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Scale-invariant rainstorm hazard modelling for slopeland warning

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ABSTRACT: Periods characterized by heavy rain and storms can trigger Multiple Damaging Hydrological Events (MDHE), in turn developing flooding, erosion, downpours and other phenomena affecting human habitats and ecosystems. However, approaches and applications to model MDHE and weather warning under specific environmental conditions are still poor. Based on the interpretation of the rainstorm – MDHE relationship, it was reconsidered and extended to a model-based rainstorms hazard index (RHI) developed in a previous paper, where rainstorm-pulsing force and resistance state are combined. In this way, landscape response was achieved by individual formative rainfall events, while the specific sequence of events that can affect landscape was only assessed in a qualitative way. A retrospective evaluation of rainstorm hazard modelling, control runs, are also given for different precipitation durations (from 1 to 240 h), to be compared with MDHE at two test-sites of Southern Italy (Benevento, Campania region; Scilla, Calabria region). For these sites, the complete series of historical MDHE which occurred during a 10 year period (1997–2008) was gathered and used to validate the results of the rainfall model. The tool is relatively simple and potentially attractive to rapidly prediction of adverse consequences of rainstorms. Perspectives for real-time applications in emergency planning are ultimately given for an agenda in future research. Copyright © 2011 Royal Meteorological Society

KEY WORDS landslide-hazard; modelling; rainstorm; Southern Italy; threshold

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1. Introduction

> *Storms and hail are very frequent in all the provinces of the kingdom of Naples, (...).*
> *It often happens that with the prevalence of a south – west wind, Naples and the west coast are deluged with rain for whole months, while not a drop falls in the eastern region; and on the other hand, when the Greek wind is blowing there may be much rain, and even abundance of snow (...), while the weather is perfectly fine in Naples.*
> Henfrey (1852)

Since historical times, Mediterranean Europe has experienced what are now called 'Multiple Damaging Hydrological Events' (MDHEs: Petrucci and Polemio, 2003), triggered by either short and intense storms or longer duration rainfall (Grove, 2001). In general, either floods or landslides occurring during MDHEs represent a source of economic loss. Over the last two decades, flash flooding (which is one of the most devastating hazards in terms of human life loss and infrastructures, Gruntfest and Handmer, 1999), caused billions of Euros of damage in Europe (APFM-WMO, http://www.apfm.info/index.htm). As far as landslides, damage caused has been particularly severe in Italy (the focus of this study), where at least 6141 people were killed or injured between 1950 and 2008 by slope failures alone (Brunetti *et al.*, 2009). In this country, centrally located in the Mediterranean basin, MDHEs usually cause victims, economical losses and major problems to activities of daily living. In general, the social and economic costs of MDHEs are not well documented, mainly because no agency is formally charged to gather data concerning them (IFRC, 2001). The great majority of available studies and databases (Catenacci, 1992; Guzzetti, 2000) report these losses as caused by different types of phenomena, without putting them in a global perspective of damaging events resulting from the simultaneous occurrence of floods and landslides.

Environmental hazards have been conventionally analysed in relation to their potential damage but, to date, not much research has been specifically focused on the study of extreme weather events for use in hydrological hazard forecasting and landscape responses (Diodato and Bellocchi, 2010). Recent improvements include operational

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use of end-to-end forecasting systems in hydrology (e.g., MAP D-PHASE, Zappa *et al*., 2008). Advances made in recent decades have also demonstrated the capability of geo-computational tools and techniques (Heneker *et al*., 2001; Dagan *et al*., 2003) and their potential for disaster mitigation (closely linked to the predictability of events and their consequences, Alexander, 1991). However, different aspects of hazards demonstrate that changes of seasonal predictability are difficult to quantify. Knowledge and technical ability are therefore required to accommodate this.

In addition, geo-computational hydrological models may need continual adjustments to meet either spatial or temporal variability (Tucker *et al*., 2002; Amengual *et al*., 2008), especially where this is important for rain forcing, land response and related economic loss for sensitive areas such as the Mediterranean region (as pointed out in Figure 1).

Geoscientists' efforts have primarily been addressed to detect regional relationships between rainfall and MDHEs (Petrucci and Polemio, 2003, 2009). For instance, specific geo-hazard methodologies were used at selected sites and calibrated according to natural disasters that have recently occurred (Iiritano *et al*., 1996). In Italy, examples are the case of Crotone's flood, which happened on October 1996 (Gabriele, 1998) or the mudflows that killed 137 people in Sarno, in May 1998 (Cassetti and Versace, 2002). For an effective use of the information, environmental hazards can be better represented as an energetic process of the natural system deviating from its 'average' or 'normal' trend (Haque, 2005) and described by means of exceeding thresholds. A threshold is the value of a selected parameter that must be reached in order for a process to take place or a state to change (White *et al*., 1996). Martina *et al*. (2005), for instance, modelled critical rainfall thresholds for a sub-basin of the Arno river (Central Italy), by using long hydrological time series combined with a Bayesian minimization function. Bayesian statistical techniques were used by Guzzetti *et al*. (2007), who reviewed worldwide-published rainfall thresholds for landslide initiation and proposed novel empirical rainfall thresholds for the Central European, Adriatic, Danubian and South-Eastern areas. Also, Monte Carlo simulations generated a considerable amount of research results but, with respect to flood risk mapping, harmonization is still incomplete (Spachinger *et al*., 2008).

Some authors sketched a global vision driving to a more complex research-based modelling, while also expanding monitoring and surveillance possibilities. One of the aims was to integrate standard GIS approaches and physically based hydrological models, either at sub-regional or regional scale (e.g., Lan *et al*., 2004; Knebl *et al*., 2005). Second, focus was put on three-dimensional models for spatial-temporal estimation of hazard triggering factors (e.g., for shallow landslide hazard, Qiu *et al*., 2007). Global thresholds are relevant where local or regional thresholds are not available, but they can result in (sometimes numerous) false occurrence predictions, i.e., predictions of damaging events that do not occur. Generally, regional and local thresholds perform reasonably well in the areas where they were developed, but cannot easily be extended to far away areas (Crosta, 1989).

To render comparable a series of rainfall thresholds assessed for different areas or regions, several investigators normalized rainfall intensity values *via* empirical parameters expressing some characteristics of the local climate. Wilson (1997) used the rainy-day normal, a climatic index that describes the occurrence of extreme storms that can trigger slope failures. Most commonly, normalization was carried out by dividing the rainfall intensity of an event by the mean annual precipitation (e.g., Wieczorek *et al*., 2000; Aleotti *et al*., 2002; Bacchini and Zannoni, 2003). However, in this case, the result is less reliable than that attainable using the rainy-day normal.

MDHEs have no instrumentally determined magnitude scale (e.g., like that conventionally used for earthquakes),

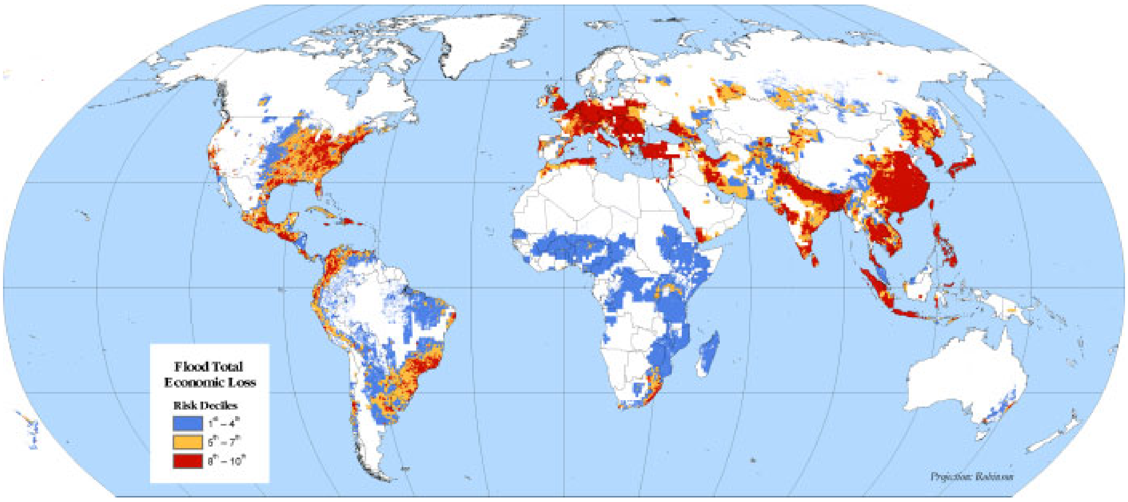

Figure 1. Global flood total economic loss risk distribution (by CIESIN World Data Center, NASA Socioeconomic Data and Applications Center SEDAC, http://sedac.ciesin.columbia.edu/wdc). This figure is available in colour online at wileyonlinelibrary.com/journal/met

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and this is why they are generally described in qualitative terms. For this reason, a quali-quantitative index (RHI, Rainstorm Hazard Index) that combines some attributes of hydrogeomorphological triggering mechanisms was recently developed as part of a model-based framework (Diodato and Ceccarelli, 2009). According to Casti (1997), a model can profitably be used by societal decision-making systems if it possesses four characteristics: simplicity, clarity, is bias-free and has tractability. These properties should be self-evident for modellers, transparent for disaster managers, and easily interpretable for non-scientific audience. Tractability should be the most important characteristic for overall design of modern computer modelling, since it relates to the ability of the model to undertake the task efficiently, thus avoiding disproportionate computational costs (Kelly *et al.*, 2004). According to these requirements, this study was set in a probabilistic, RHI-based framework within geospatial workflows to supply clues for defining hazard-warning operations in emergency management and civil defence purposes. The framework was also meant to identify critical thresholds based on the value of the ratio between pulsing forces perturbing the system (e.g., current rainstorm depth), and resistance forces represented by both storm temporal variability and antecedent weather conditions. This application was focused on Southern Italy, an area where MDHEs are frequently experienced and where the implementation of speed and inexpensive protection measures are desirable. Section 2 describes the modelling methodology, the areas under study and the data sources used to prepare the joint analysis of RHI and hydrogeological events. For inclusion in a geospatial probabilistic model (Section 3), RHI was calibrated against different precipitation durations (from 1 to 48 h) supplied by Met European Research Observatory (MetEROBS) time series (Benevento, Campania region). A control run was also made by re-running the model with a validation dataset (extrapolating until 240 h) and by comparing the results with MDHEs at an independent site (Scilla, Calabria region). Section 4 discusses and evaluates the assumptions adopted during the development of the methodology, and presents overall conclusions, areas of future development, and recommendations arising out of the findings of the study.

2. Methods, study areas and data

2.1. Spatial and time-invariant modelling

To take into account the rainstorms' erratic time pattern, storm hazards were preliminary estimated for hourly time-steps, for $h = 1$ to x hours of storm duration. According to this scheme, an empirically controlled and conceptually based model was approached, in which the identification of the critical threshold value is a temporal-spatial scale invariant indicator. For a given station and for each fixed rainstorm of duration h, hazardous events were defined based on a dimensionless ratio between rainfall amount and threshold-value. A knowledge-based system (expert system model) was designed, based on Diodato and Ceccarelli (2009), to accomplish these logical conditions. For each rainy step of duration, h, at sampled location s_o, the following power equation was developed:

$$RHI_{h(s_\alpha)} = \max : \left\{ \left[\frac{1 + RSD_h}{f_{(Rc\,\mathrm{lim})}} \right]^2_{h(s_\alpha)} \right. \qquad \forall \quad h = 1 \ldots n \ \mathrm{h} \qquad (1)$$

where RHI_h is the rainstorm hazard, expressing the occurrence-and-magnitude of the storm compared to the expected rainy-climate; RSD_h is the rainstorm depth (mm) representing the pulsing force that perturbs the system during each event of duration h, and:

$$f_{(Rclim)} = \mathrm{Med}(RSD_h) - \left(16 - \sqrt{h}\right) \times S_{\mathrm{wet}} \qquad (2)$$

is a function representing the system resistance state, that is the intrinsic ability of the system to resist to changes because of its recent and past history. Exponent 2 in Equation (1) corresponds to an empirical adaptation of the model for better discrimination of values.

Med(RSD_h), the threshold value, is the median of the annual maximum rainfall (mm) of duration h, and the correction term $(16-\sqrt{h})S_{\mathrm{wet}}$ (modified after Diodato and Ceccarelli, 2009) is a function calibrating the threshold value according to the current variations of soil humidity. In Equation (2), the term between brackets tends to be lower for short-duration rainstorms, and *vice versa*. The value of 16, whose unit is $\mathrm{mm}^{0.5}$, corresponds to a larger sensitivity to short- rather than long-duration rainstorms (when the historical memory gains more importance). It also marks the theoretical domain of validity of the equation ($h = 256$ mm). To express soil humidity, S_{wet} ($\mathrm{mm\ h}^{-0.5}$) can assume four values: −0.5, 0.25, 0.5 and 1, for dry, dry mix (only just wet), wet and saturated-soil conditions respectively, preceding the event. The duration of rainstorm (h) under the square root is to explain major accommodations of the system to rainfall spanning over longer periods. The resistance function $f(Rclim)$ includes the disorder state under which the rainstorm–pulsing forces act (after Sauchyn, 2005), and its sensitivity degree depends upon the prior climate history (after Tucker and Slingerland, 1997). In such respect, the response to a weather perturbation may depend on the degree to which the landscape retains 'memory' of past, $\approx$[Med(RSD_h)], and more recent (and anomalous) conditions, $\approx [(16-\sqrt{h})S_{\mathrm{wet}}]$. These constraints drive the trajectories of the system within critical thresholds and *RHI*–equilibrium (repellers and attractors), their final destination and stability. In synthesis, for $RHI > 1$ (Equation (1)), the pulsing forces account for a larger percentage of the system resistance state, designing hazard increase according to a power function. In this way, *RHI* can be subject to large spatial-time fluctuations around critical values, and it can identify hazards in varying hydrological conditions.

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2.2. Test areas and data sets

Two test areas, both located in Southern Italy, are considered in this study: Met European Research Observatory (MetEROBS) is located at Benevento–Monte Pino, in an inland valley of the Campano-Lucano Apennines; Scilla station is placed on the Thyrrhenian coast of Calabria (Figure 2(a)).

MetEROBS (latitude 41.1 °N, longitude 14.1 °E, elevation 184 m a.s.l.) belongs to the TEMS–Terrestrial Ecosystem Monitoring Sites of FAO (http://www.fao.org/gtos/tems/tsite_show.jsp?TSITE_ID=3730), resulting in accumulation and storage of a considerable amount of weather data of long duration and continuity. In 2009, MetEROBS was accredited by GEWEX-CEOP (Global Energy and Water Cycle Experiment-Coordinated Energy and Water Cycle Observations Project, http://www.gewex.org/ceop.htm) as part of the World Climate Research Programme (http://www.wmo.int/pages/prog/wcrp). The area around the MetEROBS site comprises about 9 km^2 of cropland with sparse and dense vegetation, located in the Benevento district and bordered by the Serretelle valley (to the east side) and Taburno mountain (to the west side).

Scilla raingauge station (latitude 38.1 °N, longitude 15.7 °E, elevation 73 m a.s.l.) is a telemetric raingauge located in the Calabria region and characterized by 20 years of sub-daily rainfall records (at 5, 10, 15, 20, and 60 min).

The climate across these regions is of Mediterranean type, but with important spatio-temporal differences in both precipitation and temperature patterns. The average annual precipitation (1957–2000) ranges from 500 to 2000 mm. Long-term periods of seasonal climatic regime are similar for the two sites (Figure 2(b) and (c)), but rainfall extremes can be very different, as shown by the map in Figure 2(a).

Especially during and after the tillage period (September to November), erosive rainfall may be very hazardous because it is driven by a mixed regime of frontal rainstorms and localized showers and thunderstorms (Figure 2(b) and (c)). Important amounts of erosion, deposition and landslides affecting roads can therefore take place at and surrounding the Monte Pino–MetEROBS site in frequent events, but also during less frequent short events, such as those which occurred on May 2001 and June 2003. Especially during pulse phenomena, occurring in summer time, most soil losses on hillslopes are deposited before reaching the main stream at the outlet of the watershed. The Monte Pino area, in particular, shows sensitivity to both spring-summer and autumn high-intensity rainfall events.

In particular, tillage on steep slopes and flash erosivity regimes produce overland flows and high rates of sediment mobilization and transport. As with the Calabrian study area, a strip of territory was selected located on the southwest coast of the region, and extending through the municipalities of Scilla and Bagnara Calabra, for about 10 km in length and 3 km in width.

The historical series of MDHEs, for the Scilla area is long, starting from the beginning of 1900. The dates in which the events occur in this area often do not coincide with regional MDHEs. In practice, this area shows a high level of susceptibility to damage. In this zone, in fact, the presence of several elements at risk located at the slope foot (a highway, a railway and a state road, besides residential areas) ensure that almost each individual landslide or flood event affect some portion of them. The number of landslide phenomena (60% of cases) prevails on falls (14%) and flash floods affecting ravines located on the deep slopes of the area (26%). These last types of phenomena, often associated with landslides along the valley sides, can become destructive concentrated flows which run from the hills down to the populated areas located near the coast, as in the case of 31 May 2005, when a train derailed and the village of Favazzina was heavily damaged (Bonavina *et al.*, 2005).

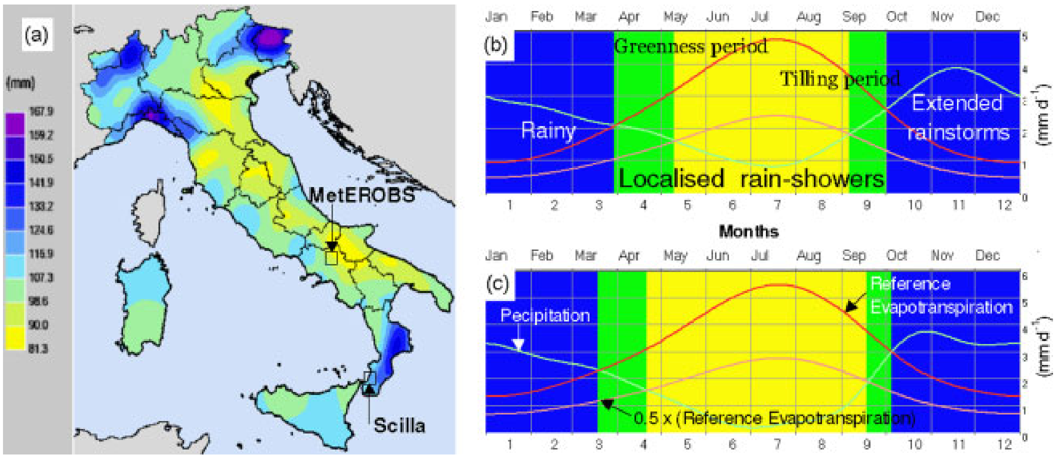

Figure 2. (a) Map of the annual maximum precipitations averaged upon the period 1961–1990 with the test-sites of MetEROBS and Scilla (from ISPRA–SCIA dataset http://www.isprambiente.it/site/it-IT), and (b and c) respective seasonal bioclimograms (shaded bands), and pluvio-evapotranspirative regimes (curves) as arranged by New LocClim–FAO software (http://www.fao.org/sd/dim_en3/en3_051002_en.htm). This figure is available in colour online at wileyonlinelibrary.com/journal/met

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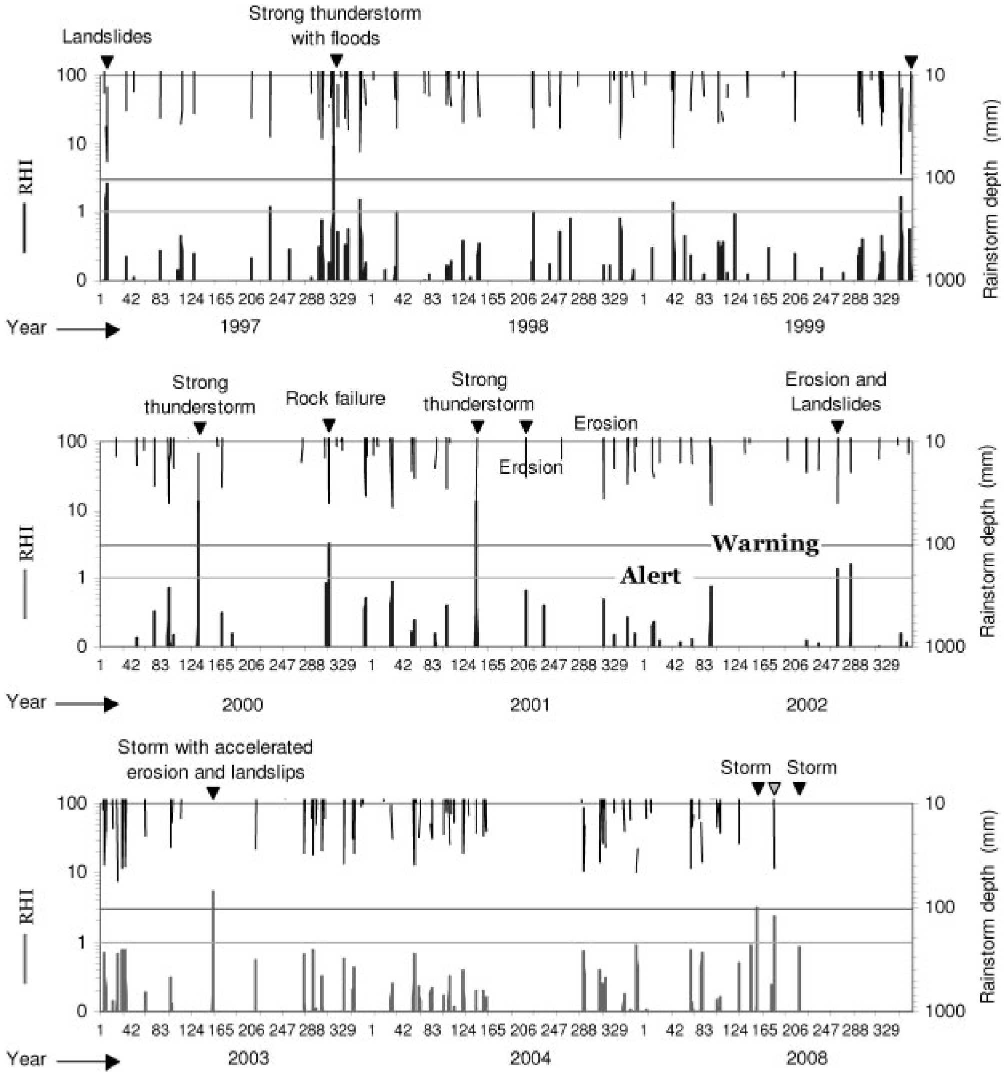

Figure 3. Daily rainstorms >20 mm day^{-1} (black bars), and simulated RHI (grey bars) with associated MDHE (▼) around OBS during 1997–2008 period. Thresholds of 1 (Alert) and 3 (Warning) are drawn too.

3. Rainstorm hazard index-based joint analysis

Due to the partial availability of a historical series of sub-daily rainfall, a joint analysis of RHI and hydrogeological events was carried out covering the more recent period 1997–2010. MDHE data were inferred from technical and scientific publications (Diodato, 2004; http://www.camilab.unical.it/oda/sito_oda_4_003.htm), as well as from regional archives (IARC, http://www.sito.regione.campania.it/agricoltura).

MetEROBS was chosen as a reference site to calibrate RHI, because both *RHI*–data and MDHE series were available for this location. The RHI run depicted in Figure 3 enables examination of how the predicted hazard met the landscape response (i.e., MDHE) over 1997–2008. The period 2005–2007 was not analysed because of the mild weather conditions registered over this interval near the MetEROBS site. RHI based predicted values, estimated over the calibration set, were tested *versus* the observations, and scored by tallying results into a standard 2×2 contingency matrix of observed and expected pairs for maximizing the percentage of the hit rate that is equal to the ratio between the number of hit events (success events) and the total sampled events.

Hit rate was estimated to be 96% when accounting for the number of all rain events with > 20 mm day^{-1}, and 63% when only accounting for occurred or predicted events with MDHE. The results indicate a high percentage of success, significant at level $\alpha = 0.10$. RHI graphs are also accompanied by daily or sub-daily rainstorms depth (black bars in Figure 3, right axis on an inverse scale), when almost 20 mm of rain has fallen.

The results show a good agreement between expected hazard (RHI bars) and occurred events around MetEROBS over 1997–2008, with only episodic events of false alerts. It is also expected that extreme events can be predicted easily, as occurred in the peak of 13 November 1997, when rainfall recorded at MetEROBS was 111 mm, 86 mm of which fell in 3 h. In this event, remarkable erosion, sediment-laden floodwaters and landslides occurred in the whole Benevento province (Diodato, 2005).

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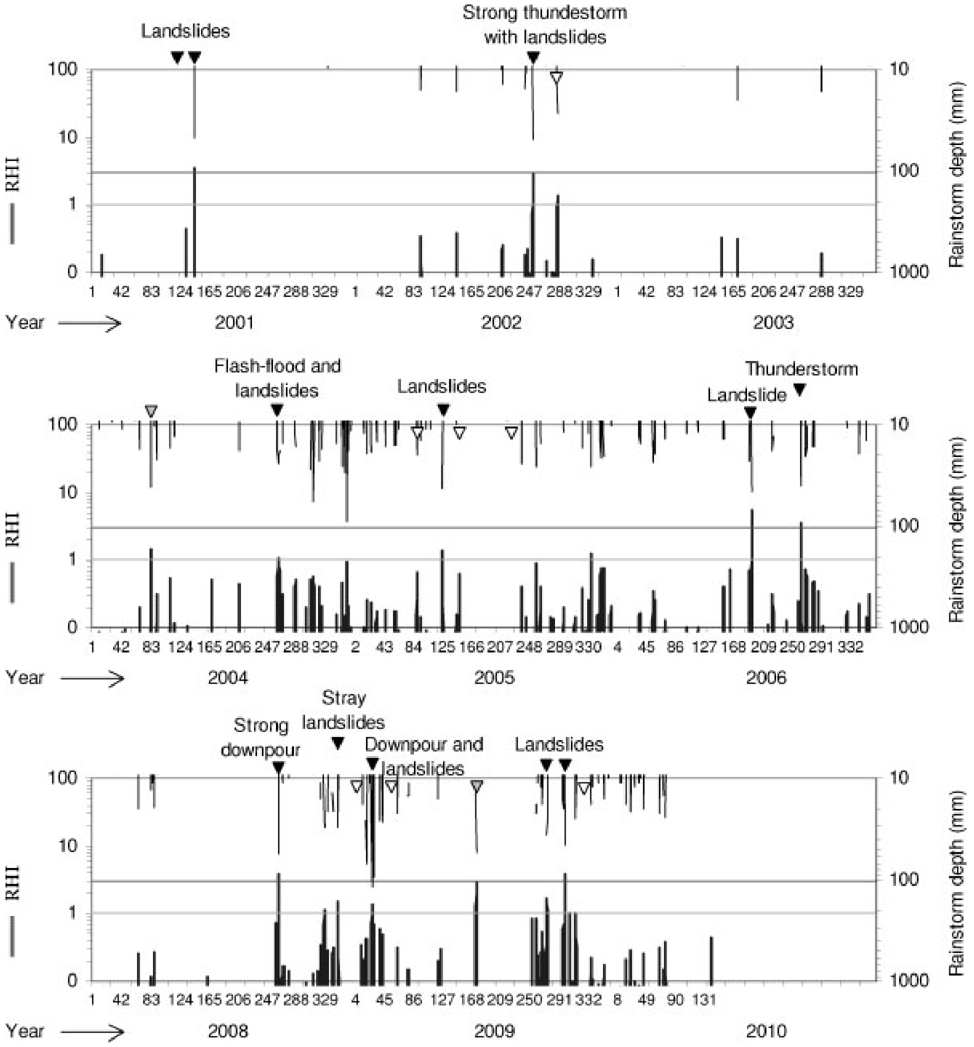

Figure 4. Daily rainstorms >20 mm day^{-1} (black bars), and simulated RHI (grey bars (blue in the online version)) with associated MDHE (▼) around Scilla station during 2001–2006. Empty triangles indicate lack alarm. Critical thresholds of 1 (Alert) and 3 (Warning) are drawn too.

For this area, the calculation of historical precipitation-frequency data referred to as 3 h rainfall (by the Gumbel method) shows that a rain amount of 86 mm has a return period of 20 years. The most intense rainstorms, but with minor spatial extent compared to those in autumn, occurred between the end of spring and summer, including the second daily peak, which occurred in May 2001 when a heavy downpour hit the agricultural lands devastating the slopes around MetEROBS. However, this location showed sensitivity to both spring-summer and autumn high-intensity rainfall events. In particular, tillage on steep slopes and flash shower regimes produced overland flows and high rates of sediment mobilization and transport.

An independent location (the Scilla station) was used as the validation study site (Figure 4). Because of the level of high risk characterizing the area, which depends on both the high frequency of landslides and/or flood activations (on average, two events *per* year between 1973 and 2010), and the high density of vulnerable elements, the rain monitoring has been recently improved. Hence, only the period between 2001 and 2010 was considered for an evaluation of the effectiveness of RHI-based procedure *via* a two-by-two contingency table analysis (Table I)) based on the calculation of an array of relevant indices and their confidence intervals (Fleiss, 1981; http://statpages.org/ctab2 × 2.html).

An Odds ratio largely greater than one indicates that the outcome of interest (‘Outcome occurred’) has a higher probability to come about with RHI $>$ 1. A Kappa higher than 0.6 indicates a good agreement between risk factor and occurrence of the event, as was also confirmed by the other indices reported calculated in this study (Table I).

In Figure 4, expected hazards (RHI bars) and actual occurrences around Scilla confirm the performance already reflected in the calibration against MetEROBS data. Total and partial hit rates estimated at the validation stage result in values very similar to those observed in the calibration set (Figure 3). However, the validation set indicates that partial hit rates of failed alert are high (i.e., 53%). This discrepancy can be due to events characterized by prolonged rainfall (>96 h) which occurred at Scilla in the period evaluated but were not registered

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Table I. Contingency table and relevant statistics for Scilla station (validation dataset).

Contingency table		Outcome occurred	Outcome did not occur	Totals
	Risk factor present ($RHI > 1$)	$a = 13$	$b = 1$	$r_1 = 14$
	Risk factor absent ($RHI < 1$)	$c = 7$	$d = 132$	$r_2 = 139$
	Totals	$c_1 = 20$	$c_2 = 133$	$t = 153$
Relevant statistics	Index	Value	0.95 confidence interval	
	Odds ratio, $(a/b)/(c/d)$	245.143	34.234	1632.214
	Relative risk, $(a/r_1)/(c/r_2)$	18.439	10.189	22.193
	Kappa, (observed-expected)/(1-expected)	0.736	0.547	0.790
	Overall fraction correct, $(a + d)/t$	0.948	0.910	0.958
	Mis-classification rate, = 1 − overall fraction correct	0.052	0.042	0.090
	Sensitivity, a/c_1	0.650	0.506	0.691
	Specificity, d/c_2	0.992	0.971	0.999
	Positive predictive value, a/r_1	0.929	0.724	0.987
	Negative predictive value, d/r_2	0.950	0.929	0.956

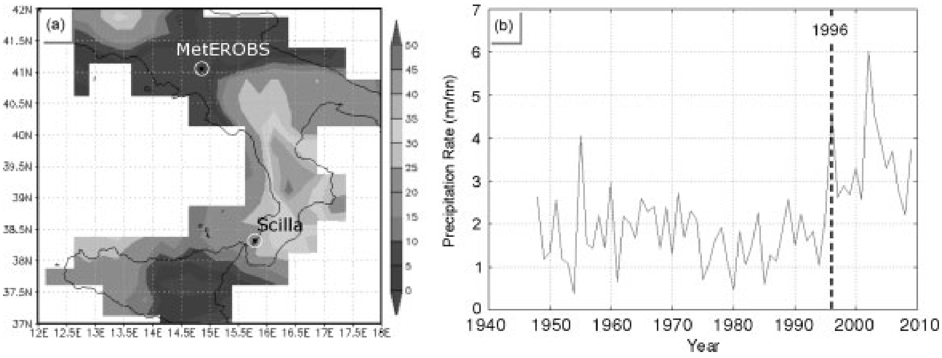

Figure 5. (a) Spatial pattern of the September rainfall anomalies (mm) during 2000–2008 compared to climatological rainfall (1950–2000) over Southern Italy (arranged from TRMM remote sensing by NASA Earth System Science Data and Services, http://nasadaacs.eos.nasa.gov); (b) September rain rate evolution from 1948 to 2009 for the region as in (a) (by National Oceanic and Atmospheric Administration, Earth System Research Laboratory, Physical Sciences Division, http://www.esrl.noaa.gov). The figure is from Diodato (2010).

in the MetEROBS data used for calibration. This calls for the need of calibration work, which is consistent with the target area's short- and long-term needs.

As already noted (rainstorm timing of Equation (1), results of Figures 3 and 4), the temporal pattern of hazard shows a remarkable complexity, which increases as rain concentration increases. This complexity is also reflected spatially, as it is possible to detect it from Figure 5(a), where extended and positive anomalies of rain amount in September occurred during the recent decade (1999–2008) compared to the climatological period (1950–2000).

The graph of Figure 5(b) also suggests that Southern Italy is subjected to increasing precipitation intensity and hazards in the month of September, spanning from 1948 to 2009. After 1996, rain rates have been observed to be unusually high, showing an abrupt change over the first decade of the twenty-first century. This can be important for the use of RHI modelling in operational procedures where climate information and human experience become essential for a successful implementation of an alert system.

4. Discussion and conclusions

Rainstorm hazards have many consequences, such as landslides, floods and intense erosion. Today, global climate change and consequent extreme weather events require a strong attention to these issues (also considering the greater risk posed by large urbanized areas). Rainstorm hazard awareness and preparedness as integral aspects of planning and development policy is needed in Southern Italy and it is receiving more and more attention by the community, scientists and engineers (Cassetti and Versace, 2005; Wieczorek and Glade, 2005).

The complexity of hydrological system responses in the proximity of critical threshold values, however, pose major difficulties. As threshold phenomena are quite often associated with environmental hazards such as floods, soil erosion and contamination of shallow groundwater resources, it is of key importance to predict whether they might occur at all and, if so, then their intensity (Zehe and Sivapala, 2008). The present study was based on concepts (e.g., intermittence of phenomena and processes as characteristic feature of threshold behaviour in environmental systems) already outlined by other authors

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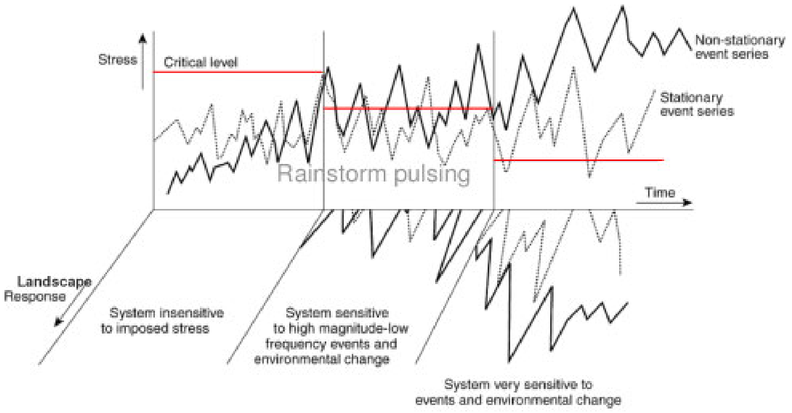

Figure 6. Scheme of the main hydrological forces approach to rain-thresholds for stable and unstable systems during rainstorm events (from Viles and Goudie, 2003, modified). This figure is available in colour online at wileyonlinelibrary.com/journal/met

(e.g., Blöschl and Zehe, 2005; Rundle *et al*., 2006). Intermittence in space and/or time, in particular, poses problems for predictability. In general, a two-level mixed discrete-continuous prediction is approached, first predicting whether or not the phenomenon/process will occur and then, if so, its strength. Ever since the introduction of catastrophe theory (see, for instance, Thom, 1989) it is known that the accuracy of predictions of threshold phenomena/processes (i.e. does it occur or not?) depends on the current state of the system and the expected forcing/boundary condition. It was, therefore, suggested that the possibility to detect the existence of threshold behaviour based on the intermittence of phenomena while predictability of system behaviour drastically decreases for certain combinations of states and expected stress conditions (Figure 6, upper panel), or in a range of states when a certain response is expected (Figure 6, lower panel).

Figure 6 is a generic scheme of how clusters of rainstorm events can produce variability in geomorphic thresholds (e.g., overtopping), although it represents a simple non-linear view of landscape response which may be an oversimplification for many geomorphic systems.

When a system is stable in the phase of small disturbances it would become sensitive to larger perturbations. The search of the system threshold governs the behaviour that underlies much research on this topic (Thomas, 2001). Assuming that the system has adapted its hydrological regime to a minimum threshold at the lowest level below which damaging phenomena do not occur, then each sudden fluctuation in this regime, especially those exceeding the critical state above minimum threshold, may trigger damaging phenomena. Several such ideas on the clustering of events and complex responses to them can be presented as conceptual diagrams of the type of Figure 6, although multiple modalities may typically occur in which spatial complexity, chaos and stochastic perturbations govern the dynamics (Scheffer *et al*., 2009).

It must also be observed how extrinsic-intrinsic thresholds are exceeded, because the time distribution of rainstorms may show either different sequence patterns (Ward and Trimble, 2004), or, in turn, different combinations of resistance and pulsing forces. Depending on the season, rainstorms may show time-varying intensity values. Winter rainfalls often have relatively low intensity, with little variation in intensity throughout the storm, spring or autumn storms may have the maximum intensity at intermediate or long durations. Furthermore, each station experiences a unique rainstorm temporal pattern and this complicates the model creation. However, while it is well known that rainstorm depth determines the occurrence of damaging hydrological events, rainstorm depth alone does not represent a sufficient condition for the triggering of flooding, erosion and other hydrological phenomena as those occurring during MDHEs (Palecki *et al*., 2005).

In MDHE-based studies, modelling and warning information are valuable sources of spatial information and they have proved useful on many occasions worldwide. However, there are many types of hazard experienced on both hourly and daily bases and their modelling solutions can vary. It may be appropriate, for instance, to provide a function of soil humidity with previous daily or hourly precipitation. Moreover, other factors that influence MDHEs could be assessed, e.g. friction angle of soil, soil suction, hydrological conditions, underground water flow, vegetation type, human factors as presence of narrow roads and houses. The paper does not cover the analysis of all different components with their respective weight on MDHEs. The proposed methodology seems, however, promising for application in real-time warning systems in areas where little data on (for example) streamflow and hillslope monitoring are available. One of the major advantages of Equation (1) is that the RHI assessed for a selected area can be compared to that of surrounding sites, because the results are scaled to indicator values for use in weather hazard maps, opposite to absolute threshold values (Diodato, 2006). It is evident, in Equation (1), that landscape response is achieved by individual formative events modelled in relation to the historical median rainfall for the same event durations. There are also specific events that can affect landscape within a sequence (Brunsden, 2001). In the present study, combinations of these events, characterized by any frequency, magnitude, and duration, were only taken into account in a qualitative way. An example is the coefficient of the soil water content in Equation 2, for which four attributes were designated and whose value can be derived in a variety of ways depending on the research context, e.g. from remote sensing data (after Ottlé *et al.*, 1989). In spite of such limitation, RHI is suitable to be included in a geospatial probabilistic model to be used for developing a soft geovisual communication in order to mitigate the uncertainty associated with downscaling and geocomputational tracking. The approach presented can be useful for the implementation of an early alert system, especially in regions where expensive systems are not at hand. The link of RHI flood-forecasting with the precipitation forecasts produced by atmospheric LAMs (Limited Area Models) could, for instance, be tested and installed in operational mode (e.g., Todini, 1999). The RHI model may also be a tool for short-range weather forecasting, covering specific geographic areas (nowcasting) and warnings for end-users when fine spatio-temporal resolution of precipitation forecast is usable.

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