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DEALING WITH HYDRO-GEOLOGICAL EVENTS: MITIGATION AND HISTORY CASES

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ABSTRACT

Past Damaging Hydrogeological Events (DHEs), which can be defined as periods characterised by heavy rainfall inducing such damaging phenomena as landslides and floods, are analysed in this article. The work is focused on the relationships between these phenomena and the characteristics of triggered rainfall, to supply useful suggestions for early detection and damage mitigation. The analysis of past DHEs allows for the characterisation of the main types of DHEs, which affected a selected area in the past and could affect it again in the future.

The proposed characterisation is based on triggering scenarios (meteorological conditions preceding the occurrence of DHEs), DHE's effects (damage caused by landslides and floods) and triggering factors (rainfall of different durations). Based on these features, the typical DHEs affecting a study area can be outlined and ranked according to their severity, thus specific emergency management can be planned to successfully manage them.

To obtain results that have a reliable statistical meaning, a large amount of data of three different types (meteorological, rainfall and damage data) must be treated, and some indices, allowing the comparative analysis of these kinds of data, have to be introduced.

In this work we describe the methodological approach, which can be applied in different climatic and anthropogenic contexts;finally, some applications of the proposed method to the region of Calabria (South Italy) are presented.

INTRODUCTION

Periods of bad weather conditions, lasting from one to several days, characterised by prolonged or intense rainfall and strong winds, can trigger almost simultaneous damaging phenomena such as landslides, floods, secondary floods (i.e., stagnancy of rain on surfaces with low permeability) and sea storms, causing casualties and damages. As a whole, the bad weather periods and triggered phenomena can be defined as Damaging Hydro-geological

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Events (DHEs) (Petrucci and Polemio, 2002; 2003; Petrucci et al., 2009; Petrucci and Polemio, 2009).

Since of the simultaneous triggering of various types of phenomena, DHEs represent a source of multiple natural hazards (AA.VV., 1983), and need a comprehensive study and managed approach. The attention paid to DHEs has recently increased because of their costly effects and the need to cope with them. On the other hand, the social and economic costs of DHEs are not well documented because no agency is formally charged with gathering data about them (I.F.R.C., 2001). In particular, damage to some elements, such as roads, is often merged with maintenance costs; therefore, they are not labelled as, for example, damage induced during DHEs by landslides (Highland, 2003). Conventional approaches have only been focused on a single type of phenomena at a time, while global approaches have only recently pursued the analysis of different types of phenomena triggered during several DHEs together (Barnikel and Becht, 2003; Diodato, 2004; Giannecchini, 2005; Luino, 2005; Petrucci and Polemio, 2009). Regarding damaging phenomena, in the following we focus on landslides, floods and secondary floods (Figure 1); sea storms are only considered where it is explicitly stated.

In the appraisal of landslide and flood damages, the underlying factors, such as triggering rainfall and antecedent meteorological conditions, can be the building blocks to outline features of DHE, which may help to plan a comprehensive defensive strategy.

Furthermore, by comparing the exceptionality of triggering rainfall and induced damage, the zonation of the study area—defined upon the different levels of damage susceptibility during DHEs—can also be pursued. This information may be helpful in defining priorities when hazard mitigation measures must be realised, and can be ranked according to susceptibility levels (Petrucci and Pasqua, 2008).

Studying DHEs presents certain difficulties, which are described below:

a) Landslides and floods are extremely complex phenomena that hit large areas dominated by a wide range of geomorphological and hydrogeological conditions.
b) The DHE analysis supplies reliable data for the mitigation and protection purposes only if it is carried out over a long historical series of DHEs (greater than 10 years).
c) The hydrological processes relevant to DHEs could involve rainfall measurements of different durations, from minutes to days (in cases in which the antecedent soil water content is a key factor). Often these data are unavailable for long periods, characterised by either low quality or spatial density, and generally too complex to be analysed.
d) The behaviour of processes is frequently assumed to be uniform and steady; based upon this assumption, the analysis of recent events enables the forecasting of similar events in the future (Remondo et al., 2008). However, urbanisation, land use changes and engineering works, especially in areas subjected to increased urbanisation, must be taken into account (Etkin, 1999; Barrera et al., 2005; Petrucci and Polemio, 2007; Polemio, 2010). Finally, climate change can also modify the frequency and seriousness of damage (Dore, 2003; Petrucci and Polemio, 2009).

Taking into account these problems, a simplified empirical methodology can be outlined to study the DHEs observed in a study area during long periods of time.

The present work, we describe research activity focused on the individuation and characterisation of the main types of DHEs affecting a selected area. The result of this activity is a methodological approach that can be used in different geological, geomorphological and climatic frameworks. At the end of the article, the results of some of the case studies regarding Calabria (Southern Italy) are also shown (Figure 2).

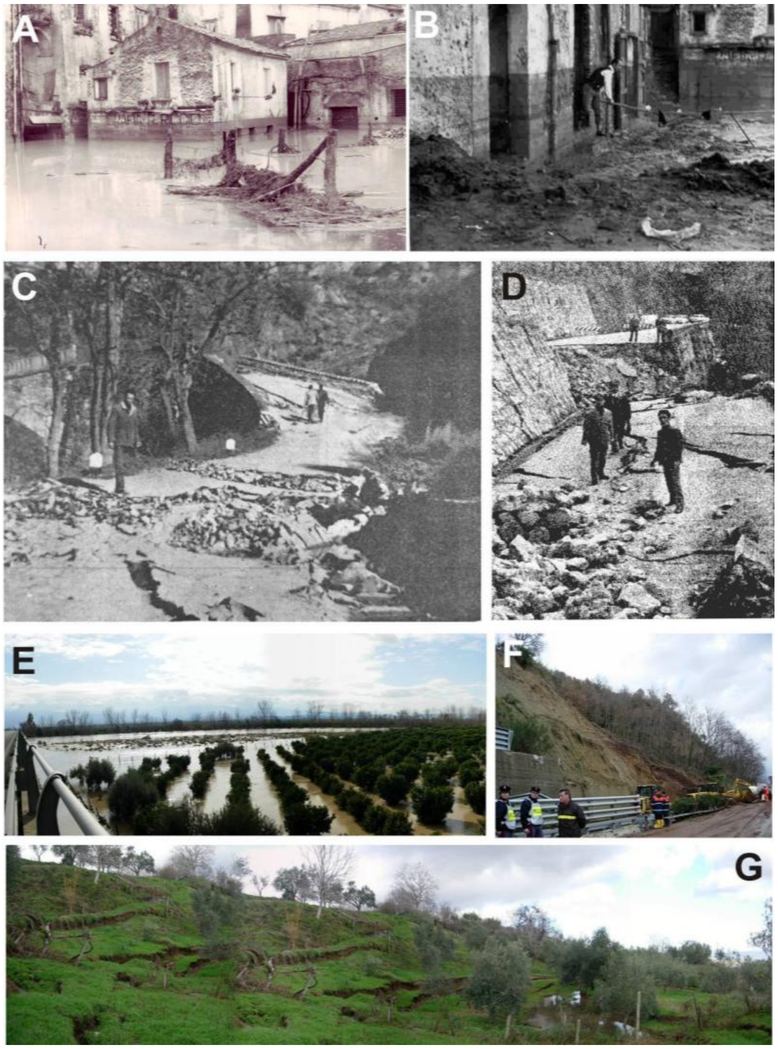

Figure 1. Effects of some DHEs that occurred in Calabria. A and B: effects to houses due to flooding of the Crati River (northern Calabria) in Cosenza town during the DHE that occurred in 1959 (Courtesy of Historical Archive of CNR-IRPI, Cosenza, Italy). In A, note that the first floor of the small house has been almost completely covered by water; in B, the track of the level reached by water is visible on the wall behind the man who is cleaning the road. C and D, effects of the DHE occurred in December 1972-January 1973 along the roads, respectively in the Reggio Calabria (C) and Cosenza (D) provinces (Photo published by the daily newspaper “La Gazzetta del Sud”). In E, F, and G, the effects of the December 2008-January 2009 DHE in Cosenza province are shown (Photos: O. Petrucci). E: the flood of Crati River, near the mouth, flooded a citrus plantation; F: a landslide along the A3 Highway that killed two people; G: toe of a wide landslide that affected a village of Cosenza province heavily damaging three houses and the state road.

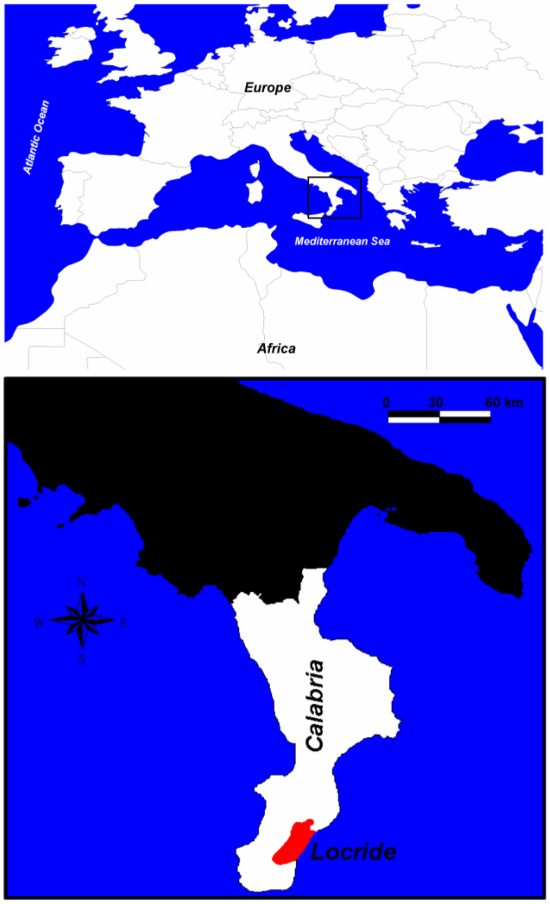

Figure 2. Study area. Top figure shows the Mediterranean area and the perimeter of the bottom figure, which corresponds to southern Italy. The bottom figure shows the two study areas: the Locride and Calabria regions.

Phenomena Caused by DHEs

The damaging phenomena triggered during DHEs can be subdivided into three main groups: *landslides* (all natural types included; all artificial slopes, cuts or embankments, excluded) *river floods* (including *flash floods*) and *secondary floods*, as previously defined.

About *landslides*, international literature widely recognises that rainfall is the most common triggering cause (Crozier, 1986; Corominas, 2001), but that the relationship between rain and slope instability is not direct. The rain that triggers landslides varies widely from one area to the next, and it can change as a function of the mean annual precipitation; moreover, the magnitude of the event depends on both rainfall intensity and the season of occurrence (Campbell, 1975; Caine, 1980; Crozier, 1986; Keefer *et al*., 1987; Wieczoreck, 1987; Sandersen *et al*., 1996; Au, 1998). Hence, the same amount of rain falling on different areas, despite similarities in geo-lithological and morphological features (Govi *et al*., 1985), can produce very different instability conditions.

Several methodologies allow for a separate analysis of phenomena triggered during DHEs. Pioneering studies regarding rainfall-triggered landslides date back to the 1930s (Zaruba, 1936). Since then, several approaches have been proposed (Polemio and Petrucci, 2000). The simplest approach, effective for shallow landslides, is based on the assessment of the *threshold*, namely the minimum rainfall height (or intensity) required for landslide initiation (Campbell, 1975; Caine, 1980; Govi et al., 1985; Au, 1998; Guzzetti et al., 2007; Floris and Bozzano, 2008; Kumar Dahal and Hasegawa, 2008). In the case of complex and deep landslides, the relationship between rainfall and landslides is more complex; in some cases, it was useful to consider the length and duration of daily cumulative rainfalls, as well as the return period assessment, which defines a worldwide standardised level of exceptionality of rainfall (Cascini and Versace, 1986; Polemio and Sdao, 1999). The results have also been used to develop warning systems and strategies for loss mitigation (Sirangelo and Braca, 2004; Aleotti, 2004; Casagli, 2009).

Concerning river *floods*, forecasts and warnings are easier to implement than with landslides (Yevjevich, 1992). In general, the flood routing can be classified into two categories: hydrologic methods and hydraulic methods.

Forecasting systems based on hydrologic methods aim to reduce flood damage that exceeds a critical level; it represents one of the most effective non-structural flood management methods. These systems consist of a telemetry network collecting hydro-meteorological data in real time and mathematical models, which simulate catchment responses during floods.

Real-time flood forecasting is based on models that rely on data sets collected by real-time hydrological monitoring systems, and ensure reliable flow forecasts, particularly for heavy floods (Ubertini, 1990; Schultz, 2000; Samuels, 2000; Krzysztofowicz, 2001).

In the meanwhile, hydraulic methods, based on the modelling of riverbed geometry and the simulation of flood propagation in simplified conditions, receive a great boost from the increasing calculation capability of modern computers (Hsu et al., 2003).

Significant advances have been achieved in the prediction and management of both large river floods (Plate, 2007) and flash floods generally arising from small basins (Hsu et al., 2003; Reed et al., 2007; Blöschl et al., 2008); some such advances include GIS technologies (Usul and Turan, 2006) and artificial intelligence (Schmitz and Cullmann, 2008). The toll from damage caused by these phenomena can be grave, especially when injuries and fatalities are involved (Jonkman and Kelman, 2005).

While long flow records are not available, a historical approach can be used to expand flood data to define flood prone areas and flood risks (Benito et al., 2004; Llasat et al., 2006; Petrucci and Polemio, 2007; Polemio, 2010). Historical databases analysing the effects of floods can also be used to assess the real effectiveness of protection measures already realised, and could represent a valid reference for further interventions (Petrucci and Polemio, 2007; Lastoria et al., 2006).

Secondary floods include what is known in the literature as urban flooding (Marco and Cayuela, 1992); this occurs when rain falls on impervious natural (impermeable soil or rocks) or unnatural locations (streets, roofs and paved areas), and produces fast-flowing runoff. Within a short period of time, if the water is not collected into the storm-water system, it can move into the ground depressions and flood them.

Secondary floods can occur due to either morphological configurations (such as endorheic or low gradient areas) or areas lacking a suitable natural or artificial drainage network (Polemio, 1998). In these conditions, water can simply flow into the basements of a few houses, or it can inundate large parts of cities for several days. One approach to studying this may be based on a simulated one-dimensional hydrodynamic model, taking into account interactions between buried pipe systems, streets and flooded areas (Mark et al., 2004). The total amount of damage from this type of flooding depends on such characteristics as the level reached by the flood, the flow's velocity and the extent and duration of flooding (Schmitt et al., 2004). Although infrequent, these phenomena can also kill people, as documented in recent cases in both Sicily in 1996 (Caloiero et al., 1996) and 2003, and in Campania, in 2007 (only quoted by newspapers).

METHODOLOGY

In the presented approach, phenomena (landslides, floods and secondary floods) simultaneously triggered during a series of DHEs are analysed together with the rainfall and meteorological conditions that underlied each analysed DHE. The aim is to individualise the features characterising the different types of DHEs that both affected the relevant study area in the past and could affect it again in the future. This information will supply useful indicators to emergency management agencies in both preventing and mitigating future damage.

The study approach is composed of the following phases:

a) gathering and elaboration of meteorological synoptic data antecedent to DHEs,
b) gathering and elaboration of rainfall data which trigger DHEs,
c) gathering and elaboration of data on damage caused by phenomena which arise in the course of DHEs,
d) comparative analysis of meteorological, rainfall and damage data aiming to define the general trend of DHEs and their spatial and temporal limits,
e) analysis of DHEs series, assessment of descriptive indices and, on this basis, individuation of DHE types affecting the study area, ranked according to their severity level.

It must be stressed that this is a large-scale approach that does not investigate damaging phenomena one-by-one; it instead analyses a wide number of DHEs in an effort to obtain general relationships between rainfall and its effects. Our main assumption is that DHEs observed in the past can be a guide for the prevention of damage caused by future events.

METEOROLOGICAL DATA GATHERING AND ELABORATION

The *meteorological synoptic conditions* preceding a past DHE can be characterised by analysing: a) isotherms, b) geo-potential synoptic maps, c) isobar synoptic maps and d) daily weather reports and forecasts. Meteorological remote sensing data, available for the most recent decades, have been used to provide reliable assessments of the evolution of heavy storms over large areas (Yang et al., 2007); this data has often helped to provide early severe weather warnings, which have helped to prevent casualties and damages due to heavy rainfall, thunderstorms, hurricanes and typhoons (Houze et al., 1990; Defu et al., 2009).

However, this type of approach suffers from some restrictions. For instance, difficulties arise in the synergetic use of remote sensing and *in situ* data, which are characterised by different spatial and time resolutions (Buchroithner, 2002). However, the main problem is that it is often impossible to complete the meteorological analysis backwards due the data unavailability for the oldest DHEs.

The availability of primary data, such as pressure, temperature and atmospheric humidity and wind data, is the starting point for meteorological analysis (Saucier, 2003). These types of data can be found in meteorological synoptic maps of isotherms, geopotential and/or bar lines, daily weather reports and forecasts. These sources generally include synoptic rainfall data and, in some cases, descriptions of extreme meteorological events.

During the last few decades, these data have been published worldwide on a daily basis by local, national and international meteorological forecasting services (in some cases maps are provided even four times a day), with some local or national differences (Saucier, 2003). Recently, free web and ftp servers have begun to supply more than one of these maps per day (http://www.ncep.noaa.gov is a useful source).

The meteorological analysis is based on a traditional meteorological approach (Barry and Chorley, 2003; Saucier, 2003) called *expert-eye-scanning* (Yang et al., 2007). Traditional analysis of the meteorological data is aimed at defining the typical antecedent meteorological conditions that produce heavy rainfalls. Meteorological analysis is focused on cases where heavy rainfalls hit the study area; the main purpose is to recognise, for each DHE, the atmospheric pattern that created the perturbations and the paths of these perturbations, as well as relate them to their effects in terms of caused phenomena and damage. Thus, the individuation of different series of meteorological rainfall and damage patterns, ranked according to the severity of induced damage, can represent an operative guide for emergency management. In fact, detecting the onslaught of typical meteorological conditions preceding a selected DHE—based on the accumulated knowledge of past DHEs—allows emergency management teams to plan the most appropriate damage mitigation measures and emergency plans.

RAINFALL DATA GATHERING AND ELABORATION

The continuous series of measured rainfall data and, if sea storms are relevant, wind, wave height and/or storm surge data have to be gathered and organised in the climatic database.

The availability of long-lasting climatic series, gauge density and frequency of measurements depend on both the site (country, state, region or province) and the study period. Since the end of the nineteenth century, rainfall data have been consistently gathered in several countries. Presently, complete series of daily rainfalls 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 both the length of the series and gauge density, thus making it more difficult to apply the method.

If a regional study of the selected time series does not exist, all available data should be gathered, using the largest period of data available, to improve the statistical reliability of the rainfall-exceptionality analysis. If the regional study exists, we only need data regarding the periods in which each DHE occurred. Rainfall data availability can, in fact, restrict the study period; for several DHEs that occurred before the twentieth century, even if detailed descriptions are available, the unavailability of continuous rainfall data impedes the application of the methodology.

Taking into account that the most widely available type of rainfall data is collected on a daily temporal basis, the return period for daily rainfall (T) observed during each DHE could be used to describe the exceptionality of the triggering rainfall. For each gauge, the series of annual maxima of daily rainfall should be evaluated, and the probability distribution function of these peak values must be assessed. One reliable choice is the GEV (Generalised 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 method supplies consistent results, particularly if outliers are not observed (Polemio and Sdao, 1999). If outliers are observed, the regionalisation approach to parameter definition is preferred. In this case, 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.

Therefore, for each gauge working during a DHE, the return period (T) of the maximum daily rainfall observed during the DHE must be assessed. This value can be assumed to be representative of the exceptional rainfall that triggered the event.

For each event, according to the maximum values of T, the gauges can be sorted into a few classes of increasing exceptionality, and the results of this classification can be mapped to visualise the spatial distribution of exceptional rainfall, and to compare it to the spatial pattern of damage on the study area.

DAMAGE DATA GATHERING AND ELABORATION

Historical research is the only way to collect data regarding past DHEs; if no specific databases are already available, this step requires a long and time-consuming procedure to find, acquire and validate data.

As a general rule, data gathering is affected by several complications (Glaser and Stangl, 2003; 2004; Glade, 2001; Glade et al., 2001; Devoli et al., 2007), which are detailed below (Petrucci and Pasqua, 2008; Petrucci and Gullà, 2009b):

1) Lack of reliable data. In most countries, any governmental agency can be responsible for the systematic data gathering on the damages caused by DHEs. The absence of standardised procedures to gather and archive information can decrease data reliability. Thus, research should focus on a period for which more than one information source is available (especially technical and scientific reports) to perform crosscheck data validation in order to fill data gaps and control the reliability of data sources. Nevertheless, it is important to remember that either the lack of data or the

presence of scarcely reliable data could cause the damage predictions to be underestimated.

2) Data accuracy. Based upon the type of historical documents and the skill of the documents' authors, we can uncover either a detailed or a sketchy description of the damage; this variance can differentiate the data's accuracy level.
3) Irregularity of data availability. The availability of data changes over time; information concerning older events is generally less plentiful than information pertaining to recent phenomena, and often the greatest amount of data surrounds the most severe events, while less severe cases are rarely mentioned.
4) Merging of damages caused by DHEs with other costs. Often DHE damage is underestimated because the costs of damage to structures, such as roads, are often included in maintenance costs and are not directly tied to DHE damage.

The historical data found in selected information sources should be uploaded into a specific database that includes the following fields: a) dates of events; b) municipality where the phenomenon occurred; c) type or types of triggered phenomena; d) damage caused.

Gathered data, classified by municipality, must be sorted chronologically to identify DHEs. These are periods (from days to up to a month, depending on the local climatic setting) during which damaging phenomena such as landslides, floods and secondary floods almost simultaneously occurred.

Usually, the names of the municipalities where the damages occurred are quoted in each datum, but place names of areas hit are often not pinpointed. Even if a place name is available, the area really affected cannot be delimited; usually, unless the document is a scientific article, the author does not supply maps of the hit areas.

To be clear, the historical data only allows us to identify the occurrence/non-occurrence of damage within the boundaries of the municipality, so for the sake of simplicity the study area can be divided into municipal cells. In those cases where the historical data allows a sub-municipal localisation of damage data, the area can be further divided into subsets obtained by intersecting municipal cells and river basin boundaries (Petrucci and Polemio, 2003).

Once the data have been organised in the database, a procedure that converts datum (a text description) into numerical damage indices—which express the effects of DHEs in a semi-quantitative manner—must be applied. Through this conversion, the ranking and comparison of DHEs (in terms of induced damage) can be carried out and finally compared to rainfall data. Several indices have been introduced to describe damages caused by natural hazards (Blong, 2003); nevertheless, procedures to convert the descriptions of damage into quantitative figures have not been standardised. This can be explained by the fact that we deal with non-instrumental data—heterogeneous text descriptions—from which phenomena and effects must be inferred.

Each damage datum can be converted into a total damage index (Petrucci and Gullà, 2009a; 2009b), which makes an accounting of the Direct, Indirect and Intangible damages caused. In our study, a simplified damage index, called the *Damage Index of the Event* (DIE), was used and only took into account direct damages. Direct damages are defined as all of the physical impact that lead to both the destruction or deformation of an element's functionality and harm to humans through injuries and fatalities (Swiss Re, 1998). The use of a simplified index is justified in dealing with the numerous and aged phenomena for which an assessment of either indirect or intangible damages are practically no longer available.

This simplified but systematic approach allows researchers to obtain a representative value for each damage datum, which can easily be compared to triggering rainfall records.

COMPARATIVE ANALYSIS OF METEOROLOGICAL, RAINFALL AND DAMAGE DATA

Once data gathered during the previous steps have been treated, comparative analysis allows us to describe the scenarios in which different types of DHEs occurred in the past and may occur again in the study area.

By treating the gathered data, some descriptive parameters can be assessed to better define the framework from which the events developed and to contribute to outlining the main characteristics of DHEs, the most frequently hit areas and the most severe scenarios that can be expected.

For this step, single DHEs should be defined. In any given rainy period, a DHE begins when a phenomenon causes damage and ends when the last of the damage is observed. In regions where rainy periods are long and continuous, a threshold lag value between two subsequent damages can be defined based upon the regional features of meteorological events and the geomorphological and hydrogeological characteristics of the hit areas. As a result, for each DHE, the following *event descriptive indices* can be defined.

- *Schematisation of antecedent meteorological conditions (AMC).* Meteorological analysis permits a qualitative distinction between typical meteorological scenarios and conditions antecedent to DHEs. The scenario is known if the atmospheric pattern that created the perturbations and the paths and duration of these perturbations are known. For each DHE, the frequency of the different meteorological scenarios can be analysed this way.
- *Return period of maximum daily rainfall* (*T*). This parameter can be used to describe the exceptionality of the rainfall causing a DHE. 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 is assumed to represent the exceptionality of the rainfall that triggered the DHE. For each event, T maxima can be mapped using the kriging approach, by sorting the gauges into different classes of exceptionality and thus having a spatial representation of rainfall data that can be compared to the damage data.
- *Index of Damaged Area (IDA).* By taking the quantitative total of the *surface* (*S*) of municipalities hit during a DHE 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 et al., 2003). *S* is greater than the area truly affected, but this simplification is necessary to by-pass the impossibility of delimiting areas really hit, since this characterises almost all of the cases. Moreover, the municipal scale is a basic level to compare rainfall, damaging phenomena and damages. By sorting DHEs according to IDA, a preliminary measure of their spatial impact can be obtained.
- *Damage Index of the Event* (*DIE*). This expresses, in a semi-quantitative way, the amount of damage induced by the event (Petrucci and Polemio, 2003). Damages are

assumed to be the product of the value of the damaged element and the level of loss that the element suffered during the event. The value of the damaged element ranges from 1 to 10 on an arbitrary scale in which the elements are sorted into nine types (Road network; Railway network; Housing areas; Public buildings; Services networks; Productive activities; Tourist and sport resorts; Hydraulic works; People). The levels of loss, which are a measure of the percentage of loss affecting an element due of the damaging phenomena, have been defined as: L1=high (1), L2=medium (0.5) and L3=low (0.25). To give the highest weight to human life, the value of people has been set to 100, and the levels of loss have been defined as: L1=more than 10 victims; L2=from 5 to 10 victims; L3=less than 5 victims. The sum of all the products of damaged elements by the respective levels of loss caused by all the phenomena that occurred during a particular DHE is the DIE value.

At this step, a cross-analysis of the AMC, T, IDA and DIE must be realised.

APPLICATIONS OF THE METHODOLOGY

One of the first applications of the proposed methodology was carried out on a test site (686 km^2) named Locride (L), which is in the SW sector of the Calabria region (Southern Italy). The study was based on a database that included 24 DHEs that occurred during an 80-year period (Petrucci and Polemio, 2003). The analysis, which in this phase was almost completely qualitative, highlighted four types of DHEs affecting the study area, and was characterised by increasing severity levels from Type A_L to D_L (Figure 3):

- Type A_L hits the coastal sectors between November and January, and causes river outflows and/or widespread secondary flooding. The most critical rainfall durations range between 1 and 20 days, whereas the return periods are less than 10 years. The damage severity is low.
- Type B_L hits the most internal sectors, and generally happens between January and March. It is associated with rainfall having return periods below 30 years. Higher return periods are due to cumulative rainfall (from 1 to 10 days in duration). The most commonly triggered phenomena are landslides, sometimes coupled with secondary floods. The severity of the damage ranges from low to medium.
- Type C_L, occurring between October and January, causes all types of phenomena. It hits from the inlands to the coast in the central and southern parts of the area. These events occur after rainy periods that generally last less than 60 days. The most exceptional cumulative rainfall lasts less than 30 days and has a return period of less than 50 years. The severity of damage ranges from medium to high.
- Type D_L, the most devastating, occurs between October and December, and is characterised by widespread effects across the whole study area. The triggering rainfall has a critical duration of less than 60 days and it has return periods exceeding 50 years. The severity of damage is high, the number of fatalities is remarkable and the social and economical impact is strong.

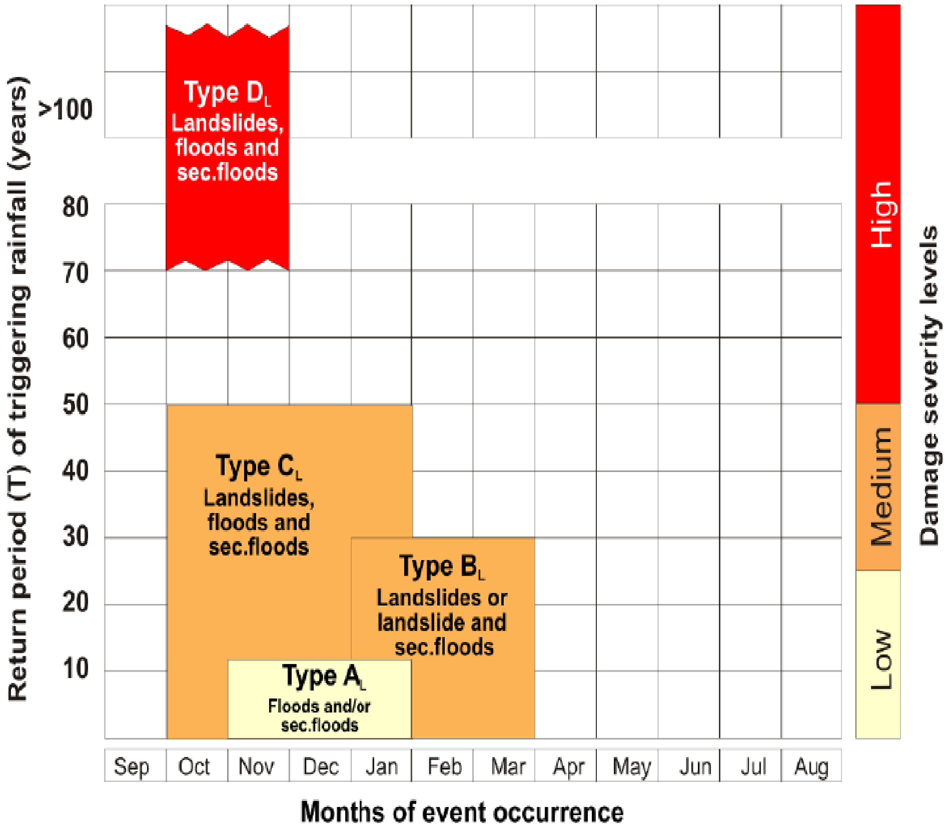

Figure 3. Different types of DHE occurring in the Locride study area (Calabria, Italy), characterised using return period of triggering rainfall, month of occurrence, damage severity level and type of triggered phenomena (from Petrucci and Polemio, 2003, modified).

The most recent application of the methodology (Petrucci and Polemio, 2009), carried out on the whole Calabria (C) region (15,230 km^2), allowed us to define the features characterising the most severe DHEs to occur between 1921 and 2005 (1921 marks the beginning of systematic rainfall data collection).

All DHEs were observed from September to February, and the only one to occur in February (Table 1) was very brief.

During each DHE, the centres of low-pressure area always developed between western Europe, the western Mediterranean Sea and north Africa and generally moved slowly, dissolving eastwards or northeastward. The cyclonic conditions were almost stable for some days or suffered short breaks (Table 2).

Ten DHEs were due to the antecedent appearance of relevant low-pressure fields in two different areas to the west. The former low-pressure field is generally located between northwestern Africa and Spain, while the latter is located northward, between the western Mediterranean Sea and western Europe. The former low-pressure field ensured the inflow of African masses of warm air, while the latter caused the inflow of very cold air masses. These kinds of antecedent conditions have been called the “double effect” to distinguish it from the usual precipitation linked to the simple movement of Atlantic depressions.

Table 1. Main features of the analysed DHEs. N: identification number of the event; Year: year of occurrence; From: day the first damage was noticed; To: day the last damage was noticed; D (days): duration of the event; L (%), F (%) and Sf (%): number of Landslides, Floods and Secondary floods expressed as a percentage of the total number of phenomena that occurred during the analysed DHE; A (km^2): sum of the area of damaged municipalities; IDA (%): Index of Damaged Area; Victims: number of fatalities caused by each event; DIE: Damage Index of the Event

N.	Year	From	To	D	L	F	Sf	A	IDA	Victims	DIE
				(days)	(%)			(km^2)			
3	1927	29-Nov	9-Dec	11	38	41	22	1103	7.24	6	105.5
4	1930	20-Feb	23-Feb	4	10	78	12	1504	9.88	1	65.5
10	1971	1-Oct	3-Oct	3	37	47	17	1772	11.63	2	63
11	1972-73	15-Dec	3-Jan	20	51	47	2	3801	24.95	4	105.5
13	2000	9-Sep	15-Sep	7	38	18	44	3795	24.91	12	173
1	1921	25-Oct	29-Oct	5	57	39	4	923	6.06	12	136.5
2	1925	22-Nov	30-Nov	9	38	27	35	748	4.91	15	137
6	1933	30-Nov	8-Dec	9	55	26	19	2807	18.43	8	99.5
9	1959	20-Nov	26-Nov	7	53	34	13	2718	17.84	10	129
12	1990	13-Dec	28-Dec	16	67	13	21	1848	12.13	0	48
5	1932	9-Nov	16-Nov	8	37	58	5	914	6.00	34	142
7	1951	7-Oct	24-Oct	18	36	64	0	1964	12.89	67	158
8	1953	21-Oct	13-Nov	24	28	64	8	4242	27.84	25	189

Because of the above-mentioned double effect of meteorological antecedent conditions, extremely exceptional daily rainfall was observed in many DHEs. The assessed T peak values were greater than 200 years in six DHEs.

During the 13 DHEs that were analysed, 263 municipalities (64% of all of Calabria's municipalities) were hit by some type of damage. Most of the municipalities had been hit by only one (28%), two (14%) or three events (11%). By classifying the municipalities according to the number of DHEs that affected them during the studied events, we can see that the great majority of municipalities of the S-SE sector of the region (where the Locride area is located) had been hit more than three times and some were hit more than five times. The municipalities that were affected by only one or two events are located along an irregular area bordering the western side of the region.

If number of victims is major an indicator of an event's severity, floods are the most severe type of phenomena in Calabria. The 196 fatalities during the 85-year analysed period were caused primarily by floods (77%) and subordinately by landslides (23%). It must be taken into account that we only analysed the most severe DHEs that occurred in the study period, so less severe events must also be investigated and accounted for to obtain the total number of fatalities caused by DHEs in the analysed period.

Table 2. Meteorological conditions for the analysed DHEs. N: DHE number, Y: year of occurrence

NY	Day/Month	Barometric minimum	Rainfall on Calabria
1 1921	23-24/10	North Mediterranean and Tyrrhenian Seas	Null
	25-26/10	From Sardinia, Sicily to Tunisia	Very high
	27/10	Central Mediterranean Sea and North Africa	High
	28/10	Sicily-North Africa	Normal
	29/10	Aegean Sea	Low
2 1925	12-14/11	Sardinia and Algeria	Low, locally normal to high
	15-21/11	Confuse situation	Normal, locally high
	22/11	South France and Spain to Morocco	Normal, locally high
	23/11	Tyrrhenian Sea to Calabria and North Africa	High to very high
	24-28/11	Confuse situation	High
	29-30/11	Dissolving eastward	Normal
3 1927	20-23/11	Southern France coast	Null, locally normal
	24-28/11	Sardinia to Sicily	Normal
	27-30/11	Mediterranean Sea	High to very High
	1/12	South Mediterranean Sea	High
	2/12	Sardinia to Tunisia	Normal
	3-4/12	Confuse situation	Low or null
	5-9/12	Spain to Sicily	High to very high
4 1930	7-9/2	Mediterranean Sea-Tunisia	Normal
	10-16/2	Spain to Tunisia	Normal to null
	17-19/2	Mediterranean-Adriatic Sea	Normal
	20-21/2	South Sicily	Normal to high
	22/2	Dissolving eastward	Normal
5 1932	7/11	Spain	Null
	8/11	Portugal and Northern France	Null
	9-12/11	Spain to Northern Africa and Sardinia to Sicily	High
	13/11	Calabria	Very high
	14/11	Moving south-eastward	Very high
	15/11	South Sicily to North Africa	Normal
	16/11	Dissolving	Low
6 1933	20-22/11	North Africa	Normal
	23-24/11	Southern Italy to Norway	Low
	25-29/11	Dissolving	Normal (wide-continuous)
	30-1/12	North Africa and France-North Atlantic Sea	Normal to very high
	2-3/12	Sicily-Calabria	Very high to high
	4-6/12	Dissolving	Normal (wide-continuous)
	7-9/12	North Africa and Atlantic Sea	Normal to null
	10-17/12	Tyrrhenian Sea to Calabria	High to very high
7 1951	27-4/10	From Spain to North Africa and from Tyrrhenian Sea, to South Italy	Null or locally normal
	5-10/10	South Tyrrhenian Sea, Calabria, North Africa	High

	11-14/10	Dissolving	Low
	15-20/10	From Spain to North Africa and from Tyrrhenian Sea, to South Italy	Very high
	21-22/10	Dissolving	Null
	23-24/10	Tyrrhenian Sea and North Africa	Normal
8 1953	6-14/10	Mediterranean Sea	Low
	15-17/10	Confuse situation	Null
	18-20/10	Confuse situation	Normal
	21-28/10	From Atlantic Sea to North Europe and North Africa to Tyrrhenian Sea	Very high
	29-30/10	Dissolving	Null
	31/10	Confuse situation	Normal
	1-5/11	From Atlantic Sea to North Europe and North Africa to Tyrrhenian Sea	High
	6/11	Moving eastward	Null
	7-11/11	West Mediterranean Sea	High to normal
	12-13/11	Dissolving	Null
9 1959	13-14/11	Spain and Tunisia	Very High
	15-20/11	Dissolving	Normal
	21-22/11	West Mediterranean Sea and Algeria	Null, locally normal
	23-26/11	Tyrrhenian Sea to Calabria	Very high
10 1971	27/9	Spain and Tunisia-Sicily	Normal
	26-28/9	Spain and Tunisia-Sicily	Very High
	29-2/10	North Africa and Italy	very high to high
	3/11	Southern Italy moving southward	Normal
11 1972-1973	20-21/12	Tunisia-central Mediterranean Sea	Null to normal
	22-24/12	Tunisia-central Mediterranean Sea	High
	25-26/12	Dissolving	Normal to Null
	27-28/12	Tunisia-Mediterranean Sea	Low to normal
	29/12-2/1	Tunisia-Mediterranean Sea	Normal to very high
	3/1	Dissolving	Normal
12 1990	6-7/12	South Italy	Normal
	8/12	Dissolving eastward	Low
	9-13/12	From Germany to North Italy and Tyrrhenian Sea to Ionian Sea	Normal
	14-16/12	Enlarging eastward	High to normal
	17-24/12	Confuse situation	Low
	25-28/12	West Sicily to Calabria and Libya	Very high to high
	29/12	Dissolving	Low
13 2000	7/9	North France	Null
	8/9	Sardinia to Calabria	High
	9/9	Southern Sicily	High to very high
	10/9	Eastern Sicily	Very High
	11/9	Aegean sea	Low
	12-13/9	Tyrrhenian sea	Null

Based on the analysed cases, the events can be defined as short—lasting less than 12 days (9 of 13 cases)—or long—lasting longer than 12 days (4 of 13 cases). No important classifications can be made by crosschecking the duration and months during which the events developed. Nevertheless, three of the five long DHEs began in December while the shortest events occurred at the beginning and end of the period of DHE occurrences (one in February and one at the beginning of October).

In this case, data elaborations allowed us to outline three main types of DHEs, characterised by severity:

- Type A_C can occur in the longest season, from September to February. In the study period, five of these events were surveyed; they start in the northernmost sectors of the region and then move to the S-SE. Floods are the prevailing type of phenomenon; secondary floods, probably tied to very intense hourly rainfall, are also numerous. Rainfall fell almost on the whole region; the T values are generally high but not exceptional. This is due to the combined effect of a sequence of a few days of high intensity rain and a low spatial incidence of very high T values. Based on the analysed period for these events the mean value of the IDA is 16% and the average DIE is 102. The number of victims ranges from one to twelve.
- Type B_C occurred five times during the study period, and hit all of the regional sectors almost simultaneously and repetitively, during periods lasting from 5 to 16 days. The season of occurrence, lasting from the end of October to the end of December, is within that of Type A_C, but this type mainly triggers landslides. The average value of the IDA is 10%, but the low values of IDA for some old DHEs have probably been underestimated due to the scarcity of data to characterise the older events. The average DIE (91) is lower than the average for the other two types of events, and this group includes the only DHE that did not cause fatalities. In the other cases, the number of DHE victims remains below 15. Extreme rainfall was observed only in narrow areas.
- Type C_C, the most devastating, developed between the end of October and the end of December and hit the east side of the region, mainly the SE sector, during periods ranging from 8 to 24 days. Floods are the most numerous triggered phenomena. The mean value of the IDA is 16%, but the IDA of the most recent (and well-documented) DHEs probably best represents the size of the hit area. This group encompasses the most severe events; the mean value of DIE is 163 (the highest among the three groups of DHEs) and the mean number of victims is 42, which is several times higher than the respective values obtained for the previous groups (5 for events of type A and 7.5 for type B). In every C-type DHE, only a meteorological scenario was observed (called “double effect” due to the contemporaneous effect of two low-pressure areas between western Europe, the western Mediterranean Sea and northern Africa); extreme daily rainfall was also observed.

The 13 DHEs that occurred in the 85-year period represent a mean of 0.15 DHE/year; there was a frequency of approximately 0.22 DHE/year during the first half of the study period (1921-1962) and this decreased to 0.10 DHE/year in the second half (1963-2005). This means that in the later decades, the frequency of DHEs was lower than in the earlier part of the past century. Furthermore, the most severe type of events (Type C_C) is confined to the first part of the twentieth century; it has been more than 50 years since the meteorological conditions leading type C_C have occurred.

It is interesting to note that the results of this work, carried out at a regional scale, confirm the preliminary work realised on the SE Calabrian sector. In fact, the three DHEs classified as maximum severity level at the regional level (occurred in 1932, 1951 and 1953) correspond to as many maximum severity level DHEs at the local level. Only one event (occurred in 1972-73) has been classified on a local scale as maximum severity level and not at the regional level, and this was tied to a major concentration of rainfall on the SE sector of Calabria.

CONCLUSION

Damaging Hydrogeological Events are a source of multiple hazardous events as they can simultaneously trigger different types of phenomena, such as landslides, floods and secondary floods. Hence, a comprehensive approach, which covers all kinds of phenomena, has been designed to reveal relationships with the concurrent triggering rainfall and antecedent meteorological conditions.

The proposed methodology is intended to evaluate DHE-related hazardous events in terms of recurrence, damage severity and extension and localisation of the affected area. It is based on the assessment of indices, which describe the exceptionality of rainfall and the level of damages of each DHE, and tie these aspects to their triggering meteorological conditions by aiming to individuate the typical DHEs affecting a study area.

If, for a sufficiently wide period (more than 10 years), the historical data on damaging phenomena, rainfall and meteorological conditions are available, the proposed methodology can be applied, regardless of the climatic and geomorphological settings. However, the methodology is limited if the historical data does not permit exact phenomenon georeferencing; thus, damage data are based upon municipal boundaries or, in more sophisticated approaches, cells that can be obtained by crossing watershed and administrative boundaries.

Several targets can be accomplished by applying this methodology:

a) The individuation and characterisation of the main types of DHEs affecting a study area in terms of triggering conditions, recurrence time and resulting effects.
b) The classification of the study area according to the vulnerability to a DHE, allowing the ability to define the areas where defensive measures are more urgent.
c) The ranking, in terms of damage severity, of different DHE scenarios that can take place in the study area to prepare emergency plans adequately calibrated according to forecasted scenarios. Particularly, these results allow emergency management teams to decide if the event can be managed using local civil protection forces and resources or if its impact requires some help from governmental agencies.
d) The analysis of past DHE scenarios can also allow individuation of the most frequently and heavily hit areas. If actual configuration of the at-risk elements is taken into account, the damage that future DHEs could cause can be roughly evaluated in each scenario, allowing the individuation of the safest places for

population gathering points. The communication lines which, basing on past experience, can be considered invulnerable during DHE events can be used in emergency phases.

e) The dissemination of information concerning the areas that were hit in the past and could be hit in the future, the expected type of damaging phenomena (considering the T class or not) and the predicted resulting damage could increase people's awareness of risk and promote a more aware behaviour.

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