

**Rainstorms able to induce flash floods in a Mediterranean-climate region
(Calabria, southern Italy)**

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Abstract

Heavy rainstorms often induce flash flooding, one of the natural disasters most responsible for damage to man-made infrastructure and loss of lives, adversely affecting also the opportunities for socio-economic development of Mediterranean Countries. The frequently dramatic damage of flash floods are often detected with sufficient accuracy by post-event surveys, but rainfall causing them are still only roughly characterized. With the aim of improving the understanding of the temporal structure and spatial distribution of heavy rainstorms in the Mediterranean context, a statistical analysis was carried out in Calabria (southern Italy) concerning rainstorms that mainly induced flash floods, but also shallow landslides and debris-flows. Thus a method is proposed – based on the overcoming of heuristically predetermined threshold values of cumulated rainfall, maximum intensity, and kinetic energy of the rainfall event – to select and characterize the rainstorms able to induce flash floods in the Mediterranean-climate Countries. Therefore the obtained (heavy) rainstorms were automatically classified and studied according to their structure in time, localization and extension. Rainfall-runoff watershed models can consequently benefit from the enhanced identification of design storms, with a realistic time structure integrated with the results of the spatial analysis. A survey of flash flood events recorded in the last decades provides a preliminary validation of the method proposed to identify the heavy rainstorms and synthetically describe their characteristics. The notable size of the employed sample, including data with a very detailed resolution in time, that relate to several rain gauges well-distributed throughout the region, give robustness to the obtained results.

Keywords: Rainfall, flash flood, time structure, regional analysis, sub-hourly scale, Mediterranean area, Calabria

1. Introduction

Many regions belonging to the Mediterranean basin are prone to a large number of catastrophic hydrological events with loss of life, injured, high economic and social impact (Jansà et al., 1994; Siccardi, 1996; Gaume et al., 2009). During the period 1960-2009, 298 floods occurred current EU member states (www.emdat.be), causing almost 5500 casualties, and resulting in close to 106 billion US \$ in damage. 33 of the floods were categorized as “flash floods”, 81 as a “flood”, 184 as a “general flood”. More recently, the event that affected the Italian regions Sardinia and Calabria on 18th and 19th November 2013 (caused by the well-known cyclone Cleopatra), produced 16 fatalities and overall losses quantified in 780 thousands US \$ (Munich RE, 2014).

In recent decades because of climate change, both violence and the frequency of torrential rain events (i.e., $> 64 \text{ mm d}^{-1}$) are increased (Alpert et al., 2002), despite the decrease of the annual rainfall in the Mediterranean basin (Piervitali et al., 1998). Analysing rainfall patterns, Lionello et al., 2006, have highlighted a huge spatial and temporal variability of precipitation in the Mediterranean basin. In Italy, Brunetti et al. (2004) detected a significant decrease in both annual precipitation and annual number of wet days, and an increase in the precipitation intensity. Working at regional scale, Brunetti et al. (2012) found a significant negative trend of total annual precipitation in Calabria (southern Italy) over the period 1923-2006. With regard to the monthly total precipitation, they detected a general negative trend, albeit not everywhere significant, for the autumn–winter period, and a slight increase in the summer total precipitation.

Flash floods occur when, in a few hours, heavy rainfall events affect, with hundreds of millimetres of rain, small basins (Creutin and Borga, 2003; Collier, 2007; Younis et al., 2008). In the Mediterranean-climate regions, low permeability and highly erodible soils often characterize these small basins (typically below a few hundred km^2), whose slopes are often very steep and susceptible to landslides. Ultimately, the runoff times of the basins considerably favours the formation of flash floods due to the processes of runoff with very fast response (Creutin et al., 2009). The huge damage caused by flash floods are notable also due to the high content of solid material (including floating materials such as timber) from the riverbed and from soil slips and mud/debris flows that take place on the slopes. The potential for damage of flash floods is highly due to the high population density of the Mediterranean coastal regions. Even in the face of increasingly more precise weather forecasting for civil protection purposes, it is still very difficult to predict with adequate accuracy the areas that will be struck by these catastrophic events. Then special attention is given to the study of spatial and temporal variability of rainfall, as these basins are very rarely equipped with sensor networks (and/or monitored by weather radar) dedicated to the direct measurement of the parameters related to the physical processes of interest. In fact, being the hydrological response controlled by rainfall, proper understanding, interpreting and forecasting of spatial and temporal variability of rainfall events is a prerequisite for the adoption of appropriate mitigation measures and reducing the connected risk. On the other side, watershed models are increasingly complex and require more detailed precipitation input to drive the hydrologic processes to be satisfactorily simulated. This input is rarely available at the appropriate time scale (at the order of minutes) and does not have sufficient coverage in space.

Because of its geographical location, its topography and for its mountainous nature – with mountain ranges perpendicular to the direction of the main wet currents – despite its small size, Calabria is affected by rains highly variable in both time and space Terranova and Iaquineta (2011). Thus, Calabrian territory appears adequate to represent the characteristics of rainfall of many geographical areas of the Mediterranean basin.

The present study is an attempt to improve, from a statistical point of view, the understanding at sub-hourly scale of the temporal and spatial structure of intense rainfall events that have hit Calabria, inducing mainly flash floods, but also shallow landslides and debris-flows.

2. Geographical framework and climatic outlines

Calabria (Fig. 1) is a long and narrow peninsula, covering an area of about 15,080 km² and stretching from North to South for 248 km. It is bounded by the Tyrrhenian Sea, on the West, and by the Ionian Sea, on the South and on the East.

Five main ridges mark, from North to South and with maximum altitudes varying from 1500 to 2000 m a.s.l., the topography of Calabria: Pollino, Catena Costiera, Sila, Serre and Aspromonte. These mountains have very steep slopes; in fact, starting from the level of the sea, only a few tens of kilometres are needed to reach the highest altitudes. The narrowest part of the Calabrian peninsula is the Isthmus of Catanzaro (a gap between the southern end of Sila and northern part of Serre mountain ridges) that is approximately 31 km in width. The maximum width, between Punta Alice and Capo Bonifati, is of ca. 111 km.

Calabria, because of its rugged orography, has a large number of small drainage basins. Only a small part of their courses flow on plains; in particular, rivers that originate from the Catena Costiera have very pronounced slopes. In fact, the extension of the Tyrrhenian side is lesser than the Ionian one (Fig. 1). On the former side, only two streams have the hydrological regime of a river: the Lao River, due to the large number of karstic springs in its basins; and the Mesima River, because of its extension. On the Ionian side, the Crati River flows in a tectonic graben draining the largest basin in Calabria, collecting waters coming from surrounding mountains and forming the Plain of Sibari. Other relatively large rivers drain the eastern side of Sila massif. In the northern and southern portions of the Ionian side of Calabria, a great deal of streams with typical braided riverbeds drains the steep slopes of the mountains and reaches the sea after passing a narrow hilly belt. These streams are the Calabrian *fiumare* (Sorriso-Valvo and Terranova, 2006), that (like most other small Calabrian streams) have a hydrological regime closely correlated with rainfall, also in reason of the low permeability of soils. Then, in the absence of direct hydrometric measurements, the peak discharge rates can be estimated only based on sub-hourly rainfall.

In Calabria, an average yearly rainfall of 1150 mm corresponds to noticeable seasonal contrasts and to a high variability over Calabria. The eastern side is less rainy than the western one, especially as the disturbances come frequently from the West and discharge some of their load of rain on the Sila plateau in their movement to the East. The Catena Costiera and the Serre mountain ranges are rainier than the Sila plateau, partially shielded from the first mountain range. Yearly average precipitation is >2000 mm on the Catena Costiera and the Aspromonte Massif, whereas precipitation on the Ionian mountain slopes is 600-1000 mm, with values of ~500 mm along the coastal plains. With reference to seasonality, the abundant rains during autumn and winter (more than 70% of yearly total precipitation falls from October to March) along the Tyrrhenian slopes and, more heavily, on the Ionian side, must be highlighted (Terranova, 2004). These features and snowfall in the mountains contrast with subtropical climatic conditions in the valley and along some stretches of coast.

Coastal mountains strongly influence the precipitation regime, because of the fronts and convective cells ascending their steep seaside slopes. *Föhn* blows to the lee-side of the mountain chains causing drier and warmer climate in the largest valleys. In all seasons, low-pressure conditions cause intense and prolonged rainstorms brought by warm fronts approaching from the SE, bringing red silt-rich rains and very uncomfortable warm and wet *Scirocco* conditions. Cold fronts from Icelandic zone may reach Calabria from the N-W especially in winter, with high intensity rainfall. In the short spring, the weather is highly unstable with scarce and drizzly rainfall. In summer, strong convective rainstorms are frequent, sometime small

tornados may form on the sea that may reach inland. In autumn, Siberian cold fronts that may approach from the N-E cause intense precipitations. Cold fronts, approaching Calabria from the N-W in winter, are the cause of extremely intense rains and, in some cases, of a thick snow cover that may form also at low elevations (Sorriso-Valvo and Terranova 2006; Terranova et al., 2009).

With regard to annual maxima of high-intensity and short-duration rainfall, Versace et al. (1989) delimited three homogeneous rainfall regions in Calabria, including: (i) a Tyrrhenian region (T, 25.8% of the region) along the western Tyrrhenian coast, (ii) a Central region (C, 44.3 %), comprising the mountain ranges along the main divide, and (iii) an Ionian region, along the eastern Ionian coast (I, 29.9 %). They found that the Tyrrhenian rainfall region is characterized by more frequent and less severe rainfall events than the Ionian rainfall region, whereas the Central rainfall region has events with intermediate characteristics.

The main part of Calabria is characterized by a typically Mediterranean climate (*Csa* - Hot-summer Mediterranean climate) in Köppen's (1948) classification, with dry and hot summers and low average temperatures. The remaining portions (inland and not vallive areas) are classified as *Csb*, or *Cfb*, or *Cfa* (Warm summer Mediterranean, or Maritime Temperate, or Humid subtropical climate, respectively - cfr. Iaquina and Terranova, 2010).

As an average, temperature features of Calabria are summarized as follows: (i) the annual values range from 10°C on the mountain slopes to 18°C along the coast; (ii) August is the hottest month and January the coldest; (iii) the daily values may exceed 40°C in July and August; (iv) January presents 10°C along the coasts and 4°C in the mountains; (v) values below 0 °C may often occur on Sila and Aspromonte (Terranova et al., 2009).

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147 **3. Rainfall data and rainfall events**

148 Thanks to the availability of observations with high temporal detail (5-minutes) related to 155 sites (one
149 rain gauge per less than 100 km²), a considerable amount of rainfall series were analysed in order to
150 contribute to the quantitative and qualitative characterization of extreme events affecting Calabria.

151 To identify a single rainfall event many criteria could be adopted, aimed at determining the time-span
152 between the end and the beginning of two consecutive individual rainfall events. The classification of
153 events on a meteorological basis shows that, in a small basin, there can be events characterized by widely
154 differing duration and extension (Houze, 1969). In the same way, a statistical analysis of rainfall time series
155 allows us to distinguish events which are independent one another without however contributing very
156 much to the aim of the present study (see, among the others, Restrepo-Posada and Eagleson, 1982). The
157 choice of the authors was based on average characteristics of watersheds in Calabria in relation to the
158 process of flash flood development (Colosimo et al., 1996; Joo et al., 2014). Based on the size of these
159 watersheds, values roughly ranging from one to a dozen hours may be assumed as the time period from
160 the end of a rainfall event to the end of its direct contribution to surface runoff. Then a minimum value of
161 6 h seems reasonable in order to ensuring that significant surface runoff cannot be added to either of two
162 subsequent events. This criterion is consistent with that proposed by Wischmeier and Smith (1978), and
163 since the flash floods are usually characterized by considerable amount of sediments resulting from the
164 dismantling of the slopes, those rainstorms were selected that, according to these authors, are to be
165 considered erosive.

166 More in detail, distinguishing individual rainstorms as rainy periods separated by at least 6 hours of dry
167 weather (Wischmeier and Smith, 1978), the study initially considers more than 152 thousands rainstorms,
168 having different durations, recorded in different seasons between 1989 and 2008 at 155 rain gauges in
169 Calabria. Accordingly, 45,533 erosive rainstorms, including 27111 rainstorms with rainfall amount (P_{EV})

greater than 12.7 mm, and 18422 having $P_{EV} \leq 12.7$ mm but exceeding 6.35 mm in 15 minutes, were selected as relevant and analysed.

4. Preliminary analysis of rainstorms

An analysis was carried out to characterize, in a simple but effective way, the rainfall events with regard to magnitude, frequency, locations, temporal structure and pattern, season of occurrence. In this phase of the study, the analysis does not refer to areal rainstorms. The 45,533 selected rainfall events:

- i) have P_{EV} comprised between 6.4 and 602.2 mm, with a mean value of 23.5 mm;
- ii) last from durations, D_{EV} , equal to 10 minutes to approximately 10 days, with a mean value of ~ 15 h;
- iii) range from negligible values of maximum rainfall intensity in 30 minutes, I_{30} , up to $154.8 \text{ mm}\cdot\text{h}^{-1}$, with mean value $11.6 \text{ mm}\cdot\text{h}^{-1}$;
- iv) have energy, E_j , ranging from 0.83 to $\sim 138 \text{ MJ}\cdot\text{ha}^{-1}$, with mean value of $\sim 4.6 \text{ MJ}\cdot\text{ha}^{-1}$.

The temporal storm structure was described as cumulative percentages of storm rainfall and storm duration, by means of the standardized rainfall profiles (SRP - Huff, 1967; 1990), allowing and simplifying the analysis, presentation and comparison of data. Moreover, Huff's study adopts the definition of rainfall event proposed by Wischmeier and Smith (1978) and adopted in this work. The main attraction of the use of SRP lies in the fact that it is based on actual data of regional precipitation; its weak point is that large samples of data are required to obtain regional profiles. The analysis of the SRP can be performed to disaggregate the precipitation totals or even to derive other types of information. At this purpose, the rainfall events can be classified according to various criteria: duration, total rainfall, maximum intensity in a fixed time or average intensity, energy of the storm, geographical area of occurrence, etc. More in detail, the proposal of Terranova and Iaquineta (2011) was adopted to better identify, in an automated environment, the shape of the profile (Fig. 2) based on the comparison between the areas A_1, A_2, A_3, A_4 – underlying the four quarter of durations of the SRP, relatively to each single event – with the corresponding four values of the uniform SRP (URSP). More precisely, a 4-digit binary shape code, BSC, was determined, as follows: the generic k -th ($k = 1, 2, 3, 4$) threshold was defined corresponding to the area A_k^* underlying the

four quarter of the uniform SRP: $A_k^* = \frac{1}{2} \tau_k^2 - A_{k-1}^*$, with $A_0^* = 0$, and $\tau_1 = 0.25, \tau_2 = 0.50, \tau_3 = 0.75, \tau_4 = 1$. The

analogous four values of the area A_k underlying the generic SRP were compared to A_k^* obtaining the Binary Shape Code, $BSC = S_1 S_2 S_3 S_4$, based on the logical condition: if $A_k > A_k^*$, $S_k = 1$; vice versa $S_k = 0$. As a result, a binary shape code, BSC, was associated to each SRP. The informative content expressed by the BSC is more complete than that expressed by Huff's quartiles. BSC describes the profile as a whole, while Huff's quartiles describes only a quarter of duration, but does not depict the rest of the profile.

In Fig. 3 the BSC classification of the four most numerous SRP recorded in Calabria are reported, also distinguishing them according to Huff's quartiles. Only eight of 16 types of BSC occur with frequencies higher than 2%. Statistical analyses showed that SRP corresponding to the eight remaining BSC do not possess, on average, high values of P_{EV} , D_{EV} , I_{30} . The SRP with 1111 BSC, typical of thunderstorms (Fig. 2), occurs in over a third of the examined events, as reported in Terranova and Iaquineta (2011). By means of the BSC code and the SRP, figure 2 aims at comparing the structures of a theoretical thunderstorm and of a convective event recorded in south-west England. The thunderstorms are a particular case of convective storms, meteorologically associated to cumulonimbus. Anyway, sometimes the thunderstorms are included in a mesoscale convective system, whose rainfall typically derive from convective clouds and from stratiform clouds. The same BSC code describes the two rainfall structures.

View to introducing the topics that will be discussed in the next paragraphs, the most severe 2% of the 45,533 erosive events were selected. More in detail, 903, 909, and 909 events were detected, characterized respectively by $P_{EV} \geq 100$ mm, $I_{30} \geq 44$ mm·h⁻¹, and $E_J \geq 20$ MJ·ha⁻¹. Focusing on rainstorms characterized by $P_{EV} \geq 100$ mm, they result characterized by the I_{30} , E_J and D_{EV} values reported in Table 1. Regarding the comparisons shown in Fig. 4a-d, just the SRP relative to $I_{30} < 44$ and $I_{30} \geq 44$ mm·h⁻¹ may be distinguished as concerns both their variability and the 50% fractile (the 50%-SRP related to $I_{30} \geq 44$ mm·h⁻¹ shows a more marked “S-shape”). From the remaining comparisons, only limited differences of the variability can be noticed. In addition, the following observations can be summarized:

- throughout the two decades of observation period, the threshold $P_{EV} \geq 100$ mm was exceeded several times (903) on over the regional territory and 9 times in at least 20 rain gauges (Fig. 5a); this threshold was more frequently exceeded from November to January;
- by operating the selection shown in Fig. 5b, the threshold $I_{30} \geq 44$ mm·h⁻¹ was exceeded 6 times in 20 or more rain gauges; such threshold was more frequently exceeded from August to November;
- the threshold $E_J \geq 20$ MJ·ha⁻¹ was exceeded 9 times at a number of rain gauges greater than or equal to 20 (Fig. 5c); this threshold was more frequently exceeded from November to January.

The events exceeding these three thresholds are more frequent in the southern portion and in south-eastern side of Calabria (Fig. 5a, b, c). More precisely, as regards the eventual interrelation between the characteristics of the SRP and the locations of the rain gauges, the comparisons between SRP of events recorded in the lowest (<600 m a.s.l.) and the highest (≥ 600 m a.s.l.) elevation class and between the SRP of events occurred in the Ionian and Tyrrhenian homogeneous rainfall regions of Calabria show significant likenesses. Just a small variability may be attributed to the Ionian side of the region. Moreover, the comparison between rainfall profiles of events occurred in the four wettest and four driest months, reported in Fig. 6, highlights a lower variability for the wet season. In addition, advanced peaks characterize the storms of the dry season, in which convective events are more frequent.

5. Method

With the purpose of analysing the spatial and temporal characteristics of very severe rainstorms, a further selection of the events was conducted, based on the values of the parameters P_{EV} , I_{30} , E_J . In this regard, to identify rainstorms with the greatest potential to produce a strong social impact and increase the perception of risk associated with the interaction between nature and society, was assumed that the above-mentioned parameters simultaneously satisfy the following constraints: $P_{EV} > 100$ mm; $I_{30} > 50$ mm·h⁻¹; $E_J > 29$ MJ·ha⁻¹. The constraints on P_{EV} , I_{30} and E_J were appropriately chosen on the base of both previous statistical analyses and other studies. For example, with reference to daily rainfall from 1951 to 1995 recorded at 265 rain gauges in the Mediterranean-climate regions (including 182 sites in Mediterranean-Spain, 42 in Italy, 3 in Cyprus and 38 in Israel), Alpert et al. (2002) selected six categories. More in detail, they proposed the following categories, in terms of power-of-two of the daily rainfall (P_D , in mm): light (0 – 4), light-moderate (4 – 16), moderate-heavy (16 – 32), heavy (32 – 64), heavy-torrential (64 – 128), and torrential (128-up). In order to determine the area hit by rainstorm events, Federico et al. (2008) classify an event as heavy rainfall if $P_D > 60$ mm at least in one rain gauge and $P_D > 20$ mm, for the same day, at least in 20 rain gauges. In this regard, the 60mm value was chosen accordingly to analogous studies in the Mediterranean area (Lana et al., 2007; Jansà et al., 2001) and in the MEDEX project (Buzzi et al., 2005). In the present investigation, the 60-value was increased to 100 mm in order to take into account the different time scale and context of interest. In fact, with reference to flash floods, Gaume et al. (2009) assume that, generally, local amounts greater than 100 mm in a few hours and covering areas of tens or at most a few hundred km² must be considered. In the case of flash floods, as in the Mediterranean region, larger scale

and longer lasting stationary rainstorms may occur, then a new criterion is proposed, based on rainfall totalized in a short duration (<24 h) and the area (<500 km²) affected by the storm.

On the basis of the above mentioned constraints, several Heavy Rainstorm Events (HRE) occurred in Calabria during the observation period were identified, by considering together the rainfall events recorded simultaneously at different rain gauges, even non-contiguous, within the region. More in detail, from the 37,174 rainfall events with $D_{EV} \leq 24$ h, those 137 having $P_{EV} \geq 100$ mm were distinguished. Next, 76 events having $I_{30} \geq 50$ mm·h⁻¹, were extracted out of these 137. Then, 49 out of these 76 events, having $E_j \geq 29$ MJ·ha⁻¹, were picked out. Finally, from an examination of the times of occurrence of these 49 events, 25 distinct HRE could be identified, some of which occurred in the same dates at two or more rain gauges. Furthermore, regardless of the values of D_{EV} , I_{30} and E_j , those characterized by $P_{EV} \geq 50$ mm were selected and added to those that have already been used to determine the HRE. Thereby the area struck by HRE (recorded in one or more rain gauges and having simultaneously $D_{EV} \leq 24$ h, $P_{EV} \geq 100$ mm, $I_{30} \geq 50$ mm·h⁻¹ and $E_j \geq 29$ MJ·ha⁻¹) was then increased by other areas affected by less severe, but still heavy, rainfall events (having $P_{EV} \geq 50$ mm). In this regard, at each rain gauge was indeed assigned a reference area using the Thiessen polygons, allowing to determine the portion of regional territory affected by each HRE. Therefore, the area struck by widespread, ^wHRE, and localized, ^lHRE, heavy rainstorm events was delimited and a spatial analysis was performed. More precisely, an HRE is defined as widespread (localized) if an area greater (smaller or equal) than 500 km² is hit by rainfall event. In both cases the above mentioned requirements have to be satisfied: (i) $P_{EV} \geq 50$ mm in all rain gauges and (ii) $D_{EV} \leq 24$ h, $P_{EV} \geq 100$ mm, $I_{30} \geq 50$ mm·h⁻¹ and $E_j \geq 29$ MJ·ha⁻¹ in at least one rain gauge.

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278 6. Results and discussion

Following an accurate description of the rainfall that hit Calabria, with special attention to the sub-hourly scale, a heuristic method was proposed to select and characterize the rainstorms capable of inducing flash floods and other physical processes to high impact on economic and social structure of the countries characterized by Mediterranean climate.

By applying the criteria mentioned in the previous paragraph, 17 ^wHRE and 8 ^lHRE were identified in Calabria, related to the period from 1989 to 2008 (Table 2). Well-known catastrophic geo-hydrological events are included among these HRE.

The spatial features of the heavy rainstorms can be mapped allowing some useful observations (Fig. 7a-i). Among the ^lHRE events, that of 2 March 1996 has concerned only one station for an area of barely 57 km² (Fig. 7a), confirming that these violent rainstorms can be extremely localized. Another ^lHRE, that of 14 October 1996, affecting an area of about 152 km² and two rain gauges (Fig. 7b), corresponds to the flash flood of the river Esaro of Crotona that caused 6 deaths and wiped out many industrial and commercial buildings (damage was estimated at ca. 70 million €). It is worth mentioning that this ^lHRE, characterized by high I_{30} but not by a very high P_{EV} , was preceded by the ^wHRE occurred on 2-4 October 1996, with P_{EV} greater than 300 mm and extended approximately 4800 km² in the same basin and in other areas of Calabria (Fig. 7c). The ^lHRE occurred on 3 July 2006 struck an area of approximately 270 km² (3 rain gauges, Fig. 7d), causing 4 casualties as a result of the flash floods in the Sant'Anna torrent and in some small streams that crossed the town of Vibo Valentia.

On the other hand, widespread events were those of 6 March 2004 with approximately 5100 km² (56 rain gauges; Fig. 7e), of 25 November 2003 (44 rain gauges, 4550 km²; Fig. 7f) and of 7-10 September 2000 (Fig. 7g). This last event has affected the Ionian Calabria, with tragic effects in the southern part, where the flash flood of the *fiumara* Soverato caused the death of 13 people (39 rain gauges, approximately 3800 km²; Fig. 7g). Also in other neighbouring *fiumare* (eg. Allaro, Amusa, Precariti, Barone, Carciamite, Vatrò,

San Giorgio, Guardavalle, Stilaro, Alatro e Portigliola, cf. Fig. 1) occurred disastrous flash floods, with a strong socio-economic impact but fortunately without further casualties. Unfortunately, this ^WHRE was followed after only 20 days by that of the 29-30 September 2000 (extended about 2800 km², 39 rain gauges; Fig. 7h) which caused further damage in approximately the same area. Detailed historical information about these geo-hydrological catastrophic events can be found in Gabriele (1998), Antronico et al. (2002), Sorriso-Valvo et al. (2004), Iovine et al. (2009).

As regard the temporal properties of the heavy localized and widespread rainstorms, some of their standardized rainfall profiles (SRP) are reported in the insets of Fig. 8a-f. At stations with $P_{EV} \geq 100$ mm, many events (see Figs. 8c-f, corresponding to events #10, #24, #18, #17 in Table 2) have the typical structure of tropical-like cyclones in the Mediterranean Sea (*medicane*). In most of the stations, event #17 (Figs. 7f, 8f, Table 2) shows a structure close to the BSC 0011 type. Even for the event #12 (Fig. 8A), occurred on 5 May 2001, results that an ^WHRE described by a single type of profile (BSC 1111, thunderstorm, as reported in figure 2) has invested a wide areas of the Serre mountain range and limited portions of the Aspromonte and Sila massifs. The structure of the event #24 (Figs. 7d, 8d) is rather different from station to station, making evident the not frequent meteorological features of this rainstorm. Although other situations are more complex, it is possible to relate (e.g. event #18, Figs. 7e, 8e) the spatial distribution of the structure of the SRP to the regional orography, to the incoming direction of perturbations and to the quantities given in the maps of Figs. 8a-f.

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321 7. Conclusions

Adopting an automatic and reproducible procedure, 25 heavy rainstorm events with different characteristics were identified in Calabria, in the period from 1989 to 2008, including some catastrophic events. Spatial features and temporal structures of those events were analysed and shown. Catastrophic events have different spatial extents and temporal patterns; damages are not connected with a greater spatial extent (cf. e.g., events #7, #9 and #24). In fact, the environmental (e.g., orography) and anthropic (e.g., urbanization and density of infrastructure) characteristics play also a relevant role in causing damage and fatalities. Generally, localized events (e.g., Fig. 8a) have temporal structures with the peak at the beginning of the event (thunderstorm-type, BSC=1111). On the contrary, wide events have mixed temporal structures (e.g., Figs. 8b, 8c, 8e), with peaks localized the second half of the Huff's curves (BSC from 0000 to 0100).

The employed database includes information characterized by a notable size of the sample, a detailed resolution in time, along with a dense network of rain gauges, determining a good robustness of the obtained results.

The application conducted in Calabria (a region representative for climate and morphological conditions of wider Mediterranean areas) has allowed verifying the validity of the proposed method for the events that have hit heavily areas more or less extensive of this territory in recent decades. As mentioned, well-known catastrophic geo-hydrological events are included among the analysed HRE, whose high frequency over time (25 heavy rainstorms in 20 years) shows that this physical phenomena has a great social and economic impact for Calabria.

The proposed method improves the knowledge regarding the input of rainfall-runoff watershed models. The identification of design storms - made using an automatic classification of the rainfall profiles - with a realistic time structure was integrated with the results of the spatial analysis. In fact, the sectors of the region more frequently affected by the most severe rain events (in terms of P_{EV} , I_{30} , E_j) were picked out in relation to their time structure. The implementation of computer tools that generate the most stringent design storms at random but based on SRP realistic (i.e. characterized by BSC, D_{EV} , P_{EV} , I_{30} , E_j peculiar to

347 certain sites/basins) is therefore facilitated. In particular, by properly integrating the proposed method into
348 a model of flood forecasting and rainfall-runoff models, those streams more frequently subject to flash
349 floods can be kept under control.

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444 Table 1 – Statistical features of the 903 rainfall events having $P_{EV} \geq 100$ mm

	P_{EV} [mm]	I_{30} [mm·h ⁻¹]	E_j [MJ·ha ⁻¹]	D_{EV} [dd:hh:mm]
Average	152.8	33.52	32.27	1:22:05
Standard deviation	61.5	23.34	14.65	1:16:37
Minimum	100.0	0.40	16.73	4:25
Maximum	602.2	154.80	137.94	10:04 :50

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448 Table 2 – Features of the determined HRE. Key: Max D_{EV} , Min D_{EV} , Max E_j , Max I_{30} , are referred to the events that
449 constitute each HRE; Type = type of HRE (L=localized HRE, W=widespread HRE); #₁₀₀ = number of rain gauges with P_{EV}
450 ≥ 100 mm; #₅₀ = number of rain gauges with $50 \leq P_{EV} < 100$ mm; Area = area affected by each HRE, evaluated by means
451 of the Thiessen polygons; $^{AV}P_{EV}$ = areal average of the rainstorm amount. Maximum (minimum) values of each column
452 are in bold (italic). The maps of figs. 9 and 10 describe some of these HRE.

Event #	Type	Starting date	Ending date	Max D_{EV} [min]	Min D_{EV} [min]	# ₁₀₀	# ₅₀	Area [km ²]	$^{AV}P_{EV}$ [mm]	Max E_j [MJ ha ⁻¹]	Max I_{30} [mm h ⁻¹]
1	L	12-oct-91	13-oct-91	1400	1025	1	1	130.8	149.2	46.2	69.6
2	L	04-jan-93	05-jan-93	1340	855	2	3	445.6	87.2	84.4	31.5
3	L	06-nov-94	06-nov-94	955	720	2	1	215.5	159.1	61.7	81.6
4	W	12-mar-95	15-mar-95	3300	815	8	19	2556.4	90.9	42.0	62.4
5	L	02-mar-96	03-mar-96	300	300	1	0	57.1	149.2	39.8	72.4
6	W	02-oct-96	05-oct-96	4215	625	35	14	4795.8	136.4	86.8	101.2
7	L	14-oct-96	14-oct-96	440	360	1	1	151.9	61.2	106.0	29.4
8	W	23-sept-97	25-sept-97	1350	765	3	7	905.8	68.2	72.4	31.9
9	W	07-sept-00	11-sept-00	4590	590	32	7	3780.2	237.1	116.6	144.4
10	W	29-sept-00	01-oct-00	2615	630	22	14	2808.4	139.9	115.2	143.6
11	W	13-jan-01	15-jan-01	1435	1105	3	7	747.6	84.9	66.4	29.1
12	W	05-may-01	07-may-01	3210	490	4	14	1353.1	76.7	36.7	99.2
13	L	01-sept-02	02-sept-02	280	265	1	2	314.1	87.0	112.8	32.1
14	W	21-nov-02	21-nov-02	1045	275	3	16	2053.9	69.9	60.4	32.6
15	W	14-oct-03	24-oct-03	14690	145	5	8	1177.4	98.2	58.4	99.6
16	W	22-nov-03	22-nov-03	550	335	2	5	575.6	83.2	37.3	72.8
17	W	25-nov-03	27-nov-03	2370	640	14	30	4550.3	88.1	47.6	91.2
18	W	06-mar-04	10-mar-04	5185	945	14	42	5219.4	85.3	50.7	53.6
19	L	20-sept-04	20-sept-04	765	270	1	3	472.3	92.5	35.8	114.8
20	W	03-nov-04	05-nov-04	2615	885	8	17	2254.1	94.0	43.4	104.0
21	W	11-nov-04	14-nov-04	4565	575	11	14	2896.8	106.4	59.7	126.0
22	W	08-dec-04	11-dec-04	3185	495	11	22	3012.7	91.3	62.4	92.0
23	W	22-oct-05	23-oct-05	990	280	3	6	713.7	97.9	61.1	154.8
24	L	03-jul-06	03-jul-06	550	305	3	0	271.4	186.8	56.1	137.6
25	W	25-sept-06	26-sept-06	1365	180	2	11	1294.5	72.7	132.0	29.1

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Figure 1 – Geographical framework of Calabria (southern Italy). The orographic map also includes: (black) indications of the main towns; (yellow) mountain ranges and place names mentioned in the text; (blue) main river and *fiumare* recently affected by flash floods and main rivers (labelled). White triangles indicate the considered rain gauges.

Figure 2 – Top: elements of a standardized rainfall profile (SRP). URSP = Uniform SRP; StAC = Storm Advancement Coefficient; BSC = binary shape code. On the vertical axis, π represents the normalized cumulative depth of the rainstorm; on the horizontal axis, τ represents the cumulative fraction of the rainstorm time (from Terranova and Iaquina, 2011 - modified). Bottom-left: binary shape codes, BSC, associated to the idealized structure of thunderstorms and of tropical cyclones. Bottom-right: binary shape codes, BSC, associated to the recorded structure of convective and stratiform rainfall events in the Brue basin, south-west England (from Moore et al., 2005 - modified).

Figure 3 - Standardized Rainfall Profiles (SRP) relative to the 90th, 50th, and 10th fractiles of the four most numerous BSC in Calabria. In the insets, with reference to each BSC, Huff's quartiles are also distinguished. On the vertical axis, π represents the normalized cumulative depth of the rainstorm; on the horizontal axis, τ represents the cumulative fraction of the rainstorm time.

Figure 4 – Comparison between SRP of the 45,534 erosive events recorded in Calabria, distinguished by (a) D_{EV} , (b) P_{EV} , (c) I_{30} , and (d) E_j . The 90th, 50th, and 10th fractiles for each class are shown. On the horizontal axis, τ represents the cumulative fraction of the rainstorm time; on the vertical axis, π represents the normalized cumulative depth of the rainstorm.

Figure 5 – Rainfall events characterized by a) $P_{EV} \geq 100$ mm; b) $I_{30} \geq 44$ mm h⁻¹, c) $E_j \geq 20$ MJ ha⁻¹. Timeline of the number of rain gauges that exceed the threshold value. The numerosness of events for each month is shown in the inset. The location and the ratio between numerosness of rainstorms and number of observation months for each rain gauge is shown in the map on the right.

Figure 6 – Comparison between SRP of the events occurred during the four wettest and four driest months in Calabria. The 90th, 50th, and 10th fractiles for each class are shown. On the horizontal axis, τ represents the cumulative fraction of the rainstorm time; on the vertical axis, π represents the normalized cumulative depth of the rainstorm.

Figure 7 – Spatial features of some significant heavy rainstorms. Numbers in each map are referred to Table 2. Brown points indicates the rain gauges in which the rainfall events used for determining the HRE are recorded. Thiessen polygons related to the 155 rain gauges are also shown and coloured according to the value of P_{EV} . (a) ^LHRE of 2 March 1996, affecting an area of 57 km². (b) ^LHRE, 4 October 1996, 152 km² with two rain gauges involved in the Esaro of Crotona basin. (c) ^WHRE of 2-4 October 1996 4800 km², Esaro of Crotona and many other basins. (d) ^LHRE, 3 July 2006, 270 km² (3 rain gauges), Vibo Valentia flooding. (e) ^WHRE, 6 March 2004, ca. 5100 km² (56 rain gauges). (f) ^WHRE, 25 November 2003 (44 rain gauges, 4550 km²). (g) ^WHRE, 7-10 September 2000 north-eastern and southern Ionian Calabria, flash flood of T. Soverato and other streams (39 rain gauges, ca. 3800 km²). (h) ^WHRE, 29-30 September 2000 (ca. 2800 km² in 39 rain gauges). (i) ^WHRE, 22 October 2005 (9 rain gauges, ca. 714 Km²), with the maximum value of I_{30} (154.8 mm h⁻¹).

Figure 8a-f – Spatial distribution of some HRE in Calabria, according to the Thiessen polygon delimitation and their binary shape code (BSC). The standard rainfall profiles (SRP) distinguished according to the BSC, are reported in the insets. The more marked SRP are those related to events with $D_{EV} \leq 24$ h, $P_{EV} \geq 100$ mm, $I_{30} \geq 50$ mm·h⁻¹ and $E_j \geq 29$ MJ·ha⁻¹. Numbers indicate the events reported in Table 2.