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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.

1 Introduction

Many regions belonging to the Mediterranean basin are prone to a large number of catastrophic geo-hydrological events with loss of life, injured, high economic and social impact (Jansà et al., 1994; Siccardi, 1996; Gaume et al., 2009). In recent decades because of climate change, both violence and the frequency of torrential rain events (i.e., $> 64\,\mathrm{mm\,d^{-1}}$) are increased (Alpert et al., 2002), despite the decrease of the annual rainfall in the Mediterranean basin (Piervitali et al., 1998). In particular, in Italy both annual precipitation and the number of wet days show a decrease, while the precipitation intensity increases (Brunetti et al., 2004).

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 addition, in the Mediterranean-climate regions, low permeability and highly erodible soils often characterize these small basins (typically below a few hundred $\mathrm{km^2}$), whose slopes are often very steep and susceptible to landslides. Ultimately, the run-off 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 Iaquinta, 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 km^2 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

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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 Cal-

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abria 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.

The climate of Calabria is typically Mediterranean; in fact, the major part of its territory is *Csa* (Hot-summer Mediterranean climate) in Köppen's (1948) classification, characterized by dry and hot summers and low average temperatures. On the base of the detailed map proposed by Iaquinta and Terranova (2010), the remaining part of Calabria (inland and not vallive areas) is classified, in order of surface, as *Csb* (Warm-summer Mediterranean climate), *Cfb* (Maritime Temperate climates) and *Cfa* (Humid subtropical climates).

Calabria is the hottest region in peninsular Italy. According to Terranova et al. (2009), the characters describing the temperature of Calabria are summarized as follows: (i) the mean annual temperature ranges from 5 °C on the Pollino, with 10 °C on the mountain slopes to 18 °C along the coast; (ii) the hottest month is August while January is the coldest; (iii) the maximum daily temperature may exceed 40 °C on some days in July and August; (iv) the average temperature in January is about 10 °C along the coasts and 4 °C in the mountains; (v) above 1500 and 1700 m a.s.l. on Sila and Aspromonte, respectively, the average temperature may frequently be below 0 °C; (vi) the months from August to December are warmer than those from February to June, as indeed is typical for areas with a Mediterranean, and more generally, maritime climate (Conrad and Pollack, 1950); (vii) the temperature differences between the months of July and December vary from a minimum of about 8 °C for locations close to the Lamezia valley

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to a maximum of 15 °C for those of Le Serre. In this regard, the excursion for the Ionian localities is higher than that of the Tyrrhenian ones.

3 Rainfall data

Thanks to the availability of observations with high temporal detail (5 min) related to 155 sites (one rain gauge per less than 100 km^2), a considerable amount of rainfall series were analysed in order to contribute to the quantitative and qualitative characterization of extreme events affecting Calabria. Distinguishing individual rainstorms as rainy periods separated by at least 6 h of dry weather, the study initially considers more than 152 thousands rainstorms, having different durations, recorded in different seasons between 1989 and 2008 at 155 rain gauges in Calabria. According to Wischmeier and Smith (1978), 45 534 erosive rainstorms were selected as relevant and analysed. First, the analysis was carried out to characterize, in a simple but effective way, the rainfall events with regard to magnitude, locations with high frequency per year and where they are most severe, within-storm temporal patterns, the season in which they occur, even in relation to their temporal structure and severity. The 45 534 selected rainfall events:

1. include 27 211 with total rainfall amount (P_{EV}) ≥ 12.7 mm and 18 323 having P_{EV} < 12.7 mm but exceeding 6.35 mm in 15 min;
2. have P_{EV} between 6.4 and 602.2 mm and mean value equal to 23.5 mm;
3. last from D_{EV} = 10 min to approximately 10 days, with a mean value of ∼ 15 h;
4. range from negligible values of maximum intensity in 30 min, I_{30}, up to 154.8 mm h^{-1} with mean value 11.6 mm h^{-1} ;
5. have E_J ranging from 0.83 to ∼ 138 MJ ha^{-1} with mean value ∼ 4.6 MJ ha^{-1}.

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4 Preliminary analysis of rainstorms

The temporal storm structure was described by means of the standardized rainfall profiles (SRP – Huff, 1967), allowing and simplifying the analysis, presentation and comparison of data. 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 Iaquinta (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 – with the corresponding four values of the uniform SRP (URSP). More precisely, a 4-digit binary shape code, BSC, was determined, summarizing information of immediate use. 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. The SRP with 1111 BSC, typical of thunderstorms (Fig. 2), occurs in over a third of the examined events. 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}.

View to introducing the topics that will be discussed in the next paragraphs, the most severe 2 % of the 45 534 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 %

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fractile (the 50 %-SRP related to $I_{30} \geq 44\,\mathrm{mm\,h^{-1}}$ 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 $P_{EV} \geq 100\,\mathrm{mm}$ was exceeded several times on over the regional territory and 9 times in at least 20 rain gauges (Fig. 5); this threshold was more frequently exceeded from November to January;
- by operating the selection shown in Fig. 6, the threshold $I_{30} \geq 44\,\mathrm{mm\,h^{-1}}$ was exceeded 6 times in 20 or more rain gauges; such threshold was more frequently exceeded from august to November;
- the threshold $E_J \geq 20\,\mathrm{MJ\,ha^{-1}}$ was exceeded 9 times at a number of rain gauges greater than or equal to 20 (Fig. 7); 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 (Figs. 5–7). 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. 8, 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.

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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 60 mm 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 km^2 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 km^2) affected by the storm.

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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, ^{W}HRE, and localized, ^{L}HRE, heavy rainstorm events was delimited and a spatial analysis was performed. More precisely, an HRE is identified as widespread (localized) if an area greater (smaller or equal) than 500 km^2 is hit by rainfall events satisfying the above mentioned requirements: (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.

6 Results and discussion

Following an accurate description of the rainfall that hit Calabria, with special attention to the sub-hourly scale, a method was proposed to select and characterize the rainstorms capable of inducing flash floods and other physical processes to high im-

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pact on economic and social structure of the Countries characterized by Mediterranean climate.

By applying the criteria mentioned in the previous paragraph, 17 ^{W}HRE and 8 ^{L}HRE 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. 9a–i). Among the ^{L}HRE events, that of 2 March 1996 has concerned only one station for an area of barely 57 km^2 (Fig. 9a), confirming that these violent rainstorms can be extremely localized. Another ^{L}HRE, that of 14 October 1996, affecting an area of about 152 km^2 and two rain gauges (Fig. 9b), corresponds to the flash flood of the river Esaro of Crotone 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 ^{L}HRE, characterized by high I_{30} but not by a very high P_{EV}, was preceded by the ^{W}HRE occurred on 2–4 October 1996, with P_{EV} greater than 300 mm and extended approximately 4800 km^2 in the same basin and in other areas of Calabria (Fig. 9c). The ^{L}HRE occurred on 3 July 2006 struck an area of approximately 270 km^2 (3 rain gauges, Fig. 9e), 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 (Fig. 9d).

On the other hand, widespread events were those of 6 March 2004 with approximately 5100 km^2 (56 rain gauges; Fig. 9e), of 25 November 2003 (44 rain gauges, 4550 km^2; Fig. 9f) and of 7–10 September 2000. 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 km^2; Fig. 9g). 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 ^{W}HRE was followed after only 20 days by that of the 29–30 September 2000 (extended about 2800 km^2, 39 rain gauges; Fig. 9h) 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. 9a–f. At stations with $P_{\mathrm{EV}} \geq 100$ mm, many events (see, events #10, #18, #17, #24 in Table 2, corresponding to Fig. 9c-F) have the typical structure of tropical-like cyclones in the Mediterranean Sea (*medicanes*). In most of the stations, event #17 (Fig. 9f, Table 2) shows a structure close to the BSC 0011 type. Even for the event #12 (Fig. 9a), occurred on 5 May 2001, results that an $^{\mathrm{W}}$HRE described by a single type of profile (BSC 1111, thunderstorm) 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 (Fig. 9d) 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, Fig. 9e) 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 Fig. 10a–f.

7 Conclusions

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

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 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.

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Table 1. Statistical features of 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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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 constitute each HRE; $\#_{100}$ = number of di rain gauges with $P_{EV} \geq 100$ mm; $\#_{50}$ = number of di rain gauges with $50 \leq P_{EV} < 100$ mm; Area = area affected by each HRE, evaluated by means of the Thiessen polygons; ${}^{AV}P_{EV}$ = areal average of the rainstorm amount. Maximum (minimum) values of each column 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 1991	13 Oct 1991	1400	1025	1	1	130.8	149.2	46.2	69.6
2	L	4 Jan 1993	5 Jan 1993	1340	855	2	3	445.6	87.2	84.4	31.5
3	L	6 Nov 1994	6 Nov 1994	955	720	2	1	215.5	159.1	61.7	81.6
4	W	12 Mar 1995	15 Mar 1995	3300	815	8	19	2556.4	90.9	42.0	62.4
5	L	2 Mar 1996	3 Mar 1996	300	300	1	0	57.1	149.2	39.8	72.4
6	W	2 Oct 1996	5 Oct 1996	4215	625	**35**	14	4795.8	136.4	86. 8	101.2
7	L	14 Oct 1996	14 Oct 1996	440	360	1	1	151.9	61.2	106.0	29.4
8	W	23 Sep 1997	25 Sep 1997	1350	765	3	7	905.8	68.2	72.4	31.9
9	W	7 Sep 2000	11 Sep 2000	4590	590	32	7	3780.2	**237.1**	116.6	144.4
10	W	29 Sep 2000	1 Oct 2000	2615	630	22	14	2808.4	139.9	115.2	143.6
11	W	13 Jan 2001	15 Jan 2001	1435	**1105**	3	7	747.6	84.9	66.4	29.1
12	W	5 May 2001	7 May 2001	3210	490	4	14	1353.1	76.7	36.7	99.2
13	L	1 Sep 2002	2 Sep 2002	280	265	1	2	314.1	87.0	112.8	32.1
14	W	21 Nov 2002	21 Nov 2002	1045	275	3	16	2053.9	69.9	60.4	32.6
15	W	14 Oct 2003	24 Oct 2003	**14 690**	145	5	8	1177.4	98.2	58.4	99.6
16	W	22 Nov 2003	22 Nov 2003	550	335	2	5	575.6	83.2	37.3	72.8
17	W	25 Nov 2003	27 Nov 2003	2370	640	14	30	4550.3	88.1	47.6	91.2
18	W	6 Mar 2004	10 Mar 2004	5185	945	14	**42**	**5219.4**	85.3	50.7	53.6
19	L	20 Sep 2004	20 Sep 2004	765	270	1	3	472.3	92.5	35.8	114.8
20	W	3 Nov 2004	5 Nov 2004	2615	885	8	17	2254.1	94.0	43.4	104.0
21	W	11 Nov 2004	14 Nov 2004	4565	575	11	14	2896.8	106.4	59.7	126.0
22	W	8 Dec 2004	11 Dec 2004	3185	495	11	22	3012.7	91.3	62.4	92.0
23	W	22 Oct 2005	23 Oct 2005	990	280	3	6	713.7	97.9	61.1	**154.8**
24	L	3 Jul 2006	3 Jul 2006	550	305	3	0	271.4	186.8	56.1	137.6
25	W	25 Sep 2006	26 Sep 2006	1365	180	2	11	1294.5	72.7	**132.0**	29.1

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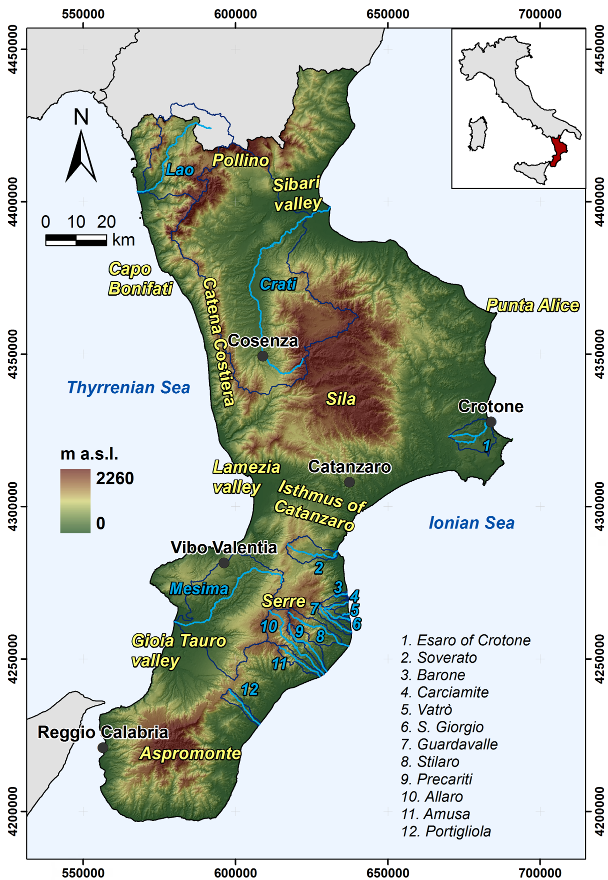

Fig. 1. Geographical framework of Calabria (southern Italy). The orographic map also includes: (black) indications of the main towns; (yellow) mountain ranges and place names mentioned in the text; (blue) *fiumare* recently affected by flash floods and main rivers.

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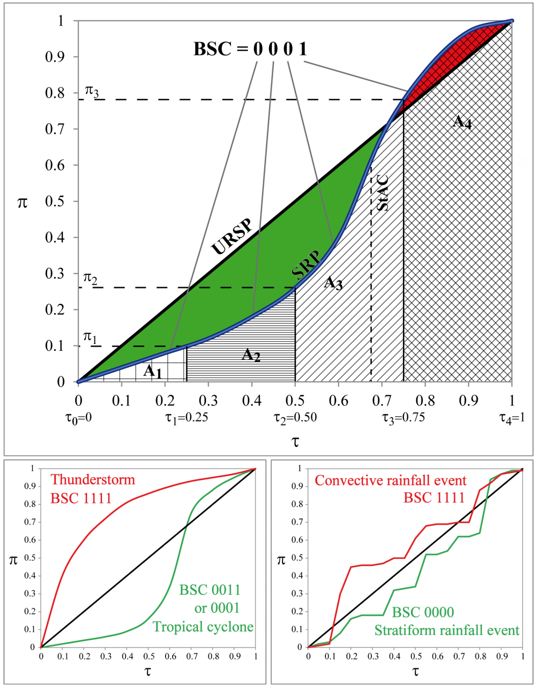

Fig. 2. Top: elements of a standardized rainfall profile (SRP). URSP = Uniform SRP; StAC = Storm Advancement Coefficient, i.e. time of occurrence of the maximum rainfall intensity; BSC = binary shape code based on the comparison between the areas A_1, A_2, A_3, A_4 – underlying the four 25 % of duration of the SRP – with the corresponding four values of the URSP. 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 Iaquinta, 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).

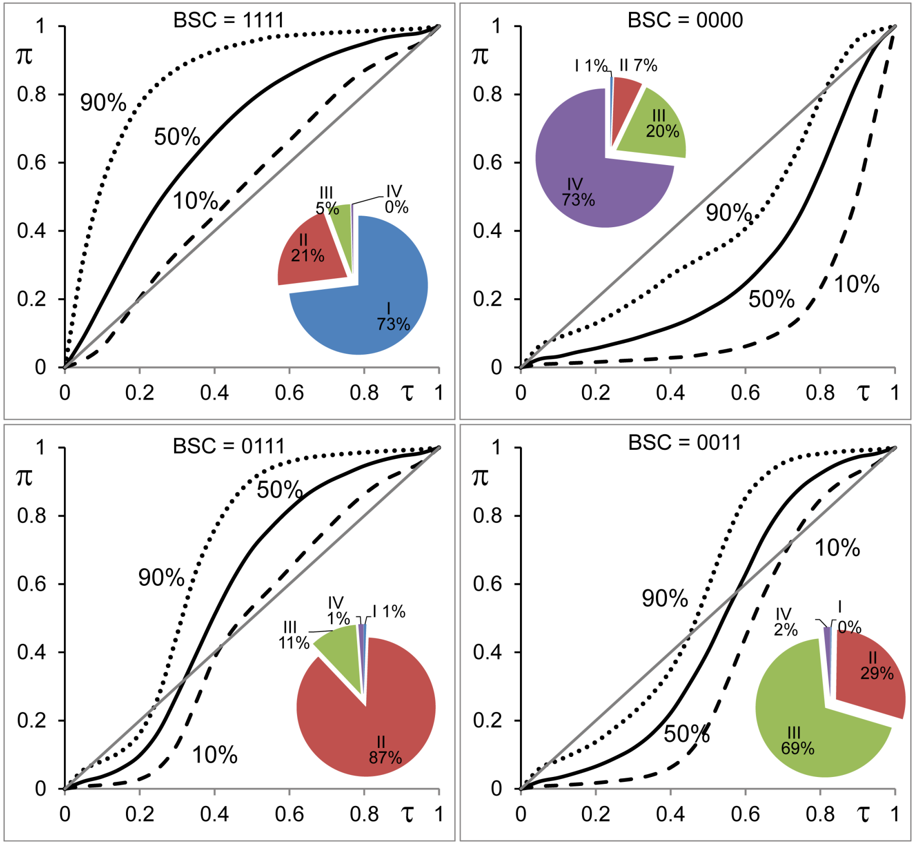

Fig. 3. Standardized Rainfall Profiles (SRP) relative to the 90th, 50th, and 10th fractiles of the four most numerous BSC in Calabria. In the insets, with reference to each BSC, Huff's quartiles are also distinguished. On the vertical axis, π represents the normalized cumulative depth of the rainstorm;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

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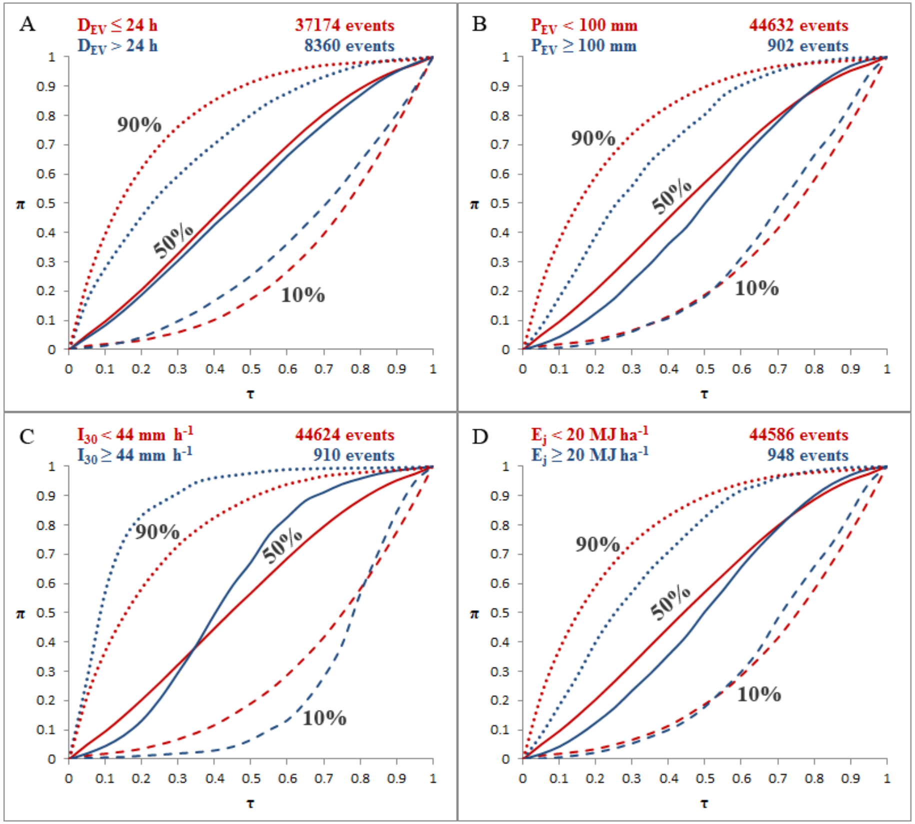

Fig. 4. Comparison between SRP of the 45 534 erosive events recorded in Calabria, distinguished by **(A)** D_{EV}, **(B)** P_{EV}, **(C)** I_{30}, and **(D)** E_J. The 90th, 50th, and 10th fractiles for each class are shown. On the horizontal axis, τ represents the cumulative fraction of the rainstorm time; on the vertical axis, π represents the normalized cumulative depth of the rainstorm.

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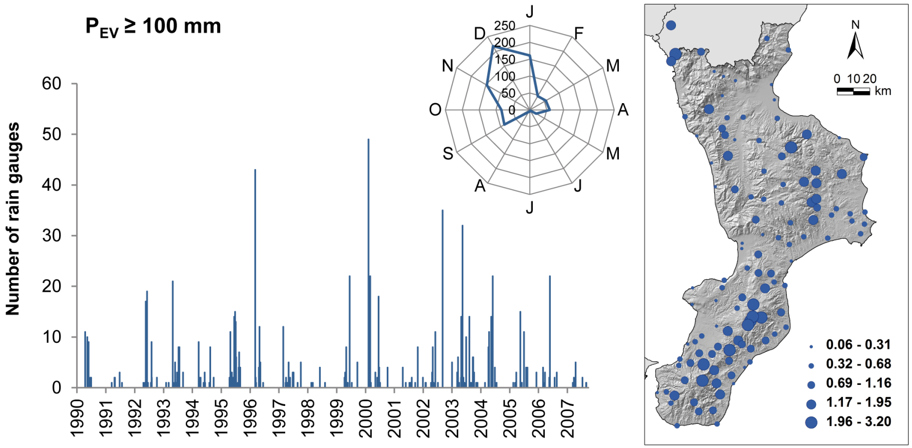

Fig. 5. Rainfall events characterized by $P_{EV} \geq 100$ mm: timeline of the number of rain gauges that exceed the threshold value. The numerousness of events for each month is shown in the inset. The location and the ratio between numerousness of rainstorms and number of observation months for each rain gauge is shown in the map on the right.

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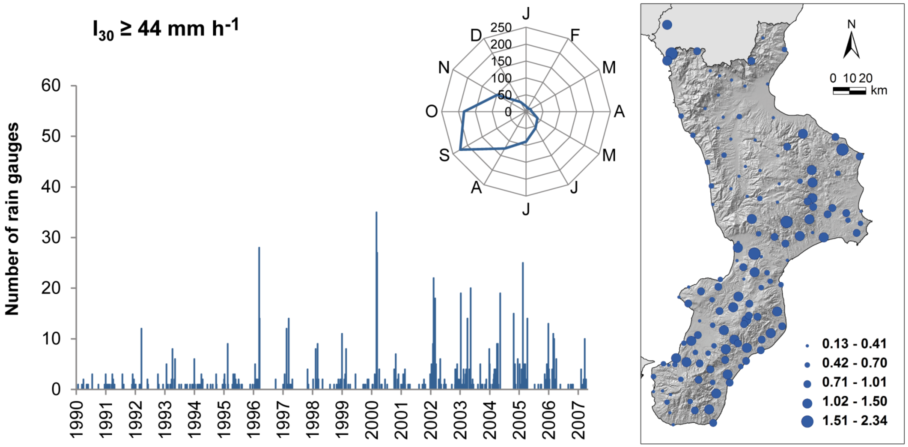

Fig. 6. Rainfall events characterized by $I_{30} \geq 44\,\mathrm{mm\,h^{-1}}$: timeline of the number of rain gauges that exceed the threshold value. The numerousness of events for each month is shown in the inset. The location and the ratio between numerousness of rainstorms and number of observation months for each rain gauge is shown in the map on the right.

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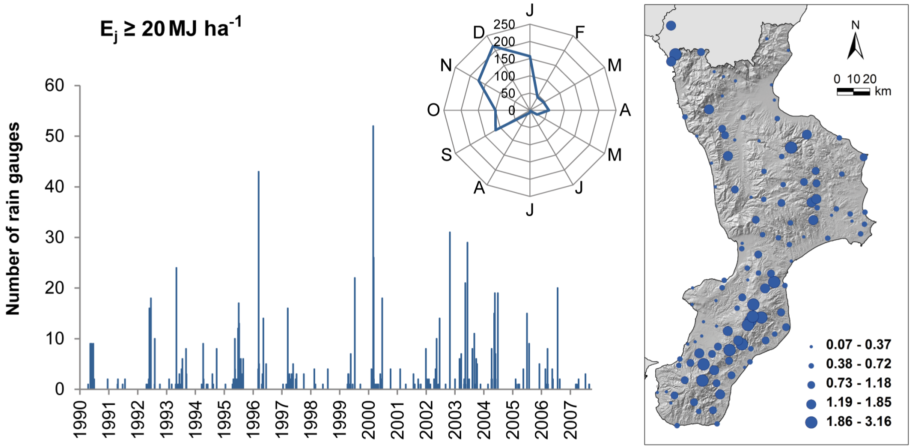

Fig. 7. Rainfall events characterized by $E_J \geq 20\,\mathrm{MJ\,ha^{-1}}$: timeline of the number of rain gauges that exceed the threshold value. The numerousness of events for each month is shown in the inset. The location and the ratio between numerousness of rainstorms and number of observation months for each rain gauge is shown in the map on the right.

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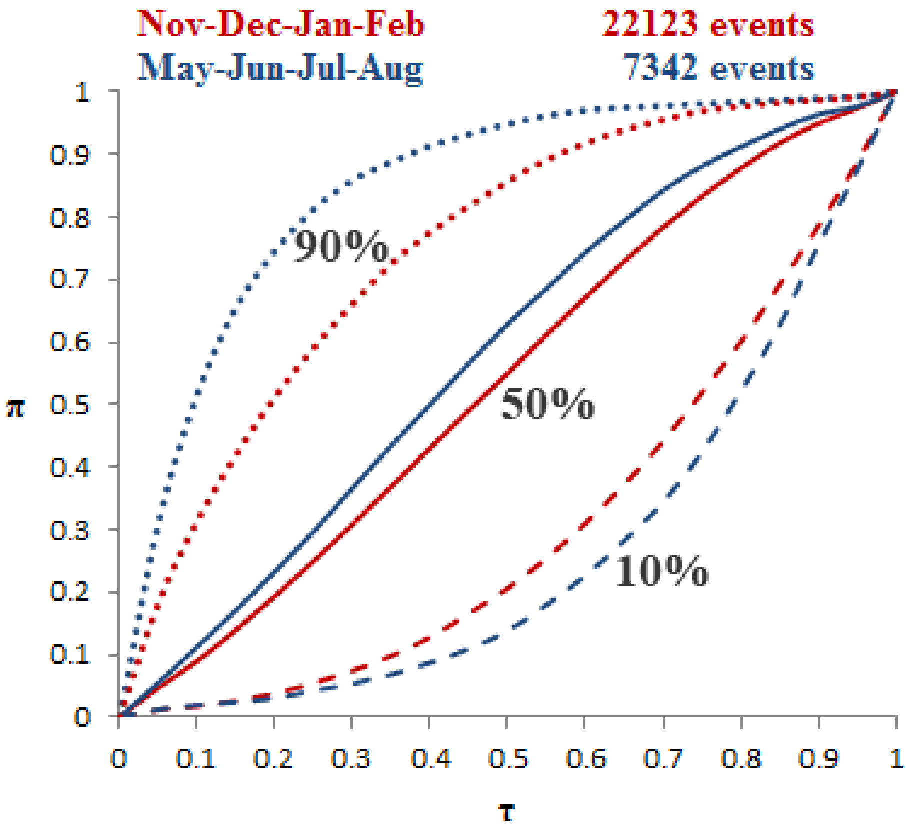

Fig. 8. Comparison between SRP of the events occurred during the four wettest and four driest months in Calabria. The 90th, 50th, and 10th fractiles for each class are shown. On the horizontal axis, τ represents the cumulative fraction of the rainstorm time; on the vertical axis, π represents the normalized cumulative depth of the rainstorm.

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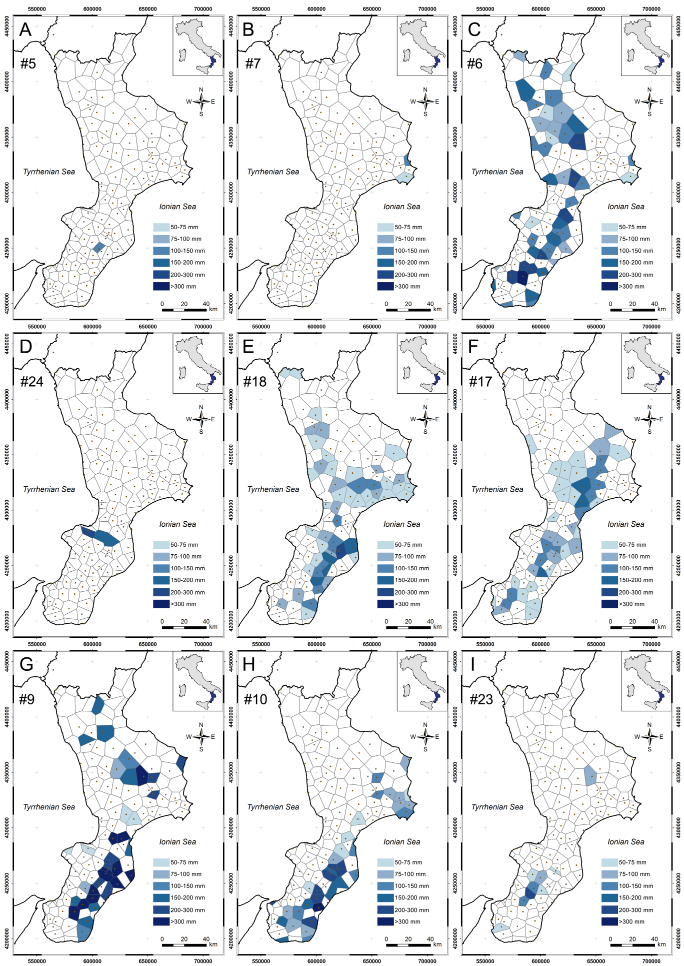

Fig. 9. Caption on next page.

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Fig. 9. 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)** ^{L}HRE of 2 March 1996, affecting an area of 57 km^2. **(B)** ^{L}HRE, 4 October 1996, 152 km^2 with two rain gauges involved in the Esaro of Crotone basin. **(C)** ^{W}HRE of 2–4 October 1996 4800 km^2, Esaro of Crotone and many other basins. **(D)** ^{L}HRE, 3 July 2006, 270 km^2 (3 rain gauges), Vibo Valentia flooding. **(E)** ^{W}HRE, 6 March 2004, ca. 5100 km^2 (56 rain gauges). **(F)** ^{W}HRE, 25 November 2003 (44 rain gauges, 4550 km^2). **(G)** ^{W}HRE, 7–10 September 2000 north-eastern and southern Ionian Calabria, flash flood of T. Soverato and other streams (39 rain gauges, ca. 3800 km^2). **(H)** ^{W}HRE del 29–30 September 2000 (ca. 2800 km^2 in 39 rain gauges). **(I)** ^{W}HRE, 22 October 2005 (9 rain gauges, ca. 714 km^2), with the maximum value of I_{30} (154.8 $mm\,h^{-1}$).

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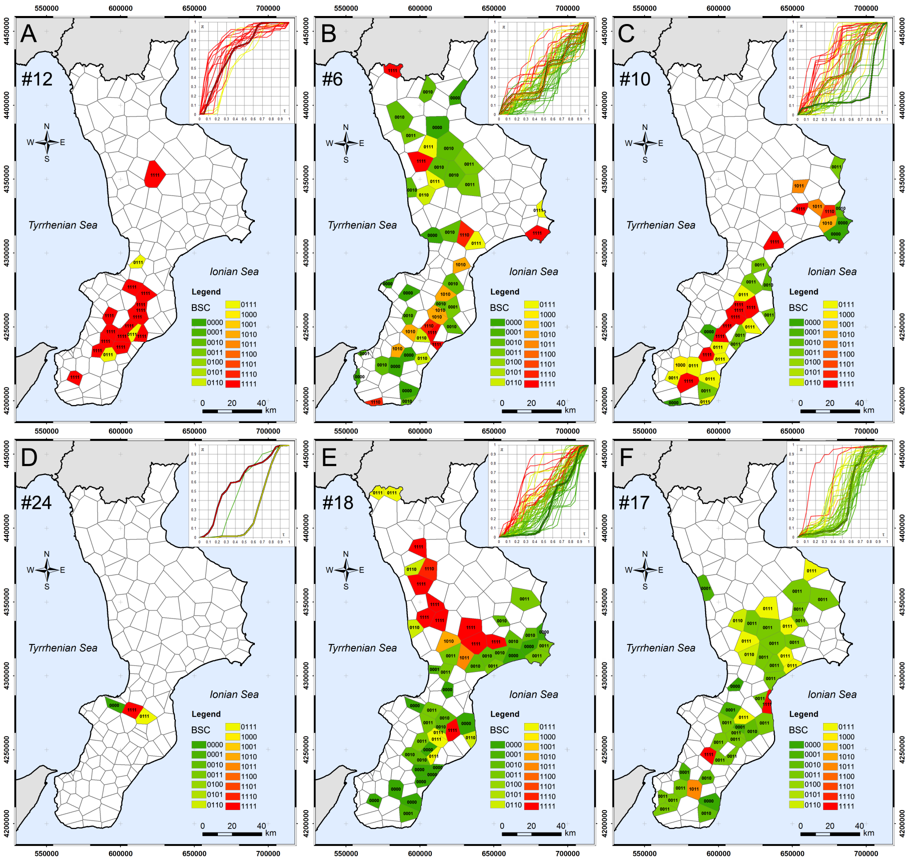

Fig. 10. (A–F) Spatial distribution of some HRE in Calabria, according to the Thiessen polygon delimitation and their binary shape code (BSC). The standard rainfall profiles (SRP) distinguished according to the BSC, are reported in the insets. The more marked SRP are those related to events with $D_{EV} \leq 24$ 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.

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