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Analysis of Damaging Hydrogeological Events: The Case of the Calabria Region (Southern Italy)

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Abstract A period of bad weather conditions due to prolonged intense rainfall and strong winds can trigger landslides, floods, secondary floods (accumulation of rain on surfaces with low permeability), and sea storms, causing damage to humans and infrastructure. As a whole, these periods of bad weather and triggered phenomena can be defined as damaging hydrogeological events (DHEs). We define a methodological approach based on seven simple indexes to analyze such events. The indexes describe the return period (T) and trend of rainfall, the extent of hit areas, and the level of damages; they can be considered attributes of georeferenced features and analyzed with GIS techniques. We tested our method in an Italian region frequently hit by DHEs. In a period of 10 years, 747 damaging phenomena (landslides, 43%; floods, 38%) and 94 DHEs have been classified. The road network and housing areas are the most frequently damaged elements, threatened by all types of damaging phenomena. T classes are almost in accordance with the level of damage. These results can be used to outline warning levels for civil protection purposes, to forecast the areas most likely to be hit and the potential ensuing damage, to disseminate information concerning vulnerable areas, and to increase people's awareness of risk.

Keywords Rainfall · Landslide · Flood · Secondary flood · Damage · Southern Italy

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A period of bad weather conditions, lasting from one to a few days, characterized by prolonged intense rainfall and strong winds, can trigger almost simultaneous damaging landslides, floods, secondary floods (i.e., accumulation of rain on surfaces with low permeability), and sea storms, causing casualties and economic and environmental damages. As a whole, these periods of bad weather conditions and triggered phenomena can be defined as damaging hydrogeological events (DHEs) (Petrucci and Polemio 2003).

The costs of DHEs are not well documented, are often extremely difficult to calculate, and depend strictly on the anthropogenic characteristics of affected areas (IFRC 2001). Some of these costs occur immediately, while others can manifest over a long time period and may be difficult to relate to DHEs (Crozier 1986).

The social, economic, environmental, and psychological damages caused by DHEs are difficult to assess. With the exclusion of human life, the economic damage induced by natural hazards can be classified as direct damage, i.e., the cost to repair or replace damaged structures and activities, and indirect damage, i.e., the economic loss linked to the event (loss of industrial productivity, fall in price of properties, loss of human productivity, and so on) (Aleotti and Polloni 2005). Several indexes have been introduced to describe damage caused by natural hazards (Blong 2003), and many efforts have been carried out to assess social vulnerability (Dwyer and others 2004).

The study of past DHEs (i.e., DHEs that happened before the study begins) can provide elements for forecasting potential damage. Disseminating information concerning the probable effects of future events could increase people's awareness of risk and promote more aware behavior.

However, past or historical events can provide only an approximate guide to the future because community vulnerability continuously varies (Dwyer 2003). Urbanization, land use changes, and engineering projects must be taken into account (Etkin 1999; Barrera and others 2005). Climate change can also modify the frequency and seriousness of damage (Dore 2003; Petrucci and Polemio 2007). Nevertheless, disaster mitigation must include lessons from the past. For each geohydrological context, it is important to know the frequency of each type of disaster, their effects, and whether the pattern is changing with time (Dore 2003).

Historical research is the only way to collect data regarding the effects of past events. Defining historical as *the period for which human recorded information is available* (Glade and others 2001), the usefulness of historical data in the study of past events has been shown by many authors (Flageollet and others 1999; Guzzetti 2000; Glade 2001; Barnikel and Becht 2003; Glaser and Stangl 2003, 2004). According to Carrara and others (2003), despite the lack of consensus on the reliability and usefulness of historical information, some investigators have used these records for single landslides or landslide-prone regions (Wieczorek and Jäger 1996; Ibsen and Brunsden 1996; Cruden 1997; Glade 2001; Calcaterra and others 2003), obtaining results that are useful, e.g.,, in landslide hazard assessment. In particular, press archives can be used to collect historical data because newspapers quite often report damage induced by natural phenomena (Cuesta and others 1999).

Methodology

The proposed methodology aims to characterize DHEs that affect large study areas to determine how to prevent and mitigate DHE damage. The data used concern hydrological or climatic conditions (mainly rainfall data), damaging phenomena, and resulting damage for a selected time period. We use geographical or political boundaries to divide the study area into subsets or provinces. These can be further divided into smaller subsets fitting with municipalities. For each of these subsets, detailed and homogeneous data on DHEs should be collected.

The methodology is composed of two phases. The first consists of data gathering and preliminary analyses of rainfall, damaging phenomena, and damages to define the general trend of DHEs and their spatial and temporal limits. The second phase involves a detailed analysis of the largest DHEs using descriptive indexes to synthetically define georeferenced characteristics of the data.

Data Gathering and Preliminary Analysis

The first phase of the research aims to gather continuous time series of climatic data and homogeneous records concerning both damaging phenomena and induced damage.

Rainfall and wind data are considered. The availability of long-lasting climatic time series, available parameters, gauge density, and frequency of measurements depend on both the site (country, state, region, or province) and the study period. If a regional study of the selected time series does not exist, data should be gathered considering the whole period of data availability in which the study period is included in order to improve the reliability of the statistical exceptionality analysis.

Since the end of the nineteenth century, rainfall data have been consistently gathered in several countries. At present, complete series of daily rainfall data for entire national gauge networks can be easily downloaded from the websites of government agencies. Using shorter time spans and other types of climatic data reduces the time series length and gauge density, making it more difficult to apply the method.

In general, statistical analysis of rainfall exceptionality is adequately consolidated.

For damaging phenomena and induced damages, however, most countries do not systematically collect data or have a method to elaborate them. In fact, we must take into account that we deal with *noninstrumental data*, that is, text descriptions from which damage must be inferred and converted into qualitative or semiquantitative values.

Quantifying damage caused by DHEs that occur today is very complicated, even though focused surveys can be performed to collect further data to help in damage assessment. Concerning past DHEs, for which no surveys can be performed, we must find alternative data sources.

The systematic analysis of newspapers to collect data about DHEs is a common practice (Cuesta and others 1999; Devoli and others 2007). The characteristics of this kind of information source can be synthesized as follows.

- Newspapers are a continuous data source. Regional newspapers are preferred to national ones: until several decades ago, news coming from regions far from the editorial unit was only related to severe events. Therefore, only an analysis of daily editions of a regional newspaper allows a complete screening of major and minor events in a selected time frame.
- Articles tend to focus mainly on damage, so details on phenomena can be scarce.
- Language is not technical, so the researcher must carefully analyze articles to correctly classify the described phenomena.

- To describe the size of a phenomenon (e.g., landslides), reporters use adjectives that are strongly affected by their personal perspective and familiarity with the type of phenomenon. The relevance of these adjectives must be assessed with caution.
- The articles must be checked in order to avoid duplication: often, newspapers report a damaging phenomenon in several editions (at least until major damage has been repaired).

Considering the pros and cons of using newspaper data, a study approach can be appropriately formulated. Some simplifications must be made in order to obtain information that cannot be achieved in other ways.

The research should focus on a sufficiently wide time frame. In this work, we tested the methodology working over a period of 10 years, but to increase the statistical significance of results, this time frame must be enlarged. In reviewing newspapers, articles concerning the occurrence of damage caused by landslides, floods, secondary floods, and sea storms must be searched. Selected articles can be acquired using a digital camera or a photocopier and transcribed in feature-length. Often, their low quality does not allow for an automatic conversion of image files to text files.

Each text file should be transformed into a database record for which the dates of events, the municipality where the phenomenon occurred, the type or types of triggered phenomena, and the damage are described. In general, the name of the municipality where damage occurred is quoted in almost all the data, but place names of areas hit are often not pinpointed. Even if a place name is available, the area really affected cannot be delimited because reporters cannot supply precise information on the size of a phenomenon.

To be strict, the data allowed us to identify the occurrence/nonoccurrence of a certain type of phenomenon only at a municipal scale. Taking into account the temporary effects of some kinds of phenomena, only detailed surveys carried out immediately after the event could supply a reliable delimitation of hit areas. We also used a municipal scale because it is congruent with the scale of the rain gauge network. In general, rain gauge networks are characterized by a municipal grid (each municipality usually has a rain gauge at least).

Main Characteristics and Trend of DHEs

The characteristics and trends of damaging phenomena and damage must be compared to the exceptionality and spatial trend of climatic triggering factors using available data (basically time series of daily rainfall). The whole daily rainfall time series of each gauge available for the region should be used.

To describe the damaging phenomena that occurred in the study period, the following parameters should be considered.

- *Density of phenomena in each province*. For each type of phenomenon in the study period, we can assess the *density of phenomena in each province* by dividing the number of phenomena by the province area (km^2). For sea storms, the number of phenomena can be normalized to the area of a coastal strip obtained by multiplying the length of the coast for each municipality by the width in which *direct* or *indirect* damage caused by sea storms is reasonable. If this width is not known along the whole coast, a unique conventional width can be set to obtain an index with the same dimension as the indexes concerning the other types of damaging phenomena.
- *Regime of rainfall and of damaging phenomena.* For each gauge, considering mean monthly values in the entire observation period, the rainfall regime can be defined. An overall analysis of damage data, chronologically sorted, allows us to assess the mean monthly frequencies of different types of damaging phenomena. The statistical significance of the regime should be considered in relation to the length of the study period, until this is almost shorter than the return period of meteorological conditions that can trigger damages. In this almost-frequent case, a preliminary regime of damaging phenomena can be considered roughly assessed if the dataset describes damaging phenomena in the whole vulnerable study area. This condition can be considered verified if each vulnerable municipality was hit by DHEs during the study period. The regime can thus be compared to the rainfall regime.
- *Annual rainfall index* (ARI). The ARI (%) can be defined as

  $$ARI = \left(\sum_{i}^{n} \frac{r_{i,j} - mr_i}{mr_i} \right) \times 100/n \qquad (1)$$

  where i is one of the n rain gauges available in the year j, and $r_{i,j}$ and mr_i are the annual rainfall of gauge i in year j and the mean yearly value in the observation period of the gauge, respectively. The ARI can be used to assess the presence of a rainfall trend in the study area and can be compared to the series of DHEs. Thus, it is possible to investigate the role of climate variability on DHEs and its interaction with increasing vulnerability due to anthropogenic expansion.

Analysis of Different Types of Events

For this step, single DHEs should be defined. During a rainy period, a DHE starts when a damaging phenomenon causes damage and ends when the last damage is observed. In regions where rainy periods are long and continuous, based on regional features of meteorological events and geomorphological and hydrogeological characteristics of the hit areas, a threshold lag value between two subsequent damages can be defined.

For each DHE, the following *event descriptive indexes* can be defined.

- *Index of damaged area (IDA).* By summing the area of municipalities hit during the DHE (S) and dividing the obtained value by the area of the regional surface, we obtain the IDA, an index that expresses the area damaged by the event (Petrucci and others 2003). S is greater than the area truly affected, but this simplification is necessary to bypass the impossibility of delimiting areas really hit that characterises most cases. Moreover, the municipal scale is the basic level for comparing rainfall, damaging phenomena, and damages.
- *Extension event index.* Based on the value of the IDA, we can classify events as: (1) *local*, if damage is confined to one province or the IDA is <2.5%; (2) *wide*, if the damage is observed in two provinces and the IDA ranges from 2.5 to 10%; and (3) *regional*, if the IDA is >10% and hits municipalities belonging to three or more provinces.
- *Local damage index (LDI).* This represents the sum of all damages D caused in a single municipality by the I damaging phenomena that occurred there. If observed damage is the product of the value of the damaged element and its level of loss, for the ith damage, the LDI can be calculated by multiplying the value of the element (ranging from 1 and 10, in the arbitrary scale of Table 1) by the *level of damage*, a measure of the percentage of loss affecting the element during the event (high = 1 for level 1; medium = 0.5 for level 2; low = 0.25 for level 3) (Petrucci and others 2003).
- *Local damage index density* (LDI_d). For each municipality hit, this parameter is assessed by dividing the LDI by the municipal area. Obtained values can be sorted into four classes (class 1, $\mathrm{LDI_d} \leq 1$; class 2, $1 < \mathrm{LDI_d} \leq 2$; class 3, $2 < \mathrm{LDI_d} \leq 3$; class 4, $\mathrm{LDI_d} > 3$). For each event, a regional map of municipalities classified according to the $\mathrm{LDI_d}$ summarizes the regional pattern of damage.
- *Regional damage index (RDI).* This is the sum of the LDIs calculated for all n municipalities affected by damage during a DHE and quantifies damage caused by each DHE on the regional scale.
- *Return period of maximum daily rainfall* (T). This parameter can be used to describe the exceptionality of rainfall causing a DHE. For each gauge, the time series of annual maxima of daily rainfall should be evaluated and the probability distribution function of these peak values should be assessed. A reliable choice could be the *GEV* (generalized extreme value) *probability distribution function* (Jenkinson 1955), which is defined by three parameters that can be assessed using the *PWM* (probability-weighted moments) *method* (Hosking 1986); this supplies consistent worldwide results without significant statistical difficulties, particularly if outliers are not observed.
  On the other hand, the regionalization approach to parameter definition should be preferred. If extremely exceptional values are observed (outliers), a four-parameter probability distribution function, like the *TCEV* (two-component extreme value) (Rossi and Versace 1982), ensures higher reliability in the assessment of T.
  Thus, for each gauge working during a DHE, the return period of the maximum daily rainfall (T) observed during the DHE must be assessed. This value can be assumed to be representative of the exceptionality of the rainfall that triggered the DHE. For each event, T maxima can be mapped using the kriging approach. The gauges can be sorted into four classes of increasing exceptionality according to T (class 1, $\mathrm{T} \leq 2$ years; class 2, $2 < \mathrm{T} \leq 10$ years; class 3, $10 < \mathrm{T} \leq 20$ years; class 4, $\mathrm{T} > 20$ years), and the number of gauges classified in each class can be expressed as a percentage of the total number of gauges available during the analyzed DHE.

To this point, the parameters assessed in the previous steps can be used to outline the main characteristics of DHEs, the areas most frequently hit, and the most severe scenarios that can be expected.

Case Study of the Calabria Region

We applied the proposed approach to Calabria, Italy (Fig. 1). Long-lasting time series with adequate gauge density are available only for daily rainfall. Homogeneous and affordable data concerning damaging phenomena and damages are available from January 1981 to December 1990 (the oldest regional newspaper, *La Gazzetta del Sud*, appeared in 1953, and does not present gaps in this period). Apart from this period, many scattered discontinuous data of variable reliabilities are also available.

The Calabria region has an area of 15,230 km^2 and a coastal perimeter of 738 km. The mean and maximum altitudes are, respectively, 418 and 2266 m above sea level (asl); 90% of regional territory is in areas of relief, and 10% is represented by coastal and fluvial plains. The region is made up of five administrative provinces divided into

Table 1 Types and subtypes of damaged elements: for each type and subtype, the value considered for damage assessment is E_i

Type	Subtype	E_i			Level 1 (1)	Level 2 (0.5)	Level 3 (0.25)
		Bridge	Tunnel	Roadway			
Road network	Highway	10	10	8	Prolonged traffic interruption due to road breakage	Temporary traffic interruption due to road breakage	Effects on road without traffic interruption
	State road	8	8	6			
	County road	6	6	4			
	Municipal road	5	5	3			
	Mule-track			1			
Railway network	State railway	10	10	8			
	Regional railway	8	8	6			
	Service railway	5	5	3			

Type	Subtype	E_i	Level 1 (1)	Level 2 (0.5)	Level 3 (0.25)
Housing areas		10	Building collapse	Building evacuation	Effects not involving evacuation
Public buildings	Hospital	10			
	City hall	10			
	School	10			
	Barracks	10			
	Fire station	10			
	Church	10			
	Airport	10			
	Cemetery	5	Collapse of a lot of construction	Collapse of some construction	Effects without collapses
Services networks	Electricity line	5	Prolonged service interruption in large areas	Temporary service interruption in large areas	Temporary service interruption in small areas
	Telephone line	5			
	Drainage system	5			
	Aqueduct	5			
Productive activities	Agriculture	4	Interruption of production and loss of productive system	Interruption of production and loss of products	Limited loss of products
	Farming	4			
	Commerce/business	5			
	Fishing	4			
	Industry	8			
Tourist and sport resorts	Hotel	10	Interruption of activity and loss of productive structure	Temporary interruption of activity	Effects without interruption of activity
	Campground	4			
	Bathing beach	2			
	Sport resorts	8			

Table 1 continued

Type	Subtype	E_i	Level 1 (1)	Level 2 (0.5)	Level 3 (0.25)
Port equipment	Wharf	8	Collapse	Loss of efficiency	Effects not involving loss of efficiency
	Seafront	3			
	Breakwater	1			
Hydraulic works	Check dam	4	Collapse	Loss of efficiency	Effects not involving loss of efficiency
	Embankment	5			
	Retaining wall	6			
	Dam	10			

Note: The columns levels 1, 2, and 3 describe the damage levels. The multiplying factors for assessing the local damage index are given in parentheses

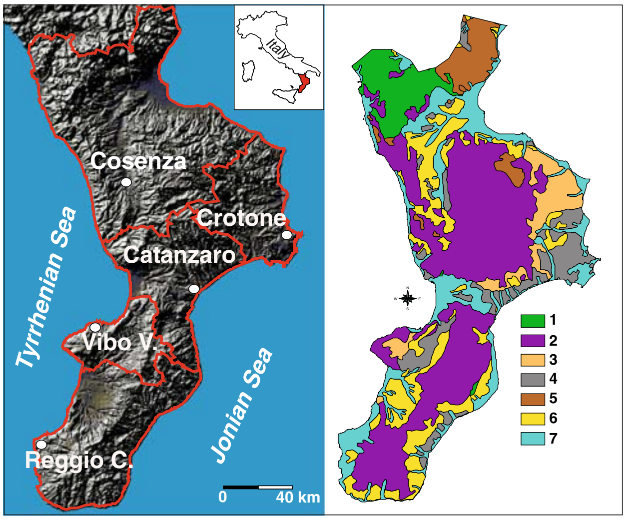


Fig. 1 (*Left*) Shaded relief map of Calabria and province boundaries. *Reggio C.* Reggio Calabria; *Vibo V.* Vibo Valentia. (*Right*) Simplified geological sketch of the region. (1) Limestone and dolostone; (2) metamorphic and igneous rocks; (3) clays, marls, and evaporitic rocks; (4) sandstones, marly clays, and limestone marls; (5) flysch and clayey formations; (6) conglomerates, sands, and sandstones; (7) alluvial deposits

409 municipalities. Population density (133 inh/km^2) is lower than the national value (198 inh/km^2) (ISTAT 2003).

Due to its peninsular character, its boundary is a physical edge, inside of which the climatic regime is homogeneous; however, concerning the statistical characteristics of peak daily rainfall, different subzones can be distinguished (Versace and others 1989). The climate is Mediterranean, with dry summers (monthly minimum rainfall in July or August) and wet winters (monthly maximum rainfall in December or January). The mean regional annual rainfall is 1151 mm, higher than the national value (970 mm). Due to the prevalent movement from west to east of meteorological perturbations, the rainiest area is the west side of the region, but the east sector often experiences heavy storms (Versace and others 1989). In the latter sector, DHEs occur during the autumn-winter, when slow movement of Mediterranean depressions can produce daily rainfall that reaches up to 30–35% of mean annual rainfall (Petrucci and Polemio 2002).

The region is made up of allochthonous crystalline rocks (from the Palaeozoic to the Jurassic), stacked, during the middle Miocene (Tortorici 1982), over carbonate units (Ogniben 1973). Neogene's flysch fills tectonic depressions. Starting from the Quaternary, the region has been subjected to still-active uplift. Tectonic stresses and climatic conditions deteriorate the characteristics of rocks, predisposing slopes to instability phenomena. Today, both deep-seated (Iovine and others 2006) and shallow (Sorriso-Valvo and others 2004) landslides are often activated by rainfall.

Because of the short distance between mountain chains and the sea, several rivers show characteristics of *fiumare*, ephemeral streams characterized by huge sediment loads and violent flash floods (Fairbridge 1968; Ibbeken and Schleyer 1991). Because of the lack of plain areas and low awareness of natural hazards, several urban settlements have developed in flood- and landslide-prone areas. This increases the number of vulnerable elements exposed to DHEs, increasing expected damage.

Data Analysis

We reviewed about 3600 daily editions of *La Gazzetta del Sud* for the study period. Articles pertaining to damages caused by landslides, floods, secondary floods, and sea storms were selected. All the gathered data were organized into the database format described under Data Gathering and Preliminary Analysis, above.

Trend of Damaging Phenomena in the Study Period

We distinguished 747 phenomena: 43% (319 cases) landslides, 7% (53 cases) floods, 31% (232 cases) secondary floods, and 19% (143 cases) sea storms (Fig. 2). The widest province (Cosenza) shows the highest number (348), with a prevalence of landslides (138 cases) and secondary floods (113 cases), followed by Reggio Calabria, with 240 phenomena, many of which are landslides (108 cases) (Fig. 2a). In general, the most numerous damaging phenomena are landslides and secondary floods (Fig. 2b).

The *density of phenomena* for landslides, floods, and secondary floods is the highest in the province of Reggio Calabria, while *sea storms* show the highest density in the province of Cosenza (Fig. 2c).

The *regime of damaging phenomena* is well correlated with the rainfall regime, as shown in Fig. 3, in which the representative regime of the Cosenza gauge is plotted.

The *landslide regime* shows one peak in January and a minor one in December, the latter mainly due to shallow landslides triggered by heavy rainfall. The third value, in decreasing order, is recorded in March: it is caused both by deep-seated landslides triggered by prolonged rainfall (in mountainous areas also coupled with snow melting) and by shallow landslides that can be triggered in soils almost saturated by antecedent winter rainfall.

Floods and *secondary floods* show high and almost-constant values from October to March, a period during which short and intense rainstorms are frequent. Considering both types of floods, the highest frequency is generally in October–January; if the sum of each monthly type is considered as a percentage of the annual total, the maximum is observed in January (28%), followed by December (17%).

Sea storms, although related only to DHEs characterized by strong winds, follow the rainfall regime, except for the low value in November. The unavailability of time series concerning winds does not allow a deeper analysis of these phenomena.

We assessed the ARI; in the eighties, it shows a decrease of −20 to −3% of the mean ARI for the period 1921–2001. This figure matches an anomalous sequence of dry or drought periods observed since 1980 in all of southern Italy (Polemio and Casarano 2008). For each year of the analyzed period, we compared the ARI to the IDA (Fig. 4).

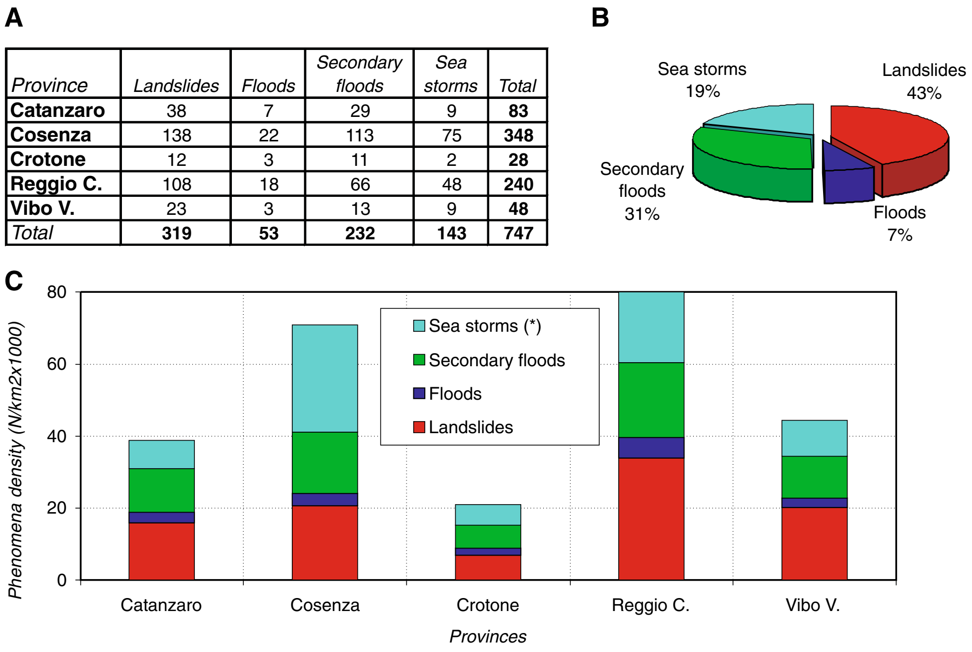


Fig. 2 Number and type of phenomena in the study period. **a** Number and type of phenomena in each province; **b** percentage of each type of phenomenon that occurred; **c** phenomenon density for each province ([number of phenomena/area (km^2)] × 1000). *Sea storms have been normalized to the coastal length of the province ([number of phenomena/coastal strip area (km^2)] × 100). Note that the multiplying factors 100 and 1000 are used only for graphical purposes

A

Province	*Landslides*	*Floods*	*Secondary floods*	*Sea storms*	*Total*
Catanzaro	38	7	29	9	**83**
Cosenza	138	22	113	75	**348**
Crotone	12	3	11	2	**28**
Reggio C.	108	18	66	48	**240**
Vibo V.	23	3	13	9	**48**
Total	**319**	**53**	**232**	**143**	**747**

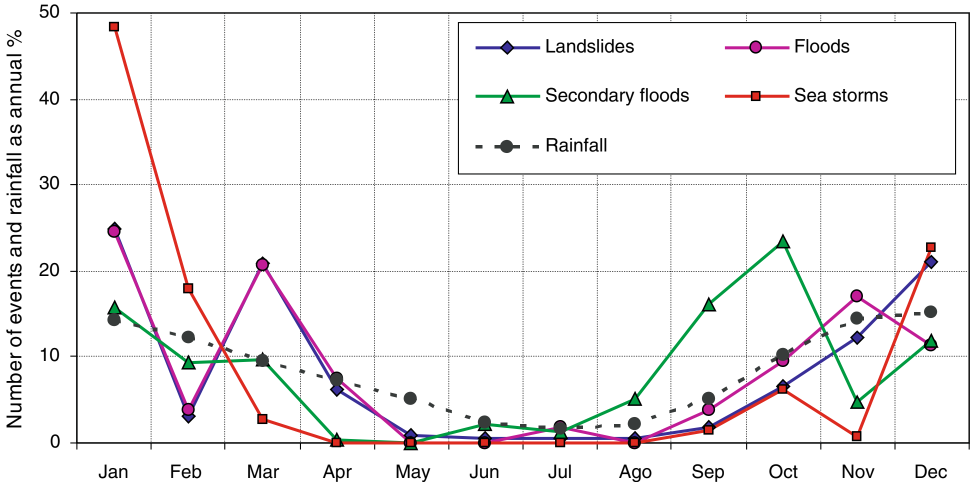


Fig. 3 Regime of damaging phenomena types and rainfall (Cosenza gauge), as a percentage of the yearly total

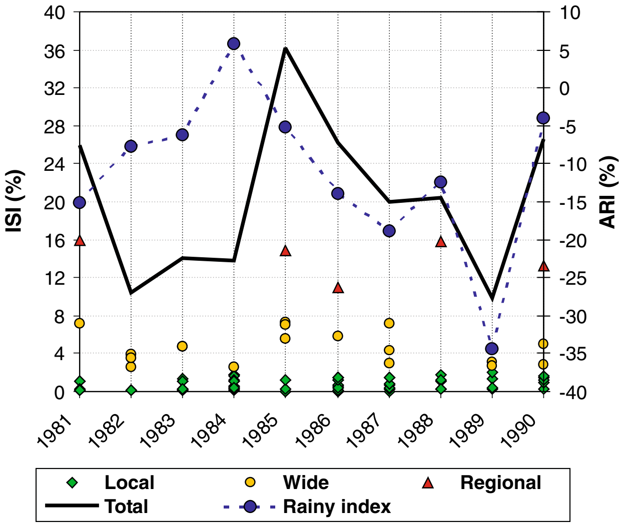
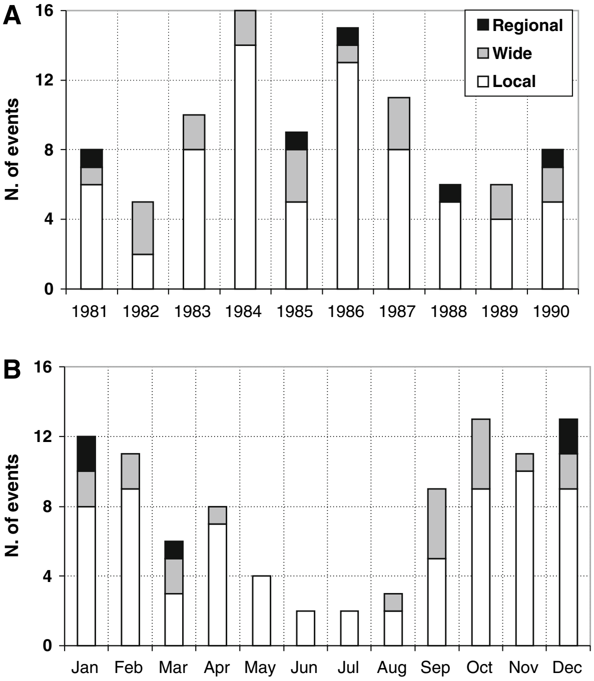


Fig. 4 Annual rain index (ARI; %) and annual index of damaged area (IDA; %) assessed separately for local, wide, and regional events and as total annual values



C

Event	*N.*	*N. municipalities*			*IDA*			*Duration (days)*		
		Min	Med	Max	Min	Med	Max	Min	Med	Max
Local	70	1	2.21	10	0.0004	0.69	1.99	1	1.50	9
Wide	19	3	13.89	35	2.58	4.52	7.24	1	3.74	17
Regional	5	37	48.8	59	10.98	14.20	15.97	2	13.20	20

Fig. 5 Classification of events on a yearly basis (**a**), on a monthly basis (**b**), and as summarized values (**c**)

Based on total yearly IDA values, the percentage of regional area hit during each year ranges from 36% (in 1985) to 9% (1989), with a mean value of 20%. This is almost well correlated with the ARI values (the apparent 1-year lag observed from 1984 to 1986 is mainly due to the effect of autumn rainfall at the beginning of the rainy season). As the significance of selected indexes confirms, the forecast of the ARI index can be used to qualitatively assess the expected wideness of damaged areas.

Local and Wide Events During the Study Period

During the study period, 94 damaging events occurred. Between 1983 and 1987, a clustering of events of each type can be noted (Fig. 5a). These can be classified as 70 local, 19 wide, and 5 regional events (Fig. 5c). October and December show the highest number of events (13), and during December each type of event can be observed (2 regional, 2 wide, and 9 local). Unlike regional events, local and wide events are observed every year (Fig. 5b).

Taking into account the duration/frequency of meteorological perturbations and the regional geomorphological features, a maximum lag between two subsequent damaging phenomena in a DHE can be set equal to a week.

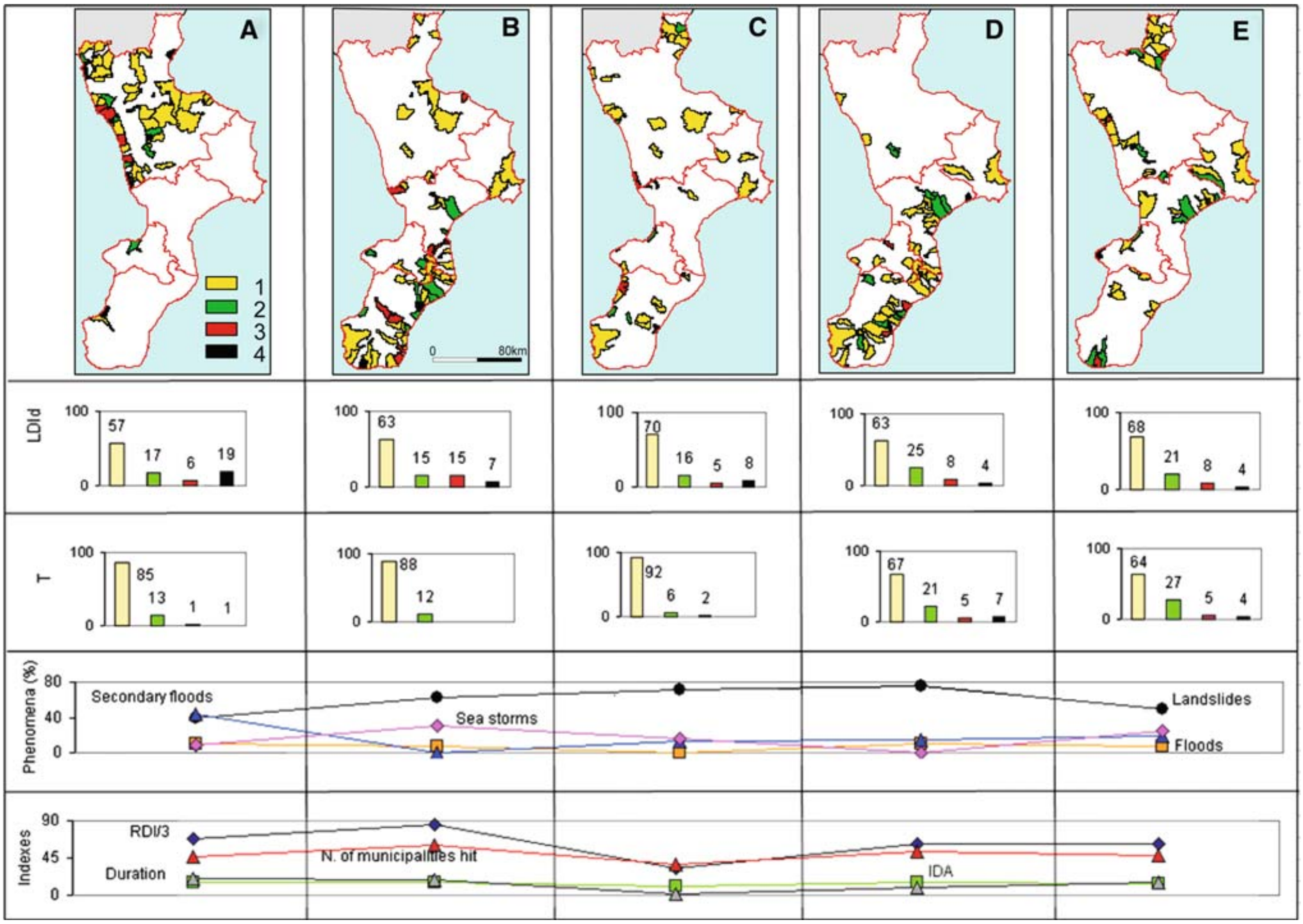


Fig. 6 Summarized table of regional events: each column represents an event, labeled with the letter in the right-hand corner of the map. Maps represent municipalities, classified according to four classes of LDI_d [(LDI/municipal area) × 10]; red lines are boundaries of provinces. LDI_d values are also expressed as a percentage in the first row of histograms. The second row represents the percentage of rain gauges classified according to the maximum return period of daily rainfall. Phenomena (as percentage of total) and indexes are represented in the other two diagrams. RDI is divided by 3 for graphical needs; duration of events is given as days

Ninety-two percent of DHEs were shorter than a week; the maximum observed length was 20 days.

Local events. The IDA ranges from 0.0004 to 1.99 (mean, 0.69). The number of municipalities hit ranges from 1 to 10 (mean, 2.21). These primarily concern sea storms, in which only a coastal strip of each municipality was considered as having been hit. The duration of these events ranges from 1 to 4 days.

Wide events. The IDA ranges from 2.58 to 7.24 (mean, 4.52). The maximum number of municipalities hit is 35, the minimum is 3, and the mean 3.89. The event duration is < 8 days. The only event with a markedly different duration occurred in March (17 days; 23 municipalities damaged).

Regional Events During the Study Period

During the study period, five regional events occurred in the winter and spring: two in January (A and B), one in March (D), and two in December (C and E). Figure 6 provides an analysis and comparison of all gathered elements for each regional event. The LDI_d is expressed as the percentage of municipalities hit, classified in the four classes described under Analysis of Different Types of Events, above. The exceptionality of rainfall is expressed as the percentage of rain gauges; the return period of maximum daily rainfall is classified into the four defined classes. The different types of triggered phenomena are expressed as the percentage of the total that occurred during each event. As indexes, the RDI (divided by 3 for graphical purposes) and IDA are assessed. The numbers of municipalities hit and the event durations, expressed as days, are also reported for each event. For these events, the IDA ranges from 11.0 to 16.9 (mean, 14.2); the number of municipalities hit ranges from 37 to 59, and the number of provinces hit is between 3 and 5. For rainfall analysis, the number of available rain gauges was 189, 182, 185, 174, and 160, respectively, for events A, B, C, D, and E.

The maximum return period (T) of daily rainfall was assessed using the approach proposed by Versace and others (1989). According to these authors, in Calabria, three rainfall subzones can be recognized: the Tyrrhenian, Central, and Ionian subzones. For each subzone, we have evaluated the probability distribution function using the TCEV function. T was assessed by the growth factor of daily rainfall (X'):

$$X' = h_{\mathrm{d}}/\mathrm{mH} \tag{2}$$

where h_{d} is the daily rainfall for which T should be assessed, and mH is the average of the annual maxima of daily rainfall observed at the same gauge. For each subzone, the best-fitting function to estimate T, on the basis of X', is known. Using this approach, for each gauge and each event, we assessed the maximum T values. For each event, we converted this information into a regional map of T values; the peak T at each gauge in each event was used to plot the max-map (Fig. 7). Rain is observed in each regional event on the western regional side, but very exceptional rains are observed mainly on the eastern side (D and E events).

From the gathered data, the main features of the analyzed regional events can be outlined as follows.

- *Event A: 3 January–5 February 1981*. This is the only event almost confined to the northwestern sector of the region. Eighty-five percent of the gauges record rainfall with return periods <2 years, and 13% between 2 and 10 years. The very few values classified into classes 3 and 4 (1%; not visible in Fig. 7a) pertain to gauges located in the northwestern sector, along the western coast. Secondary floods and landslides, at almost the same frequency, are the most abundant types of phenomena. The comparison of $\mathrm{LDI_d}$ and maximum T maps shows some discrepancies between the two compared variables, due to the flood effect in the widest

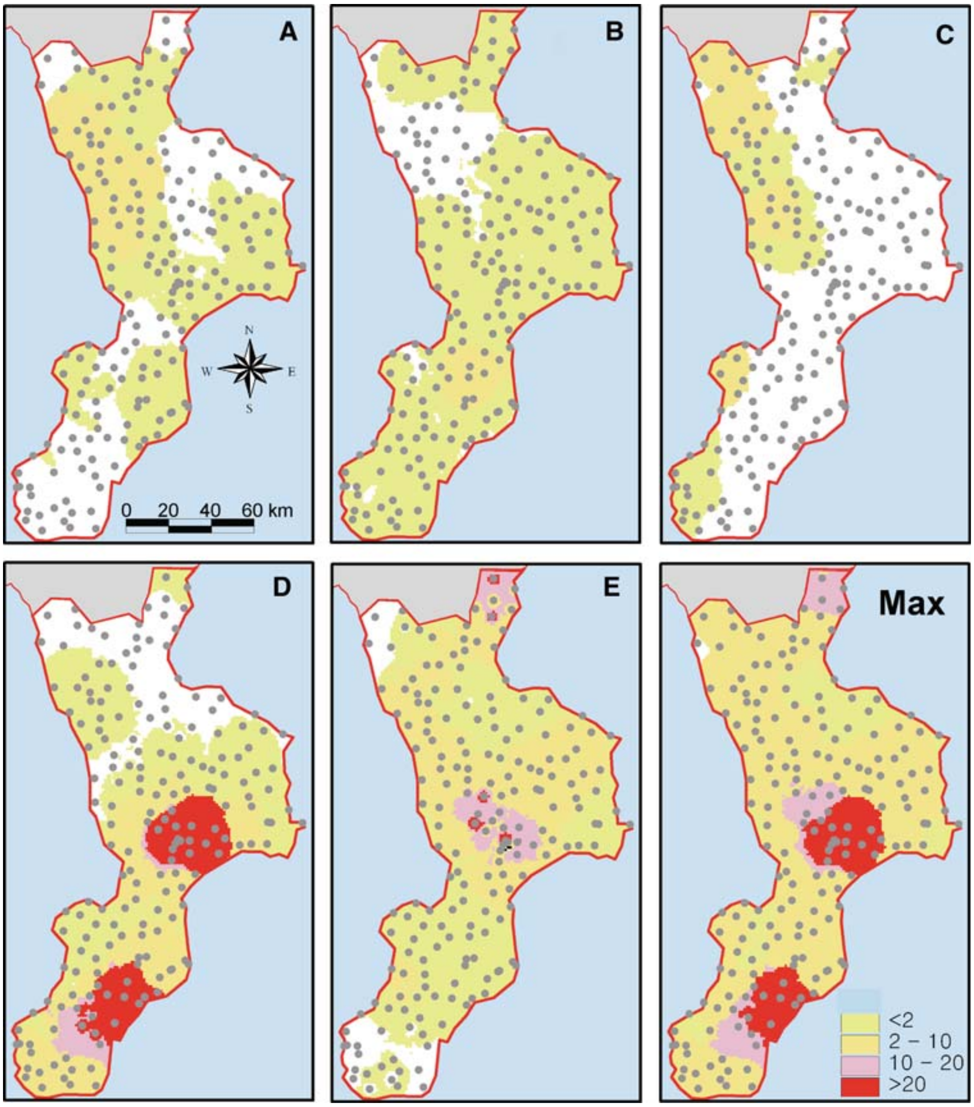


Fig. 7 Return period maps and location of available rain gauges (T; years). **a** Event A; **b** event B; **c** event C; **d** event D; **e** event E. Max: maximum T of each gauge for each event was used to define the T maximum map

Table 2 Number of cases of damage for different kinds of elements in each regional event

Type of element	Event				
	A	B	C	D	E
Road network	12	39	10	36	30
Railway network	3	4		3	3
Housing estates	14	18	27	12	14
Public buildings	3			3	2
Services networks	35	8	3	4	5
Productive activities	10	15	6	5	4
Tourist and sport resorts		7			5
Port equipment	1	8	2		6
Hydraulic works	1	3		2	2

regional river basin, which covers this part of the region. According to the $\mathrm{LDI_d}$, municipalities hit by the event are classified as follows: class 1, 57%; class 2, 17%, class 3, 6%; and class 4, 19%. The high RDI is mainly due to damage to service networks (35 cases), followed by damage to housing areas (14 cases and road networks (12 cases) (Table 2).

- *Event B: 2–19 January 1985*. This event mainly affected the eastern sector. The return period of rainfall remains in class 1 for 88% of the gauges and class 2 for 12%. Landslides and sea storms prevailed over the other types of damaging phenomena: during this event, the latter reached the highest value recorded during all the other events. Sixty-three percent of municipalities hit underwent $\mathrm{LDI_d}$ of class 1, 15% of class 2, 15% of class 3, and 7% of class 4. The value of RDI, the highest among all the analyzed events, was mainly due to damage affecting roads (39 cases), housing areas (18 cases) and productive activities (15 cases).
- *Event C: 20–21 December 1986*. Damaged municipalities were widespread on the regional surface. Ninety-two percent of the gauges showed return periods of <2 years; 6%, between 2 and 10 years; and 2%, between 10 and 20 years. The highest values were mainly observed along the western coast. This event was characterized by the lowest duration (2 days) and number of municipalities hit (37). It was the least damaging of the analyzed events: 70% of involved municipalities showed $\mathrm{LDI_d}$ of class 1, 16% of class 2, 5% of class 3, and 8% of class 4. The value of RDI (32; the lowest of all) was also in accordance with the least exceptional levels of rainfall. Damage mainly affected housing areas (27 cases).
- *Event D: 2–11 March 1988*. This event resulted in 63% of municipalities in class 1, 25% in class 2, 8% in class 3, and 4% in class 4. In terms of return period of rainfall, this was the most exceptional event. Sixty-seven percent of gauges show return periods of class 1, 21 of class 2, 5% of class 3, and 7% of class 4. Values of the latter two classes were mainly recorded in the central part of the region, where the peak value was more than 100 years. Damaging phenomena were mainly represented by landslides (75%). The RDI was not particularly high compared to the rainfall exceptionality, which can be considered an indicator of the low vulnerability of the area. It affected the eastern sector, mainly in the central and southern zones. We classified municipalities according to $\mathrm{LDI_d}$: damaged elements consisted of roads (36 cases) and housing areas (12 cases) (Table 2).
- *Event E: 11–28 December 1990*. This event affected both the eastern and the western sectors. Return periods were low for 64% of the gauges (class 1), medium for 27% (class 2), high for 5% (class 3), and very high for 4% (class 4). The highest values characterized the central part of the region, where the peak value was about 70 years. Landslides and sea storms were the most frequent types of phenomena. The areas hit mainly belonged to the Ionian and Inland subzones. We characterized damage by $\mathrm{LDI_d}$ of class 1 for 68%, 2 for 21%, 3 for 8%, and 4 for 4% of hit municipalities. Damaged elements mainly consisted of roads (30 cases) and housing areas (14 cases).

Based on the collected data, similar features of the DHEs can be outlined, despite having been obtained from a 10-year period.

- Landslides are the most frequent type of damaging phenomenon during DHEs; Reggio Calabria province shows the highest landslide density (Fig. 2c). The *landslide regime* shows one peak in January and a minor one in December (Fig. 3).
- During regional DHEs, more than 40% of phenomena are landslides, while the other types show fluctuating values from one event to the other. This denotes, in almost all regional sectors, a higher sensitivity to landslides than to the other types of phenomena.
- The road network is the most damaged element, threatened by all types of damaging phenomena during each regional event. The number of cases of damage ranges from 10 (event C) to 39 (event B). The damage to housing areas, which in many cases required evacuating inhabitants, depends on the combination of the intrinsic fragility of the historical urban settlements and the damaging power of the events. The number of cases, for this element, ranges from 12 (event D) to 27 (event E).
- The IDA shows a very low variability from one event to the other, with a maximum of 16.

- The northern sector of the region, hit by event A, seems to be the most vulnerable zone. Here, rainfall characterized by low exceptionality values can trigger phenomena (mainly landslides and secondary floods), causing severe damage. Of all the analyzed events, A shows the highest percentage of municipalities in class 4. Service networks, followed by housing areas, are the most damaged elements. As damage to people is not included in the proposed quantification of damage, we should report that, during this event, four victims died in a railway accident caused by a landslide. This considerably increases the severity of the event, confirming the vulnerability of this regional sector.
- The eastern side of the region, affected by many DHEs outside of the study period, can display two different behaviors, as in events B and D. In B, low-exceptionality rainfall produced the highest value of RDI. In D, the relation is more linear: high damage is triggered by high-exceptionality rainfall. This can be explained by the fact that, in B, part of the damage was caused by sea storms (see the location of high LDI_d on the map in Fig. 6), which are more related to wind than to rainfall. From these data we can infer that, in this area, starting from low–medium exceptionality values of rainfall ($T < 10$ years), damaging hydrogeological phenomena can occur. In both cases, roads and housing areas are the most damaged elements.

Concluding Remarks

We have defined a methodological approach, based on seven simple indexes, for studying hydrogeological damaging phenomena triggered by rainfall. The indexes describe the exceptionality and trend of rainfall, the extent of hit areas, and the level of damages; these can be considered attributes of georeferenced features and analyzed with GIS techniques.

We tested our method in an Italian region frequently hit by DHEs. Using the regionalization approach and the four-parameter TCEV function, we assessed T for each day/gauge during a DHE. Instrumental damage data obtained from daily newspapers (in a period of 10 years) allowed us to recognize 747 damaging phenomena during 94 DHEs. All available data have been converted into index values.

Almost all the regional sectors are landslide-prone: more than 40% of triggered phenomena are landslides, reaching the highest density in the southernmost province (Reggio Calabria). The road network and housing areas are the most frequently damaged elements, and are threatened by all types of damaging phenomena.

The *regime of damaging phenomena* seems to be well correlated with the rainfall regime. The *landslide regime* shows one peak in January and a minor one in December; *floods* and *secondary floods* show high and almost-constant values from October to March. As the IDA is reasonably correlated with the ARI, the forecast of ARI could be used to quantitatively assess the expected total wideness of damaged areas.

According to their spatial relevance, we classified the events into local, wide, and regional: 70 local, 19 wide, and 5 regional events have been recognized. Deepening the analysis of regional events, we were able to outline some distinctive features of DHEs affecting the different regional sectors.

The most severely damaged area is the eastern side of the region, which experienced severe damage after both ordinary (event B) and exceptional (event D) rainfall events. From the data analyzed at present, we can infer that rainfall of low–medium exceptionality ($T < 10$ years) can trigger DHEs in this area. The vulnerability of the northern part of the region appears to be high, as it experienced severe damage after rainfall of low–medium exceptionality. This high vulnerability, which seems to be distinctive of this area, is mainly due to the role of flooding in the largest drainage basin. In the case of regional events, T classes almost justify the level of damages. This figure can be easily used with real-time rainfall monitoring to define warning levels for civil protection purposes.

Even simple outlines of damage scenarios of past DHEs can provide useful information for forecasting potential damage. The dissemination of information concerning the areas that were hit in the past and could be hit in the future, as well as the expected type of damaging phenomena, considering the T class or not, and resulting damage, could increase people's awareness of risk and promote more aware behavior.

Forecasting the size of the area that could be hit, based on ARI forecasting, and the possible event scenario obtained for the different regional sectors should be useful for regional civil protection offices, either in organization of common operative activities or in emergency management during DHEs. In future work, we will extend the study period and, in selected areas, investigate the roles of other climatic parameters and the significance of rainfall thresholds.

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