al., 2007). Fig. 1 aims at describing the general climatic context of the studied flash floods. Some watersheds, especially those covering a wide range in elevation, encompass different climatic classes. The date of flood occurrence is also reported in the figure. Although the spatial coverage on Europe is not complete, the events encompass a wide range of climatic conditions. Fig. 1 shows that the selected floods are mainly located in a geographical belt crossing Europe from Catalonia (Spain) to the Black Sea in Romania, covering southern France, northern Italy, Slovenia, Austria and Slovakia, with a few more events from UK, Germany and Crete (Greece). This spatial pattern results from the requirements of using radar rainfall estimates for event analysis and to ensure that flood data originate from accurate and standardised post-event analyses. Even though this selection allows to pool extreme events from different hydroclimatic regions, some regions (notably central and eastern Mediterranean) are likely to be underrepresented in the archive. This points out to the need to extend in future works the analysis to incorporate more data from these areas.

The occurrence months generally agree with the seasonality pattern of flash flood-generating rainfall over the various European regions and with the observations from Gaume et al. (2009) and from Parajka et al. (in press). Over much of continental Europe, thunderstorms are typically a summer phenomenon (Trewartha, 1981). Frequency of flash flood-generating storms increases with the rise in surface temperatures in early summer and reaches a maximum in June in central-eastern Europe; in July over much of central and northern Europe, including Italian Alps; in September and October in the western Mediterranean and in winter over southern Italy and eastern part of the Mediterranean basin. The contribution of snowmelt is null for most of the studied flash floods, which occurred in summer or autumn in watersheds of low or moderate elevation (Table 1). For an event, occurred on 2006 on the Isarco river system (northern Italy), ice-melt was observed. However, its contribution to the runoff was negligible (Norbiato et al., 2009).

Table 1
Summary information on the flash floods.

Region/catchment impacted	Date of flood peak	Country	Climatic region	No. of studied watersheds	Range in watershed area (km ²)	Range in average elevation (m)	Storm duration (h)	Previous studies
Giofyros River	January 13, 1994	Greece	Mediterranean	1	166	331	14	Koutroulis and Tsanis (2010)
Avène River	October 6, 1997	France	Mediterranean	2	33.7–55	228–384	18	
Aude River	November 13, 1999	France	Mediterranean	2	9.5–305	202–402	24	Gaume et al. (2004)
Magarola River	June 10, 2000	Spain	Mediterranean	1	94.3	388	8.4	Llasat et al. (2003)
Gard River	September 8–9, 2002	France	Mediterranean	12	38.1–1856	164–607	28	Gaume and Bouvier (2004); Agència Catalana de l'Aigua (2006)
Costa Brava	October 13, 2005	Spain	Mediterranean	2	57.3–73.8	170–223	9	
Almyrida River	October 16, 2006	Greece	Mediterranean	1	24.7	212	15	
Posina River	September 20, 1999	Italy	Alpine–Mediterranean	1	116	1045	24	
Sesia River	June 5, 2002	Italy	Alpine–Mediterranean	5	75–983	494–1512	22	Sangati et al. (2009)
Fella River	August 29, 2003	Italy	Alpine–Mediterranean	4	23.9–623	1172–1370	12	Borga et al. (2007)
Selška Sora River	September 18, 2007	Slovenia	Alpine–Mediterranean	3	31.9–212	847–992	16.5	Rusjan et al. (2009)
Trisanna River	August 23, 2005	Austria	Alpine	1	122	2409	25	
Isarco and Passirio Rivers	October 3–4, 2006	Italy	Alpine	6	12–342	1809–2863	12.5	Norbiato et al. (2009)
Malá Svinka and Dubovický Creek	July 20, 1998	Slovakia	Continental	2	15.8–35.4	599–686	4	
Štrbský Creek	July 24, 2001	Slovakia	Continental	1	12.7	861	1	Majerčáková et al. (2004)
Kamp River	August 7, 2002	Austria	Continental	4	70.1–622	480–873	31	Gutknecht et al. (2002)
Weisseritz River	August 13, 2002	Germany	Continental	2	49.7–54.3	492–526	34	James et al. (2004)
Turniansky Creek	June 19, 2004	Slovakia	Continental	1	70.4	331	1.25	
Casimcea River	August 29, 2004	Romania	Continental	1	500	145	19	
Feernic River	August 23, 2005	Romania	Continental	1	168	683	5.5	
Ilisua River	June 20, 2006	Romania	Continental	1	139	672	9	
Clit River	June 30, 2006	Romania	Continental	1	36	570	4	
Grinties River	August 4, 2007	Romania	Continental	1	52	1039	4	
Starzel River	June 2, 2008	Germany	Continental	3	15.1–124	643–797	8	Roca and Davison (2010)
Valency River, Boscastle area	August 16, 2004	United Kingdom	Oceanic	1	20	192	6.75	

3.2. Rainfall data

For all the events, but three cases (Giofyros event of 1994, Almyrida event of 2006, and the Posina event of 1999), radar rainfall observations were made available for rainfall estimation together with raingauge data. The quantitative precipitation estimation (QPE) problem is particularly crucial and difficult in the context of flash floods since the causative rain events may develop at very short space and time scales (Krajewski and Smith, 2002; Bouilloud et al., in press). The rainfall QPE problem in the context of the re-analysis of flash flood events presents a number of specificities. On the one hand, and as shown later in this paper, flash floods often occur in mountainous or hilly regions resulting in increased enhanced radar visibility problems associated with the intervening relief. On the other hand, flash floods generally result from convective rainfall which makes the visibility problem less stringent due to the extended vertical dimension of the precipitating clouds; in addition, the ice–water changes of phase, resulting

for instance in bright bands, may have relatively less impact on the radar QPE compared to more stratiform precipitation conditions. Moreover, the small spatial scale of the flash floods-generating storms, combined with the density of most raingauge networks, is such that just a few raingauge data are available for checking the radar observations at fine time resolution. However, more raingauge data are available for re-analysis (particularly at the event duration scale) than for real-time applications.

A methodology was specifically devised for rainfall estimation with use of radar and raingauge data (Bouilloud et al., in press). Depending on the relative locations of the impacted regions and the radar systems available, as well as their operating protocols and maintenance, the quality of the radar datasets may vary a lot for such “event-driven” analyses. The methodology is therefore based on: (1) detailed collection of data and metadata about the radar systems and the raingauge networks (including raingauge data from amateurs and from bucket analysis), (2) analysis of the detection domain and the ground/anthropic clutter for the considered

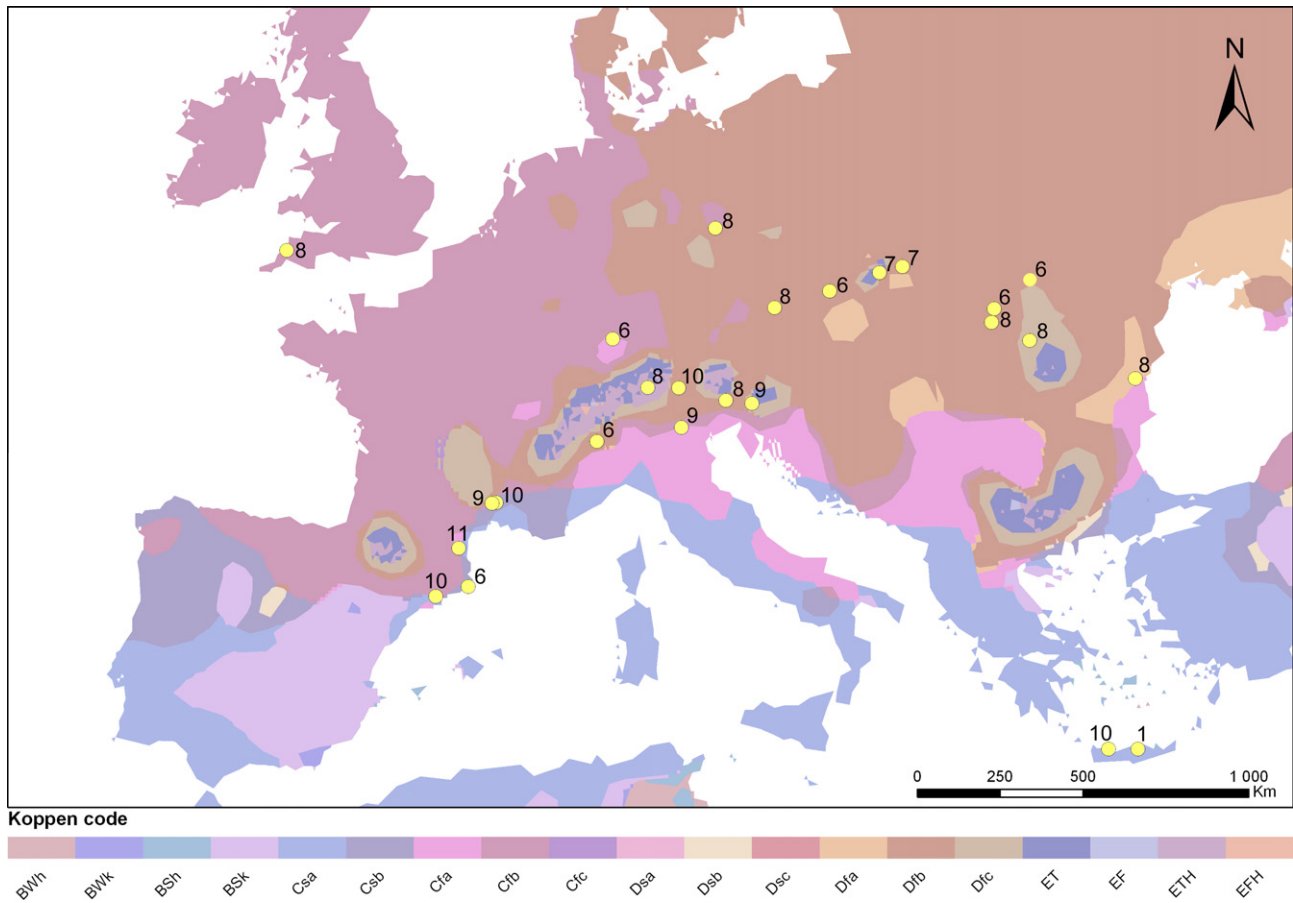


Fig. 1. Location and climatic context of studied flash floods; the numbers indicate the months of flash-flood occurrence (map of Köppen–Geiger climate classification from Peel et al., 2007).

case (Pellarin et al., 2002), (3) implementation of corrections for range-dependent errors (e.g. screening, attenuation, vertical profiles of reflectivity), and (4) optimisation of the rainfall estimation procedure by means of radar-raingauge comparisons at the event duration scale (Bouilloud et al., in press). The methodology was applied consistently over most of the events, but for the cases where only radar products were made available (Valency River flood, occurred in UK in 2004, and the floods observed in Slovakia).

3.3. Discharge data

Both discharge data from streamgauge stations and from post-flood analysis were available in the study. Discharge data from streamgauge stations were available for 29 cases, whereas data from post-flood analysis were used in the remaining 31 cases. Post-event analysis methods include a range of procedures for indirect estimation of peak discharges, generally encompassing the following steps: identification of the flow process (which was categorised into the following classes: liquid flow, hyperconcentrated flow, debris flow), high-water marks identification, post-flood river geometry survey, and application of appropriate hydraulic methods for peak flood computation (Costa and Jarrett, 2008). With regard to the classification of the flow process, only liquid flows were considered in this study. Together with peak discharge values, post-flood analysis methods were used also to derive time of the raising flow, flood peak time, and rate of recession. Timing estimates were obtained based on eyewitnesses interviews and accounts. A standardised method for post-event analysis was used throughout the study (Gaume and Borga, 2008; Borga et al., 2008;

Marchi et al., 2009). Estimates of flood peak for the earlier events were reviewed considering the original field notes, photographs, reports, and documentation, and conducting field visits to the flood locations. Discharge data from streamgauges were obtained based on extrapolation of rating curves from smaller observed flows. The rating curves were checked to evaluate the degree of extrapolation required and to assess the quality of the final estimates. Although great care was devoted to the various steps of discharge estimations, we should note that all the peak flood data should be regarded as affected by considerable uncertainty. An accuracy of 15–20 min has been reported for the timing estimates obtained by means of eyewitnesses interviews (Gaume, 2006).

The large percentage of discharge data obtained from post-event analysis underlines the importance of indirect discharge estimates in setting up catalogues of flash floods. This is particularly the case for events which impact small catchment areas. Table 2 categorises catchment areas according to the method used to derive the peak flood data (streamgauge versus post-event analysis). Discharge data from gauging stations generally concern catchments which are significantly larger (p -value smaller than 0.001 according to the Mann–Whitney U test) than those for which estimates are obtained from post-event analysis. This is not an unexpected finding: larger scale flash floods events have higher probability to be recorded by streamflow measuring stations, whereas events with smaller spatial extent generally impact ungauged basins. An implication of this finding is that systematic survey of flash floods is particularly important in the European regions where these events are climatologically characterised by smaller spatial extent, such as in the Continental areas. Without

Table 2Summary statistics for drainage areas (km²) for the two classes of peak discharge assessment (streamgauge versus post-event analysis).

Peak discharge assessment method	No. of cases	Mean	Standard deviation	Median	Interquartile range
Streamgauge	29	341	394	207	121.5–342
Post-event analysis	31	64.6	48.9	52.6	31.9–94.3

systematic post-event analysis, it may be unlikely to develop reliable flash flood catalogues in these areas.

3.4. Climate, annual water balance, land use and geology data

For each catchment, values concerning the mean annual estimates of precipitation, runoff and potential evapotranspiration were collected from climate atlas or computed from available long-term rainfall, runoff and temperature data. For the ungauged catchments, mean annual runoff values were derived based on data from available downstream stations and from regional runoff relationships.

Data were also collected for the characterisation of the soil moisture status at the event start; these were rainfall and runoff (when available) data over the 30 days period before the event. Corresponding long-term data were also collected over the same period.

Geographical data include digital elevation models of the watersheds and thematic information (land use, lithology and soil maps). Digital elevation models were available at grid resolution from 20 m to 100 m. Only a short summary of the information about geology, land use and soil property is reported here, since ongoing research aims to investigate the quality and the homogeneity of this information and how these catchment properties, together with rainfall characteristics, control the event runoff coefficient.

The studied watersheds show a wide range of land uses. However, since most of the catchments are located in mountainous or hilly regions, urban and suburban land cover represents usually a limited fraction of the catchment surface. Conversely, urban areas are often located close to the outlet of the catchments. Agricultural areas prevail in hilly watersheds, whereas forests are widespread in mountainous areas. In Alpine and Alpine-Mediterranean watersheds, large areas without vegetation cover (bare rock and scree) are found at the highest elevations. Very different geolithological conditions characterise the basins, with karst areas reported a number of catchments. Lakes and artificial reservoirs are present in some of the largest catchments considered here. However, their drainage areas are minor, in relation to the overall catchment, and the corresponding attenuation effects on the flood hydrograph was considered to be small.

3.5. Distributed rainfall–runoff model

A distributed hydrological model was implemented over all the catchments here analysed to simulate the flood hydrographs. The purpose of the model application was twofold: (i) to ensure consistency among the disparate type of event data and (ii) to enable estimation of the event runoff coefficient (defined as the ratio of event runoff to total storm rainfall depth) for the cases where only peak flow and timing data are available. The consistency check aimed to identify possible inconsistencies in the available data, both in terms of rainfall and runoff volumes, and in terms of timing of the runoff response with respect to the space–time structure of rain fields. When inconsistencies were identified, data were scrutinised again, and, when it was the case, field visits, surveys and interviews were organised and carried out to ensure either error correction or data removal. In the latter

case, other event characteristics, such as stages or other evidences of flood, were retained.

The main requirements for the choice of the model were a structure consistent with the available observations (i.e., able to use efficiently spatially-distributed rainfall data) and a limited number of calibration parameters.

In the model, the SCS-Curve Number (SCS-CN) procedure (Ponce and Hawkins, 1996) is applied on a grid-by-grid way for the spatially distributed representation of runoff generating processes. The distributed runoff propagation procedure is based on the identification of drainage paths, and requires the characterisation of hillslope paths and channelled paths. A channelisation support area (A_s) (km²), which is considered constant at the subbasin scale, is used to distinguish hillslope elements from channel elements. Discharge at any location along the river network is computed by:

$$Q(t) = \int_A q[t - \tau(x), x] dx \quad (2)$$

where A (km²) indicates the area draining to the specified outlet location, $q(t, x)$ is the runoff at time t and location x , and $\tau(x)$ is the routing time from the location x to the outlet of the basin specified by the region A . The routing time $\tau(x)$ is defined as:

$$\tau(x) = \frac{L_h(x)}{v_h} + \frac{L_c(x)}{v_c} \quad (3)$$

where $L_h(x)$ is the distance from the generic point x to the channel network following the steepest descent path, $L_c(x)$ is the length of the subsequent drainage path through streams down to the watershed outlet, and v_h and v_c (m s⁻¹) are two invariant hillslope and channel velocities, respectively.

The model includes also a linear conceptual reservoir for base flow modelling. A more complete description of the model is reported in Borga et al. (2007). The model was applied by using the available topographical information (with grid size resolution ranging from 20 m to 100 m) and at time step ranging from 15 to 30 min, depending on the event.

The model parameters were estimated over the catchments available for each event by means of a combination of manual and automatic calibration to minimize either the Nash–Sutcliffe efficiency index over the flood hydrographs (for the gauged catchments) or the mean square error over the flood peak and the timing data (rise, peak and recession) (for catchments where runoff data were provided from post-event surveys). Example of model application over the studied events are reported by Borga et al. (2007) and by Sangati et al. (2009). The combination of the SCS-CN method and of the conceptual single store for the representation of the subsurface flow dynamics provided an efficient representation of the two main flow pathways – surface and subsurface – contributing to runoff generation at the event time scale.

4. Flash floods characterisation: climate and physiographic factors

4.1. Climate and annual water balance

Climate variability strongly impacts the mechanisms of flood generation in two ways: in a direct way through the variability of storm characteristics, and indirectly through the seasonality of

rainfall and evapotranspiration that affect the antecedent catchment conditions for individual storm events (Sivapalan et al., 2005). Furthermore, climate may influence the runoff generation processes by controlling the geomorphological structure of catchments, through soil formation and erosion processes, as exemplified, for instance, by the positive relationship between drainage density and mean annual precipitation (Gregory and Gardiner, 1975).

Two main objectives drive the climatic characterisation in this section: (i) to evaluate the range of climates of the considered case studies and (ii) to identify the distribution of the events under the different climatic conditions. We applied the Budyko's climatic classification scheme (Budyko, 1974) to display the climatic characteristics of the catchments. This is achieved by presenting the specific response of each catchment on the Budyko plot (Fig. 2), which expresses E/P , the ratio of average annual evapotranspiration (E) to average annual precipitation (P) as a function of E_p/P , the ratio of average annual potential evapotranspiration (E_p) to average annual precipitation. Actual evapotranspiration (E) for each catchment was derived as the long-term difference between P and R (runoff) for the basins. The ratio E_p/P is a measure of the climate, and is called the dryness index (or index of dryness). Large E_p/P (>1) represents dry climate (water-limited conditions), while small E_p/P (<1) represents a wet climate (energy-limited conditions). Thus the Budyko diagram encapsulates a major climatic control on annual water balance.

In Fig. 2, as well as in the next sections of this paper, a subdivision of climate into five classes is adopted: Mediterranean, Alpine–Mediterranean, Alpine, Continental and Oceanic. With reference to the Köppen–Geiger classification (Fig. 1), Mediterranean corresponds to *Csa* and *Csb*, Continental corresponds to *Dfa*, *Dfb* and *Dfc*, and Oceanic to *Cfb*. As a consequence of the wide range in elevation of the watersheds, the two classes related to mountainous regions (Alpine–Mediterranean and Alpine), encompass various climates of the Köppen–Geiger classification, from *Cfb* to *ETH* or *EFH* at the highest elevations. Each point in Fig. 2 represents a flash flood event. The figure shows that the sample of events considered here represents a wide interval of climatic controls on the annual water balance, ranging from very wet to semi-arid conditions. Twenty out of the 25 floods occurred under energy-limited conditions. Conversely, almost all the flash floods in the Mediterranean region occur in water limited conditions, with the notable exception of the Gard area (flash floods of Avène 1997 and Gard 2002), where large values of evapotranspiration fluxes are balanced by abundant mean annual precipitation. It is worth noting that local dry conditions characterise also one catchment under Continental

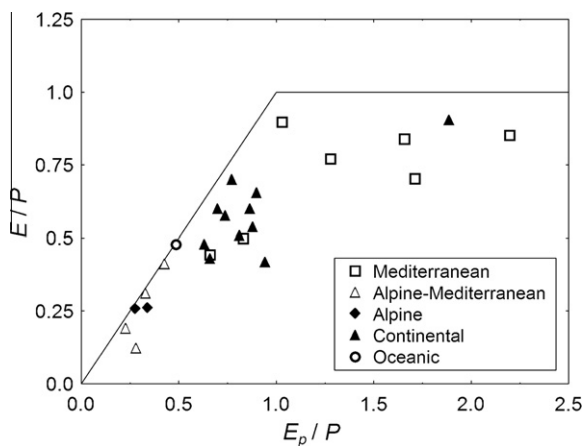


Fig. 2. Plot of mass balance data from the study catchments on the Budyko diagram (P : mean annual precipitation, E : mean annual actual evapotranspiration, E_p : mean annual potential evapotranspiration).

climate (Casimcea, Romania), located close to the Black Sea with low mean annual precipitation. On the contrary, Alpine and Alpine–Mediterranean flash flood watersheds, as well as the Boscaille flash flood (Oceanic or Marine West Coast Climate) display typically humid climatic conditions, with values of actual evaporation E close to potential evaporation E_p .

The concentration of flash flood catchments under energy-limited conditions may suggest that more humid climatic conditions affect the initial soil moisture status for individual storm events, and thus have an indirect effect on flash flood occurrence. On the other hand, this may result from a sampling effect due to the under-representation of flash flood events in the Mediterranean region. Given the available observations, we are not in a position to clarify this issue, and future efforts should be aimed to increase the observations of flash flood events in these undersampled areas.

The occurrence of most of European flash floods under energy-limited conditions is in strike contrast with observations reported for the US, where all major flash floods were reported to occur in arid or semi-arid part of western and southwestern United States (Costa, 1987). This needs to be considered when comparing flash floods events and hazards in Europe and US and when discussing flash flood forecasting models and procedures.

4.2. Physiographic factors and characteristics of the channel network

Physiographic factors may affect flash flood occurrence in specific catchments by combination of two main mechanisms: orographic effects augmenting precipitation, and topographic relief promoting rapid concentration of streamflow. Both effects have been documented in the literature (Costa, 1987; O'Connor and Costa, 2004). Storm quasi-stationarity is a characterising feature of several flash flood-generating rainfalls, with very intense precipitation insisting on the same locations for enough time to produce heavy accumulations. One of the elements that favour the anchoring of convective system is the orography, which play an important role in regulating of atmospheric moisture inflow to the storm and in controlling storm motion and evolution (Smith et al., 1996; Davolio et al., 2006). Relief is necessary for promoting flow concentration along drainage ways, which results in high unit discharges and relevant geomorphic effects of flash floods in sloping watersheds. Heavy convective precipitation may occur also in plain areas, but the ensuing flood generally lack the kinematic component, which characterises the propagation and the hazard potential of flash floods. Collier and Fox (2003) and Collier (2007) incorporated the two relief effects in their procedure for assessing the susceptibility of catchments to flooding due to extreme rainfall. They identified two catchment morphological characteristics that may affect baseline susceptibility to flooding: catchment slope, and ratio of catchment area to mean drainage path length. In a similar vein, in this section we analyse morphometric characteristics of the studied catchments both in the vertical and in the horizontal plane. This is carried out by investigating two specific morphological relationships: basin steepness to basin size, and channel length to basin size.

The steepness of a river basin is considered in terms of the relief ratio, the ratio of the total basin relief to the total basin length. The total relief is the elevational difference between the highest and the lowest points in the basin and the total length is the length of the main channel from watershed divide to outlet. The relief ratio is a dimensionless number that has found wide use in the comparison of basins (Schumm, 1956, 1963). The relation between basin area and relief ratio is presented in Fig. 3. As expected, a decrease in basin steepness is observed with increasing basin area, following general relationships reported in the literature (Dade, 2001). Values of the relief ratio range between 0.008 and 0.19, with an average value of 0.055. The lowest values are observed in low

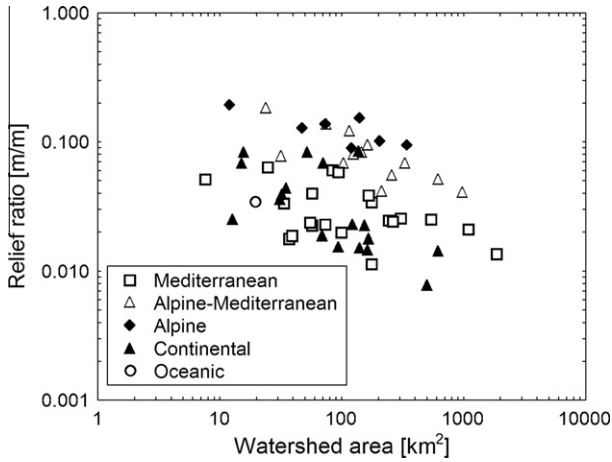


Fig. 3. Watershed area versus relief ratio.

elevation watershed under Continental (Kamp River; Casimcea River) or Mediterranean (Gard River) climates. The highest values are reported for rugged catchments in the Alpine or Alpine-Mediterranean flash floods (Sesia River, Fella River, Isarco River). The range in relief ratio is comparable with values reported in other studies (Costa, 1987). As expected, the sample does not include merely plain catchments (the smallest difference in elevation is 130 m in a hilly watershed of 12.7 km²): slope enhances the capacity to promote rapid concentration of streamflow, which is one of the defining features of flash floods.

The relationship between channel length and watershed area is explored in Fig. 4, where both maximum stream length L and mean stream length L_m are reported. Maximum stream length is measured from basin outlet to the crest of the drainage divide along the stream channel (Hack, 1957); mean stream length is computed as the average distance from basin outlet to each point in the basin. Power-law relations are used to relate watershed area A to L and L_m , respectively, as follows:

$$L = 1.514 \cdot A^{0.557} \quad (4)$$

(No. of cases: 60; $R^2 = 0.86$)

$$L_m = 0.867 \cdot A^{0.551} \quad (5)$$

(No. of cases: 60; $R^2 = 0.88$)

Since the aim in the study here is to describe the functional relationship between the two variables with the primary interest in the slope coefficient (the exponent), the line of organic correla-

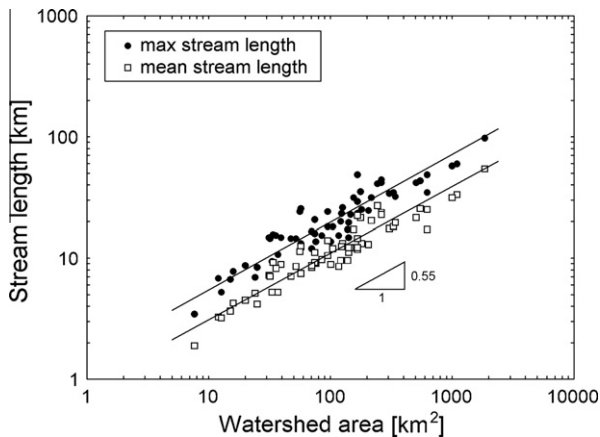


Fig. 4. Watershed area versus maximum stream length and mean stream length.

tion (also called geometric mean functional regression) (Helsel and Hirsch, 2002) was preferred to ordinary least squares regression for deriving the relationships.

Eq. (4) is a version of the classical Hack's law, following Hack (1957) who reported $L \propto A^{0.6}$ for streams in the Shenandoah Valley and adjacent mountains of Virginia. The exponent in Eq. (4) is in the range 0.55–0.59 reported by Rigon et al. (1996) for the Hack's law in basins ranging from 50 to 2000 km². Explanations for the exponent being larger than 0.5 (implying positive allometry) emphasised the role of basin elongation as well as the fractal characteristic of river networks (Rigon et al., 1996). The statistically significant equivalence of the exponents in Eqs. (4) and (5) indicates constant scale relations between the length of the flow path along the maximum stream from the watershed divide and the average length of the flow paths in the drainage basin. This finding supports the results by Maritan et al. (2002), who defined the relation between basin area and mean stream length as a “strong version of Hack's law and a proof of the embedded similarity in the network structure” and found that the maximum stream length is proportional to the mean stream length.

Overall, the relationships between upstream watershed area and relief ratio, maximum stream length and mean flow length point out that flash flood basins are generally characterised by a non negligible topographic relief, whereas the other physiographic features are in the range reported for basins of similar size.

5. Flash floods characterisation: rainfall and flood response

5.1. Flood-generating rainfall: amount and duration

This section examines the characteristics of the rainfall that produced the flash floods by using two variables: rainfall amount and rainfall duration. Fig. 5 plots the relations between these variables taking into account the largest watershed for each flash flood. The largest watersheds have been chosen because rainstorm duration over watersheds of different size has small variability for the studied events and the largest watersheds are more affected by the longest durations. Moreover, choosing the largest watersheds for each flood reduces the scatter of the plot and increases its readability. The combination of rainfall duration and amount is influenced by the local climate and strongly affects the runoff generation during the event. Rainstorm duration is defined here as the time duration of the flood-generating rainfall episodes which are separated by less than 6 h of rainfall hiatus.

Fig. 5a shows the relation between total event rainfall versus duration for the different climatic regions considered in this study. For these rainfall events (storms) the range of values is from 33 mm in 1 h (Turniansky Creek, June 2004) (the smallest humid region storm event) to 700 mm in 24 h (Aude River basin, November 1999). Examination of Fig. 5a shows that the events can be grouped into three different classes. The first group includes storm events which lasted up to 7 h. The corresponding rainfall amount is less than 100 mm, and almost all these events occurred under a Continental climate. The second group includes storm events with duration from 7 to 22 h. The maximum rainfall amounts reported for these events is 300 mm. Almost all these events are from the Mediterranean and the Alpine-Mediterranean region. Finally, the third group is made of events of longer duration, up to 34 h, and with storm cumulated amount up to 700 mm. As such, these events are in the transition between flash flood and flood events. Most of these events are from the Mediterranean region. However, two cases are also reported from the Continental region. These correspond to the Weisseritz flash flood event close to Dresden (2002) and to the Kamp flash flood in Austria (2002), both with very high precipitation amounts. These episodes were embedded within the

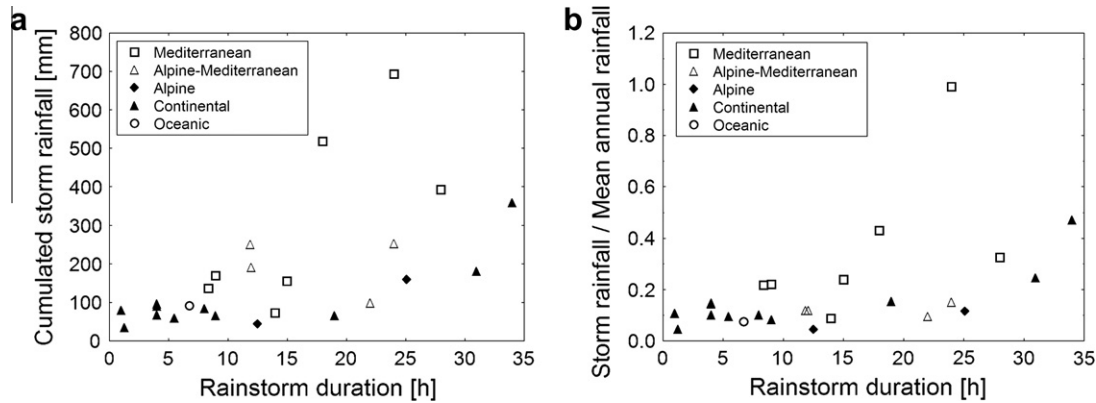


Fig. 5. Rainstorm characteristics: (a) rainstorm duration versus cumulated event rainfall and (b) rainstorm duration versus ratio of cumulated event rainfall to mean annual precipitation. For each flood, the largest watershed and the corresponding rainstorm duration were considered.

large flood event which impacted the Central European region in the summer 2002 (Kundzewicz et al., 2005).

The plot of rainstorm duration versus the ratio of total event rainfall to mean annual precipitation (Fig. 5b) affords comparison of rainstorms under different climatic conditions, taking into account the differences in the mean annual precipitation. Whereas the relative ranking of the flash floods in the various climatic regions does not show significant differences between Fig. 5a and b, inspection of Fig. 5b shows the different impacts of the flash flood-generating rainfalls on the local annual water balance for the various climates. In the Mediterranean climate, the ratio of event to annual precipitation is generally greater than 0.2, indicating a relatively large impact of these precipitations on the annual water balance. Conversely, for the Continental, Alpine and Alpine-Mediterranean regions, the ratio is less than 0.2, showing a relatively less significant influence on the annual water balance.

The spatial and temporal scales of the events are represented in Fig. 6, which plots the area of the largest watershed for each flood versus the duration of the causative rainstorm. The use of the largest watershed area to surrogate the spatial scale of the flash flood event is made on a convenience basis. A more direct way would imply the use of the radar rainfall information. However, this would require use of data from a radar network, instead of use of the radar information from the closest radar site, as it was done

in this study. Anyway, the selection of the study watersheds reflects the severity of the flash floods and as such represent a suitable indicator of the spatial scale of flash floods.

The positive correlation between these two variables is especially apparent in the lower limit, which defines a minimum rainstorm duration required to trigger a flash flood in a catchment of given size. The figure also shows that flash floods are essentially associated to Mesoscale Convective Systems, accordingly with the classification of Orlandi (1975), who introduced a subdivision into space and time scales for the atmospheric processes.

Table 3 presents the range of drainage areas of the largest impacted watersheds under different climates (events under Alpine and Oceanic climates are not included owing to the small number of cases). The largest flash flood basins are preferentially located in the Mediterranean and the Alpine-Mediterranean climate, where flash floods are generated also by longer storm events generally occurring during the fall season. Smaller spatial scales characterise the events occurring in the Continental region, with generally shorter rainstorms (although with a few relevant exceptions: cf. Fig. 5), which occur preferentially during the summer season. This is consistent with the general outline of European flash floods reported by Gaume et al. (2009).

5.2. Unit peak discharges and relation with catchment area

The dependence of peak discharge on watershed area is widely accepted, and there is a substantial body of literature describing the relationship between discharge and basin area, both for single-event peak flows and for mean annual peak flows (Smith, 1992; Gupta et al., 1996; Furey and Gupta, 2005, among the others). The relationship between the catchment area and the unit peak discharge (i.e., the ratio between the peak discharge and the upstream catchment area) was investigated for our database plotting the data in a log-log diagram and analyzing the envelope curve. When data from all the regions are grouped together, the unit peak discharges exhibit a marked dependence on area (Fig. 7). The envelope curve reported in Fig. 7 is as follows:

Table 3 Range of drainage areas of flash flood watersheds under different climatic conditions. Only the areas corresponding to the largest watershed per event are reported.

	No. of flash floods	Range in watershed area (km ²)
Mediterranean	7	55.0–1856
Alpine-Mediterranean	4	116–983
Inland Continental	11	12.7–622

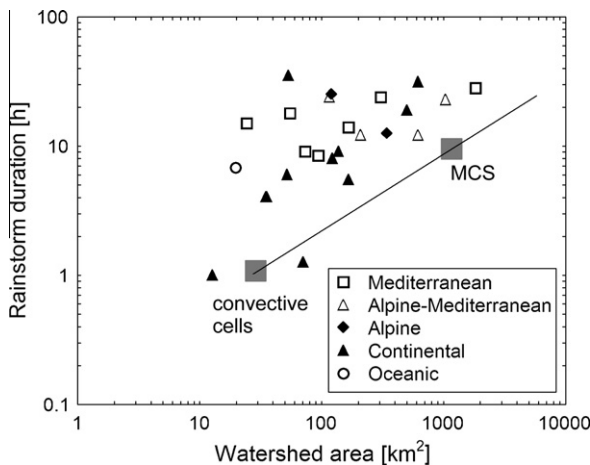


Fig. 6. Spatial and temporal scales for the selected flash floods. For each flood, the largest watershed and the corresponding rainstorm duration were considered. Scales of convective cells and Mesoscale Convective Systems (MCS) are taken from Orlandi (1975).

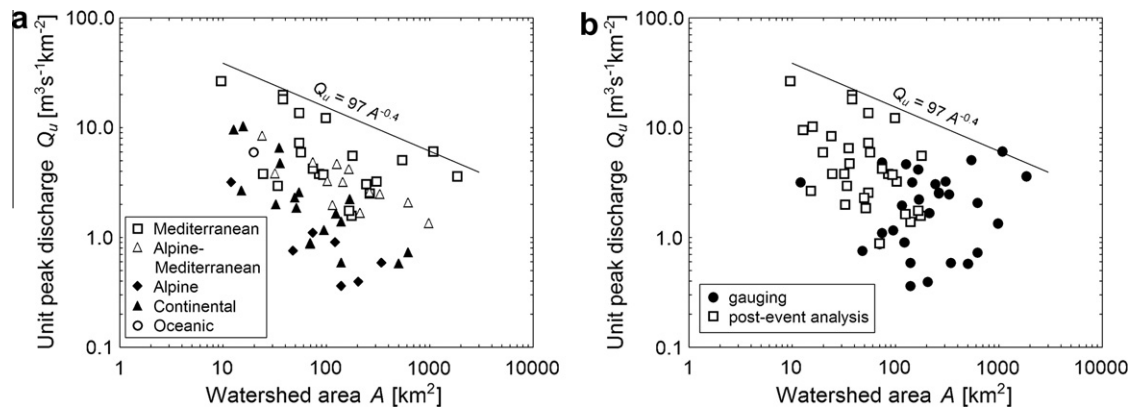


Fig. 7. Unit peak discharges versus drainage areas; the envelope curve derived from Gaume et al. (2009) is also reported: (a) climatic regions and (b) discharge assessment method.

$$Q_u = 97.0 \cdot A^{-0.4} \quad (6)$$

where Q_u is the unit peak discharge ($\text{m}^3 \text{s}^{-1} \text{km}^{-2}$) and A is the upstream area (km^2). The relationship is the same as that reported by Gaume et al. (2009). Since the highest unit peak discharges in the two samples are the same and correspond to events from the Mediterranean region, it is not surprising that the envelope curves are overlapping. For small basin areas, the flash floods observed under Continental climate, namely in Slovakia, also attain high values of unit discharge, even though these unit peaks seem to decrease with upstream area in a faster way than for the Mediterranean events. This behaviour points out once more the different space and time scales of the generating storm events.

The exponent in the power-law relationship in Eq. (6) is smaller than that reported in the literature for extreme floods in the world (Hersch and Fairbridge, 1998) and for Europe (Hersch, 2002). Hersch and Fairbridge (1998) considered 41 maximum floods from the world to develop the following envelope equations:

$$Q_u = 850 \cdot A^{-0.643} \quad A \geq 100 \text{ km}^2 \quad (7)$$

For the maximum floods in Europe, Hersch (2002) proposed the following equation:

$$Q_u = 230 A^{-0.57} \quad (8)$$

Interestingly, the archive used by Hersch included relatively few flash flood events, reflecting more accurately the behaviour of riverine flood.

Relatively low unit peak discharges, less than $1 \text{ m}^3/\text{s}/\text{km}^2$, are reported for some Alpine and Continental catchments in the area range between 50 and 500 km^2 . It is worth recalling that areas of moderate unit peak flows do not necessarily equate to areas of moderate flood risk, since the flood risk for any particular location is in part due to local forecasting, warning, and communication systems, existing flood protection works, as well as the community's social, political, and regulatory setting. Some of the flash flood events exhibiting moderate unit peak values resulted in high loss of human lives and large damages. These effects are exemplified by the flash flood events occurred in Romania during the 2005 summer season, which led to 76 casualties and to overall economic losses as high as 1.6% of the gross national product (Constantin-Horia et al., 2009).

Fig. 7b shows that the highest unit peak discharge were collected by means of post-flood surveys. This can be referred to the small areas of watersheds concerned, as well as to the choice of the streams investigated in post-flood surveys, which commonly focus on the areas most severely hit by the flood, and points out the unique role of post-flood survey in flash flood analysis. For wa-

tershed areas in the range of $50\text{--}200 \text{ km}^2$ the sample includes data from both gauging and post-flood reconstruction: the overlapping of unit peak discharge values indicates that the use of different methods for assessing peak discharge did not result in systematic differences.

5.3. Runoff coefficient

The event runoff coefficient is a key concept in hydrology and an important diagnostic variable for catchment response. Examination of runoff coefficients is useful for catchment comparison to understand how different landscapes filter rainfall into event-based runoff. Specific questions in the case of flash floods concern: (i) quantification of runoff coefficients and analysis of possible differentiations with climatic regions and (ii) investigating the relationship between runoff coefficients and antecedent moisture conditions.

Event runoff coefficients are usually estimated as the ratio of event runoff volume to event rainfall volume. This requires the separation of the event hydrograph into the two components of baseflow and event flow, and then the determination of starting time and end time of event flow. In this study, starting time was identified as the time of the first rise of discharge, and the corresponding runoff value was used to determine the baseflow. The time corresponding to the end of event runoff was estimated by separating the recession curve into the components of surface and saturated flow by plotting the recession curve in a semilogarithmic paper (Tallaksen, 1995). These two components are thought to represent different flow paths in the catchment, each characterised by different residence time, the outflow rate of groundwater flow being lower than the recession rate of the surface flow component. The separation between baseflow and event flow was carried out by continuing the baseflow until the major flood peak and then connecting with a straight line to the recession curve as defined above. For consistency, the same procedure of hydrograph analysis was applied both to recorded hydrographs and to hydrographs simulated by means of the rainfall-runoff model. The latter hydrographs were used for the ungauged basins where only the magnitude and time of the peak were reported together with time of first rise and recession. The ratio of baseflow to peakflow is low in all the floods analysed here: this implies that the uncertainties in the separation between baseflow and event flow regard essentially the definition of the end time of event flow and hence to the analysis of the recession curve. We checked that the distribution of runoff coefficients derived by means of hydrological modelling was close to that derived from hydrograph analysis. To this purpose, the analysis based on hydrological modelling

was applied to the cases for which complete hydrograph data were available. The runoff coefficients derived in this way compared favourably with those obtained from observations, with a mean relative error of -0.05 (the runoff coefficients from hydrological modelling show a slightly underestimation with respect to those obtained from direct observations) and a Nash–Sutcliffe efficiency value of 0.89.

Fig. 8 shows the frequency distribution of the runoff coefficient; the mean value is 0.35, with standard deviation 0.18, median 0.37, and interquartile range 0.20–0.45.

These results compare well with the values obtained by Merz and Blöschl (2003) and Merz et al. (2006) for flash flood cases occurred in Austria. Merz and Blöschl (2003) were able to compare runoff coefficients for different flood types (they considered the following flood types: short rain floods, long rain floods, rain-on-snow floods and snowmelt floods). These authors reported that, based on their data from Austria, runoff coefficients are smallest for flash floods, and they increase, in that order, for short rain floods, long rain floods, rain-on-snow floods and snowmelt floods. Relatively low values of event runoff coefficient were also reported by Goodrich (1990) in his analysis of flash flood events on the semi-arid Walnut Gulch catchment. In five of the largest flash flood events observed in a 20 years period, the runoff coefficients range between 0.07 and 0.21. On the other hand, large values of runoff coefficient (close to 0.9) have been reported by a number of authors for extremely intense storm events characterised by wet initial conditions (Smith et al., 1996, 2005).

Table 4 compares the values of the runoff coefficients in the various climatic regions (but Oceanic climate, for which only one event is reported in the archive). Runoff coefficients are relatively higher for Mediterranean flash floods, while the smallest values are reported for the Alpine watersheds (even though the small sample size suggests that the significance of this comparison should be considered with caution). The higher runoff coefficients of Mediterranean flash floods are likely due to the type of flood-generating storm events, which are longer and characterised by larger rainfall amount than for the other cases.

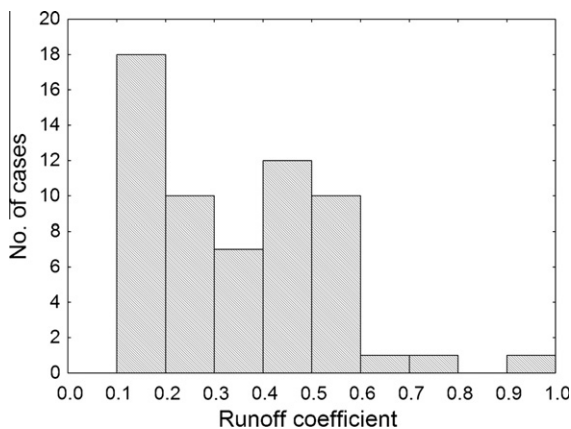


Fig. 8. Frequency distribution of event runoff coefficient.

The relation between event runoff coefficient and the event cumulated rainfall is reported in Fig. 9. Overall, there is a slight dependence of runoff coefficient on the water input and the scatter is very large, with values of the runoff coefficients distributed in a wide interval over the range of precipitation depth. There are several possible explanations for the wide scatter reported in Fig. 9. Considering the meteorological factors, for flash flood events it is not only the rainfall depth but also rainfall intensity that likely controls the magnitude of the runoff coefficient. A further potential source of scatter is the variability of the initial soil moisture conditions which combines with the subsurface water storage capacity to determine the amount of water input that needs to be stored in the soil before event runoff may start, i.e., the so-called initial losses. Wood et al. (1990) note that for large floods the role of antecedent soil moisture for flood response should decrease with increasing return interval. However, a number of studies (Sturdevant-Rees et al., 2001; Gaume et al., 2004; Borga et al., 2007) showed considerable impact of initial soil moisture conditions on runoff from extreme flash floods.

We developed an antecedent precipitation index to assess the impact of initial soil moisture conditions on runoff coefficients. Since we are considering different events occurring under various climates, the index needs to account also for the climatic variability. The index was computed as the ratio of the precipitation in the 30 days before the flash flood event to the long-term 30 days average for the same period. The number of years considered for the long-term mean varies from site to site, ranging generally from 20 to 30. We chosen a 30 days antecedent period because in several ungauged basins only monthly long term-average rainfall data are available. Moreover, use of 30 days (instead of shorter duration) helps to reduce the sampling spatial error associated to the use of point rainfall in order to represent basin average precipitation. Three classes of antecedent saturation were considered: Dry (index of antecedent saturation ≤ 0.5), Normal (from 0.5 to 1.5), and Wet (>1.5). The index capability to evaluate the initial soil moisture conditions compared well with the predictions from a continuous soil moisture accounting hydrological model (Norbiato

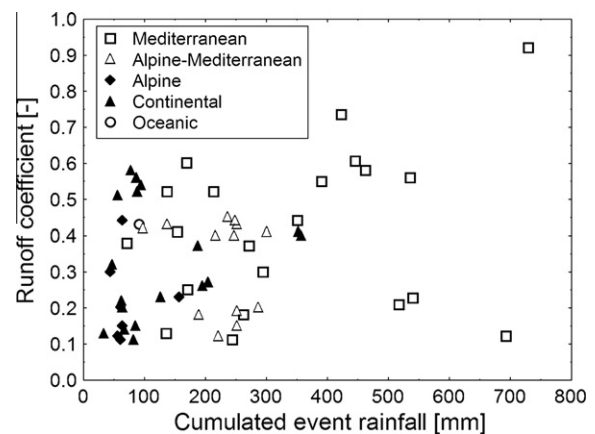


Fig. 9. Event runoff coefficient versus event cumulated rainfall.

Table 4
Summary statistics of runoff coefficient for different climatic regions.

Climatic region	No. of cases	Mean	Standard deviation	Median	Interquartile range
Mediterranean	21	0.41	0.22	0.41	0.23–0.56
Alpine–Mediterranean	13	0.32	0.13	0.40	0.19–0.43
Alpine	7	0.22	0.12	0.20	0.12–0.30
Continental	18	0.33	0.16	0.30	0.20–0.51

Table 5
Summary statistics of runoff coefficient for different antecedent saturation conditions.

Saturation class	No. of cases	Mean	Standard deviation	Median	Interquartile range
Dry	17	0.31	0.22	0.20	0.15–0.44
Normal	30	0.35	0.17	0.37	0.19–0.45
Wet	11	0.40	0.13	0.43	0.23–0.51

et al., 2008). Snowmelt is not considered in the index: however, snowmelt was a significant contribution to basin saturation only for one event (Sesia River basin, northern Italy, June 2002), which was also characterised by abundant precipitation in the 30 days before the event. Data for assessing antecedent saturation were not available for two cases; the analysis was thus carried out on a sample of 58 basins. Table 5 compares runoff coefficients in the three classes of antecedent precipitation index. Values of the runoff coefficient increase with moving from Dry to Normal and Wet antecedent conditions, even though the variability of the runoff coefficient within the same class is relatively high. The variability is highest within the “Dry” class, as expected, and decreases with increasing the initial soil moisture. Application of the Mann–Whitney test shows that differences are statistically significant (at $\alpha = 0.07$) when comparing the “Dry” and “Wet” classes. This shows that antecedent moisture conditions can play a significant role in determining land-surface response to extreme rainfall events.

It is interesting to note that only 11 cases were characterised by “Wet” conditions, whereas 17 cases occurred at the end of periods characterised by precipitation significantly lower than the long-term monthly average.

The influence of the initial soil moisture status on triggering of flash floods was investigated by counting the number of cases in the Dry, Normal and Wet classes stratified in the various climatic regions (Table 6). This comparison shows that usually the events in the Mediterranean climatic region occur with Dry and Normal antecedent conditions, whereas the events in the Continental region occur with Normal and Wet conditions. The Alpine–Mediterranean region is characterised by occurrences over all the different antecedent conditions. Although the small sample size affords only preliminary considerations, examination of these results suggests that abundant and relatively long-lasting precipitation in Mediterranean regions may trigger flash floods overcoming low initial wetness, whereas in Continental areas moderate or high initial saturation is required for flash flood occurrence. This could be referred to prevalently short duration and low rainfall amounts of summer storms that cause flash floods under Continental climate.

5.4. Response time

The specific problem of flash flood risk management is that these floods interact with social organisation at space and time scales that imply unusually short warning lead times (Creutin et al., 2009). This section is devoted to the quantification of the response time for the considered events and to relate the response time to morphological parameters such as the catchment area.

As a measure of the response time, we used the concept of lag-to-peak (Dingman, 2002) or lag time in the following. In this study,

Table 6
Antecedent saturation conditions under different climatic regions (no. of basins). Alpine and Oceanic regions are not reported owing to the small number of cases.

	Dry	Normal	Wet
Mediterranean	7	14	0
Alpine–Mediterranean	4	4	5
Continental	0	12	6

we defined the lag time as the duration between the time of the centroid of the generating rainfall sequence and the time of the discharge peak. We used the centroid of rainfall, instead of the more physically sound centroid of the excess rainfall (Morin et al., 2002), due to the difficulties to reconstruct the excess rainfall sequence for each event. When multiple peaks were observed for one flood, the largest one was used for the analysis. The lag time was assessed for 50 out of 60 cases of the sample of flash floods. In the remaining cases, the uncertainties in the time occurrence of the flood peak led to exclude the event from the analysis of lag time.

Fig. 10 shows the frequency distribution of lag time. While the range of values covers a relatively large interval of times (up to 16 h), in 37 out of 50 cases lag time is less than 6 h, which is an often used threshold to distinguish flash floods from slow-rising floods (Georgakakos, 1986). Average lag time is 4.98 with a standard deviation of 4.19; the median value is 3.09.

Fig. 11 reports the relationship between lag time and watershed area, with indications of the climate regions. The examination of this relationship requires consideration of the sampling process used to collect the data for the individual catchments. Indeed, for some flash floods, multiple catchments are reported, with very similar storm duration and similar time to peak but with different watershed areas. For these cases, the lag time is almost constant with varying the watershed areas. Owing to this reason, we derived the lower bounded curve enclosing all lag time values in the plot for each value of watershed area to represent the relationship between lag time and watershed area.

We used power-law relationships to represent the envelope curves defining the lower limit of lag time T_L (h) versus basin area A (km^2) (Robinson and Sivapalan, 1997). The relationship exhibits a break point in slope at a basin area equal to 350 km^2 when plotted on a log–log plot (Fig. 11):

$$T_L = 0.08 \cdot A^{0.55} \quad \text{for } A \leq 350 \text{ km}^2 \quad (9)$$

$$T_L = 0.003 \cdot A^{1.10} \quad \text{for } A > 350 \text{ km}^2 \quad (10)$$

The relationships show that the lag time amounts to 45 min, 1 h and 6 h for basin areas equal to 50 km^2 , 100 km^2 and 1000 km^2 , respectively. The higher value of the exponent in Eq. (10) for larger

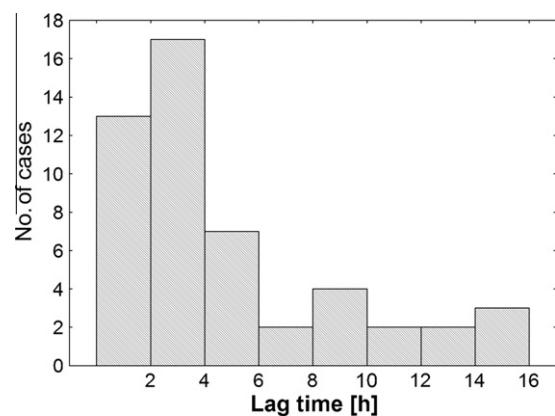


Fig. 10. Frequency distribution of lag time.

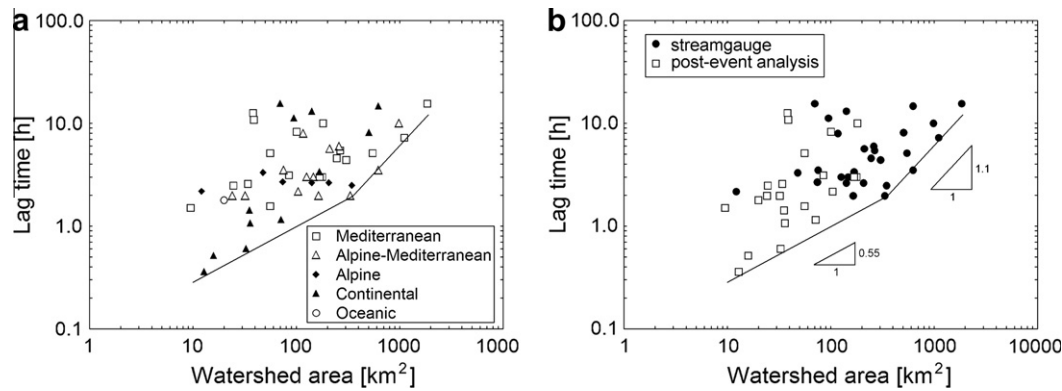


Fig. 11. Lag time versus watershed area. The lower limits of the scatterplot are discussed in the text: (a) subdivision by climate and (b) subdivision based on the source of data for lag time assessment.

basin areas reflects a faster increase of lag times with increasing basin area. Eq. (9) is close to that reported by Creutin et al. (2009) for a sample that includes also some events considered in this study. The exponent in Eq. (9) is also close to the relationship derived by D'Odorico and Rigon (2003), which is particularly well matched when it is possible to disregard the increase of water velocity with the basin area and the residence time in the hillslope system. Both these assumptions can be reasonably met with flash flood events.

Lag time, i.e. mean residence time in the basin, depends on two factors. One factor is the distance between the basin outlet and the geometrical center of mass of the event runoff (Woods and Sivapalan, 1999). With the assumption of spatial homogeneity for rainfall and runoff, this factor may be related to the mean stream length, which is determined by the planar geometry of the catchment and its associated network. The other factor is the velocity of travel, which is determined by the hydraulics of flow, governed by stream slope, roughness and the elevation geometry of the channel network, and both at-a-site and downstream hydraulic geometry variations. In general, stream velocity could vary in space and in time, governed by the spatial and temporal variability of rainfall inputs and catchment characteristics. It is interesting to note that the exponent in the relationship between mean stream length and basin area (Eq. (5)) is very similar to the exponent in Eq. (9). This similarity indicates that for the events and the catchments considered here, the lag time and the stream length increase in the same way for basin areas less than 350 km², implying that the velocity of travel is remarkably constant in the given range of areas (Sivapalan et al., 2002). When using the values reported for Eqs. (5) and (9), this velocity is equal to 3 m s⁻¹. This value represents the characteristic velocity of the flash flood process (at basin scales less than 350 km²), defined as the ratio of characteristic length (mean river length) and time (response time or lag time), and it is related to the celerity with which the flood wave moves through the catchment.

The values of response time defined here may be used to derive recommendations concerning the time resolution and the spatial density of the observation network required for monitoring the flood-generating storms. Based on Berne et al. (2004) and considering a minimum catchment area of 50 km², the required temporal resolution ranges between 10 and 15 min, with a spatial raingauge density of 1 station per 20–35 km². If weather radar observations are used to derive the rainfall fields, Sangati et al. (2009) recommends a maximum element size of 2 km to avoid biases in rainfall volume estimation.

The break point arising in the slopes of the envelope curves (Eqs. (9) and (10)) is likely to depend on the transition in topographic and hydraulic properties of the floodplain and channel sys-

tem with increasing basin size. In almost all the cases considered here the peak discharge exceeded the riverbank's holding capacity, with water spreading out into the floodplain. When the peak discharge exceeds river capacity and the floodplain is inundated, a channel-dominated flow transitions into a valley bottom-dominated flow. This transition, which we speculatively associate to a basin area of 350 km², tends to attenuate the flood wave propagation and thus increase lag time, depending on floodplain topography and surface roughness. Flood peak attenuation is largely a result of storage (or greatly reduced velocity) of a portion of the runoff on overbank surfaces (Woltemade and Potter, 1994; Jothityangkoon and Sivapalan, 2003). This storage and the later release of a portion of the total flood volume produce flood hydrographs that are delayed, low and broad compared to those of similar watersheds that lack floodplain storage, such as gullies or mountain streams (Turner-Gillespie et al., 2003).

Detailed analyses by Woltemade and Potter (1994) reveal that moderate-magnitude floods (5- to 50-year recurrence interval) with relatively high peak-to-volume ratios are attenuated most, since the storage of a relatively small volume of water can significantly reduce the peak discharge. In contrast, both small and large floods are attenuated relatively little. Our results contrast with this view and shows that even extreme flash floods may be strongly attenuated with the transition to a valley bottom-dominated flow, probably because the runoff volume is anyway reduced with respect to that characterising large riverine floods. Ongoing investigation is aimed to combine data collection and hydraulic modelling effort to provide more insight into this issue.

Fig. 11b reports data accordingly with the method used to derive the peak time: from streamgauge data or from observations collected and checked during the post-event analysis. Examination of the figure shows that lag times for basin areas less than 100 km² are mostly derived from post-event analyses. Ruin et al. (2008) show that, during the September 2002 storm in the Gard region, almost half of the casualties occurred on watersheds less than 100 km². Understanding basin response times and warning lead times in these situations compel for a more extensive and systematic effort on collection of timing data about peak flow during post-event analysis. This is the only resource for documentation of flood dynamics at small spatial scale during these extreme events (Marchi et al., 2009).

6. Conclusions and implications for flood risk management

High-resolution hydrological data concerning 25 major flash floods occurred in Europe in the period 1994–2008 were collected to explore the properties of the impacted catchments, the storm

characteristics and the features of the rainfall to runoff transformation, including the peak discharges and the runoff volumes. Data from 60 catchments located in a belt from Spain to the Black Sea, and with few cases from Germany, UK and Crete, were analysed in the study. The main results are summarised below.

- Data for more than half of the catchments considered in this study, and around 80% of the data for basins less than 100 km², were provided by post-event analysis. These proportions identify the observational problem which characterises flash floods. On one hand this means that effective analysis of flash flooding requires a systematic effort aimed to carry out in a routine way the program of field visits and post-event analysis after each flash flood event. On the other hand, this implies that new techniques for flash flood hazard should be developed which benefit from the availability of this kind of data. This is exemplified by the work of Gaume et al. (in press), which provides a method for using major flash flood events occurred at ungauged catchments to reduce the uncertainties in estimating regional flood quantiles. The method is based on standard regionalization methods assuming that the flood peak distribution rescaled by a site dependent index flood is uniform within a homogeneous region. Other avenues may be represented by the 'causal information expansion' advocated by Merz and Blöschl (2008) to use hydrological understanding of the local flood producing factors to improve the flood frequency estimation at-a-site. Causal information expansion is particularly important in small catchments, both because fewer and shorter records tend to be available than in larger catchments and because the flood processes are more amenable to analysis than in larger catchments where the regional combination of controls can be relatively more important.
- Examination of data shows a peculiar seasonality effect on flash flood occurrence, with events in the Mediterranean and Alpine-Mediterranean regions (Catalonia, Crete, France, Italy and Slovenia) mostly occurring in autumn, whereas events in the inland Continental region (Austria, Romania and Slovakia) 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. Differences in the spatial and temporal scales of the events should be taken into account in the design of flash flood forecasting and warning systems. Models and procedures specifically fitted to a specific climatic setting may not work equally well in different settings.
- A distinctive morphological features of flash flood catchments is represented by their steepness. Catchments do not need to be particularly steep to favour flash flooding. However, relief is important since it may affect flash flood occurrence in specific catchments by combination of two main mechanisms: orographic effects augmenting precipitation and anchoring convection, and topographic relief promoting rapid concentration of streamflow. This result agrees with earlier scoring procedures proposed by Collier and Fox (2003) and by Collier (2007) to assess flooding susceptibility to extreme rainfall. Since flash flooding results from unique combinations of meteorological and hydrological conditions, more efforts should be devoted to identify specific morphological catchment characteristics affecting this susceptibility. Limitations in Numerical Weather Prediction models and monitoring systems will inevitably limit our ability to forecast flash floods. Owing to this reason, decision support systems are needed to provide timely information and aid those who have to make key decisions at critical times under pressure.
- The event runoff coefficients of the extreme flash floods considered here are rather low, with a mean value of 0.35. This agrees with earlier results obtained by Merz and Blöschl (2003) who reported that, based on their data from Austria, runoff coefficients are smallest for flash floods. There are two important implications for this result. On one hand, it shows the need to account for hydrological conditions in the forecasting of flash floods. On the other hand, it indicates the potential effects of land use change on runoff generation for these events. Land cover, typically, is a local phenomenon, so the impact of any disturbance is likely to strongly decrease with catchment size. However, if the disturbed watershed is impacted by a flash flood-generating storm, the potential for extreme runoff generation is greatly enhanced.
- The influence of antecedent saturation conditions on runoff coefficient has been analysed by considering the ratio of the precipitation in the 30 days before the event to the long-term average precipitation in the same period. Analysis of these results shows a significant impact of the antecedent conditions on event runoff coefficients. These results challenge the common wisdom that antecedent soil moisture is of little importance in determining the magnitude of extreme flash floods. Hence, accounting for antecedent soil moisture conditions is paramount for operational flash flood forecasting. In the typical data-poor conditions which characterise flash flood forecasting and warning, surrogate indexes which can take implicitly into account the soil moisture initial conditions are often extremely useful. This is the case of the Flash Flood Guidance, which tags rainfall accumulations needed to produce a flood of a given magnitude accordingly with the current soil moisture conditions. Norbiato et al. (2009) have shown how Flash Flood Guidance may be applied in ungauged basins with operationally useful results.
- The runoff formation and propagation displays short response times (generally less than 6 h) and a relationship between upstream watershed area and response time was derived. For catchment areas less than 350 km², the response time and the mean stream length increase in the same way, implying that the velocity of travel (equal to 3 m s⁻¹) is remarkably constant in the given range of areas. This value represents the characteristic velocity of the flash flood process (at basin scales less than 350 km²), defined as the ratio of characteristic length (mean river length) and time (response time or lag time), and it is related to the celerity with which the flood wave moves through the catchment.

Acknowledgements

The research presented in this paper has been carried out as part of the project Hydrate (European Commission, Sixth Framework Programme, Contract No. 037024). This study would not have been possible without the support from the HYDRATE project partners for the collection and analysis of the data and observations. The authors wish to thank the Slovenian Environment Agency and the German Weather Service for the assistance in gathering essential rainfall observations and for their collaboration in weather radar data interpretation. We thank Arianna Mariotti, Marco Sangati and Francesco Zanon for help and assistance in the model-based data consistency check. We greatly appreciate the recommendations of Luca Brocca and two anonymous reviewers for improvements to the manuscript.

References

- Agència Catalana de l'Aigua, 2006. Estudi d'evaluació de riscos hidràulics pels desbordaments de les lleres de les conques nord afectades pels aiguats de l'11 al 18 d'octubre de 2005. Proposta d'actuacions. Generalitat de Catalunya, Barcelona. Technical Report, 633 pp. (in Catalan).

- Archer, D.R., Leesch, F., Harwood, K., 2007. Learning from the extreme River Tyne flood in January 2005. *Water and Environment Journal* 21 (2), 133–141.
- Barredo, J.I., 2007. Major flood disasters in Europe: 1950–2005. *Natural Hazards* 42 (1), 125–148. doi:10.1007/s11069-006-9065-2.
- Berne, A., Delrieu, G., Creutin, J.-D., Obled, C., 2004. Temporal and spatial resolution of rainfall measurements required for urban hydrology. *Journal of Hydrology* 299 (3–4), 166–179.
- Borga, M., Boscolo, P., Zanon, F., Sangati, M., 2007. Hydrometeorological analysis of the August 29, 2003 flash flood in the eastern Italian Alps. *Journal of Hydrometeorology* 8 (5), 1049–1067.
- Borga, M., Gaume, E., Creutin, J.D., Marchi, L., 2008. Surveying flash floods: gauging the ungauged extremes. *Hydrological Processes* 22 (18), 3883–3885. doi:10.1002/hyp.7111.
- Bouilloud, L., Delrieu, G., Boudevillain, B., Kirstetter, P.E., in press. Radar rainfall estimation in the context of post-event analysis of flash floods. *Journal of Hydrology*. 394 (1–2), 17–27. doi:10.1016/j.jhydrol.2010.02.035.
- Budyko, M.I., 1974. *Climate and Life*. Academic Press, New York.
- Collier, C., 2007. Flash flood forecasting: what are the limits of predictability? *Quarterly Journal of the Royal Meteorological Society* 133 (622A), 3–23.
- Collier, C., Fox, N.J., 2003. Assessing the flooding susceptibility of river catchments to extreme rainfall in the United Kingdom. *International Journal of River Basin Management* 1 (3), 1–11.
- Constantin-Horia, B., Simona, S., Gabriela, P., Adrian, S., 2009. Human factors in the floods of Romania. In: Jones, J.A.A., Vardanian, T.G., Hakopian, C. (Eds.), *Threats to Global Water Security*. NATO Science for Peace and Security, Series C: Environmental Security. Springer, Dordrecht, The Netherlands, pp. 187–192.
- Costa, J.E., 1987. Hydraulics and basin morphology of the largest flash floods in the conterminous United States. *Journal of Hydrology* 93 (3–4), 313–338.
- Costa, J.E., Jarrett, R.D., 2008. An evaluation of selected extraordinary floods in the United States reported by the US geological survey and implications for future Advancement of Flood Science. US Geological Survey, Scientific Investigations Report 2008-5164, 52 pp.
- Creutin, J.-D., Borga, M., Lutoff, C., Scoblog, A., Ruin, U.I., Créton-Cazanave, L., 2009. Catchment dynamics and social response during flash floods: the potential of radar rainfall monitoring for warning procedures. *Meteorological Applications* 16 (1), 115–125.
- D'Odorico, P., Rigon, R., 2003. Hillslope and channel contributions to the hydrologic response. *Water Resources Research* 39 (5), 1113. doi:10.1029/2002WR001708.
- Dade, W.B., 2001. Multiple scales in river basin morphology. *American Journal of Science* 301, 60–73. doi:10.2475/ajs.301.1.60.
- Davolio, S., Buzzi, A., Malguzzi, P., 2006. Orographic influence on deep convection: case study and sensitivity experiments. *Meteorologische Zeitschrift* 15 (2), 215–223.
- Delrieu, G., Nicol, J., Yates, E., Kirstetter, P.-E., Creutin, J.-D., Anquetin, S., Obled, Ch., Saulnier, G.-M., Ducrocq, V., Gaume, E., Payrastra, O., Andrieu, H., Ayrat, P.-A., Bouvier, C., Neppel, L., Livet, M., Lang, M., Parent du-Châtelet, J., Walpersdorf, A., Wobrock, W., 2005. The catastrophic flash-flood event of 8–9 September 2002 in the Gard Region, France: a first case study for the Cévennes–Vivarais Mediterranean hydrometeorological observatory. *Journal of Hydrometeorology* 6 (1), 34–52.
- Dingman, S.L., 2002. *Physical Hydrology*. Prentice Hall, Upper Saddle River, New Jersey (USA).
- Drobot, S., Parker, D.J., 2007. Advances and challenges in flash flood warnings. *Environmental Hazards* 7 (3), 173–178.
- Furey, P.R., Gupta, V.K., 2005. Effects of excess rainfall on the temporal variability of observed peak-discharge power laws. *Advances in Water Resources* 28 (11), 1240–1253.
- Gaume, E., 2006. Post Flash-flood investigation – methodological note. Floodsite European Research Project, Report D23.2, 62 pp. <<http://www.floodsite.net/>>.
- Gaume, E., Livet, M., Desbordes, M., 2003. Study of the hydrological processes during the Avene river extraordinary flood (south of France): 6–7 October 1997. *Physics and Chemistry of the Earth* 28 (6–7), 263–267.
- Gaume, E., Bouvier, C., 2004. Analyse hydro-pluviométrique des crues du Gard et du Vidourle des 8 et 9 septembre 2002. *La Houille Blanche* 6, 99–106.
- Gaume, E., Livet, M., Desbordes, M., Villeneuve, J.-P., 2004. Hydrologic analysis of the Aude, France, flash-flood 12 and 13 November 1999. *Journal of Hydrology* 286 (1–4), 135–154.
- Gaume, E., Borga, M., 2008. Post-flood field investigations in upland catchments after major flash floods: proposal of a methodology and illustrations. *Journal of Flood Risk Management* 1 (4), 175–189.
- Gaume, E., Bain, V., Bernardara, P., Newinger, O., Barbuc, M., Bateman, A., Blaškovičová, L., Blöschl, G., Borga, M., Dumitrescu, A., Daliakopoulos, I., Garcia, J., Irimescu, A., Kohnova, S., Koutroulis, A., Marchi, L., Matreata, S., Medina, V., Preciso, E., Sempere-Torres, D., Stancalie, G., Szolgay, J., Tsanis, I., Velasco, D., Viglione, A., 2009. A compilation of data on European flash floods. *Journal of Hydrology* 367 (1–2), 70–78.
- Gaume, E., Gaál, L., Viglione, A., Szolgay, J., Kohnová, S., Blöschl, G., in press. Bayesian MCMC approach to regional flood frequency analyses involving extraordinary flood events on ungauged sites. *Journal of Hydrology*. 394 (1–2), 101–177. doi:10.1016/j.jhydrol.2010.01.008.
- Georgakakos, K.P., 1986. On the design of national, real-time warning systems with capability for site-specific, flash-flood forecasts. *Bulletin of the American Meteorological Society* 67 (10), 1233–1239.
- Goodrich, D.C., 1990. Geometric simplification of a distributed rainfall-runoff model over a range of basin scales. PhD Dissertation, Department of Hydrology and Water Resources, The University of Arizona, Tucson, USA.
- Gregory, K.J., Gardiner, V., 1975. Drainage density and climate. *Zeitschrift für Geomorphologie* 19, 287–298.
- Groisman, P.Y., Knight, R.W., Karl, T.R., Easterling, D.R., Sun, B., Lawrimore, J., 2004. Contemporary changes of the hydrological cycle over the contiguous United States: trends. *Journal of Hydrometeorology* 5 (1), 64–85.
- Groisman, P.Y., Knight, R.W., Easterling, D.R., Karl, T.R., Hegerl, G.C., Razuvaev, V.N., 2005. Trends in intense precipitation in the climate record. *Journal of Climate* 18 (9), 1326–1350.
- Gupta, V.K., Castro, S.L., Over, T.M., 1996. On scaling exponents of spatial peak flows from rainfall and river network geometry. *Journal of Hydrology* 187 (1–2), 81–104.
- Gutknecht, D., Reszler, C., Blöschl, G., 2002. Jahrtausend-Hochwasser am Kamp? <<http://www.tuwien.ac.at/forschung/nachrichten/a-kamp.htm>>.
- Hack, J.T., 1957. *Studies of longitudinal stream profiles in Virginia and Maryland*. US Geological Survey Professional Paper 294-B, pp. 45–94.
- Helsel, D.R., Hirsch, R.M., 2002. *Statistical methods in water resources*. US Geological Survey. <<http://water.usgs.gov/pubs/twri/twri4a3/>>.
- Hershfield, D.M., 1961. *Rainfall frequency atlas of the United States for durations from 30 min to 24 h and return periods from 10 to 100 years*. US Weather Bureau Technical Paper 40, 61 pp.
- Hersch, R.W., 2002. The world's maximum observed floods. *Flow Measurement and Instrumentation* 13 (5–6), 231–235.
- Hersch, R.W., Fairbridge, R.W., 1998. *Encyclopedia of Hydrology and Water Resources*. Kluwer, Dordrecht, The Netherlands.
- Huntington, T.G., 2006. Evidence for intensification of the global water cycle: review and synthesis. *Journal of Hydrology* 319 (1–4), 83–95.
- James, P., Stohl, A., Spichtinger, N., Eckhardt, S., Forster, C., 2004. Climatological aspects of the extreme European rainfall of August 2002 and a trajectory method for estimating the associated evaporative source regions. *Natural Hazards and Earth System Sciences* 4 (5–6), 733–746.
- Jothityangkoon, C., Sivapalan, M., 2003. Towards estimation of extreme floods: examination of the roles of runoff process changes and floodplain flows. *Journal of Hydrology* 281 (3), 206–229.
- Koutroulis, A.G., Tsanis, I.K., 2010. A method for estimating flash flood peak discharge in a poorly gauged basin: Case study for the 13–14 January 1994 flood, Giofiros basin, Crete, Greece. *Journal of Hydrology* 385 (1–4), 150–164. doi:10.1016/j.jhydrol.2010.02.012.
- Krajewski, W.F., Smith, J.A., 2002. Radar hydrology: rainfall estimation. *Advances in Water Resources* 25 (8–12), 1387–1394.
- Kundzewicz, Z.W., Ulbrich, U., Brücher, T., Graczyk, D., Krüger, A., Leckebusch, G.C., Menzel, L., Pińskwar, I., Radziejewski, M., Szwed, M., 2005. Summer floods in Central Europe – climate change track? *Natural Hazards* 36 (1–2), 165–189.
- Llasat, M.C., Rigo, T., Barriendos, M., 2003. The “Montserrat-2000” flash-flood event: a comparison with the floods that have occurred in the northeast Iberian Peninsula since the 14th century. *International Journal of Climatology* 23 (4), 453–469.
- Majerčáková, O., Makeľ, M., Šťastný, P., Kupčo, M., Rončák, P., 2004. Selected Flash Floods in the Slovak Republic. Technical Report, Bratislava, 34 pp.
- Marchi, L., Borga, M., Preciso, E., Sangati, M., Gaume, E., Bain, V., Delrieu, G., Bonnifait, L., Pogačnik, N., 2009. Comprehensive post-event survey of a flash flood in Western Slovenia: observation strategy and lessons learned. *Hydrological Processes* 23 (26), 3761–3770. doi:10.1002/hyp.7542.
- Maritan, A., Rigon, R., Banavar, J.R., Rinaldo, A., 2002. Network allometry. *Geophysical Research Letters* 29 (11), 1508. doi:10.1029/2001GL014533.
- Merz, R., Blöschl, G., 2003. A process typology of regional floods. *Water Resources Research* 39 (12), 1340. doi:10.1029/2002WR001952.
- Merz, R., Blöschl, G., 2008. Flood frequency hydrology: 1. Temporal, spatial, and causal expansion of information. *Water Resources Research* 44 (8), W08432. doi:10.1029/2007WR006744.
- Merz, R., Blöschl, G., Parajka, J., 2006. Spatio-temporal variability of event runoff coefficients. *Journal of Hydrology* 331 (3–4), 591–604.
- Morin, E., Georgakakos, K.P., Shamir, U., Garti, R., Enzel, Y., 2002. Objective, observations-based, automatic estimation of the catchment response timescale. *Water Resources Research* 38 (10), 1212. doi:10.1029/2001WR000808.
- Norbiato, D., Borga, M., Sangati, M., Zanon, F., 2007. Regional frequency analysis of extreme precipitation in the eastern Italian Alps and the August 29, 2003 flash flood. *Journal of Hydrology* 345 (3–4), 149–166. doi:10.1016/j.jhydrol.2007.07.009.
- Norbiato, D., Borga, M., Degli Esposti, S., Gaume, E., Anquetin, S., 2008. Flash flood warning based on rainfall depth-duration thresholds and soil moisture conditions: an assessment for gauged and ungauged basins. *Journal of Hydrology* 362 (3–4), 274–290. doi:10.1016/j.jhydrol.2008.08.023.
- Norbiato, D., Borga, M., Dinale, R., 2009. Flash flood warning in ungauged basins by use of the Flash Flood Guidance and model-based runoff thresholds. *Meteorological Applications* 16 (1), 65–75. doi:10.1002/met.126. <<http://dx.doi.org/10.1002/met.126>>.
- O'Connor, J.E., Costa, J.E., 2004. Spatial distribution of the largest rainfall-runoff floods from basins between 2.6 and 26,000 km² in the United States and Puerto Rico. *Water Resources Research* 40 (1), W01107. doi:10.1029/2003WR002247.
- Orlanski, I., 1975. A rational subdivision of scales for atmospheric processes. *Bulletin of the American Meteorological Society* 56 (5), 527–530.
- Parajka, J., Kohnová, S., Bálint, G., Barbuc, M., Borga, M., Claps, P., Cheval, S., Gaume, E., Hlavčová, K., Merz, R., Pfaundler, M., Stancalie, G., Szolgay, J., Blöschl, G., in

- press. Seasonal characteristics of flood regimes across the Alpine–Carpathian range. *Journal of Hydrology*. 394 (1–2), 78–89. doi:10.1016/j.jhydrol.2010.05.015.
- Peel, M.C., Finlayson, B.L., McMahon, T.A., 2007. Updated world map of the Köppen–Geiger climate classification. *Hydrology and Earth System Sciences* 11 (5), 1633–1644.
- Pellarin, T., Delrieu, G., Saulnier, G.M., Andrieu, H., Vignal, B., Creutin, J.D., 2002. Hydrologic visibility of weather radar systems operating in mountainous regions: case study for the Ardeche catchment (France). *Journal of Hydrometeorology* 3 (5), 539–555.
- Ponce, V.M., Hawkins, E.R.H., 1996. Runoff curve number: has it reached maturity? *Journal of Hydrologic Engineering* 1 (1), 11–19.
- Rigon, R., Rodriguez-Iturbe, I., Giacometti, A., Maritan, A., Rinaldo, A., 1996. On Hack's law. *Water Resources Research* 32 (11), 3367–3374.
- Robinson, J.S., Sivapalan, M., 1997. An investigation into the physical causes of scaling and heterogeneity of regional flood frequency. *Water Resources Research* 33 (5), 1045–1059.
- Roca, M., Davison, M., 2010. 2D model analysis of flash-flood processes. Application to the Boscastle event. *Journal of Flood Risk Management* 3 (1), 63–71.
- Ruin, I., Creutin, J.-D., Anquetin, S., Lutoff, C., 2008. Human exposure to flash-floods – relation between flood parameters and human vulnerability during a storm of September 2002 in Southern France. *Journal of Hydrology* 361 (1–2), 199–213. doi:10.1016/j.jhydrol.2008.07.044.
- Rusjan, S., Kobold, M., Mikoš, M., 2009. Characteristics of the extreme rainfall event and consequent flash floods in W Slovenia in September 2007. *Natural Hazards Earth System Sciences* 9 (3), 947–956.
- Sangati, M., Borga, M., Rabuffetti, D., Bechini, R., 2009. Influence of rainfall and soil properties spatial aggregation on extreme flash flood response modelling: an evaluation based on the Sesia river basin, North Western Italy. *Advances in Water Resources* 32 (7), 1090–1106.
- Schumacher, R.S., Johnson, R.H., 2006. Characteristics of US extreme rain events during 1999–2003. *Weather and Forecasting* 21 (1), 69–85.
- Schumm, S.A., 1956. Evolution of drainage systems and slopes in badlands at Perth Amboy, New Jersey. *Bulletin of the Geological Society of America* 67, 597–646.
- Schumm, S.A., 1963. The disparity between present rates of denudation and orogeny. *United States Geological Survey Prof. Paper* 454-H, 13 pp.
- Sivapalan, M., Jothityangkoon, C., Menabde, M., 2002. Linearity and nonlinearity of basin response as a function of scale: discussion of alternative definitions. *Water Resources Research* 38 (2). doi:10.1029/2001WR000482.
- Sivapalan, M., Blöschl, G., Merz, R., Gutknecht, D., 2005. Linking flood frequency to long-term water balance: Incorporating effects of seasonality. *Water Resources Research* 41 (6), W06012. doi:10.1029/2004WR003439.
- Smith, J.A., 1992. Representation of basin scale in flood peak distribution. *Water Resources Research* 28 (11), 2993–2999.
- Smith, J.A., Baeck, M.L., Steiner, M., Miller, A.J., 1996. Catastrophic rainfall from an upslope thunderstorm in the central Appalachians: the Rapidan storm of June 27, 1995. *Water Resources Research* 32 (10), 3099–3113.
- Smith, J.A., Sturdevant-Rees, P., Baeck, M.L., Larsen, M.C., 2005. Tropical cyclones and the flood hydrology of Puerto Rico. *Water Resources Research* 41 (6), W06020. doi:10.1029/2004WR003530.
- Sturdevant-Rees, P., Smith, J.A., Morrison, J., Baeck, M.L., 2001. Tropical storms and the flood hydrology of the central Appalachians. *Water Resources Research* 37 (8), 2143–2168.
- Tallaksen, L.M., 1995. A review of baseflow recession analysis. *Journal of Hydrology* 165 (1–4), 349–370.
- Trewartha, G.T., 1981. *The Earth's Problem Climates*, second ed. University of Wisconsin Press, Madison.
- Turner-Gillespie, D.F., Smith, J.A., Bates, P.D., 2003. Attenuating reaches and the regional flood response of an urbanizing drainage basin. *Advances in Water Resources* 26 (6), 673–684.
- Viglione, A., Borga, M., Balabanis, P., Blöschl, G., in press. Barriers to the exchange of hydrometeorological data across Europe – results from a survey and implications for data policy. *Journal of Hydrology*. 394 (1–2), 63–77. doi:10.1016/j.jhydrol.2010.03.023.
- Woltemade, C.J., Potter, K.W., 1994. A watershed modeling analysis of fluvial geomorphic influences on flood peak attenuation. *Water Resources Research* 30 (6), 1933–1942.
- Wood, E.F., Sivapalan, M., Beven, K., 1990. Similarity and scale in catchment storm response. *Reviews of Geophysics* 28 (1), 1–18.
- Woods, R.A., Sivapalan, M., 1999. A synthesis of space–time variability in storm response: rainfall, runoff generation and routing. *Water Resources Research* 35 (8), 2469–2485.