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Identification of rainfall triggering damaging hydrogeological events: a methodological approach applied to Calabria (Italy)

LUIGI ACETO & OLGA PETRUCCI

CNR-IRPI (National Research Council-Research Institute for Geo-Hydrological Protection), U.O.S. of Cosenza, Via Cavour, 4/6, 87036 - Rende (CS), Italy

o.petrucci@irpi.cnr.it

Abstract The paper deals with Damaging Hydrogeological Events (DHEs), defined as periods of severe weather affecting wide regions for several days, and during which landslides and floods cause economic damage and there are victims. The great variability of DHEs in both space and time is the cause of one of the main problems to solve in performing analyses of these events. Dealing with events affecting wide areas for several days, it is problematic to isolate the rainy days that can be considered as factors triggering the observed damaging phenomena. We develop a methodological approach aiming to select and analyse rainfall events that triggered damage. The analysis allows the highlighting of some seasonal characteristics of Calabrian DHEs. The approach can be used for an in-depth analysis leading to the identification of both rainfall thresholds for DHE triggering and rain/damage relationships.

Key words damaging hydrogeological events; rain, landslides; floods; damage; Calabria, Italy

INTRODUCTION

Damaging Hydrogeological Events (DHEs) are defined as severe weather conditions during which heavy and/or prolonged rainfalls trigger landslides and floods on wide regions, causing damage to people and properties (Petrucci and Polemio 2009, Petrucci and Pasqua 2012). Although during storms all these phenomena occur roughly in the same period, often strongly amplifying damage and obstructing emergency management, studies in the literature tend to analyse each type of phenomenon separately, supplying a fragmentary framework of either causes (rainfall) or effects (damage).

Usually, damage data related to DHEs are not available, but have to be gathered by systematic surveys looking into information sources such as newspapers articles, requests for damage reimbursement, restoration projects, and so on. Moreover, it must be taken into account that the total number of damaging phenomena which occurred during a DHE does not coincide with the total number of phenomena triggered by rain. This happens because, when either landslides or floods occur without affecting people or goods, they are not *damaging* phenomena, and probably they will not be recorded by the kind of sources used to collect damage data. So, to obtain a complete framework, the rainfall analysis must be performed on the entire affected region, regardless of the specific points where damage occurred, because the geographical distribution of damage is strictly related to the distribution of vulnerable elements.

In this paper, focusing on the understanding of temporal relationships between the *Rain Event* (RE) and the *Damage Event* (DE) resulting in a *Damaging Hydrogeological Event*, a simplified procedure to select the significant REs causing DEs is reported. The proposed approach was tested on a series of 30 DHEs that occurred in Calabria (southern Italy) between 1981 and 2010.

METHODOLOGIAL APPROACH

Each DHE can be considered as made of a triggering Rainfall Event (RE) and a Damage Event (DE) that is the result of all the damaging phenomena that have been caused by rain. DHEs can affect entire regions and may last for more than one day, and, accordingly, they can show high variability, both in space and in time (Petrucci and Polemio 2002, Petrucci *et al*. 2009a).

Thus the problem is how to select, through space and time, the rain significant for the triggering of a certain DE (Llasat *et al*. 2013). To do this, data concerning damage caused by hydrogeological phenomena must be available for the period in which the DHE occurred. Once these data have been chronologically sorted, we can identify the duration of the DE, defined as the duration in days between the first and the last day during which some type of damage related to rain occurred. For the same period, daily rain affecting the damaged region is also required.

While the duration of a DE is quite simple to determine, the duration of the RE that caused damage is challenging to define, and cannot be obtained without some basic assumptions to simplify the problem. Actually, we must compare a defined duration – the DE duration – to the poorly-defined duration characterising the RE. The difficulties can be easily demonstrated by looking at the differences characterising the sequences of rainy days in a selected period for two raingauges, even gauges located at a short distance from one another. Problems increase notably when more than 100 gauges, located in the far sectors of a study region, have to be analysed altogether. We propose a structured approach that can be repeated for all the gauges working during the analysed DHEs, trying to anticipate one procedural step for each of the possible configurations of rainy-day sequences. The criteria used to build the approach are to some extent arbitrary and they have been set so as to provide an approach that can be easily repeated, even though future elaborations could improve the objectiveness in defining the various steps.

Compiling and organising data

We analysed 30 catastrophic DHEs (Llasat *et al*. 2013) that occurred in Calabria (15 230 km^2) between 1981 and 2010. For this region, a database collecting data on the damage caused by landslides and floods is available, as well as several data collections that are accessible on Google Books (Petrucci and Versace 2005, 2007, Petrucci *et al*. 2009b, Palmieri *et al*. 2011).

For each DE, we sorted the damage data chronologically, and this allowed us to identify both the first and the last days in which damage occurred, thus the duration of the DE. Then, the daily rain data were collected from the archive of Centro Funzionale Multirischi della Calabria (www.cfd.calabria.it). In this way, a sample of 3493 rainy-day patterns, coinciding with the total number of gauges available during the 30 DHEs, was examined. We elaborated a procedure aiming to identify REs. The assumptions required to by-pass the differences in rainfall patterns characterising the gauges involved in each event were also highlighted.

Step 1: Identification of the study period We selected all the raingauges working at the time of the event and organised the historical series of *daily rain* recorded in these gauges in an Excel sheet, placing the gauges in the columns and the days on the rows. Then, we highlighted the days corresponding to the duration of the DE and we selected a sort of buffering, made of 10 days before and 10 days after the DE. In this way we focused on a matrix having a defined number of columns (approx. 100 and corresponding to the number of available gauges) and rows (typically between 25 and 30 days, made of the DE duration plus the buffering).

Step 2: Identification of Rainfall Event Looking for severe rain events, able to cause catastrophic damage, we made the assumption that *a rainy day* is a day with precipitation greater or equal to 1 mm. Then, for each gauge, the rainfall event is defined as the *continuous sequence of rainy days* either included in, or intersecting, the DE. Basing on the analysed data, a series of cases can occur:

(a) A gauge presents a RE made of a continuous sequence of rainy days *totally included in the days of the DE*. In this case the continuous sequence of rainy days represents the RE.

(b) If in the study period a gauge presents *rainy days only after the days of DE*, these rainy days are neglected because they cannot be responsible for effects that occurred several days before. Then we assumed that the gauge was not affected by the event.

(c) If a gauge presents *rainy days starting during the days of DE* and lasting in the buffering after DE, the sequence considered as RE starts in DE and extends up to the first dry day in the post-DE buffering.

(d) If a gauge recorded *rainy days starting in the buffering before the DE* and extending to the days of the DE, we considered the RE as starting in the buffering and ending in the first dry day, even if at that date the DE has not ended. This can happen because some kinds of phenomena can last after the end of the rain (i.e. deep seated landslides: once triggered they can continue to move even after rain ends).

(e) When during the DE a gauge presents *two continuous sequences of rainy days* separated by one or more dry days, we assumed that the RE is that sequence of rainy days in which the maximum daily rain is included. If this value is included in both the sequences, we selected as RE that one characterised by the highest 3-day cumulative rainfall, and we neglected the other sequence.

Step 3: Parameters characterising the rainfall event at regional scale Once the analysis was performed, some summary parameters to describe the RE at a regional scale can be outlined. The first is the regional *duration* of the RE, which is the number of days between the early beginning and the latest end of rainy days among all the gauges affected by the event. For each RE, we can also assess maximum, mean and mode of the duration, using all the rainy days sequences of the gauges working at the time of the event. Then, for each event we can assess the day/days in which the highest percentage of gauges recorded rain, and both the maximum and the average value of daily rain among all the gauges.

DATA PRESENTATION AND DISCUSSION

In Table 1, data concerning the analysed DHEs, listed per hydrological year (from 1 October to 30 September) are shown. Reflecting the climate of Calabria, where precipitation mainly occurs during the winter season, 50% of the events occurred in that season, 33% in autumn, and only 17% during spring and summer months.

Table 1 Summary of analysed damaging hydrogeological events.

N.	*G*	B_{DE} (d/m/y)	E_{DE} (d/m/y)	B_{RE} (d/m/y)	E_{RE} (d/m/y)	$D_{max\text{-}RE}$ (d)	$D_{med\text{-}RE}$ (d)	$D_{mod\text{-}RE}$ (d)	$Day_{max\text{-}freq}$ (d/m/y)	*M* (mm)	*A* (mm)
1	113	16/01/81	22/01/81	12/01/81	25/01/81	14	4.54	2	21/01/81	173.4	51.7
2	121	28/10/82	30/10/82	22/10/82	31/10/82	7	2.69	2	29/10/82	260.1	65.7
3	121	07/04/84	10/04/84	02/04/84	16/04/84	12	2.70	2	07/04/84	134.1	31.7
4	102	16/01/85	21/01/85	12/01/85	22/01/85	11	4.61	3	17/01/85	197.4	49.7
5	104	08/03/85	10/03/85	02/03/85	16/03/85	11	4.63	3	09/03/85	280.1	39.9
6	103	16/04/85	19/04/85	13/04/85	21/04/85	7	3.80	3	17/04/85	165.1	39.5
7	105	30/10/85	31/10/85	24/10/85	07/11/85	10	2.06	2	30/10/85	158.1	26.8
8	101	16/11/87	16/11/87	09/11/87	23/11/87	8	1.69	1	16/11/87	490.1	52.9
9	123	04/03/88	09/03/88	28/02/88	13/03/88	15	5.36	5	06/03/88	351.7	77.5
10	87	12/11/90	16/11/90	10/11/90	21/11/90	9	4.93	6	16/11/90	143.7	48.4
11	91	25/12/96	27/12/96	19/12/96	02/01/97	15	2.77	2	26/12/96	70	28.5
12	92	29/01/96	31/01/96	23/01/96	02/02/96	11	2.75	2	31/01/96	226.1	59.7
13	91	04/10/96	06/10/96	02/10/96	12/10/96	9	3.54	4	04/10/96	230.1	82.5
14	142	11/01/00	16/01/00	08/01/00	19/01/00	10	2.68	3	14/01/00	220.4	30.9
15	142	18/04/00	21/04/00	12/04/00	25/04/00	6	1.34	1	12/04/00	125.2	14.7
16	142	08/09/20	11/09/00	07/09/00	14/09/00	5	3.56	4	09/09/00	301.6	91.6
17	157	13/01/01	15/01/01	08/01/01	21/01/01	8	2.15	2	14/01/01	196.8	48.9
18	115	24/05/02	25/05/02	20/05/02	29/05/02	6	1.99	2	24/05/02	81.8	37.0
19	120	29/12/02	01/01/03	23/12/02	06/01/03	10	2.37	2	01/01/03	114.8	35.9
20	128	10/12/03	13/12/03	04/12/03	18/12/03	11	4.83	4	12/12/03	320.2	51.7
21	123	26/01/04	30/01/04	21/01/04	01/02/04	7	3.22	4	27/01/04	165.8	25.2
22	113	11/11/04	16/11/04	06/11/04	17/11/04	11	5.23	6	08/11/04	221.8	51.6
23	114	07/12/04	12/12/04	06/12/04	15/12/04	10	3.53	2	09/12/04	237.8	51.8
24	124	02/07/06	04/07/06	01/07/06	05/07/06	4	1.22	1	04/07/06	202.6	14.9
25	119	10/12/08	13/12/08	04/12/08	18/12/08	9	3.34	3	11/12/08	357.4	81.0
26	118	09/01/09	13/01/09	04/01/09	17/01/09	10	3.74	3	13/01/09	310.2	89.5
27	116	22/09/09	27/09/09	16/09/09	28/09/09	10	6.19	9	25/09/09	336.8	73.3
28	120	26/01/10	27/01/10	21/01/10	02/02/10	10	5.18	7	27/01/10	276.4	65.3
29	122	10/02/10	18/02/10	07/02/10	21/02/10	15	6.57	2	10/02/10	121	41.3
30	124	01/11/10	03/11/10	26/10/10	05/11/10	6	2.20	1	02/11/10	214.2	57.1

N., event number; *G*, number of rain gauges available for the event; B_{DE}, beginning of Damage Event; E_{DE}, end of Damage Event; B_{RE}, beginning of Rainfall Event; E_{RE}, end of Rainfall Event; $D_{max\text{-}RE}$, maximum duration of RE; $D_{med\text{-}RE}$, mean duration of RE; $D_{mod\text{-}RE}$, mode of duration of RE; $Day_{max\text{-}freq}$, the day that was rainy for the highest percentage of available gauges; M, maximum daily rain recorded during the event; A: average of maxima daily rain recorded during the event.

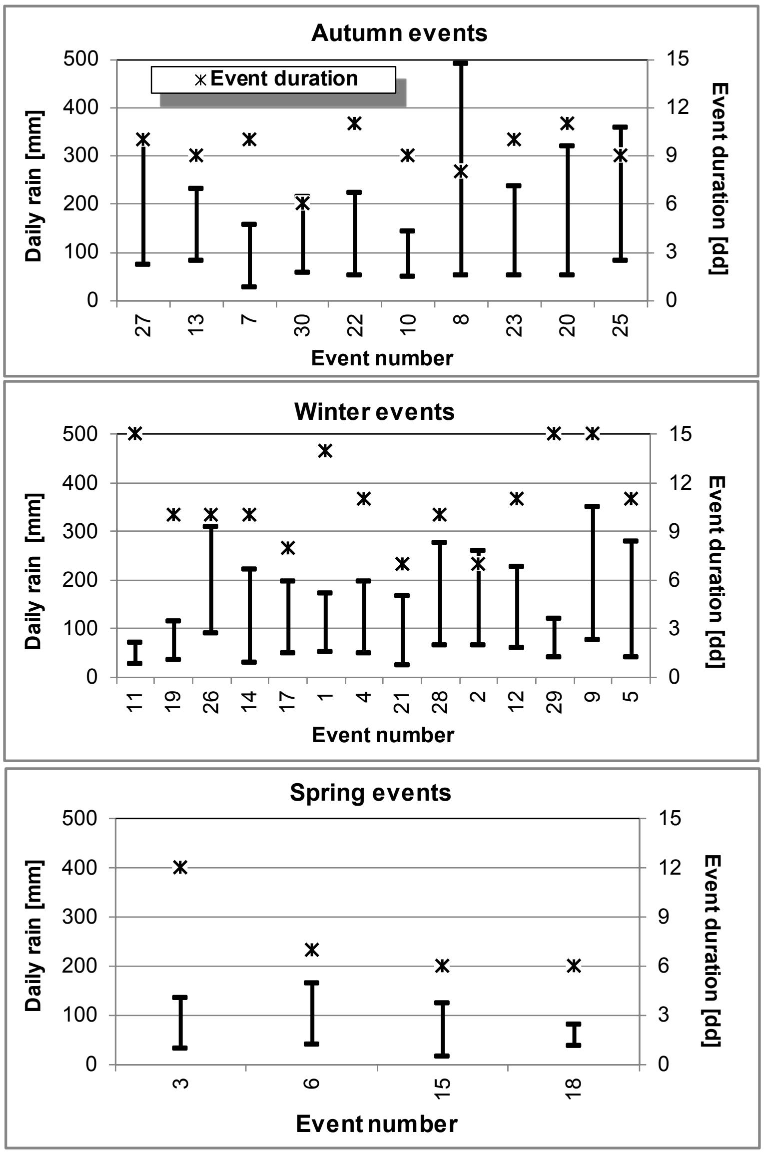

Fig. 1 Daily rain and duration of DHEs clustered according to the season of occurrence.

Excluding four cases, the number of available gauges per event is greater than 100, and on average it is 116, with an average density of one gauge for about 150 km^2. In terms of rainfall, the events occurring in autumn seem most severe, having the highest average of both maxima of the event (271 mm) and mean of the maxima of the event (58 mm). In terms of duration, however, winter events seem to be the worst, lasting on average 4 days, and having 11 days as the average of maxima duration of the event (Fig. 1).

Regarding the distribution of rainy days, we found three main patterns. A bi-modal distribution characterises 43% of the events (69% of which occurred in January, and the remaining 31% in November). This distribution starts with a day that is rainy for around 10% of the gauges, followed by some days with lower frequency, and then by a day with the highest frequency of the event, during which between 40 and 60% of gauges recorded rain.

The second type of distribution, that characterises 47% of events, shows a single peak in the temporal distribution of rainy days, generally lasting 1 day but may extend to a continuous sequence of 3–4 days, during which more than 10% of the gauges recorded rain. This distribution seems typical of the events occurring in autumn (43% of the cases) and in spring and summer (36%), and less typical for winter events (21%).

The third pattern is only represented in 10% of the analysed DHEs; it shows a decreasing trend, with two peaks of rainy days, the first of which is higher than the second one, separated by some days of low frequency.

In terms of phenomena, landslides and floods caused damage in all the events, and snow and hail increased damage during some of winter events (nos 9, 11, 16, 26, 28, 8 and 7). The road network has been damaged in all the DHEs, but this depends more on the fact that this element has a quite homogeneous regional distribution, than on its intrinsic fragility (Fig. 2). In previous papers, an Index of Damaged Area (IDA) was introduced to roughly assess the impact of each event; it represents the area of damaged municipalities expressed as percentage of regional area (Petrucci and Polemio 2010, Petrucci 2012). The events which occurred in autumn show the highest value of IDA-average (22% of the regional surface), followed by winter events (20%) and events which occurred in spring and summer (9%).

Fig. 2 Effects of DHEs in Calabria. Left, flood damage in Catanzaro province during DHE N. 8 (photo by D. Caloiero); right, a landslide on the road to Montalto Uffugo (Cosenza) triggered by DHE N. 26 (photo by O. Petrucci).

CONCLUSIONS

The paper analyses Damaging Hydrogeological Events (DHEs), defined as periods of severe weather affecting wide regions for several days, and triggering damaging landslides and floods. The approach analyses landslides and floods together, as they actually occur during DHEs, in order to provide a complete framework of both causes (rainfall) and effects (damage) recorded during the events.

Assuming that each DHE is made of both a triggering rainfall event and a resulting damage event, a methodological approach aiming to systematically identify the rainfall event that can be considered the cause of the damage has been presented. The procedure was developed based on the analysis of 30 catastrophic DHEs which occurred in Calabria between 1981 and 2010. Fifty percent of the events occurred in winter, and they show the highest duration of Rainfall Event. In terms of rainfall amount, autumn events are the most severe, showing the highest average of maximum daily rain, and this also corresponds to a wider affected area, as the average value of the Index of Damaged Area confirms.

The analysis highlights that very serious damage all around Calabria can be caused by different patterns of rainy days. The majority of DHEs (43%) shows a bi-modal temporal distribution of rainy days that seems typical of January. In this case, during 10 rainy days two peaks are observed, the first corresponding to a day that is rainy for about 10% of the gauges and, after some days, a day that is rainy for 40–60% of the gauges. The second type of distribution (47% of events), showing a single peak during the temporal distribution of rainy days, lasting from 1 to 4 days, seems typical of the events occurring in autumn (43% of the cases) and in spring and summer (36%), and less typical for winter events (21%). The third pattern is only represented in 10% of cases, and shows a decreasing trend, with two peaks of rainy days, separated by some days of low frequency, the first peak being higher than the second.

The proposed approach can be used in regions affected by DHEs for which damage and rainfall data are available. Practical results that could be obtained concern: (a) identification of rainfall thresholds for the triggering of DHEs, at both regional and sub-regional scale; (b) identification of relationships between the temporal distribution of rain and types of phenomena triggered; (c) identification of rain/damage relationships at sub-regional scale; and (d) analysis of the pattern of rainy days which triggered a long historical series of DHEs, in order to highlight whether the most recent events affecting the study area were mainly caused by short and intense rain, as seems the tendency related to the climate change.

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