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A compilation of data on European flash floods

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SUMMARY

Flash floods are one of the most significant natural hazards in Europe, causing serious risk to life and destruction of buildings and infrastructure. This type of flood, often affecting ungauged watersheds, remains nevertheless a poorly documented phenomenon. To address the gap in available information, and particularly to assess the possible ranges for peak discharges on watersheds with area smaller than 500 km^2 and to describe the geography of the hazard across Europe, an intensive data compilation has been carried out for seven European hydrometeorological regions. This inventory is the first step towards an atlas of extreme flash floods in Europe. It contains over 550 documented events. This paper aims at presenting the data compilation strategy, the content of the elaborated data base and some preliminary data analysis results. The initial observations show that the most extreme flash floods are greater in magnitude in the Mediterranean countries than in the inner continental countries and that there is a strong seasonality to flash flood occurrence revealing different climatic forcing mechanisms in each region.

Introduction

Flash floods are one of the most significant natural hazards and cause serious loss of life and economic damage. The average annual economic loss due to natural hazards over the world has been estimated at €40 billion (Münich Re, 2003). This can be compared to the total economic damages estimated at €1.2 billion for the Gard 2002 single flash flood event (Huet et al., 2003) and €3.3 billion for the Aude 1999 flash flood (Lefrou et al., 2000). In Europe, lowland floods are rarely associated with fatalities except in cases of levee failures; in contrast flash floods often result in loss of life. The most striking examples are the Lynmouth flood in the UK in 1952 – 34 deaths (Dobbie and Wolf, 1953), the Barcelona flood in Spain in 1962 – over 400 deaths (López Bustos, 1964), the Piedmont region floods in Italy in 1968 and 1994 – respectively, 72 and 69 deaths (Ferro, 2005; Guzzetti et al., 2005) and the Aude flood in France in 1999 – 35 victims (Gaume et al., 2004).

Despite being a serious natural hazard that affects countries throughout Europe, flash floods remain a poorly understood and

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documented natural phenomenon. The occurrence of extreme events in ungauged watersheds generally means that there is no measured discharge information or formal records of the magnitude of the event. Furthermore, data on previous flash floods is scattered among local authorities where flooding has occurred and various companies and research units that may have unpublished technical reports. These sources of information are often difficult to obtain and are generally in the national language of the country where the flood occurred. Existing inventories of past floods (Barredo, 2007; Herschy, 2005; Costa, 1987a; Unesco, 1976; Pardé, 1961) contain only few data on flash floods occurred in Europe and lack quantitative information on the meteo-hydrological and hydraulic characteristics of the events. The lack of centralised national and international databases for storing meteo-hydrological, hydraulic and socio-economic data relating to past flash flood events within Europe hinders the development of understanding of their magnitude and occurrence (Creutin and Borga, 2003).

To address the gap in available information, and particularly to assess the possible ranges for peak discharges on small watersheds and to describe the geography of the hazard across Europe, an intensive data compilation has been carried out initially for the seven European regions listed below:

- Catalonia region, Spain, Mediterranean region,
- Cevennes-Vivarais, France, Mediterranean region,
- Italian Alps and Ligury, Alpine Mediterranean and Mediterranean region,
- Slovakia, Inland Continental region,
- Greece, Mediterranean region,
- Romania, Inland Continental region,
- Austria, Alpine Inland Continental region.

This inventory is the first step towards an atlas of extreme flash floods over Europe. This paper presents the data collection strategy, the data set and some first interpretations. This work has been carried out for Hydrate, which is a currently ongoing European Commission funded project that is aiming to improve techniques for flash flood forecasting. Such inventories can never be perfectly consistent and comprehensive. The very first analyses provided hereafter nevertheless illustrate their usefulness for understanding magnitude, occurrence, and geographical distribution of hydrological extremes.

Data collection strategy

The initial aim of the data compilation was to develop a catalogue for each region that included the most extreme flash flood events between 1946 and 2007. In this research, extreme flood events induced by severe stationary storms have been considered as flash floods. This relatively broad definition includes almost all the past events reported as flash floods in Europe, except dam break floods. The duration and spatial extension of the area affected by such floods depend on the causative storm and hence on the climatic setting. Most generally, the storms inducing flash floods lead to local rainfall accumulations exceeding 100 mm over a few hours and affect limited areas: some tens to some hundreds of square kilometres. Larger scale and longer lasting stationary storm events may, however, occur in some meteorological contexts, especially in the Mediterranean region. As an example, an area larger than 3000 km^2 received more than 300 mm rainfall within about 12 h on the 8th and 9th of September 2002 in the Gard region of France (Delrieu et al., 2004). On the basis of these considerations, it has been decided that the most extreme floods in watersheds of an area of less than 500 km^2, generally induced by short duration storms (i.e. less than 24 h) should be considered as flash floods. Matthai (1969) and Stanescu (2000, 2004) used a similar watershed area threshold when compiling data on flash floods. This initial criterion was, however, relaxed for several cases of floods in France and Catalonia which occurred over watersheds of much greater areas but which were created by short duration and very high accumulation storms. Examples are the Gard 2002 floods in France that has already been mentioned; other large scale flash floods include events on the Llobregat River in Catalonia in 1971, the Segre River in Catalonia in 1982, and the Ardèche River in France in 1982, 1995 and 1996, reported in the Hydrate data base.

The objective was to document a minimum number of 30 floods in each region: if possible the events considered as the most extreme or "top 30" flash floods and homogeneously distributed over the selected period. The number of described events was chosen to build representative samples of large flash floods in the various regions, not limited to the very extreme events. The timeframe was selected based on the hypotheses that firstly, over a 60 year period it would be likely that several extreme events would have occurred in each region; and secondly, that it would be feasible to find hydrometeorological data from this period but that extending the record to earlier dates, with the objective of building an inventory as exhaustive as possible, may not be possible for most regions.

Data was collated by local researchers in each region. Several different types of data sources were used to identify the dates and location of extreme flood events and gather detailed information on these events. Typically, information came from available discharge and rainfall records, scientific and technical reports, local flood risk mapping studies and site investigation data.

Data was collated using a standardised template containing sections on geographic, meteorological, hydrological and hydraulic data, as well as information on damages and casualties that were caused by the flood. The content of the data catalogue will be described in more detail in the next section. As much as possible information was collated on the considered flood event and if possible the sources of documentation were scanned and appended to the templates. The minimum requirement for an event to be listed in the database is that at least one peak discharge estimation for one given cross-section is available and that the corresponding watershed area could be computed (i.e. the cross-section could be located).

Validation of the datasets was carried out, when possible, by cross-checking reported rainfall accumulations with peak discharge estimates and identifying outliers from the rest of the dataset for the region. Overall, intraregional comparisons and comparisons with other inventories did not reveal significant discordances in peak discharge estimates except for isolated events. For example, the reported estimated peak discharge for the event on the Rubí Torrent in Catalonia in 1962 was thought to be dubious, because the resulting unit peak discharge (72 m^3/s/km^2) is considerably higher than any of the other reported unit peak discharges in the inventory for similar watershed areas and indeed higher than the world envelope curve. This led to a re-analysis of the cross-section surveys realized just after this flood and of the initial peak discharge estimates (López Bustos, 1964). The peak discharge of 1750 m^3/s corresponds to a river cross-section area of about 100 m^2, which means an average flow velocity of more than 17 m/s. Velocities are hardly greater than 4–5 m/s for liquid flows in natural channels with shallow slopes, typically slopes lower than 2% (Gaume et al., 2004; Jarrett, 1987). The discharge is clearly largely over-estimated. Many reasons can be put forward to explain such an error and a more accurate guess would deserve a thorough analysis and the compilation of additional field data: pictures or accounts that could help to evaluate the possible range of flow velocities and their repartitions in the considered cross-sections for instance. The 1962 event is not included in the initial data set, however, after a critical re-analysis of the event is completed, it will be added to the data catalogue.

Table 1
Content of the hydrate flash flood database (required data for all events in normal style and optional additional data in italics).

Section identification	Basin data	Discharge data	Rainfall data	Damages and casualties
Data				
Event code	Basin area (km^2)	Peak discharge (m^3/s)	Total point rainfall (mm)	*Total damages* (€)
Date of the event	Time of concentration (h)	Estimation method	Rainfall duration (h)	*Displaced persons*
River name	*Minimum elevation* (*m*)	Estimation quality rate	*Av. rainfall on the basin* (*mm*)	*Population affected*
Cross-section name	*Maximal elevation* (*m*)	Regulated stream (y/n)	*No. of raingauges*	*Direct private damages* (€)
Section longitude	*Average elevation* (*m*)	*Peak discharge Maxi*	*No of raingauges in the basin*	*Direct public damages* (€)
Section latitude	*Average basin slope* (%)	*Peak discharge mini*	*Quality of data*	*Indirect damages* (€)
Section elevation (m)	*Glacial areas* (%)	*10-year discharge* (*m^3/s*)	*Type of event*	*Origin of the data*
	Land use	*100-year discharge* (*m^3/s*)	*Spatial extent* (*km^2*)	*No of casualties*
	Soils	*Sediment processes* (*y/n*)	*Max. Intens. over Tc* (*mm/h*)	*No of injured people*
	Av. soil thickness (*m*)	*Flood duration* (*h*)	*Hailfall* (*y/n*)	*Medical causes*
	Geology		*Initial wetness* (*wet/dry*)	*Circumstances*
			Annual precipitation (*mm*)	*Timing*
			Observation period (*years*)	*Gender*
				Age
Attached documents				
Comments and notes				
Photos	*Location map*	*Flood hydrograph*	*Rainfall map*	*Report on the damages*
Attached reports	*Geographical doc.*	*Past-historical floods*	*Radar data*	*Report on casualties*
References list		*Cross-section survey*	*Local IDF curves*	
		Pictures of the section	*Monthly precipitations*	

The data catalogue

The data catalogue is composed of a series of filled data templates. Their content is presented in Table 1. Each record in the inventory provides data on the flood characteristics at a particular cross-section. For any flood event there may be several records, each with details of the peak discharge at a different cross-sections and, often, different sub-catchments. The records contain fields with basic geographic information such as the name of the river, the name of the cross-section and the longitude and latitude of the site in WGS84 coordinates for all inventories. There is also a group of fields with information on the watershed upstream from the cross-section to which the record relates. Its area should be defined and where possible, an estimation of its time of concentration is also indicated. Information is given on the elevation and the average basin slope. For Alpine basins, the proportion of the watershed which is glacial is estimated. The main land cover for the watershed is reported. Land cover is recorded following CORINE land cover definitions from the European Environmental Agency (http://dataservice.eea.europa.eu). The predominant watershed soil types and soil thickness is reported as well as the geology. Maps of soil, geology and topography are appended to the inventory where available.

The discharge data that is given in the inventory aims to provide details of the specific event that is being documented and also give some information on the characteristics of previous floods on the watershed. The event peak discharge (and upper and lower bounds on the estimate) at the given cross-section is recorded as well as an indication of the method used for determining it. Most common methods for the estimation of peak discharges are the reconstruction by means of indirect methods, the reconstruction from reservoir operations and the extrapolation of stage–discharge curves (Table 2). The quality of discharge estimate is rated into four classes: (1) Very good; (2) Good; (3) Fair and (4) Poor. Because the inventories for each region were completed by different organisations, this quality rating is indicative only since each organisation used their own metrics to determine the score. Scientific reports and papers relating to the peak discharge estimation, information on the flood hydrograph and the cross-section survey are appended to the inventory. Where possible, the 10 year return period and 100 year return period discharges for the river at the specific cross-section are given as well as any specific details that exist for other flood events on the same watershed.

The inventory also records if needed what the predominant sediment transport processes during the event were. In the scientific literature, many classifications of water–sediment flows have been proposed. For the Hydrate project, three classes are proposed and the event record identifies which of the three best describes the event:

- *Water flood*,
- *Debris flood or hyperconcentrated flow*,
- *Debris flow or mudflow*.

The term *debris flood* indicates a process intermediate between *water floods* and *debris flows*. It is similar, although non synonymous of *hyperconcentrated flow* (Pierson and Costa, 1987). A *mudflow* is a debris flow without large clasts. *Debris flow* and *mudflow*

Table 2
Methods of estimating the peak discharge of events (%).

	Number of records	Manning Strickler formula estimation	Extrapolation of calibrated stage–discharge relation	Hydraulic 1D simulation	Hydraulic 2D simulation	Reconstruction from reservoir operation	Direct current meter measurement	Other	Unknown
Catalonia	10	56	11	33	0	0	0	0	0
France	236	20	33	17	0	7	0	0	23
Italy	73	64	23	13	0	0	0	0	0
Slovakia	52	0	73	0	0	0	0	27	0
Greece	21	66	0	0	17	0	17	0	0
Romania	152	0	53	0	0	47	0	0	0
Austria	34	0	94	6	0	0	0	0	0

are non-Newtonian and conventional discharge estimation methods are not applicable. Different threshold values have been proposed for differentiating between various types of water–sediment mixtures. As an example, Costa (1988) indicates sediment concentration by volume up to 0.2 for *water floods* with sediment transport, from 0.2 to 0.47 for *hyperconcentrated flows*, and from 0.47 to 0.77 for *debris flows*. Other classifications, however, do exist. It is well known that, in addition to concentration, particle size can influence the behaviour of flow: clay and very fine silt can induce non-Newtonian behaviour also in concentrations by volume lower than 10% (Ning and Zhaohui, 1986). Collecting data on *debris flows* is of great interest, but *debris flows* are a process basically different from *water floods* and data on *debris flow* peak discharge are not homogeneous with *water flood* data. Quantitative data on *debris flows* as estimated discharges, amounts of sediments eroded and deposited, are only included for a very few number of flash floods in this inventory as they deserve a separate analysis.

Rainfall data relating to the event are given in a section of the inventory. The number of rain gauges within and around the watershed and the number of nearby radar stations as well as the data for the event and the preceding days are given. When available, the maximum total accumulated point rainfall is recorded as well as the spatial extent of the rain, thus enabling an estimate of the average accumulated rainfall on the watershed. Details of the maximum intensity, initial watershed wetness and whether there was hail fall are also noted. The type of hydrometeorological event is identified as being one of two classes:

- Storm (intense rainfall event),
- Storm on snow.

These two classes define two types of causative processes of flash floods. Hail fall often occurs during high-intensity storms, but its influence on the formation of flash floods is not particularly relevant.

There is a section of the inventory that provides details of the climatic characteristics of the watershed; however, these fields are not always complete due to difficulties of obtaining the data. The fields include details of the average annual precipitation and the observation period from which the estimate was made, the 1, 10 and 100 year return period hourly and daily rainfall and the intensity duration frequency curve.

Finally, there are sections within the inventory on damages and casualties. Estimates (and sources of the estimates) of total economic damages, direct damages to private properties and activities, direct damage to public infrastructure and indirect damages are given where possible. There are also fields for recording the number of inhabitants within the affected areas and the number of displaced people. In terms of casualties, the inventory records the number of fatalities as well as the number of injured people. Information on the circumstances of death and injury and the age and gender of the victims is given. Any available reports on damages and casualties are appended to the inventory.

Each inventory is completed with relevant additional notes, appended reports and photographs and a list of references on the event. Not all records within each regional inventory have successfully completed all fields described above but in most cases the minimum data requirements as specified by the data compilation template were completed.

The final data set includes 578 flood event records in seven European regions (Table 3). While the data compilation aimed to be consistent and comprehensive in each region, the quality and quantity of data that could be collected varied from country to country, depending on the available sources of information and the institutional frameworks for collecting and recording data. Only in France does the catalogue cover the full 60 year time period (Fig. 1). Compilation of data on extreme events in France was efficient due to the existence of a systematic program for flood hazard mapping since 1982 (http://www.prim.net) which has produced easily accessible information on flood hazard. The peak discharge computation methods and the corresponding discharge accuracy rate relate to the nature of the sources of information used. It can be noted that most of the discharge estimates in the catalogues for Austria, Slovakia and Romania have been obtained from stage–discharge relationships, indicating that a large part of the data comes from gauging stations. In Catalonia, Italy, France and Greece, many estimates are based on hydraulic calculations, indicating that a significant proportion of the information is on ungauged sites and has been collected from scientific reports, papers and studies. In most regions, the values closest to the envelope curve (see following discussion), correspond dominantly to ungauged sites, justifying the efforts for retrieving data from ungauged watersheds.

To improve the consistency of the data and enable first intercomparisons, the complete data set has been refined by selecting the most extreme events, identifying those events which are closest to the envelope curve for each region. The selected envelope curve approach is presented in the next sections. The 30 events with the highest "reduced peak discharge (see next sections for a definition)" were selected for each region, the reduced discharge formula being linked to the shape of the envelope curves. Several of the original data sets contained multiple records for the same rainfall event, distinguishing different peak discharge estimates at different locations within the affected catchments. In refining the data sets to 30 events, it was specified that no more than two records within the set of 30 should be of the same date in a region. This condition was selected to maintain a diversity of case studies and representativeness of the refined data base. It only applied to the French refined data set which otherwise, due to the spatial extension of some extreme storm events in this region, would have had more than half of its records corresponding to two storm events only: the September 2002 and October 1958 storms. Note that this imposed constraint does not affect the envelope curve (see following comment).

Not all of the refined data sets selected meet the target number of 30 records and the refined data set only counts 150 records over the seven considered regions (Table 3). The data sets for Catalonia and

Table 3
Number of flash flood events listed in the Hydrate database for each region.

	Area (km^2)	Nb of events	Dates	Cov[a]	D[b]	Refined number	Dates	Cov[a]	D[b]
Catalonia	32,000	10	1962–2005	1.4	7	9	1971–2005	1.1	8
France	18,000	236	1953–2006	0.9	255	30	1953–2006	0.9	32
Italy	95,000	73	1968–2006	3.6	20	30	1968–2006	3.6	8
Slovakia	49,000	52	1995–2004	0.4	120	30	1995–2004	0.4	70
Greece	132,000	21	1960–2006	6.0	3	4	1989–2006	2.2	2
Romania	240,000	152	1973–2007	8.1	19	30	1979–2007	6.7	5
Austria	85,000	34	1987–2005	1.5	22	17	1987–2005	1.5	11

[a] Cov: Coverage in $yr10^6$ km^2.
[b] D: density in records/yr/10^6 km^2.

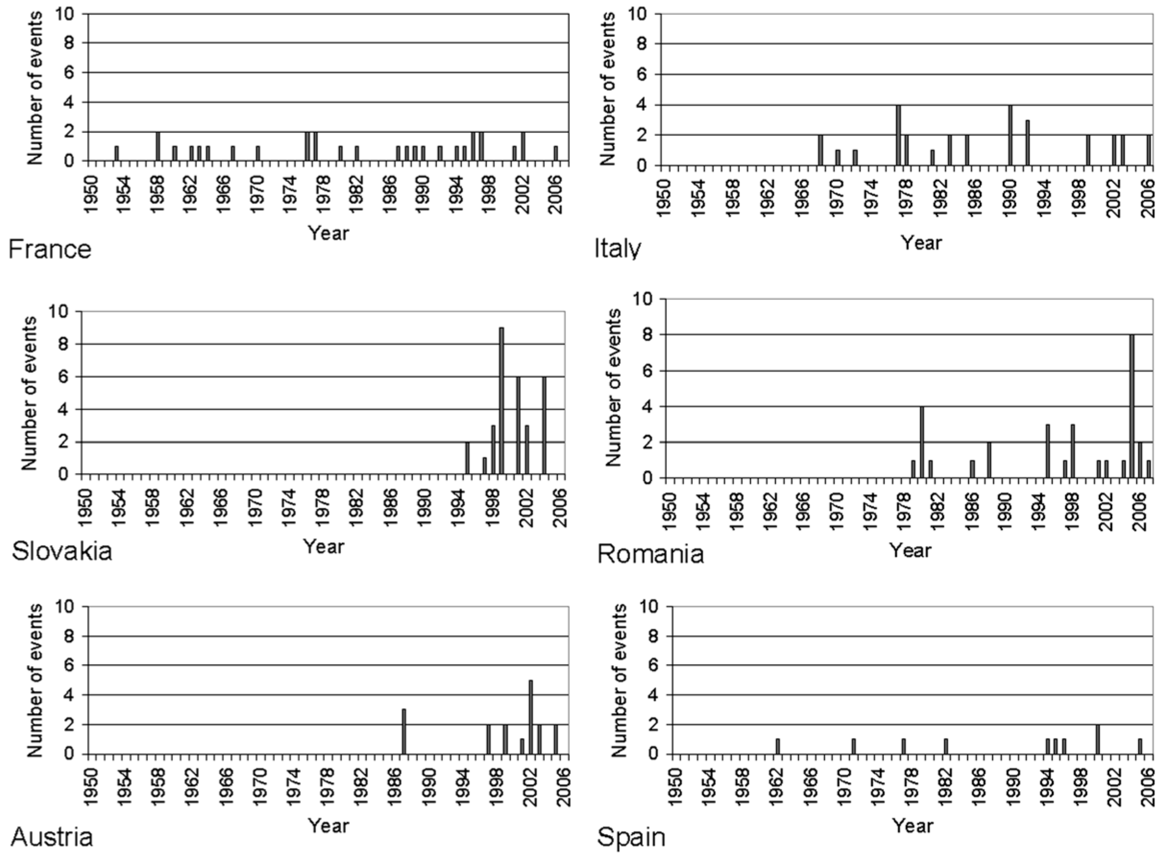

Fig. 1. Examples of distributions of the reported extreme events for 1947–2007.

Crete, for instance, are small so it will be difficult to draw generalisations about floods in these regions or make comparisons with other datasets. The data set for Austria is also below the target of 30 records and contains no peak discharge estimates on ungauged watersheds, which will have to be taken into account while making comparisons with the other sets. Two indices help to compare the various datasets (reported in Table 3): the compilation coverage (watershed area multiplied by period of time considered) and the compilation density (number of documented events divided by the coverage). The periods of time as well as the areas covered by the inventories are varied. Let us comment qualitatively on how this can affect the inter-comparison. The number of observed events exceeding a given magnitude threshold increases on average linearly with the considered area and period of time in a statistically consistent region if there is a temporal and spatial independence between events. These two conditions, consistency and independence, are not fulfilled but the general conclusion remains valid. If we assume that the major floods have been reported in the inventory, the proportion of high magnitude events in the 30 event sets will have a general tendency to grow with the coverage of the inventory. This means that the Italian, Greek and Romanian inventories are more likely to contain higher magnitude events. In contrast, this can be partly compensated by the density of the inventories for France and Slovakia; the proportion of missed extreme events, especially events that occurred on ungauged watersheds, reduces as the comprehensiveness of the inventory increases. As a consequence, the envelope curves are affected by the coverage of the inventories. The magnitude of the most extreme floods defining the envelope curve have a general tendency to grow as the coverage grows. Likewise, the number of records close to the envelope curve increases with the density of the inventory.

Having presented the limitations of the available data, the remaining discussion explores some initial interpretations from the data analysis, essentially flood peak discharge analysis. Despite the variability in the quality of each data set resulting in limitations for comparing the data, there are patterns that can be observed.

First analysis of the resulting data sets

Comparison of envelope curves

Envelope curves provide an effective graphical summary of previous floods in a given region. They have been widely used in past publications on extreme floods (Castellarin, 2007; Herschy, 2005; Bayazit and Onoz, 2004; Stanescu, 2000; Kadoya, 1992; Anselmo, 1985; Mimikou, 1984; Crippen and Bue, 1977; Marchetti, 1953; Jarvis, 1924) and have the advantage of being relatively unaffected by the data compilation density because they are determined by the maximum values of a sample. Generally, the most extreme flood events in a region have had dramatic consequences except for floods affecting very small and unpopulated headwater streams. They remain remembered within communities and are often well documented. They are therefore easy to identify and count among the first events reported in regional extreme flood inventories. The maximum discharge values of such datasets do, however, have a general tendency to grow with the coverage of the inventory: area and period of time considered (Castellarin, 2007). The highest coverage values do not correspond necessarily to the highest number of recorded events (see Table 3).

Envelope curves, adjusted for each region, have been plotted (Fig. 2). For sake of clarity, a simple envelope curve formula, often

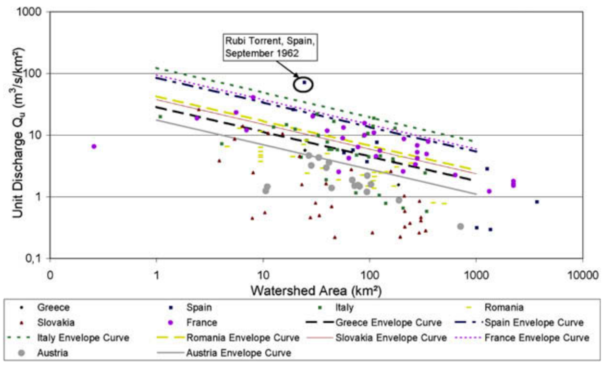

Fig. 2. Peak unit discharges of extreme events in the European HOs and envelope curves.

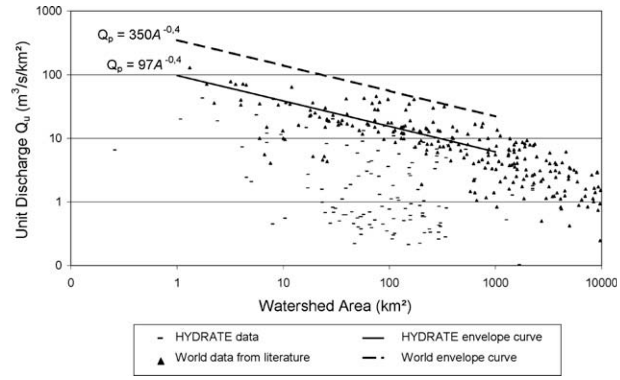

Fig. 3. Comparison between the unit discharges collected for this study, Hydrate (the dashes) and the unit discharges reported in literature for the world (triangles). The literature referenced is Costa (1987a,b), Pardé (1961), Rodier and Roche (1984), Alcoverro et al. (1999) and Mimikou (1984).

used in previous studies, has been selected (Eq. (1)). According to this formula, the envelopes appear as straight lines on the chosen log–log representation.

$$Q_s = aA^{\beta} \tag{1}$$

Here Q_s is the unit discharge in (m^3/s/km^2), A (km^2) is the catchment area, α is a coefficient supposed to be independent on the catchment area also called "reduced" discharge in (m^3/s/km$^{2(1+\beta)}$), and β is a scaling exponent. As suggested by Castellarin (2007), the value of the exponent β has been estimated through a linear regression between $\log(Q_s)$ and $\log(A)$ based on each of the refined data sets. An average value of $\beta = -0.4$ appears to be the best suited to the available data sets. It lies in the range of previously calibrated envelope curve parameters for various climatic contexts (Castellarin, 2007; Jarvis, 1924).

The comparison of the envelope curves shows at least two groups of curves that appear to correspond to two different climatic influences; Italy, France and Catalonia appear to form one group and Slovakia and Romania form another. The maximum peak discharges collated in the regions under Mediterranean climatic influence are more than twice as high as the maximum peak discharges reported in Central Europe for a given watershed area. Some very high peak discharge values are observed under the inner continental climate but they lie far from the maximum values observed in the Mediterranean area. At this stage, no real conclusions can be drawn for Greece due to the limited number of documented floods in the database.

The envelope curves for each climatic region are consistent. The lower position of the Austrian envelope curve remains to be explained. It may be due to hydro-climatic factors but it may also be a consequence of the absence of data on ungauged catchments in this inventory: the inventory coverage is necessarily lower in a given area if only the gauged catchments are considered. Despite the high diversity of sources on flash flood discharges used, the retrieved values lie in similar ranges. Except for the case of the Rubi Torrent flood in 1962 in Catalonia, no obvious outliers appear in the inventories. The Italian envelope curve lies slightly higher than the French and Spanish curves, which can be explained by the much higher coverage of the Italian data base. As illustrated in Fig. 3 the data sets and calibrated envelope curves appear also to be consistent in magnitude with previously conducted inventories on extreme floods in the Mediterranean area (Alcoverro et al., 1999; Mimikou, 1984; Pardé, 1961) and over the world (Herschy, 2005; Costa, 1987b; Rodier and Roche, 1984; Unesco, 1976). Note that a limited number reported flood peak discharges over the world exceed the calibrated Mediterranean envelope curve, especially for the smaller catchment areas.

A practical conclusion can be drawn from this overall good agreement between inventories and envelope curves: provided that some quality checks are conducted, indirect peak discharge estimation methods may provide correct approximate if not accurate discharge estimates.

Flash flood magnitude and occurrence

The data sets mix peak discharge estimates from watershed areas ranging from some tens of square kilometres to about 2000 km^2. According to the adjusted envelope curves and especially the value of the power β (-0.4), a reduced peak discharge Q_r has been selected as an indicator of the magnitude of the floods to aggregate the data and limit the influence of the watershed areas on the analyses: $Q_r = Q/A^{0.6}$. Q is in m^3/s, A in km^2 and Q_r in m^3/s/(km^2)$^{0.6}$. The atlas of extreme floods over Europe thus plots the reduced discharge of events in each region (Fig. 4). The atlas maps the spatial distribution of flash floods in the seven areas included in this study. Differences appear on this map that are confirmed by examining the proportion of the flash flood events in each reduced discharge category for each considered region based on analysis of the refined data sets (Table 4). There appears to be a significant proportion of events of over 75 m^3/s/(km^2)$^{0.6}$ in France (13%), northern Italy (17%) and in Catalonia (11%), and the lower category events ($Q_{ps} < 25$ m^3/s/(km^2)$^{0.6}$) in these regions are a minority. This lower category represents three quarters of all other inventories. This reinforces the conclusions drawn on the envelope curves: the values defining the curves are not isolated in each region and it is possible to conclude that the differences observed between regions are not an effect of randomness but correspond to a real trend.

No significant difference between French and Italian samples appears upon first inspection of the data. There are, however, some differences between the distribution of floods in each discharge category in the samples as there is an over-representation of extreme events in the Italian sample due to the larger coverage, but a lower number of second class floods that can be explained by a lower sampling density. There are heterogeneities within the considered regions as well, especially in northern Italy where the extreme events are concentrated in the Piedmont and Liguria regions (western area). Likewise, a thorough statistical analysis of the French sample revealed clear differences in flood magnitude and occurrence within the considered French Mediterranean area (Newinger, 2007).

Finally, the flash flood geographical pattern revealed by the Hydrate data base appears to be correlated to the spatial pattern of the intense rainfall hazard as shown by the distribution of estimated 100-year return period daily rainfall accumulations

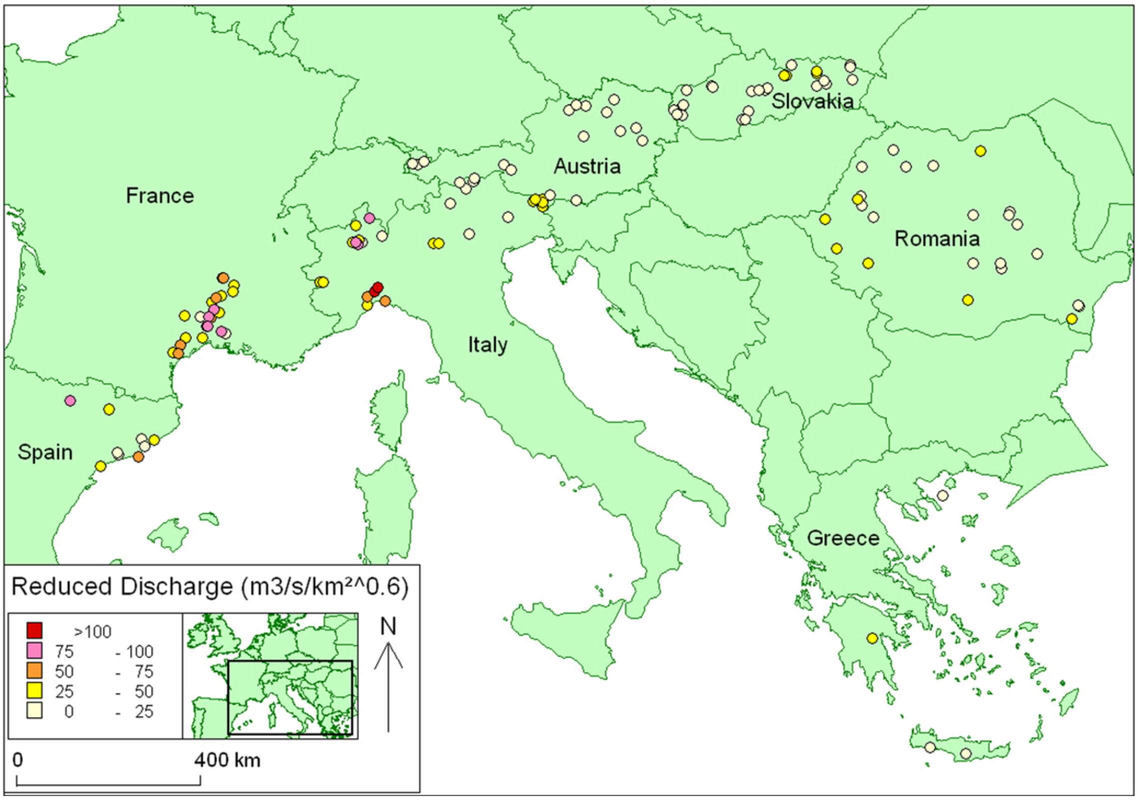

Fig. 4. Atlas of reduced peak discharges of extreme events in Europe.

Table 4
Proportion of events in each reduced peak discharge category in the refined data set (%).

	0–25	25–50	50–75	75–100	>100
Catalonia	45	33	11	11	0
France	17	43	27	13	0
Italy	33	43	7	10	7
Slovakia	87	13	0	0	0
Greece	75	25	0	0	0
Romania	77	23	0	0	0
Austria	100	0	0	0	0

in the hydrometeorological regions (Fig. 5). This is a sign of both, the predominant role played by the rainfall forcing in explaining flash flood hazard and the relevance of the data base. The detailed analysis of the data nevertheless reveals a more nuanced pattern especially in inner continental countries and particularly the influence of the local meteorological settings and of the characteristics of the watersheds (Mertz and Blöschl, 2003).

Flash flood seasonal distribution

The inventory also provides information on the patterns of seasonality of flash floods over the European regions. The number of records reported for each month is shown for each region on Fig. 6. The extreme floods in Catalonia and France, without exception, occurred in autumn, with a possible slight shift of the autumn season from year to year, while in the Central European countries (Austria, Slovakia and Romania) these extremes occur only in the late spring and summer seasons. Northern Italy lies in an intermediate position with a dominant proportion of extreme floods in autumn but also some in spring. This feature is not modified if the complete dataset is taken into account. This difference in the seasonality shows that the most extreme flash floods in the Mediterranean and in the inland continental regions are not induced by the same types of meteorological events. Flash floods in the study area encompass a diversity of meteorological and hydrological processes.

Intense autumn storm events delivering very high amounts of rain water within a short period of time and sometimes over large areas appear to be a specificity of the Mediterranean area. Intense summer thunderstorms also take place frequently in this area. But they almost never induce significant floods except in the arid part of Catalonia, due to the high infiltration capacities of the dry soils in this season. Moreover, even in autumn, daily rainfall accumulations exceeding 200 mm, rarely observed under continental climate, are needed to generate significant floods on vegetated catchments in the Mediterranean area as revealed by recent post flash flood field investigations (Delrieu et al., 2004; Gaume et al., 2004; Cosandey, 1993). The initial wetness conditions of the watersheds can play a major role in their response to a rainfall event (Borga and Gaume, 2007). These conditions are linked to the climatic settings and can also explain the differences observed between the hydrometeorological regions. In the same line of thinking, Mertz and Blöschl (2003) found that flash floods in Austria are most extreme in the eastern part of the country, which corresponds with the flash flood atlas presented here. These authors suggest that the hilly terrain in this region increases the instability of the boundary layer and therefore increases the potential for convective storms.

Flash flood occurrence and magnitude are controlled by the combination of meteorological and hydrological factors that flash flood mapping efforts, as the one presented here for Europe, will progressively help to reveal.

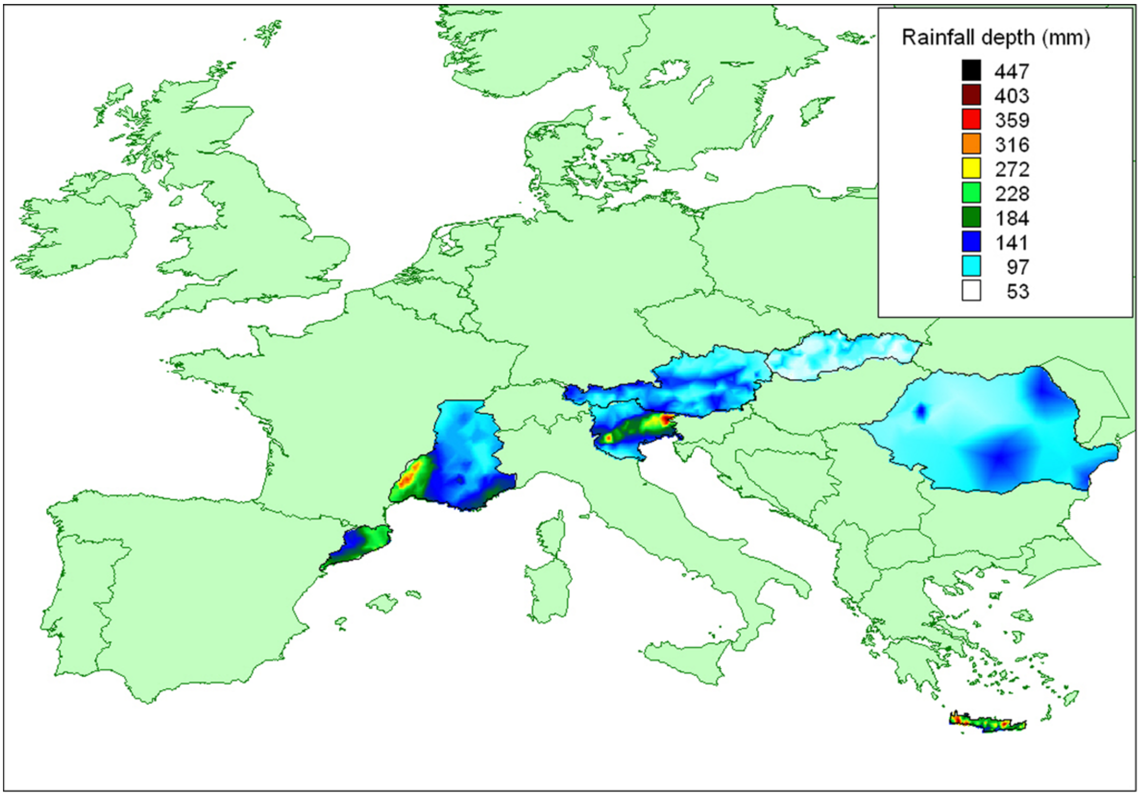

Fig. 5. Distribution of the estimated 100-year return period daily rainfall amounts.

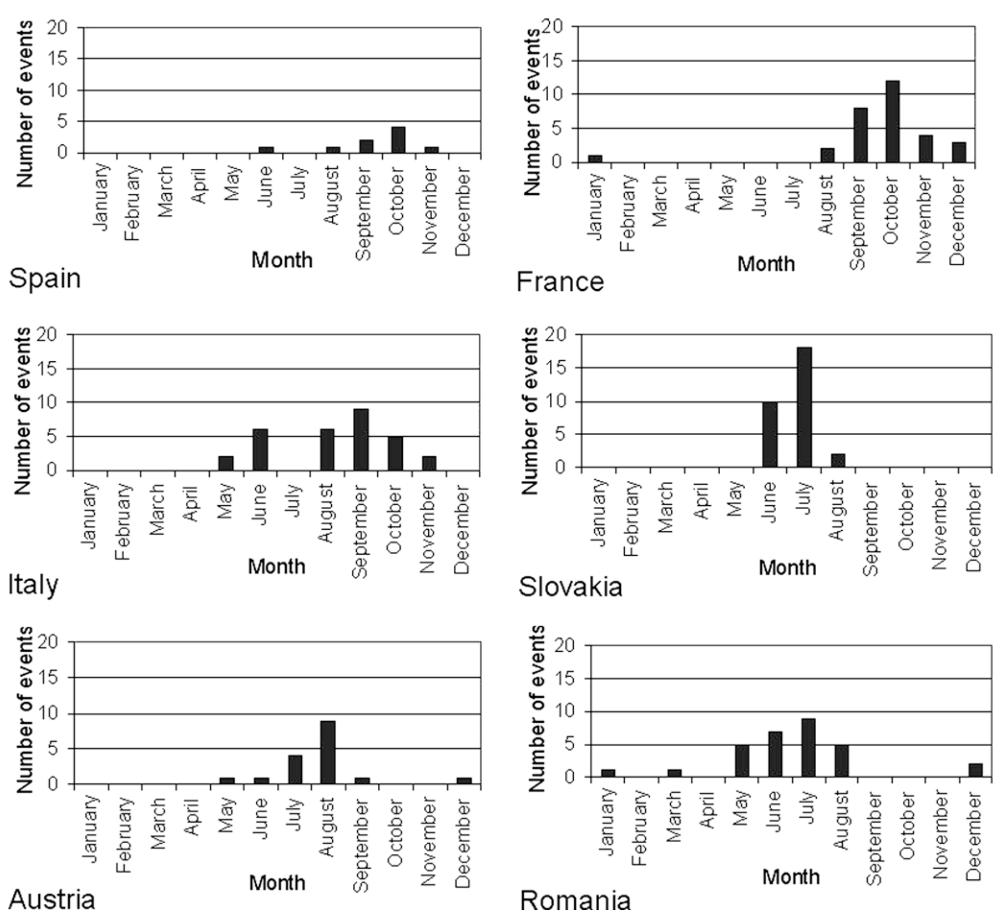

Fig. 6. Number of flash flood occurrences in each month.

Conclusions

Flash flood data from seven hydrometeorological regions in Europe have been collated. The resulting data base is provided at http://www.Hydrate.tesaf.unipd.it/ (European flash flood data center page). The data set is a step towards a European Flash Flood database and atlas of extreme events. Events that occurred between 1946 and 2007 on watersheds of an area less than 500 km^2 were collated. Analysis of the data sets shows that flash floods in each region occur in watersheds of various sizes less than 500 km^2. Nevertheless, in Catalonia and France some records of flash flood events affecting areas greater than 500 km^2 had to be considered as convective storms in the Mediterranean region may potentially cover wide areas (more than 1000 km^2) and cause intense rainfall over a long duration – up to 12 h. The magnitude of the flash flood event is measured in this study by reduced peak discharge. The reduced discharges for past floods in Italy, France and Catalonia have been greater in magnitude than reduced discharges for Romania, Austria and Slovakia, which suggests that flooding in the Mediterranean region is generally more extreme than in inland continental regions. With regard to the time of year during which the flash floods occur in each region, it is observed from the data sets that the most extreme flash floods in the Mediterranean region occur in the autumn months and flash floods in the inland continental region occur in the summer months, revealing different climatic forcing.

The data catalogue may be developed further by extending the inventories within the existing regions and also by including other countries within the data base. With the introduction of the European Floods Directive in 2007 requiring EU member states to have prepared flood risk maps by 2013, there is likely to be an increase in efforts to research and document historic floods as part of the work done to meet the Directive. This may enable access to data that was not readily available to this study. In addition to further developing the data catalogue, it may be interesting to further develop the analyses of the data. This may include statistical approaches to drawing inter-comparisons of the data especially to reveal the heterogeneity of the data between and within the considered regions and to evaluate the return period of the reported extreme events.

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