Forecasting Landslides and the Associated Risk to the Population of Italy

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Abstract. Italy has a long history of landslides and of related catastrophes. In Italy, landslides occur every year in response to meteorological and geophysical triggers, causing extensive economic damage and casualties. The Italian Department of Civil Protection, an Office of the Prime Minister, and IRPI, a research institute of the Italian National Research Council, are designing a prototype system for the quasi-real-time forecasting of rainfall induced landslides in Italy. The system is based on two components: (i) a set of empirical rainfall thresholds for the possible occurrence of landslides, and (ii) synoptic (small scale) assessments of landslide hazard and risk to the population in Italy. The two system components will be combined to form a national landslide warning system. To determine the geographical distribution of landslide hazards and risk in Italy, existing catalogues of historical damaging landslide events and of landslide events with human consequences are used, together with synoptic thematic and environmental data. Existing rainfall thresholds for the possible occurrence of landslides are validated, and new rainfall thresholds are determined using catalogues of rainfall events that have or have not resulted in landslides, and detailed records of rainfall measurements. When established, the system will exploit real-time rainfall measurements from a dense network of rain gauges, quantitative rainfall estimates obtained from a network of weather radars, and quantitative rainfall forecasts obtained from advanced numerical weather forecasts.

Keywords. Landslide, hazard, risk, rainfall threshold, civil protection, Italy.

1. Introduction

In Italy, landslides are widespread and recurrent phenomena. Historical investigations have revealed that, in the 1148-year period between 860 and 2007, 1474 single or multiple landslides have caused at least 13,534 deaths and 2735 injured people, in 10% (829) of the 8102 Italian municipalities. In the period from 1950 to 2007, landslide mortality was higher than the mortality caused by any other natural hazard, including earthquakes, floods and volcanic activity (Guzzetti 2000; Salvati et al. 2003; Guzzetti et al. 2005b,c). Natural landslides in Italy are caused primarily by meteorological triggers, chiefly intense or prolonged rainfall and subordinately rapid snowmelt, and by geophysical triggers, including earthquakes and volcanic activity.

The Italian Department of Civil Protection (DPC), an Office of the Prime Minister, has the responsibility to protect individuals and communities from natural and technological hazards, including landslides. To accomplish this challenging task, the DPC performs multiple actions, including monitoring water discharge and precipitation from a dense network of measuring stations, and issuing daily meteorological warnings based on numerical weather forecasts. The DPC is also involved in the determination of landslide hazard and risk at different geographical scales.

In 2007, the DPC asked IRPI, a research institute of the Italian National Research Council, to design a prototype system for the quasi-real-time forecasting of rainfall induced landslides in Italy. The system is based on two main components: (i) a set of empirical rainfall thresholds for the possible occurrence of landslides, and (ii) a synoptic zonation of landslide hazard and risk in Italy, based on historical landslide information and small scale environmental data.

2. Rainfall thresholds

Determining the amount of precipitation that can result in landslides is a challenging task of scientific and societal interest (Guzzetti et al. 2007). The problem is complicated by the fact that the pattern and intensity of rainfall varies with time, driven by natural and human induced environmental variations and changes in climate. For rainfall-induced landslides, multiple investigators have attempted to establish thresholds for the possible initiation of failures. Thresholds may define the rainfall, soil moisture, or hydrological conditions that, when reached or exceeded, are likely to trigger landslides (Reichenbach et al. 1998a; Guzzetti et al. 2007).

Review of the literature reveals that rainfall thresholds for the possible initiation of landslides can be physically-based or empirical (Crosta and Frattini 2001; Aleotti 2004; Wieczorek and Glade 2005; Guzzetti et al. 2007, 2008). Physically-based thresholds are models linking – through infiltration – rainfall pattern and history to slope stability/instability conditions. Empirical thresholds are obtained statistically, studying past rainfall events that have or have not resulted in landslides. Empirical thresholds can be classified based on (Guzzetti et al. 2007): (i) the extent of the geographical area for which they were defined, and (ii) the type of rainfall measurement used to establish the thresholds. Based on their geographical extent, rainfall thresholds can be loosely subdivided as global, regional, or local. The rainfall measurements most commonly used to determine the empirical thresholds include rainfall duration (D), rainfall intensity (I), and the total event rainfall (Guzzetti et al. 2007).

Guzzetti et al. (2007, 2008) have compiled a world-wide catalogue of empirical rainfall thresholds for the possible initiation of landslides. The catalogue lists more than 190 thresholds, of different types, including intensity-duration (ID) thresholds (http://rainfallthresholds.irpi.cnr.it). Fig. 1 portrays 25 rainfall ID thresholds for the possible initiation of landslides proposed for Italy, or for selected areas in Italy. These empirical thresholds can be used to forecast the possible occurrence of landslides, based on rainfall measurements, estimates, and quantitative forecasts.

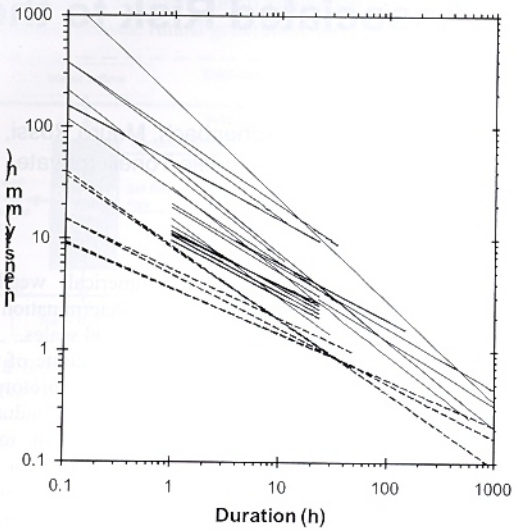

Fig. 1 Twenty-five rainfall intensity-duration (ID) thresholds for the possible initiation of landslides in Italy. Dashed lines show global thresholds applicable to the Mediterranean and the Mountain climates. Modified after Guzzetti et al. (2007; 2008)

To design and implement the prototype system for the quasi-real-time forecasting of rainfall induced landslides in Italy, existing empirical thresholds will be validated (Fig. 1), and new thresholds will be defined. The new rainfall thresholds, chiefly of the intensity-duration (ID) and normalized-ID types (Guzzetti et al. 2007, 2008), will be established using innovative and objective statistical techniques, an historical catalogue of rainfall events that have or have not resulted in landslides, and detailed records of rainfall measurements. When established, the prototype system will exploit: (i) rainfall measurements obtained from a dense and homogeneous network of rain gauges comprising more than 1500 measuring stations, (ii) quantitative rainfall estimates obtained from a network of ground-based weather radars installed or networked by the DPC, and (iii) quantitative rainfall estimates obtained from meteorological satellites and advanced numerical weather forecasts.

3. Landslide hazards and risk in Italy

Risk analysis aims to determine the probability that a specific hazard (e.g., a landslide) will cause harm, and it investigates the relationships between the frequency of the damaging events and the intensity of their consequences. Determining landslide risk for an entire nation is a difficult task, chiefly because of the complexity and variability of the landslide phenomena, and the lack of relevant and accurate, spatially distributed, thematic and environmental data. In Italy, information exists on historical damaging landslide events (Guzzetti et al. 1994; Cardinali et al. 1998; Reichenbach et al. 1998b; Guzzetti and Tonelli 2004), and on historical landslide events with human consequences (Guzzetti 2000; Salvati et al. 2003; Guzzetti et al. 2005b,c). This information, and small-scale thematic and environmental data, can be used to attempt the determination of landslide hazards and risk at the national (synoptic) scale.

The map shown in Fig. 2 portrays the geographical distribution of 749 municipalities in Italy that have experienced fatal landslides in the 108-year period from 1900 to 2007. The number of fatalities (deaths and missing persons) and the number of casualties (fatalities and injured people) caused by landslides are a measure of the intensity of a disaster, and can be used to evaluate landslide risk to the population. For Italy, levels of individual and societal landslide risk were established e.g., by Guzzetti (2000) and Salvati et al. (2003), and revised by Guzzetti et al. (2005a,b).

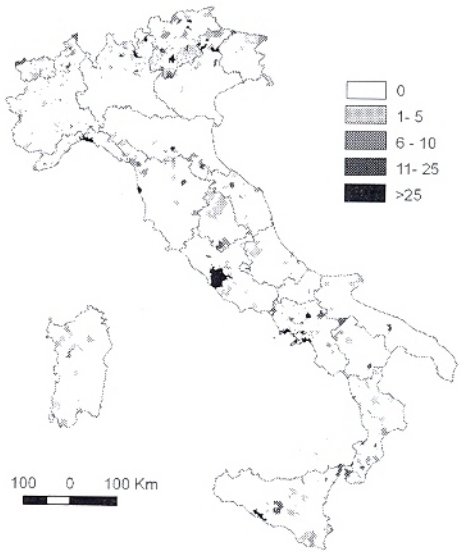

Fig. 2 The map portrays the geographical distribution of 749 municipalities in Italy that experienced fatal landslides in the 108-year period from 1900 to 2007. Shades of gray show different numbers of casualties, including deaths, missing persons, and injured people

To establish the prototype system for the forecasting of rainfall induced landslides in Italy, the existing catalogues of historical damaging landslide events and historical landslide events with human consequences were exploited to determine landslide hazard and risk. For this purpose, a simplified version of a probabilistic model proposed to determine landslide hazard at the catchment scale was adopted (Guzzetti et al. 2005a, 2006). The simplified model ascertains hazard/risk as the joint probability: (i) of the spatial (geographical) probability of landslide events (i.e., "where" landslides are expected), and (ii) of the temporal probability of landslide occurrence (i.e., "when" or "how frequently" landslides are expected). Two separate models were prepared. The first model forecasts the occurrence of all damaging landslide events (landslide hazard model), and the second model predicts landslide events that may result in casualties (landslide risk to the population model). To determine hazard and risk, the municipality (an administrative and political subdivision) was selected as the mapping unit of reference.

To prepare the hazard/risk models, two lists of damaging landslide events and of landslide events with human consequences in Italy were prepared. The two lists were extracted from the existing historical catalogues to cover the 52-year period from 1950 to 2001. For modeling purposes, the individual lists were further split in two sub-sets: (i) a

model training set covering the 41-year period from 1950 to 1990, and (ii) a model validation set covering the 11-year period between 1991 and 2001.

To obtain a quantitative estimate for the temporal probability of landslide occurrence (i.e., "when" or "how frequently" landslide events are expected), the average recurrence of landslide events in each municipality was determined. This was obtained dividing the total number of damaging landslide events (or the total number of landslide events with casualties) in each municipality by the time span of the investigated period (41 year period from 1950 to 1990). Next, the recurrence time of damaging landslide events (or of landslide events with casualties) was assumed constant, and a Poisson probability model was adopted to describe the temporal distribution of the events. Finally, the exceedance probability of having one or more damaging landslide event (or one or more landslide event with casualties) in each municipality was computed for different periods, from 1 to 20 years.

The spatial probability of damaging landslide events and of landslide events with human consequences (i.e., "where" landslide events are expected) was obtained through multivariate analysis of synoptic thematic and environmental information (explanatory variables), including lithological, soil, and climate data, and a set of morphometric variables obtained from a 90 m × 90 m digital elevation model. As the dependent variable, the presence or absence of damaging landslide events (or of landslide events that have resulted in casualties) in each municipality was used. For this purpose, the landslide modeling sets were used, i.e., the lists of damaging landslide events and of landslide events with human consequences in the period from 1950 to 1990. The map shown in Fig. 3 portrays the modeled spatial probability of damaging landslides.

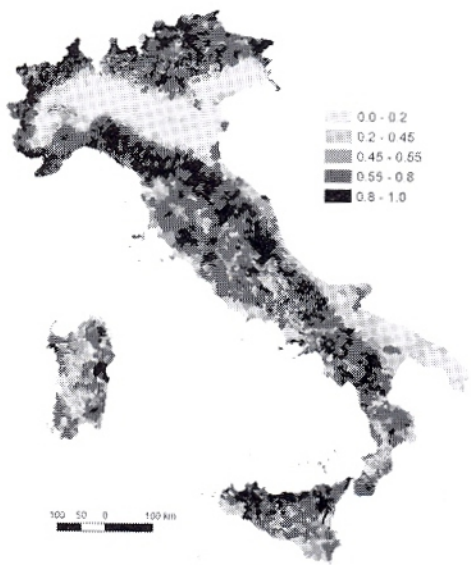

Fig. 3 The map shows spatial probability of landslide occurrence (landslide susceptibility) prepared for damaging landslides, obtained through discriminant analysis. Shades of gray indicate classes of landslide susceptibility

The temporal and spatial prediction models were tested to evaluate the degree of model fit and the model prediction skills. First, the degree of model fit was ascertained preparing contingency tables, four-fold plots, and ROC curves. Next, the model prediction skills were determined using independent landslide information not used to construct the models, i.e., the landslide validation sets covering the 11-year period between 1991 and 2001. In the prototype system for the forecasting of rainfall induced landslides in Italy, the temporal and spatial models will be used both separately and in combined form.

Conclusions

The Italian Department of Civil Protection (DPC) and IRPI, a research institute of the Italian National Research Council, are designing a prototype system for the near-real-time forecasting of rainfall induced landslides in Italy. The system exploits existing and new rainfall thresholds for the possible occurrence of landslides, and synoptic landslide hazard and risk zonations. The zonations adopt the municipality, an administrative and political subdivision, as the mapping unit of reference, and were obtained through multivariate statistical modeling of historical landslide information, and small-scale thematic and environmental data. When operational, the system will be used by the DPC to issue daily national and regional warnings for the possible occurrence of rainfall induced landslides, based on precipitation measurements, estimates, and numerical weather forecasts. The system will contribute to mitigate – through prevention – the risk posed by rainfall induced landslides in Italy, with emphasis on the reduction of the risk to the population.

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