**Natural Hazards
and Earth
System Sciences**

Local models for rainstorm-induced hazard analysis on Mediterranean river-torrential geomorphological systems

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Abstract. Damaging hydrogeomorphological events are defined as one or more simultaneous phenomena (e.g. accelerated erosions, landslides, flash floods and river floods), occurring in a spatially and temporal random way and triggered by rainfall with different intensity and extent. The storm rainfall values are highly dependent on weather condition and relief. However, the impact of rainstorms in Mediterranean mountain environments depend mainly on climatic fluctuations in the short and long term, especially in rainfall quantity. An algorithm for the characterisation of this impact, called Rainfall Hazard Index (RHI), is developed with a less expensive methodology. In RHI modelling, we assume that the river-torrential system has adapted to the natural hydrological regime, and a sudden fluctuation in this regime, especially those exceeding thresholds for an acceptable range of flexibility, may have disastrous consequences for the mountain environment. RHI integrate two rainfall variables based upon storm depth current and historical data, both of a fixed duration, and a one-dimensionless parameter representative of the degree ecosystem flexibility. The approach was applied to a test site in the Benevento river-torrential landscape, Campania (Southern Italy). So, a database including data from 27 events which have occurred during an 77-year period (1926–2002) was compared with Benevento-station $RHI_{(24h)}$, for a qualitative validation. Trends in RHIx for annual maximum storms of duration 1, 3 and 24 h were also examined. Little change is observed at the 3- and 24-h duration of a storm, but a significant increase results in hazard of a short and intense storm ($RHIx_{(1h)}$), in agreement with a reduction in return period for extreme rainfall events.

1 Introduction

In the Mediterranean river-torrential landscape, the fluctuation in extreme rainfall quantity and drought periods are probably more important than changes in annual precipitation amounts (Mulligan, 1998; Crisci et al., 2002; Ramos and Mulligan, 2003; Reinhard et al., 2003). Long phenomena-free periods can be suddenly interrupted by stormwater, during which one or more simultaneous phenomena (soil erosion, landslides, flash floods and river floods), known as damaging hydrogeomorphological events (after Petrucci and Polemio, 2003), are triggered. According to the registered natural disasters which occurred in Europe between 1900 and 1999 (EM-DAT database), 36% of them were related to storms, 27% to floods and 4% to landslides (Alcántara-Ayala, 2002). During the last years, Europe experienced some of the most disastrous hydrogeological events from weather phenomena (European Environment Agency, 2001), including accelerated erosional soil degradation (Rebetez et al., 1997; Kömüscü, 1998; Martìnez-Casasnovas et al., 2002; De Luis et al., 2003), probably exacerbated by climate change that, over mid-latitude land areas, should be accompanied from an increase in atmosphere convective activity (Trenberth, 1999; Balling, Jr. and Cerveny, 2003). Rainstorms are very significant for soil hydrology in river-torrential environments and croplands, often exhibiting very high spatial variability (Bull et al., 2000; Gardner and Gerrard, 2003), and provoking high magnitude geomorphological processes and disastrous consequences in soil erosion (Coppus and Imeson, 2002; Renschler and Harbor, 2002).

The interaction of extreme rainfall on natural systems is complex, because their combined impact is worth studying as this is expected to increase (Easterling et al., 2000). The phenomena induced by very intense and short rainstorms are commonly associated with accelerated soil erosion. A commonly used approach to calculate the probabilities of exceeding the geomorphological threshold is to simulate long-term meteorological conditions. As indicated by Kuipers et al. (2000), this approach is especially suitable for calculating the probabilities of exceedance for events that occur at relatively high frequencies. Conversely, the most important geomorphologic processes are often dominated by a few severe storms (Larson et al., 1997; Coppus and Imeson, 2002). For example, examining the impact of climatic variability on hydrology and vegetation cover with a pattern ecosystem

model, Mulligan (1998) indicates the temporally, erratic nature of erosion events and the tendency for most erosion to occur in very few cases of extreme rainfall. Recently, extreme weather events have been emphasised by employing a variety of extreme rainfall statistics indices. For this purpose, Haylock and Nicholls (2000) found an increase in both the intensity and the frequency of daily rainfalls over the Australian region using thresholds based on long-term percentiles. The historical extreme rainfall series of duration 1, 3, 6, 12 and 24 h are computed by Crisci et al. (2002), to detect a possible trend over the Tuscany (Central Italy), using Pearson's linear correlation and the Mann-Kendall test. A bootstrap technique is used by Fowler and Kilsby (2003) to assess the uncertainty in the fitted decadal growth curves and to identify the significant trends in multi-day rainfall events over the United Kingdom. Despite the fact that extreme weather conditions were favorable for severe storm activity, non-meteorological factors, including topography, geomorphology and land-use, can contribute to the flooding to a great extent (Kömüscü, 1998), and gross erosion (Brath et al., 2002), including overland flow erratic spatial pattern. To answer this question, Beeson et al. (2001) applied a spatially distributed model for assessing spatial changes in the upland hydrologic response following a landscape-scale disturbance using SPLASH simulator for 2-year and 100-year design storms. Ramesh and Davison (2002) describes, instead, semi-parametric approaches to trend analysis using local likelihood fitting of annual maximum and partial duration series to explore the change in extremes in sea level and river flow data.

The relationship between rain and slope instability is not as direct as in the case of floods. The mechanisms that cause slope instability due to the effect of water are complex and difficult to quantify (Irigaray et al., 2000), especially for large-scale regions. Polloni et al. (1996) suggested that antecedent rainfall controls the pre-storm soil moisture content, and that this is critical to the initiation time of a debris flow. Rebetez et al. (1997) have observed, instead, that debris flow linked to rain is likely to be triggered when total rainfall amount over a three-day period exceeds four standard deviations, i.e. a significant extreme precipitation event. Among the various aspects of pluviometric and hydrological events, the geomorphic hazards were studied by GarcÍa-Ruiz et al. (2002) as the intensity of the events exceeds different geomorphic thresholds, as, for example, the reactivation of large, deep mass movements that are linked to rainfalls of around a 100-year return period (between 130 and 160 mm in 24 h). The concept of Antecedent Rainfall Percentage Exceedance Time (ARPET) were presented by Chowdhury and Flentje (2002), for determining threshold rainfall magnitudes for the initiation of slope movement or instability. A logistic regression model was integrated in a geographical information system by Dai and Lee (2003), using geolitological factors, land cover and rolling 24-h rainfall as independent variables. In order to test the potential for a completely distributed model for storm-triggered landslides, radar detected rainfall intensity has been used by Crosta and Frattini (2003).

These models can also achieve great accuracy. They provided homogeneous and sufficient reliable data from the monitoring of landslide movement and also a good historical record of daily and hourly rainfall. However, these conditions are not always available, mainly because the geomorphological processes monitoring is expensive and time consuming. Therefore, alternative, less expensive approaches, at least in a preliminary analysis of weather phenomena hazard, are desirable.

In this paper an attempt has been made to develop a less expensive methodology to predict extreme rainfalls' hydrogeomorphological impact using the probabilities of exceedance for stormwater threshold levels. An algorithm for the characterization of this impact, called Rainfall Hazard Index (RHI), is developed to be used in temporal data exploration. RHI integrates three variables: a dynamic variable which is the rain depth of the current storm and two relative static variables which represent the median of the annual maximum of h hours rainfall, and a dimensionless parameter indicative of the degree of ecosystem flexibility. The RHI doesn't contain information about hydrological antecedent conditions, which are fundamental for runoff and for actual infiltration processes, so it can be used only as an indicator of a hydrogeomorphological events triggering condition.

The approach was applied to a test site in the Benevento river-torrential landscape, northern Campania (Southern Italy). For this site a research activity based on numerical and qualitative historical data was made to compare geomorhological events with RHI of a 24-h duration storm, in order to test RHI. Furthermore, trends in annual maximum Rainstorm Hazard Index (RHIx) for storms of duration 1, 3 and 24 h were examined for the Benevento based-station and S. Croce Sannio site. A reduction in return period was observed for a very intense storm (RHIx$_{(1\,h)}$). This is very important for central-southern Italy for purposes of water management, soil erosion and flash floods impacts. Future research for spatial comparison and aggregation of the results are in any case desirable.

2   Data collection and design method

The period from 1856 to 2002 has been selected as a study period. Due to the partial availability of a historical series of hourly and daily rainfall, the investigation has covered the 1926–2002 period, for a joint analysis of RHI$_{(24\,h)}$ and hydrogeomorphological events, and the 1949–2002 period, for trend analysis of the RHIx associated with storms of duration 1, 3, and 24 h. Daily and extreme rainfall data were referred by Rossi and Villani (1995), and SIMN (1951–1997) and UCEA (1994–2002) data sets. Data on the hydrogeomorphological events was inferred, instead, from technical and scientific publications (Lolli et al., 1995; AVI Project Catalogue, 1998; Diodato, 1999), as well as from regional archives (Ispettorato Agricoltura of the Campania Region, 2003).

Hydrogeomorphological events, unfortunately, have no instrumentally determined magnitude scale, like that conventionally used for earthquakes, and this is why they are generally described in qualitative terms. For this reason, a semi-quantitative index (RHI) has been developed here that combines some attributes of hydrogeomorphological triggering mechanisms.

2.1 Rainstorm Hazard Index modelling

Extreme weather events can be defined as infrequent meteorological events that have a significant impact upon the society or ecosystem at a particular location (Singh and Sen Roy, 2002). In accordance with that stated above, in Rainstorm Hazard Index (RHI) modelling, we assume that the river-torrential system has adapted to the natural hydrological regime, and a sudden fluctuation in this regime, especially those exceeding thresholds for an acceptable level of disturbance, may have disastrous consequences for the mountain environment.

The RHI model predicted outputs were derived from the modified intensity pattern algorithm, utilised by Kuipers et al. (2000) in risk analysis of water systems:

$$\text{RHI}_{(h)i} = \frac{R_{\text{sto}(h)i}}{f(\text{Med}(R_{(h)}))} \left[\ln \left(\frac{R_{\text{sto}(h)i}}{f(\text{Med}(R_{(h)}))} \right) - 0.1 \right], \quad (1)$$

where $R_{\text{sto}(h)i}$ is the rain depth of the storm (mm) of h hours in the ith year, that can be subject to a large time fluctuation; $\text{Med}(R_{(h)})$ is the median of the annual maximum of h hours rainfall (mm) expected on N years, and represents a threshold for natural hydrologic regime; h is the duration of the rainfall event in hours (in this study h=1, 3 and 24); f is a coefficient that explains the degree of local ecosystem flexibility assumed to 1. However, for geomorphological risk assessment, f should be evaluated in order to assess ecosystem features. In fact, natural land-based ecosystems are generally flexible and capable of absorbing stresses caused by various forms of disturbance (Mendoza et al., 2002), including damages from weather events (Evans, 1993; De Luís et al., 2001; Ferrero et al., 2002), so that $f > 1$. Contrarily, landscapes strongly disturbed or degraded (e.g. intensive cropland, indiscriminate urbanisation, landscape post-fire) are usually less flexible, so that $f < 1$. From Eq. (1) it follows that rain aggressiveness reaches the critical threshold value of 0 when the R_{sto} is close to Med(R). It's obvious that for RHI>0, the hydrogeomorphological system results are unstable and the rainstorm-induced hazard is relatively high; conversely, the system results are stable for RHI≤0 and hazard is negligible.

A verification approach that assesses a model's ability to accurately predict a hydrogeomorphological event at a specific site was developed following the criteria of the contingency tables (Doswell et al., 1990). During verification for a RHI threshold value, the information tallies are kept in a 2×2 contingency table (C) (Fig. 3), consisting of C_{YY}, C_{YN}, C_{NY}, C_{NN} dichotomous predicting values. For this purpose, a Total
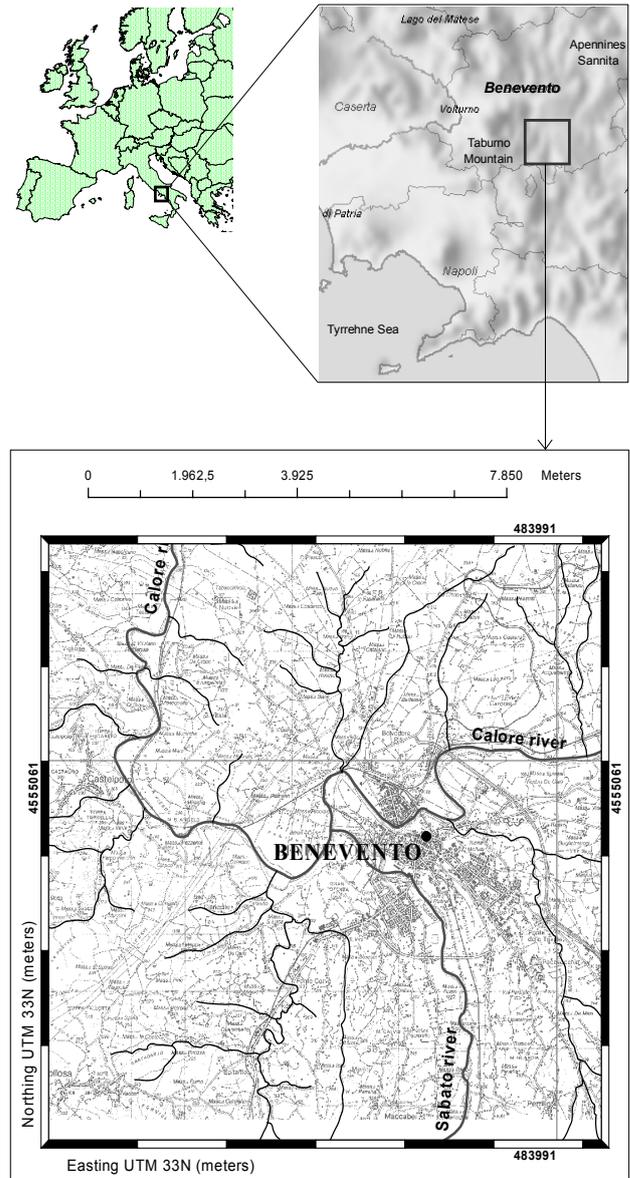
Fig. 1. Benevento river-torrential landscape with based-raingauge (circle). Based map: RouteBundle Italia.lnk and Istituto Geografico Militare.

Success Indicator (TSI) was employed in term percentages:

$$\text{TSI} = \frac{C_{YY} + C_{NN}}{C_{YY} + C_{YN} + C_{NY} + C_{NN}}. \quad (2)$$

In order to assess the impact of the climatic change along the 1949–2002 series, the Return Period (RP) for the annual maximum Rainstorm Hazard Index (RHIx) falling above the 75th percentile, has been ranked using the Gumbel method and the Gringorton formula (Gringorton, 1963):

$$P(x) = \frac{r - 0.44}{n + 0.12}, \quad (3)$$

where n is the number of data, r is the number in the ranked list of annual RHI, and $P(x)$ is the probability of RHIx>x, with x=RHIx 75th percentile.

Table 1. Data concerning the hydrogeomorphological events recorded in the Benevento river-torrential landscape. $R_{sto}(24\,h)$ is the rain depth of the storm (mm) in the 24 h before of the event, with the corresponding RHI. Abbreviation: F=Flood, Ff=Flash-flood, L=Landslides, AE=Accelerated erosion.

No	Year	Month	Days	Rsto (24h)	RHI (24h)	Weather Phenomena	Event Type	Area interested by the event
1	1935	March	1	60	0,07	Continuous and intense rain	L	Calore and Sabato rivers
2	1938	February	18	84	0,66	Rainfall and snowmelt	F - L	Calore and Sabato rivers
3	1942	February	7	46	-0,18	Continuous rain	F	Calore and Sabato rivers
4	1949	October	2	71	0,32	Downpour	F - L - AE	Calore river
5	1951	November	12	68	0,25	Continuous and intense rain	F	Calore and Sabato rivers
6	1952	December	15	60	0,07	Continuous and intense rain	F	Calore river
7	1955	October	24	93	0,91	Continuous and intense rain	F	Calore and Sabato rivers
8	1956	November	18-21	61	0,1	Continuous and intense rain	F	Calore river
9	1957	October	21	56	-0,01	Downpour	F	-
10	1960	November	11-12	57	0,01	Downpour	F	-
11	1961	October	18	76	0,45	Downpour	F	Calore and Sabato rivers
12	1962	October	18-29	34	-0,34	Continuous and intense rain	F - L	Calore river
13	1963	December	12	70	0,3	Continuous and intense rain	F -L	Sabato river
14	1964	December	19	70	0,3	Continuous and intense rain	L	Calore river
15	1966	October	25	70	0,3	Continuous and intense rain	F	-
16	1968	December	16-17	85	0,69	Continuous and intense rain	F	Calore and Sabato rivers
17	1969	January	7	68	0,25	Continuous and intense rain	F	Sabato river
18	1970	January	5	60	0,07	Rain	L	-
19	1976	June	29	66	0,2	Downpour	AE	Hillslopes
20	1979	February	19	41	-0,26	Continuous and intense rain	L	-
21	1982	July	26	64	0,16	Downpour	AE	Hillslopes
22	1985	November	18	128	2,1	Downpour	L	-
23	1989	July	26	58	0,03	Downpour	AE	Hillslopes
24	1993	December	26	60	0,07	Continuous rain	F	Calore river
25	1997	November	13	70	0,3	Downpour	F - L - AE	Serretelle river and hillslopes
26	1999	July	29	73	0,37	Downpour	Ff - AE	Torrents and hillslopes
27	2001	May	23	42	-0,24	Downpour	Ff - AE - L	Torrents and hillslopes

## 3 A case study: the Benevento river-torrential landscape

The described methodology has been tested in a selected agricultural region extending approximately 130 km² located north-east of Campania (Southern Italy), between the Sannita Apennines (1000 m) and Taburno-Camposauro Mountains (1400 m) (Fig. 1). The morphology of the land is characterised by a meandering river area from the Calore and Sabato rivers, and surrounded by hills, with a topography ranging from 110 m to 450 m in altitude. However, the boundaries of this region have a high degree of instability of the ecosystem and the greatest sensitivity of their components to various forms of pressure occurring there. The clayey-marly-arenaceous nature of the sediments that make up most of the hills around the river plain are particularly susceptible to erosive phenomena in general, or more specifically, to landslide-type instability, and climatic effects have a certain relevance in the morphoevolution of the relief, including antropogenic activity (Leone et al., 1997).

3.1 Rainstorm types observational approach

Due to the Mediterranean area, geographical features (i.e. Alps and Apennines chain, the plain and sea), and their effects on the mesoscale circulation generate a variety of precipitation (Meneguzzo et al., 1996; Paolucci et al., 1999). In the cold season, the rain may be principally due to fronts associated with Mediterranean cyclones. The airflow activity is particularly important on the surrounding Apennines chain, where the lifting of the air masses causes frequent orographic precipitation, so that there the rainfall is abundant in the early winter and the spring, when the thermic sea-atmosphere contrast is also more marked. In Benevento river-torrential landscape mean annual rainfall totals are of the order of 700–900 mm/year. However, interannual variability is considerable, e.g. totals of 483 mm in 1945 and 1876 mm in 1915 (Diodato, 2002).

Based on the concept of geomorphological effectiveness (after Molnar et al., 2002), three different types of pluviometrical events can be defined: a) rainstorms have extraordinary intensity (80–140 mm/h), but have very short duration, typical of the afternoons at the end of spring or of the summer period. Examples of these types are heavy showers or thunderstorms commonly localised, causing surface erosion by overland flow in the form of rill and gully erosion with remarkable mass movements on the torrential landscape, as that which happened recently in May and July 1999, May and June 2000, May 2001 and June 2003; b) rainstorms
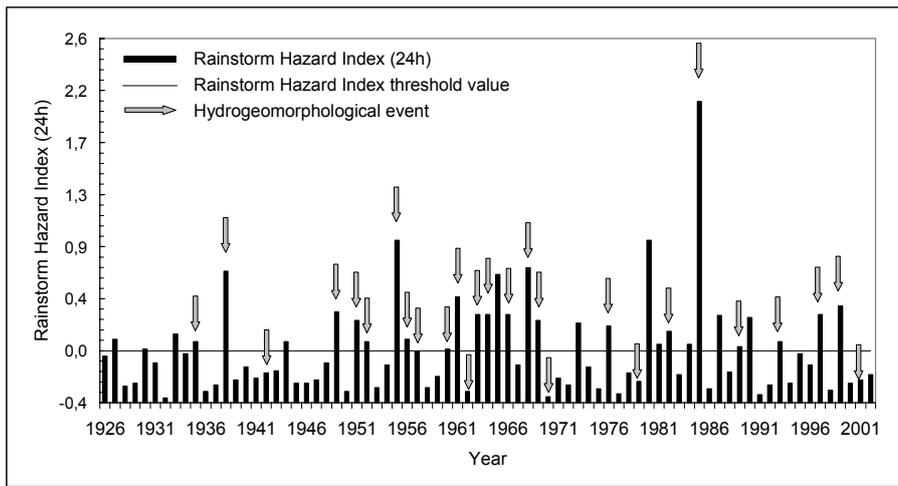
Fig. 2. Rainstorm Hazard Index (hystogram) relates to the 24 h before the hydrogeomorphological event (arrow).

Fig. 3. Contingency table of YY, YN, NY, NN prediction/observation pairs.

have high intensity (40–80 mm/h) and extension, and are of a more longer duration, exhibiting relevant geomorphological effectiveness. They are associated with a high erosion rate, floods in the form of flash floods, landslides and dramatic changes in channel shape and form, as that which happened in September 1857, October 1875, September and November 1889, October 1899, 1949 and 1961, November 1985 and 1997 (Diodato, 1999); c) rainfall of long duration but low intensity (5–40 mm/h), sometimes with snowmelts. They can be associated with floods commonly occurring in the large lowland Tammaro and Calore river of the Benevento region, and deep landslides, as that which happened in January 1895 and 1900, February 1905 and 1938, October 1961, December 1968 and January 2003.

3.2 RHI (24 h) testing for Benevento-station

RHI can also be defined, after Singh and Sen Roy (2002), as an indicator of weather short-term perturbation that provides magnitudes much outside the normal spectrum, with possible hydrogeomorphological consequences. To verify the relation between RHI and hydrogeomorphological events, we use RHI in relation to storms of duration 24 h, because from them, the effects produced on the territory are well known.

Then, 27 hydrogeomorphological events which have occurred during a 77-year period were collected with $RHI_{(24 h)}$ and presented in Table 1. All 27 documented events were supposed to have been rainfall-induced. In order to validate this assumption and the RHI model, 24 h antecedent rainfall has been analysed with $RHI_{(24 h)}$ for all the years of the period 1922–2002 comprising the events, which is the time covered by recordings at the Benevento raingauge (Fig. 2). The RHI predicted values in the 24 h before the event are tested versus the observations and scored by tallying results into a standard 2×2 contingency table of YY, YN, NY, NN prediction/observation pairs (Fig. 3), so that a Total Success Indicator of the $RHI_{(24 h)}$ was estimated to be 79%, exhibiting a high percentage of success, significant at level a=0.1.

3.3 RHIx trend and climatic change

The studies aimed at analysing the variation in heavy and extreme precipitation are particularly interesting, as these events cause considerable damage worldwide each year. For Europe, the number of extreme rainfall events capable of triggering debris flow is increased in the Swiss Alps (Rebetez et al., 1997), and in Pyrennez Mountains of Spain (García-Ruiz et al., 2002). Floods multi-day rainfall-induced are increased in Scotland and northern England during 1961–2000 (Fowler and Kilsby, 2003), whereas they do not show a clear increase in central Europe (Mudelsee et al., 2003). For northeastern Italy, Brunetti et al. (2001) have observed a reduction in return period for extremes pluviometrical events. These results were confirmed by Alpert et al. (2002), who analysed the
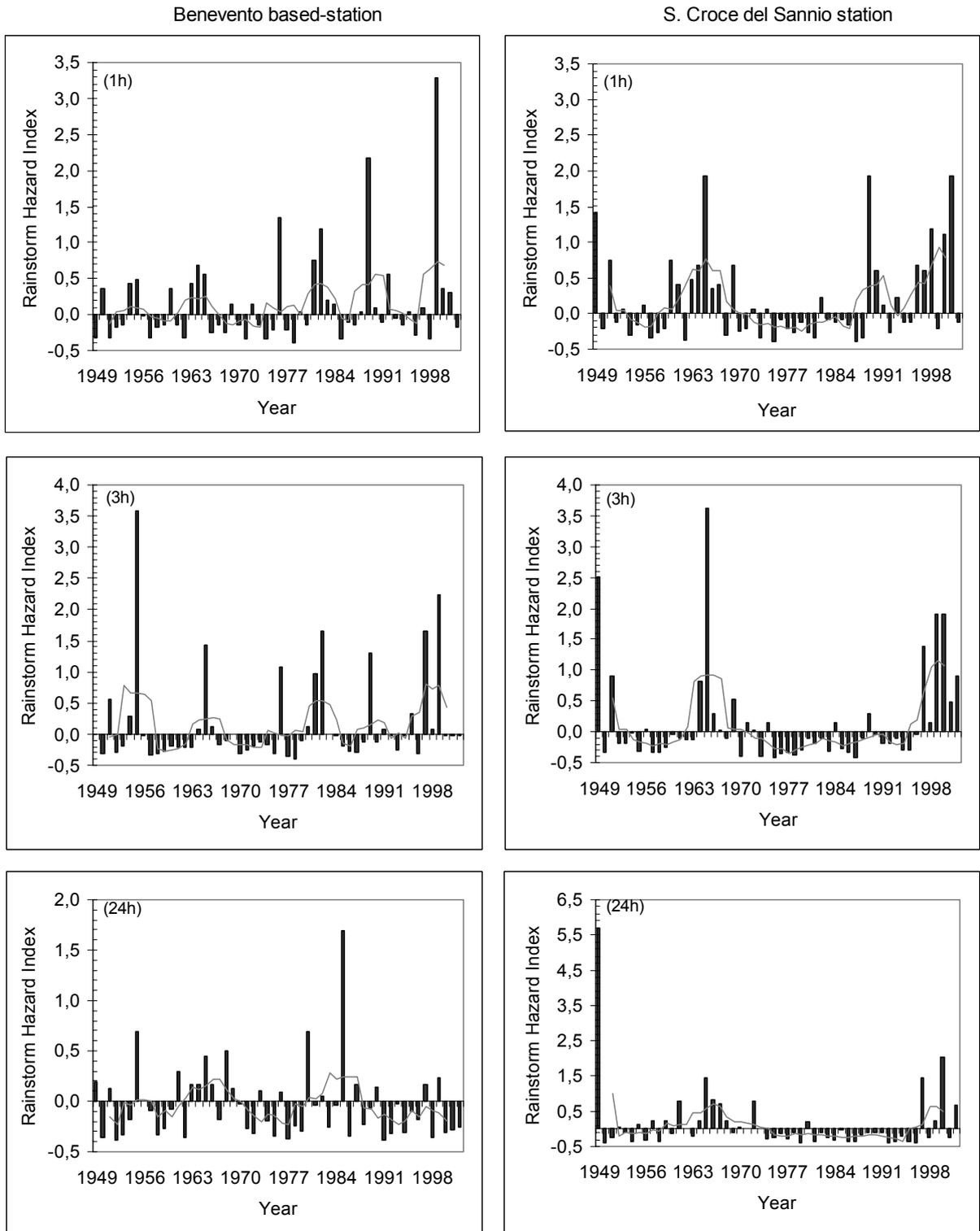
Fig. 4. Rainstorm Hazard Index (histograms) for annual hourly maximum rainfall for Benevento based-station (left graphs) and S. Croce del annio (right graphs), with moving average of the order of 5 (grey curves).
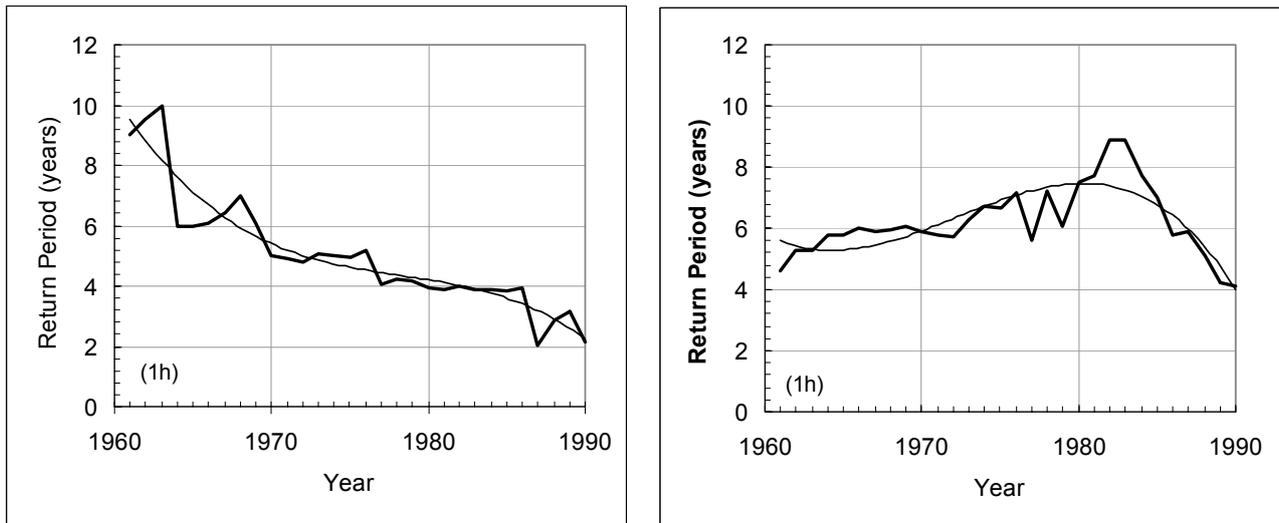
Fig. 5. Twenty-five-year running Return Period (RP) of the Rainstorm Hazard Index (falling above the 75th percentile) for 1 h of annual maximum rainfall (bold lines). Each RP value is dated with the middle year of the 25-year window. The curves indicate the sixth-order polynomial fitting.

torrential rainfall for the whole Italian territory during 1951–1995, detecting that rainfall increased percentage-wise by a factor of 4 with strong peaks during the El-Nino years. In order to improve the understanding of the RHI behaviour as an indicator of the climate change impact in the 1949–2002 period, annual maximum of 1, 3 and 24 h rainfall series must be analysed. Considering that one raingauge data could not be significant for a specific area-RHIx, the trend of the other gauge (S. Croce del Sannio station), about 30 km from the Benevento-station, has been verified. Both stations show RHIx fluctuations around its threshold value, but the trends are more evident on the series with a storm of 1 h in duration (Fig. 4). In order to verify this assumption, we evaluate the Return Period (RP) for $RHIx_{(1 h)}$ on all periods. Figure 4 shows the results of the calculation of the 25-year running RP for the rainfall events falling above the 75th percentile (corresponding to RHIx range 0.36–0.46); each value is dated with the middle year of the 25-year window. There is a strong decrease in RP of $RHI_{(1 h)}$, indicating that very extreme events were becoming more and more frequent during the last forty years. The curve in the left graph of Fig. 5 (Benevento raingauge) decreases slowly until 1963–1970, then it drops sharply, remains almost constant between 1977 and 1986, with a common decrease at two stations after the 1982. This is in agreement with the multiplicative cascade process of the rainfall events over Italy (Mazzarella, 1999), which is responsible for the concentration of water and energy fluxes into successively smaller parts of the atmosphere.

3.4 Hydrological scenario and global warming

Changes in rainfall distributions could have far more impact than the more-often-cited risk of global warming (Allen and Ingram, 2002). This is very important for the arid and

sub-humid regions of the Mediterranean Europe, including central-southern Italy, for purposes of water management, soil erosion and flash floods impacts. Most of the disasters which affects the territory are linked to the water cycle and consequently, to extreme meteorological scenarios; if slope stability phenomena are quite clearly influenced by heavy and prolonged rainfall, the temperature seems to play a secondary role in the triggering mechanism (Delmonaco et al., 1999). An issue of downscaling the results from the global climate model (GCMs) to a scale relevant for hydrological impact studies was examined by Prudhomme et al. (2002) for the time horizon 2050 s. The three scenarios proposed lead to an increase in the magnitude and the frequency of the extreme flood events, but the impact is strongly influenced by type of daily rainfall scenario applied.

4 Discussions and conclusions

In this study, the RHI index was forced to expound the rainstorms' hydrogeomorphological impact in a river-torrential system with a less expensive mthodology. Single-station analysis performed is an adaptation of the intensity pattern algorithm, which was assumed to be an indicator of short-term perturbation of the weather that provides magnitudes which are far outside the normal spectrum.

To select the threshold we consider the median, which represents percentiles of practical interest, and perform diagnostic tests to confirm the extreme character of the resulting events. Considering the temporal behaviour of the rainstorm models, analyses exhibit significant trends strongly increasing for $RHI_{(1 h)}$, in accordance with a reduction in the return period for extreme events. In contrast, RHI (3 h and 24 h) reveals no statistically significant trends to a long period.

However, $RHI_{(3\,h)}$ was rising after 1980. Therefore, the geomorphological consequences of this climate variability are demonstrated to have a major impact on the scenario that seem to subject the cropland to a major vulnerability, under the occurrence of very extreme and localised events in the form of accelerated erosion and flash floods. The main advantage of the RHI algorithm is that it can be compared with the surrounding sites because the results are scaled and can be used in weather hazard maps. In addition, RHI can capture all meteo-climatological information, especially those geomorphologic processes dominated by short and severe storms. Conversely, the disadvantages are: 1) that it is a predictor of general hydrogeomorphologic events; 2) that it needed historical data (at least 40 years) with high temporal resolution, and 3) that it doesn't regard the prolonged rainfall preceding the event, so it can be used only as an indicator of hydrogeomorphological events triggering conditions. However, the effects of antecedent rainfall are generally negligible for accelerated erosions, flash floods and surfaces landslides (at least in the Mediterranean climates), than for deep landslides.

Finally, a qualitative test of $RHI_{(24\,h)}$ for a single-station showed very good results, but in the future spatial research comparison and aggregation of the results is necessary.

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