A prototype system to forecast rainfall induced landslides in Italy

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ABSTRACT: We are designing a system to forecast rainfall-induced landslides in Italy. The system is based on a set of rainfall thresholds for the possible initiation of landslides, and an ensemble of small scale landslide hazard and risk zonations. Rainfall thresholds include existing and new, national, regional and local empirical thresholds of the intensity-duration (ID) and normalized-ID types. The new thresholds were calculated using objective methods and robust statistical techniques, exploiting existing and new data on rainfall events that have resulted in landslides. The synoptic landslide hazard zonation was obtained through multivariate statistical analysis of small scale environmental information, and catalogues of historical landslides. Similarly, the risk zonation was prepared exploiting a catalogue of historical landslides with human consequences in Italy. The information obtained from the rainfall thresholds and the hazard and risk zonations is combined in a national-scale warning system for rainfall-induced landslides to support civil defense decisions.

1 INTRODUCTION

In Italy, landslides are frequent and widespread phenomena triggered chiefly by intense or prolonged rainfall, and subordinately by rapid snow-melting and earthquakes. A nationwide investigation completed by the Italian Geological Survey has identified $\approx 5\times10^5$ landslides in Italy, corresponding to an average of 1.6 slope failure per square kilometer (Trigila, 2008). Recent investigations indicate that this estimate is locally much higher (e.g., Guzzetti et al. 2008).

Damage caused by landslides is particularly severe in Italy. In the 59-year period between 1950 and 2008, at least 6141 people were killed or injured by slope failures in Italy. In the same period, the mortality of landslides was larger than that of any other natural hazard, including floods, earthquakes, volcanic eruptions, and snow avalanches (Guzzetti 2000, Salvati et al. 2003, Guzzetti et al. 2005). This is evidence of the considerable risk posed by landslides to the population of Italy.

In Italy, the national Department of Civil Protection (DPC), an Office of the Prime Minister, is responsible for the protection of individuals and communities against all natural hazards, including landslides.

At present, we are designing a prototype warning system to help the DPC managing landslide risk in Italy. The system is aimed at forecasting the possible occurrence of rainfall-induced landslides, using empirical rainfall thresholds and small scale zonations of landslide hazard and risk.

In this report, we first describe the rationale for the system, we present a set of empirical thresholds for the possible occurrence of rainfall-induced landslides in Italy, we introduce objective methods for determining new thresholds, and we discuss the small scale landslide hazard and risk zonations. Next, we show a preliminary application of the system to forecast rainfall-induced landslides in the Abruzzo Region, Central Italy. We conclude by summarizing the results obtained.

2 THE PROTOTYPE WARNING SYSTEM

2.1 *Rationale*

The prototype landslide warning system is based on two main components: (i) a set of empirical thresholds for the possible occurrence of rainfall-induced landslides, and (ii) an ensemble of small scale, national (synoptic) landslide hazard and risk zonations.

The warning system compares rainfall measurements (obtained from networks of rain gauges or weather radars) and quantitative rainfall forecasts (an output of limited-area meteorological models) with empirical rainfall thresholds, to inform "where" and "when" landslides are expected in a given region. The hazard and risk zonations are used to establish if the expected slope failures occur in areas that are considered highly susceptible to landslides, or where landslide risk is severe or significant.

2.2 *Rainfall thresholds*

The set of rainfall thresholds used in the prototype system includes existing (Guzzetti et al. 2007, 2008, and references therein) and new national, regional and local thresholds of the intensity-duration (ID) and normalized-ID types (Fig. 1).

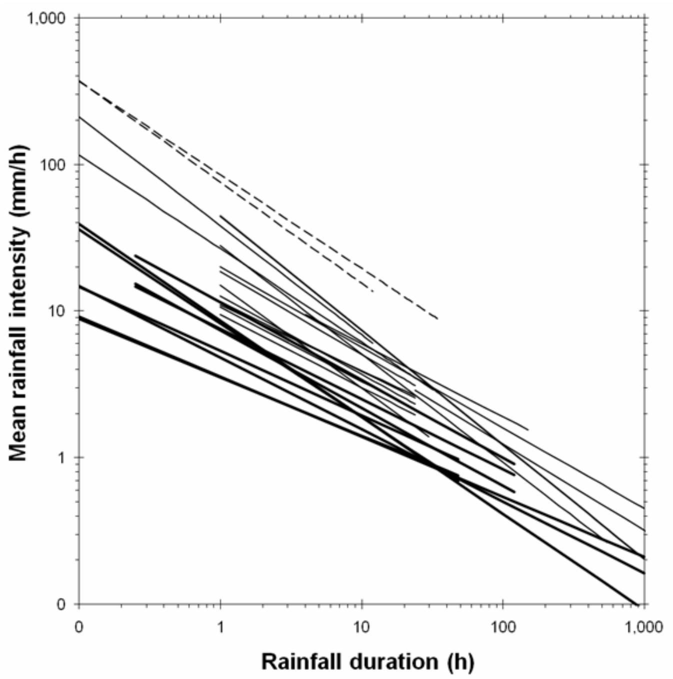


Figure 1. Twenty-six rainfall intensity-duration (ID) thresholds for the possible occurrence of landslides in Italy. Very thick lines are national (global) thresholds, thick lines are regional thresholds, thin lines are local thresholds, and dashed lines are thresholds for catastrophic events. Modified after Guzzetti et al. (2007, 2008).

New thresholds for the system are established using objective methods and robust statistical techniques. The methods exploit existing and new data on rainfall events that have resulted in landslides. For the purpose, we have compiled a catalogue of more than 600 rainfall events in Italy that have resulted in landslides. The rainfall and landslide information was obtained mainly from the literature, including international journals, proceedings of regional, national and international conferences, and national, regional and local technical and event reports describing single or multiple rainfall-induced landslides. For the most recent period, information on individual landslide events was obtained from local newspapers.

To define the new thresholds, we start by plotting the empirical rainfall intensity (I) and duration (D) values in logarithmic coordinates. Next, we calculate the threshold curves using two objective statistical techniques. The first technique exploits Bayesian inference (Guzzetti et al. 2007, 2008), whereas the second technique uses an innovative modeling approach implemented in the R free software environment for statistical computing (http://www.r-project.org/). The two techniques avoid subjective criteria in the determination of the thresholds, that are common in many of the published rainfall thresholds for the possible initiation of landslides (Guzzetti et al. 2007, 2008).

2.3 *Synoptic hazard and risk zonations*

To obtain the synoptic (national-scale) landslide hazard and risk zonations, a set of statistical models were prepared. The models exploit small scale thematic and landslide information available to us. The thematic information includes: (i) morphometry, obtained from a 90 m × 90 m DEM acquired by the Shuttle Radar Topography Mission (SRTM) in February of 2000 (Farr et al. 2004), (ii) lithology, obtained from the Geological Map of Italy compiled at 1:500,000 scale by Compagnoni et al. (1976-1983), (iii) soil types, obtained from the Soil Map of Italy prepared at 1:1,000,000 scale by Mancini et al. (1966), and (iv) climate, obtained from the Data Distribution Centre of the Intergovernmental Panel on Climate Change (http://ipcc-ddc.cru.uea.ac.uk/) (New et al. 1999). The landslide information consists of: (i) a catalogue of historical damaging landslides in Italy (Guzzetti et al. 1994, Guzzetti & Tonelli 2004, Reichenbach et al. 1998) and, (ii) a catalogue of historical landslides with human consequences in Italy (Guzzetti et al. 2005, Salvati et al. 2003).

To determine landslide susceptibility, i.e., the spatial component of landslide hazard (Guzzetti et al. 2005), a set of multivariate classification techniques are adopted, including linear discriminant analysis, quadratic discriminant analysis, logistic regression, and a neural network. The individual classifications are then combined into an "optimal" susceptibility zonation, obtained adopting a regression approach (Rossi et al. submitted). For landslide susceptibility, the 8102 Italian municipalities are used as the mapping unit of reference.

To evaluate the temporal probability of landslide occurrence in Italy, we start by counting the number of landslide events and the number of landslide events with human consequences in 126 hydrological alert zones established by the DPC. Assuming landslides are random point events in time, and adopting a Poisson distribution to describe the temporal distribution of the events, the exceedence probability of experiencing damaging landslides and landslides with human consequences is computed for different periods, from 1 to 10 years.

To test the performance of the spatial and the temporal models, the two catalogues of damaging landslides and of landslides with human consequences in Italy, are split in two sets: (i) a calibration set, used to construct the models, and (ii) a validation set, used to evaluate the model prediction skills. The period for the calibration and the validation sets are different for the susceptibility and the temporal models.

3 THE ABRUZZO TEST CASE

On 6 April 2009, at 01:32:39 UTC (03:32.39 local time), the Abruzzo Region, central Italy, was shaken by a severe earthquake of local magnitude $\mathbf{M_L} = 5.8$ (moment magnitude $\mathbf{M_W} = 6.3$). The epicenter of the earthquake was located WSW of L'Aquila at a depth of about 8.8 km. On April 7 and April 9, two earthquakes of $\mathbf{M_L} > 5$ occurred in the same general area: the first ($\mathbf{M_L} = 5.3$) was located 11 km SSE of L'Aquila, and the second ($\mathbf{M_L} = 5.1$) 15 km NNW of L'Aquila. In the period 6-30 April 2009, at least 32 earthquakes with $\mathbf{M_L} > 3.5$ were recorded in the area by the Istituto Nazionale di Geofisica e Vulcanologia. The main shocks and some of the most severe aftershocks triggered landslides, chiefly rock falls and minor rock slides. Some of these landslides caused severe damage to towns (e.g., Fossa, AQ), individual houses (e.g., San Demetrio ne' Vestini, AQ), and the transportation network (e.g., the San Venanzo gorges).

In the period from October 2008 to March 2009 (i.e., before the earthquakes), the epicentral zone and the neighboring areas received a considerable amount of precipitation (rainfall and snowfall). Field surveys conducted immediately after the main shocks revealed a few recent, shallow landslides of the slide type. The failures type, the distance of the failures from the fault rupture zone, and the moderate magnitude of the earthquakes (Keefer 1984, 2002, Rodríguez et al. 1999), concur in establishing that the slope failures (most probably) preceded the earthquake sequence, and hence they were meteorologically-induced. However, some of the landslides (e.g. near Campotosto, Fig. 2) were caused or reactivated by the earthquake sequence.

The fact that pre-existing and reactivated rainfall-induced landslides exist in the area, and that during the earthquake sequence parts of the Abruzzo region – including the epicentral area – received a considerable amount of rainfall (locally exceeding 70 mm per day), persuaded us of the opportunity to test the prototype warning system in the Abruzzo Region, to help the local activities of the DPC.

We first identified 25 continuously recording rain gauges in the Abruzzo Region for which rainfall measurements were available to the DPC. The rain gauges cover more or less uniformly the study area (Fig. 3). Next, we had to select a rainfall threshold for the possible occurrence of landslides in the Abruzzo Region. So far, no specific, local or regional threshold exists for this area (see e.g. http://rainfalltresholds.irpi.cnr.it). For this reason: (i) we adopted a national ID threshold established through the statistical analysis of 562 rainfall events with landslides in Italy, and (ii) we began collecting and analyzing specific information on rainfall events that had resulted in landslides in the Abruzzo Region. Finally, we implemented a specific protocol (a procedure) to obtain the landslide forecast, and to dispatch it to the DPC.

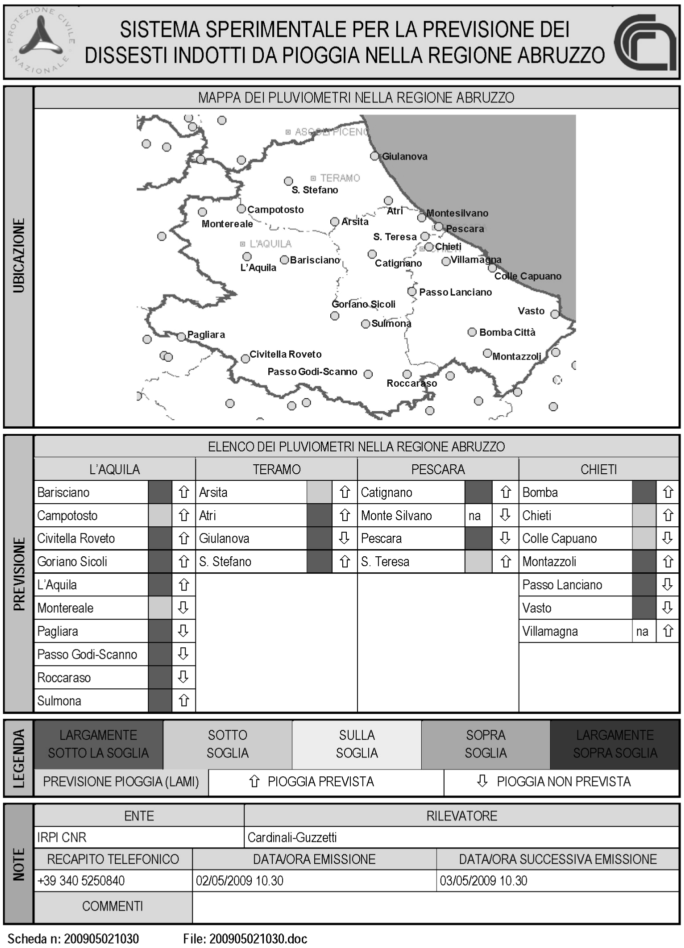
Figure 2. Landslide of the slide type near the Campotosto lake, Abruzzo, Central Italy.

The procedure is prototypal, and it is based on the following five steps:

- First, the cumulated rainfall for each of the 25 selected rain gauges is calculated, for four periods (24, 48, 72 and 96 hours).
- Next, for each rain gauge, the average rainfall intensity (I, $mm \cdot h^{-1}$) is calculated for the four periods, and compared to a set of pre-defined values to determine if the measured rainfall conditions at each rain gauge are: (1) well below, (2) below, (3) on, (4) above, or (5) well above the adopted (national) ID threshold. For each rain gauge, the largest rainfall rate for the four periods is selected as representative of the rainfall conditions that may have resulted in landslides in the study area. The limits for the five classes were established based on probability, and adopting the scheme shown in Table 1. When the average rainfall intensity (I) for a given duration (D, from 1 to 4 days) is lower than the corresponding 0.005% probability level (i.e., 99.995% of the rainfall events used to construct the reference threshold occurred with a higher I), the condition is considered to be "well below" the reference threshold. Similarly, when the probability level is in the range [0.5 – 1.5[the condition is considered to be "on the threshold", and when the probability level is in the range [1.5 – 5.0[the condition is set to be "above the threshold".

Table 1. Scheme used to attribute the measured rainfall condition to a probability class, based on the adopted ID reference threshold.

Class		Probability range
(1)	Well below the threshold	[0.0 – 0.005[
(2)	Below the threshold	[0.005 – 0.5[
(3)	On the threshold	[0.5– 1.5[
(4)	Above the threshold	[1.5 – 5 [
(5)	Well above the threshold	[5 – 100]


SISTEMA SPERIMENTALE PER LA PREVISIONE DEI DISSESTI INDOTTI DA PIOGGIA NELLA REGIONE ABRUZZO

UBICAZIONE

MAPPA DEI PLUVIOMETRI NELLA REGIONE ABRUZZO

PREVISIONE

ELENCO DEI PLUVIOMETRI NELLA REGIONE ABRUZZO

L'AQUILA			TERAMO			PESCARA			CHIETI		
Barisciano		⇧	Arsita		⇧	Catignano		⇧	Bomba		⇧
Campotosto		⇧	Atri		⇧	Monte Silvano	na	⇩	Chieti		⇧
Civitella Roveto		⇧	Giulanova		⇩	Pescara		⇩	Colle Capuano		⇩
Goriano Sicoli		⇧	S. Stefano		⇧	S. Teresa		⇧	Montazzoli		⇧
L'Aquila		⇧							Passo Lanciano		⇩
Montereale		⇩							Vasto		⇩
Pagliara		⇩							Villamagna	na	⇧
Passo Godi-Scanno		⇩									
Roccaraso		⇩									
Sulmona		⇧									

LEGENDA

LARGAMENTE SOTTO LA SOGLIA	SOTTO SOGLIA	SULLA SOGLIA	SOPRA SOGLIA	LARGAMENTE SOPRA SOGLIA

PREVISIONE PIOGGIA (LAMI)	⇧ PIOGGIA PREVISTA	⇩ PIOGGIA NON PREVISTA

NOTE

ENTE	RILEVATORE	
IRPI CNR	Cardinali-Guzzetti	
RECAPITO TELEFONICO	DATA/ORA EMISSIONE	DATA/ORA SUCCESSIVA EMISSIONE
+39 340 5250840	02/05/2009 10.30	03/05/2009 10.30
COMMENTI		

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Figure 3. Form (in Italian) used to summarize the daily landslide forecast for the Abruzzo Region, central Italy.

- Next, a 24-h quantitative rainfall forecast provided by the Limited Area Model Italy (LAMI) is examined visually, to determine if rainfall is expected at – or in the vicinity of – each rain gauge.
- Next, a bulletin is prepared using a pre-defined form (Fig. 3). For each rain gauge, the form provides information on: (i) the geographical location of the rain gauge, (ii) the rainfall threshold condition, and (iii) if precipitation is – or is not – expected in the next 24 h. For each rain gauge, an expanded traffic-light coloring scheme is used to show the probability level, compared to the corresponding threshold value. Information on the rainfall prediction is given using symbols: (i) an arrow pointing up when rainfall is expected, and (ii) an arrow pointing down when rainfall is not expected.
- Lastly, the bulletin is dispatched by email to the DPC.

From 29 April to 12 May, 2009, we have dispatched to the DPC daily bulletins summarizing information on the possible occurrence of rainfall-induced landslides in the Abruzzo Region. The bulletin is prepared every morning, and sent to the DPC via email before 10:30 local time (08:30 UTC). In the short operational test period, none of the bulletins predicted the possible occurrence of rainfall-induced landslides; and to the best of our knowledge rainfall-induced landslides have not occurred in the Abruzzo Region. Simulations performed using information on rainfall events that have resulted in landslides before the earthquake sequence indicate that the system would have predicted the rainfall-induced slope failures.

4 CONCLUSIONS

We are developing a prototype warning system for the national Department of Civil Protection (DPC) to forecast the possible occurrence of rainfall-induced landslides in Italy. The system is based on a set of empirical rainfall thresholds, and on small scale (synoptic) zonations of landslide hazard and of landslide risk to the population of Italy. The system is currently being tested in the Abruzzo Region, an area recently affected by earthquakes and where rainfall-induced landslides are common. Preliminary results of this test are encouraging.

When fully operational, the system will help the DPC to issue national and regional warnings for the possible occurrence of rainfall-induced landslides. With this respect, the system will contribute to mitigate – through prevention – the risk posed by landslides in Italy. A measure of the success of the system will be a reduced number of fatalities and injured people caused by rainfall-induced landslides in Italy.

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RAINFALL-INDUCED LANDSLIDES

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