Mediterranean extreme floods and flash floods

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1.3.4. Mediterranean extreme floods and flash floods

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The Mediterranean area is particularly exposed to flash floods

Floods are weather-related hazards and their patterns are likely to be significantly affected by climate change. Floods are already the most frequent and among the costliest and deadliest natural disasters worldwide (Munich RE, NatCat Service; Swiss RE, 2015). This is also true in the Mediterranean area. The EM-DAT international disaster database (http://www.emdat.be/) lists for instance 200 billion Euros damages related to various disasters since 1900 in the countries surrounding the Mediterranean Sea, out of which 85 billion are related to river flooding.

Disastrous flash-floods[1] are much more frequent in some parts of the Mediterranean region than in the rest of Europe (Gaume et al. 2009; Llassat et al. 2010). This is due to the local climate, which is prone to short intense bursts of rainfall. The reliefs surrounding the Mediterranean Sea force the convergence of low-level atmospheric flows and the uplift of warm wet air masses that drift from the Mediterranean Sea to the coasts, thereby creating active convection. In addition, population growth is particularly high along the Mediterranean coasts, leading to a rapid increase in urban settlements and populations exposed to flooding.

The Mediterranean region is a large area extending more than 4,000 km from west to east and 1,500 km from south to north with spatially variable climatic patterns and population densities. It is characterized by diverse climates, synoptic meteorological conditions and hydrological properties: bedrock and soil types, land use and vegetation cover. The flood regimes and the types of dominant flood generating rainfall events vary significantly along the coasts of the Mediterranean Sea (Llasat, 2016). Damaging floods are mainly produced by:

1. Short-lived (often less than 1 hour) strongly convective intense precipitation events (up to 180 mm/h in only 5 minutes) but limited total rainfall amounts (generally less than 100 mm). Such events have a limited areal extent (typically less than 100 km^2) and generate local flash floods of small headwater streams. A typical example of such flash floods is the catastrophic flood that occurred in Algiers in November 2001.
2. Mesoscale convective systems can produce stationary rain lasting several hours leading to rainfall amounts exceeding 200 mm in a few hours. In France, up to 700 mm of rainfall within 12 hours was locally recorded during floods in the Aude region in November 1999 and in the Gard region in September 2002. The areal extent of such events ranges from several hundred to several thousand km^2. These events mainly occur in fall and affect the north-western coast of the Mediterranean Sea. The flash floods that occurred in Genoa, Italy, in October 1970 and in the Var region of France in June 2010 belong to this category.

[1] Flash floods are induced by short duration - from less than one hour to 24 hours - and heavy rainfall convective events – typically 100 mm or more rainfall accumulated over a few hours. The affected areas are often limited to a few hundred square kilometers, with rapid hydrological responses – generally less than 6 hours delay between peak rainfall intensity and the peak discharge downstream.

3. On some occasions, heavy and sustained rainfall may be part of a large scale perturbation lasting several days. In such cases, extreme rainfall accumulation may be observed locally: 1,500 mm over four days and a record of close to 1,000 mm in 24 hours in October 1940 in the eastern Pyrenees in France. These events cover a large area. Typical examples were the October 1969 heavy rainfall and flash flood in South Tunisia (more than 300 killed) and the October 1940 event that affected both sides of the Pyrenees: the Ter river valley in Spain (90 killed) and the Tech and Têt river valleys in France (44 killed).

Total rainfall amounts as well as land use, soil and bedrock types and the initial soil moisture content influence the responses of watersheds to heavy rainfall events and especially their runoff rates: the estimated proportion of the incident rainfall contributing to the observed stream discharges. The runoff rates during flash floods are often limited to 10% to 30%. In some rare cases, when large cumulated rainfall amounts lead to saturation of the watersheds, runoff rates may reach 100% (Marchi et al. 2010). The observed variability of flood frequencies and discharge magnitudes is therefore the result of complex interplay between the characteristics of the generating rainfall events (spatial extent, duration, maximum intensities) and the factors that control the response of the watersheds, especially rainfall rates.

Sources of information about flood magnitudes and impacts

Information on flood characteristics and magnitudes comes from a wide range of sources (databases, the press, local technical reports) that are incomplete and often not entirely accurate. It is therefore difficult to build comprehensive databases to better understand the spatial pattern and climatology of large flood events. The number of fatalities, sometimes damage estimates, is the type of information that can be collected most easily, mainly from press reports, and is typically the type of information collected in the EM-DAT International Disaster Database (http://www.emdat.be/) or the Dartmouth global archive of large flood events (http://www.dartmouth.edu/~floods/) or in the Italian AVI flood database or the database on Mediterranean floods created in the framework of the HYMEX European research project (Llasat et al. 2013). Re-insurance companies such the Munich Re (CAT NAT Service) and the Swiss Re (Sigma reports) also gather information on damage costs worldwide but which is nevertheless only accessible in a synthetic form. As illustrated in figure 1, such databases should be interpreted with caution. The information collation efficiency is for instance increasing with time and thanks to the improved circulation of information on Internet and the social networks. The EM-DAT seeks to collect information on disastrous events that meet one of the following criteria: at least 10 people killed, 100 people affected, a state of emergency was declared and there was a call for international assistance. Clearly, the number of floods documented in this database has increased since its creation. Can this be interpreted as a sign of a trend? The total number of reported annual fatalities does not show the same trend, suggesting that a larger number of moderate floods have been included in this database in the recent period, but that the number of catastrophic events has not significantly changed. Lasatt et al. (2013) came to the same conclusion.

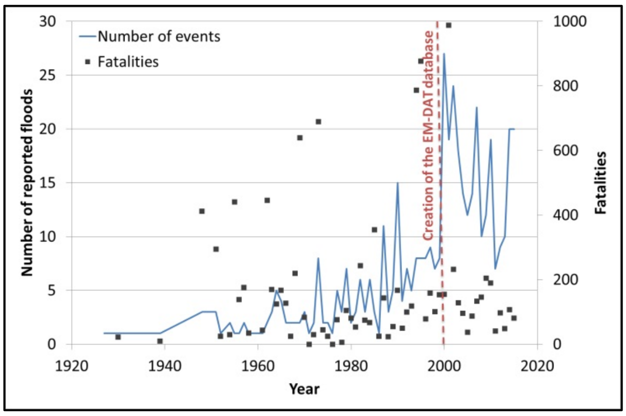

Figure 1. Changes in the number of damaging floods in the countries surrounding the Mediterranean Sea in the EM-DAT database (source: emdat.be)

Moreover, the amount of damage and the number of fatalities are only indirectly related to the magnitude of the floods and are also strongly determined by local exposure and vulnerability. Both vary in space and over time. Major population and economic growth has taken place along the Mediterranean coast in the past century, with both huge densification and extension of urban settlements outside but also inside flood prone areas. This has led - and continues to lead - to a general increase in flood exposure and in economic vulnerability and costs. At the same time, newly constructed buildings are more resistant to flooding, thereby providing better shelter; warning systems and emergency management has improved and may reduce the number of fatalities. Observed spatial distributions of costs and fatalities are the result of complex interplay between different explanatory factors. It is useful information that reveals the economic and social impact of floods on our societies but its interpretation is questionable.

Table 1. Contents of the database of notable Mediterranean flash flood events for the period 1940-2015.

Country	**Number of events**	**With discharge estimates**	**Sources**
Algeria	20	1	Sardou et al. (2016), Recouvreur (2005), press
Egypt	3	0	Internet and press
France	40	38	Hydrate, recent surveys by the authors, press
Greece	22	5	Hydrate, press, Pappanagiakis et al. (2013), Diakakis et al. (2015)
Israel	11	11	Tarolli *et al.* (2012)
Italy	46	36	Hydrate, Anselmo (1985), Barredo (2007), recent surveys, press
Lebanon	1	0	Press
Morocco	7	7	Hymex database
Portugal	1	0	Press
Slovenia	1	1	Survey by the authors
Spain	16	11	Hydrate, LLasat et al. (2013), Barredo (2007)
Tunisia	3	2	Press and technical reports
Turkey	1	0	Press
Total	**172**	**112**	

Flood discharge estimates are therefore indispensable to describe and analyze the geographical patterns of floods, detect possible trends and enable comparisons between countries and sub-regions. But major floods and especially flash floods are difficult to document, as they affect small headwater watersheds that are not monitored. Direct discharge measurements are seldom available and discharge values have to be estimated using indirect methods that may sometimes lead to large errors, especially overestimations, even if significant progress has been made in recent years. Thanks to various European (HYMEX, HYDRATE, FLASH) and national research projects, the number of documented extreme floods has increased significantly in recent years. For the purpose of this paper, we collected information to build a sample of 172 documented extreme floods (Table 1). The database covers the largest floods since 1940 reported in the countries concerned either according to their estimated discharges or to the number of deaths: events with more than 10 deaths were selected when no discharge estimates were available (39 events) except for Greece for which a larger dataset was available.

Estimated discharge was available for 112 reported flood events. Despite the large number of values available, only one representative value – not necessarily the largest one, as it could be overestimated - was selected for each flood event on any one date in one region. Events including dam failures were not included: the Moulouya valley floods in Morocco (May 23, 1963, 170 killed), the Fréjus catastrophe in France (October 2, 1959, 423 killed), the Vajon dam failure in Italy (October 9, 1963, 2400 killed), and the Val di Stava dam failure in Italy (July 19, 1985, 268 killed).

Magnitudes and seasonality of extreme floods around the Mediterranean Sea

Analysis of deaths related to flood events

Figure 2 shows a clear contrast between the reported deaths in the eastern and western parts of the Mediterranean region. The contrast concerns both the spatial density of the events that killed more than 10 people and the average number of deaths per event. This conclusion remains valid even if the two most dramatic events occurred in Algiers (2001, 896 killed) and the town of Rubi near Barcelona in Spain (1962, 815 killed) are removed. Floods generally caused few casualties in the eastern part of the Mediterranean region, with the notable exception of the flood in Tripoli Lebanon on December 17, 1955 (around 160 deaths) induced by a rainfall event of short duration: 100 mm of rain fell on the city of Tripoli and its surroundings in two hours (De Vaumas, 1957).

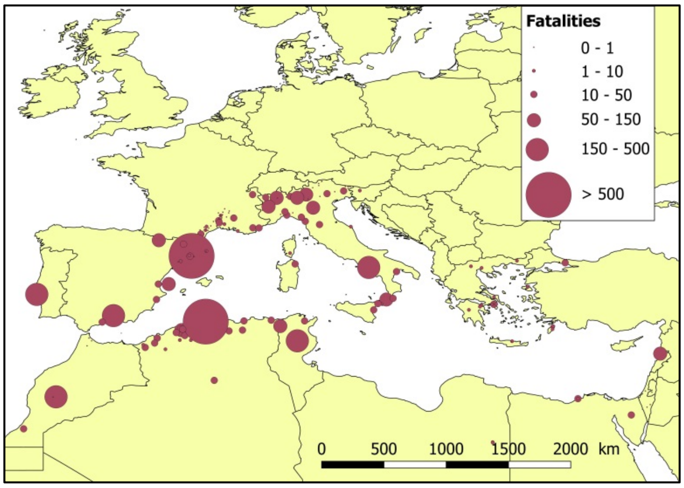

Figure 2. Number of people reported killed in each documented flood event over the period 1940-2015

The contrast was confirmed by analysis of the EM-DAT database (see Figure 3). The average number of people killed each year during river floods ranges between seven in France, most of which in the Mediterranean region, and 30 in Algeria, both western Mediterranean countries, whereas in eastern

Mediterranean countries, the number does not exceed two. These figures are also underestimated since moderate floods are not recorded in the EM-DAT database, despite being in the correct range of magnitude. For instance, the average number of people killed due to floods in Greece is four based on comprehensive flood databases established for Greece (Pappagianaki et al. 2013; Diakakis and Deligiannakis, 2015).

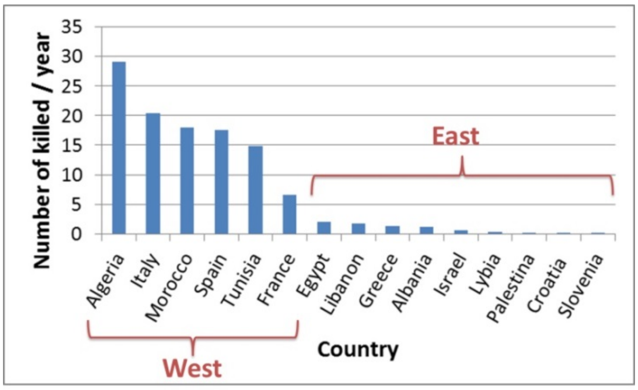

Figure 3. Average number of people reported killed per country and per year by floods over the period 1940-2015 in the EM-DAT database (source: emdat.be)

Analysis of major flood peak discharges

The estimated peak discharges of the major floods confirm the observed contrast based on the number of deaths, even if the information concerning eastern Mediterranean countries in the database is not complete (figure 4). To be able to compare discharge values for a large range of watershed areas and to rate the magnitudes of the reported floods, reduced discharges are mapped in figure 4 according the suggestion of Gaume et al. (2009). The reduced discharge Q_r is the ratio of the discharge value Q (m^3/s) to the upstream watershed area A (km^2) at a power 0.6: $Q_r = Q / A^{0.6}$.

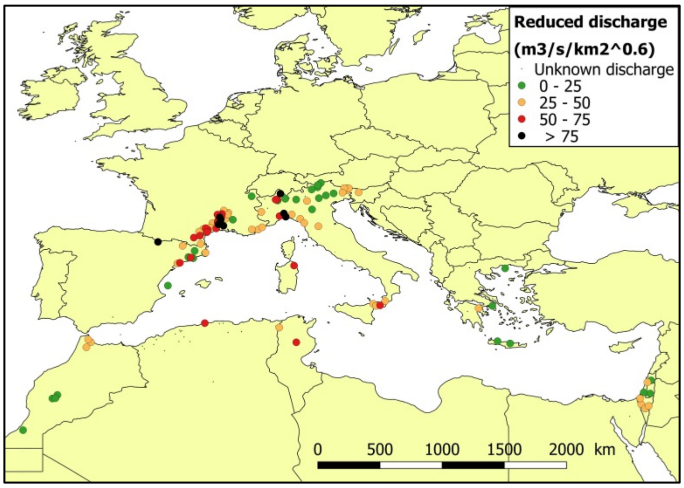

Figure 4. Estimated reduced peak discharge of the documented flood events over the period 1940-2015. The reduced discharge Q_r is $Q/A^{0.6}$, Q is the peak discharge (m^3/s) and A is the watershed area (km^2).

Reduced discharges exceeding 50 have only been reported in the western part of the Mediterranean region. Such extreme discharges appear to be more frequent in the north-western Mediterranean region, more particularly in some hot-spots: the Piedmont and Liguria regions in Italy, the Cevennes-Vivarais-Roussillon region in France and Catalonia in Spain. These areas are preferentially affected by longer lasting stationary rainfall events in the fall, leading to high runoff rates and hence high discharge values (Gaume et al. 2009).

The spatial heterogeneity of extreme discharge magnitudes is clear in Italy and France, and the flood database is close to complete for these two countries. It needs completing for Spain and North Africa for which only partial datasets are available at the present time.

Seasonal distribution of extreme flood events

Fall is the main season but not the only one in which extreme floods occur in the Mediterranean region (Figure 5).

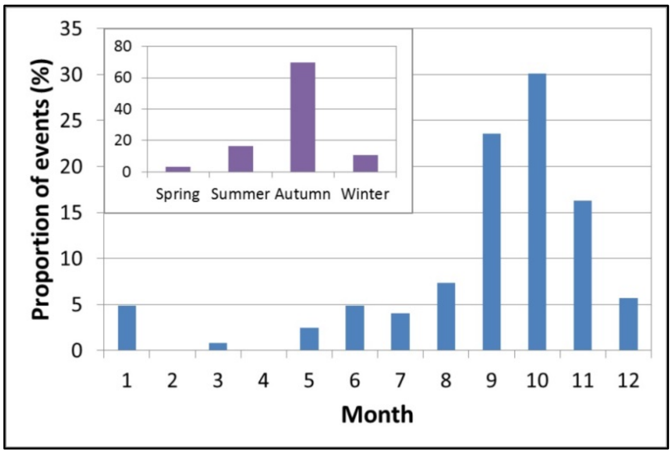

Figure 1. Monthly and seasonal distributions of the documented floods over the period 1940-2015

The same seasonal distribution is observed in the eastern part of the area even if it is less pronounced – however, this conclusion is based on an incomplete dataset. The occurrence of summer floods is notable in the Alps and more generally in mountain areas, as illustrated by the Ourika flood in the Moroccan Atlas (August 8, 1995) or the Barronco de Aras flood in the Spanish Pyrenees (August 8, 1996). Spring floods are indeed rare but when they do occur, can have significant impacts, as did the Sarno flood in Italy (May 5, 1998, 147 killed) and the Var floods in France (June 6, 2010, 25 killed). Extreme floods in winter mainly occur in North Africa and Greece.

Extreme Mediterranean floods compared to world figures

Figure 6 compares the dataset of extreme peak discharges in the Mediterranean region analyzed here with values extracted from other flood catalogues. Some major events are highlighted in the figure to illustrate two facts:

1. The most fatal events (Algiers 2001 and Barcelona 1962) do not necessarily have the largest peak discharge values. This confirms that the local risk is the result of the interplay between hazard – described by the possible magnitude of the peak discharge and local exposure and vulnerability.
2. Few reported world records exceed the proposed envelope curve for the Mediterranean ($Q = 100\ A^{0.6}$). It should also be noted that several past records may have been overestimated (Lumbroso et al. 2012). Some sub-regions of the Mediterranean area, Liguria, Cévennes-Vivarais, appear to be exposed to floods whose magnitudes are comparable to world records.

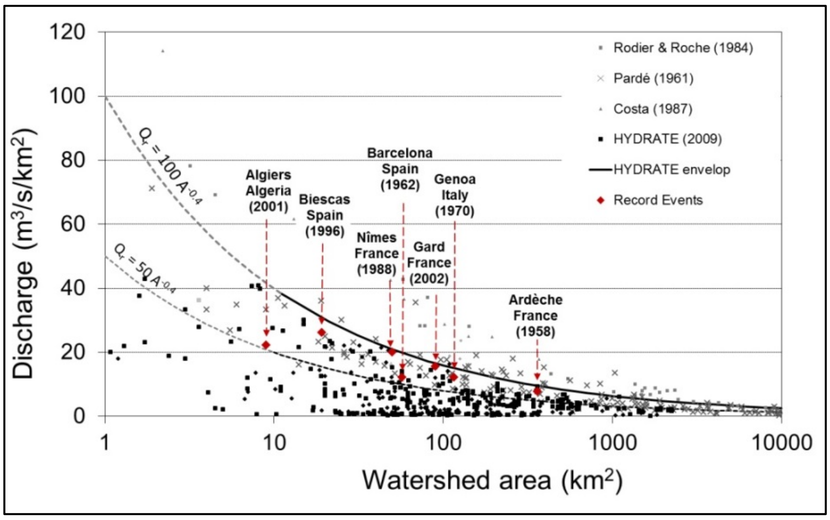

Figure 2. Reported estimated world records from different sources, proposed European envelope curve and some selected European record events since 1940

Observed trends in flood magnitudes and frequency and projections

The numerous studies conducted, especially in Europe, report contrasted trends for extreme streamflow with both positive and negative trends, with variable statistical significance and no clear structured pattern (Madsen et al. 2014). There are no clear national or large-scale regions in Europe with uniform statistically significant increases in flood discharges in recent years, although some trends appear for smaller regions.

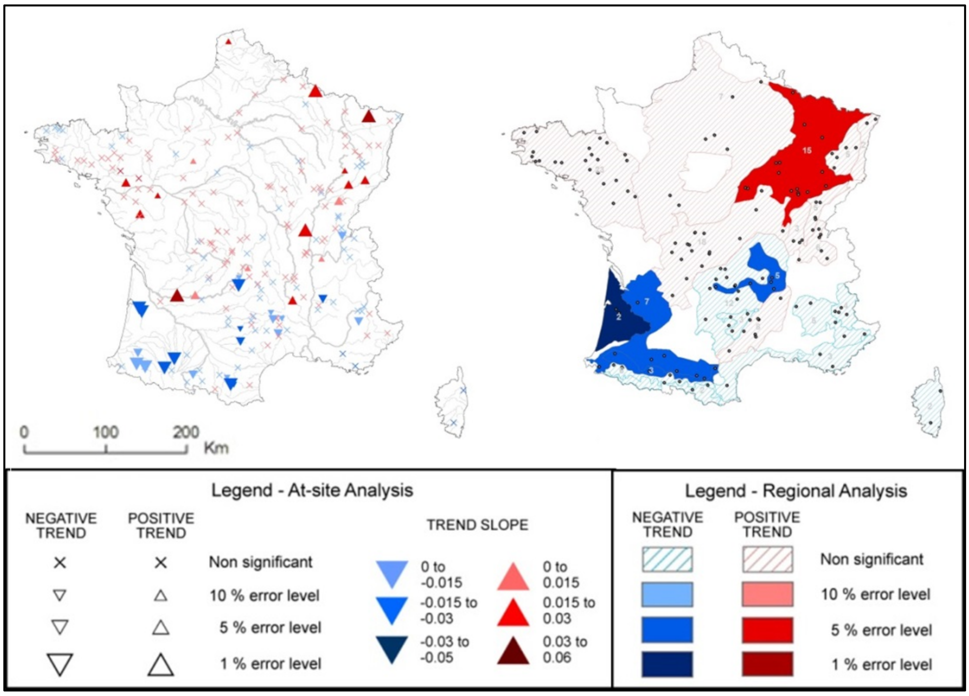

Figure 3. Trends in annual maximum streamflow in France based on local and regional tests (Giuntoli *et al.*, 2012).

Figure 7 illustrates the type of results of trend detection studies in France: trends in annual maximum peak discharges (Giuntoli et al. 2012). The analysis was based on a rich dataset of 209 stream gauge measurements covering the period 1968-2008 and two statistical tests conducted on each individual series (local test) and on regional samples of series to gain robustness (regional test). A limited number of series or regions showed a statistically significant trend. It is interesting to note a general and unexpected decreasing tendency in southern France that is spatially consistent if not statistically significant. The main conclusion is that if some trends exist, they are almost impossible to detect due to the limitations of the available datasets, especially on extreme events. Likewise, recent streamflow projections based on Euro-Cordex climate projections led to significant forecasted changes in river flood frequencies in Europe but to less clear results for the Mediterranean region (Alfieri et al. 2015).

Conclusions

Our knowledge of floods in the Mediterranean area has advanced substantially in recent years thanks to the development of databases and focused research programs. A general pattern of the spatial and seasonal distribution of flood magnitudes can now be established as reported here. The main characteristics of the floods around the Mediterranean Sea are the following:

1. The magnitude and impact of extreme floods vary significantly over the Mediterranean region with a clear contrast between west and east. The western part of the area is much more exposed to high impact and high magnitude events. This is probably due to the proximity of the Atlantic Ocean and oceanic climatic influences at latitudes where eastward atmospheric flows dominate.

2. Some sub-regions, including Liguria and Piedmont in Italy, Cévennes-Vivarais-Roussillon in France, and Catalonia and the Valencian province in Spain are particularly exposed to extremely severe floods whose peak discharge values may be close to world records. This particular pattern is the result of the interplay between the dominant atmospheric low level flow circulation patterns and the relief and orientations of the northern Mediterranean coast, which force convergence and trigger convection (Ducrocq et al. 2014).

3. Fall is clearly the main season - but not the only season - for extreme and damaging floods. This is particularly the case of mesoscale convective systems producing long lasting and stationary rainfall events that lead to strong responses by the watersheds concerned (i.e. high runoff rates due to soil and subsoil saturation) and to extraordinary peak discharge values.

4. No significant trend was detected in the frequency and magnitude of extreme floods in the Mediterranean region to date, probably due to the limitations of the available datasets and some complex overlapping signals (e.g. decadal and inter-decadal variability). Likewise, the existing projections do not clearly point to a change in extreme flood patterns in the Mediterranean region linked to climate change. But, whatever the case may be, the risk of flooding is likely to increase due to population growth and urban development in flood prone areas in the coming years.

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