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LANDSLIDE HAZARD ASSESSMENT, VULNERABILITY ESTIMATION AND RISK EVALUATION: AN EXAMPLE FROM THE COLLAZZONE AREA (CENTRAL UMBRIA, ITALY)

ABSTRACT: GUZZETTI F., REICHENBACH P., ARDIZZONE F., CARDINALI M. & GALLI M., *Landslide hazard assessment, vulnerability estimation and risk evaluation: an example from the Collazzone area (Central Umbria, Italy).* (IT ISSN 0391-9838, 2009).

For the Collazzone area, central Umbria, landslide hazard was ascertained, landslide vulnerability was determined, and landslide risk was evaluated, for different scenarios. To ascertain landslide hazard, a probabilistic model was adopted that predicts where landslides will occur, how frequently they will occur, and how large they will be in a given area. For the purpose, a multi-temporal landslide inventory map prepared through the interpretation of five sets of aerial photographs and field surveys covering the period from 1941 to 2004 was exploited. Using a 10 m × 10 m DEM, the study area was partitioned into 894 slope units, and the probability of spatial landslide occurrence was obtained through discriminant analysis of thematic and environmental variables. For each slope unit, the probability of experiencing one or more landslides in different periods was determined adopting a Poisson probability model for the temporal occurrence of landslides. The probability of landslide size was obtained by analyzing the frequency-area statistics of landslides. Assuming independence, landslide hazard was ascertained as the joint probability of landslide size, of landslide temporal occurrence, and of landslide spatial occurrence. For the Umbria region, landslide vulnerability curves exist. The curves were established exploiting information on landslide damage to buildings and roads caused by individual landslides of the slide type. Assuming independence of hazard and vulnerability, and exploiting (i) the multi-temporal landslide inventory map, (ii) the obtained landslide hazard assessment, and (iii) the available landslide vulnerability curves, landslide risk to the road network was evaluated, for different scenarios. Results indicate that landslide risk can be determined quantitatively over large areas, provided adequate forecasting models are adopted and reliable landslide and thematic information is available.

KEY WORDS: Landslides, Hazard, Vulnerability, Risk, Umbria (Italy).

ABSTRACT: GUZZETTI F., REICHENBACH P., ARDIZZONE F., CARDINALI M. & GALLI M., *Valutazione della pericolosità, stima della vulnerabilità e analisi del rischio da frana: l'esempio dell'area di Collazzone, in Umbria centrale.* (IT ISSN 0391-9838, 2009).

Per l'area di Collazzone, in Umbria centrale, abbiamo valutato, per i diversi scenari, la pericolosità, la vulnerabilità ed il rischio da frana. Per determinare la pericolosità da frana, è stato utilizzato un modello probabilistico, che prevede la stima della probabilità temporale, della probabilità dimensionale, e della probabilità spaziale di occorrenza delle frane. A tale scopo, attraverso l'interpretazione di cinque voli di fotografie aeree associata a sopralluoghi di campagna, è stata preparata una carta inventario multi-temporale che copre il periodo 1941-2004. Utilizzando un modello digitale del terreno (DEM con una cella 10 m × 10 m), l'area di studio è stata suddivisa in 894 unità di versante (slope units), e per ogni unità di versante è stata calcolata la probabilità di occorrenza spaziale delle frane mediante l'analisi discriminante di variabili tematiche e territoriali. Per ogni unità di versante, adottando un modello di probabilità di Poisson, è stata determinata la probabilità temporale di occorrenza delle frane per diversi periodi di ritorno. Infine la probabilità dimensionale delle frane è stata ottenuta dall'analisi della distribuzione di frequenza delle aree in frana. Assumendo indipendenza tra le tre probabilità, è stata stimata la pericolosità da frana, come probabilità congiunta della probabilità dimensionale, temporale e spaziale.

Per la regione dell'Umbria sono disponibili curve di vulnerabilità da frana. Le curve sono state calcolate utilizzando informazioni relative ai danni ad edifici e strade causate da frane di tipo scorrimento. Assumendo indipendenza tra la pericolosità e la vulnerabilità, e utilizzando (i) la carta inventario multi-temporale delle frane, (ii) la zonazione della pericolosità da frana, e (iii) le curve di vulnerabilità da frana, è stato stimato il rischio da frana per la rete stradale. I risultati dimostrano che il rischio da frana può essere definito quantitativamente per grandi aree, a condizione che vengano utilizzati adeguati modelli di previsione e siano disponibili dati tematici e informazioni sulla distribuzione delle frane.

TERMINI CHIAVE: Movimenti franosi, Pericolosità, Vulnerabilità, Rischio, Umbria.

INTRODUCTION

The ultimate goal of many landslide studies is the determination of the risk posed by existing or future slope

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While we mourn his premature departure, we dedicate this work to our dear friend Mirco. We are grateful to Kang-tsung Chang and to a second anonymous referee for their comments.

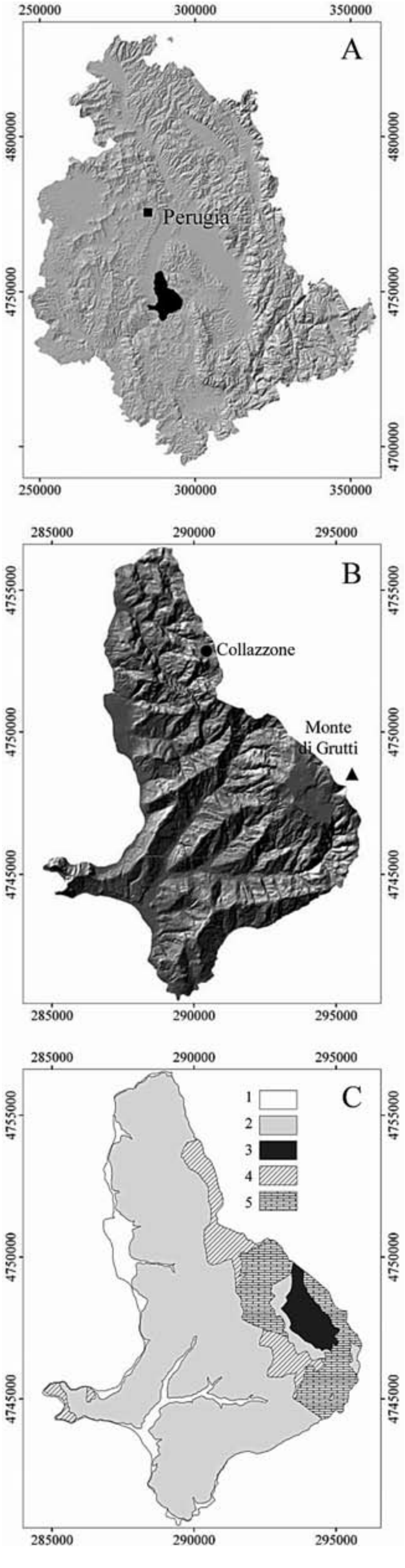

FIG. 1 - (A) Shaded relief image showing the Umbria region (central Italy) where the study area is located. (B) Shaded relief image showing morphology in the Collazzone area. (C) Lithological map for the Collazzone area: (1) alluvial deposit, (2) continental deposit, (3) travertine, (4) layered sandstone and marl, (5) thinly layered limestone.

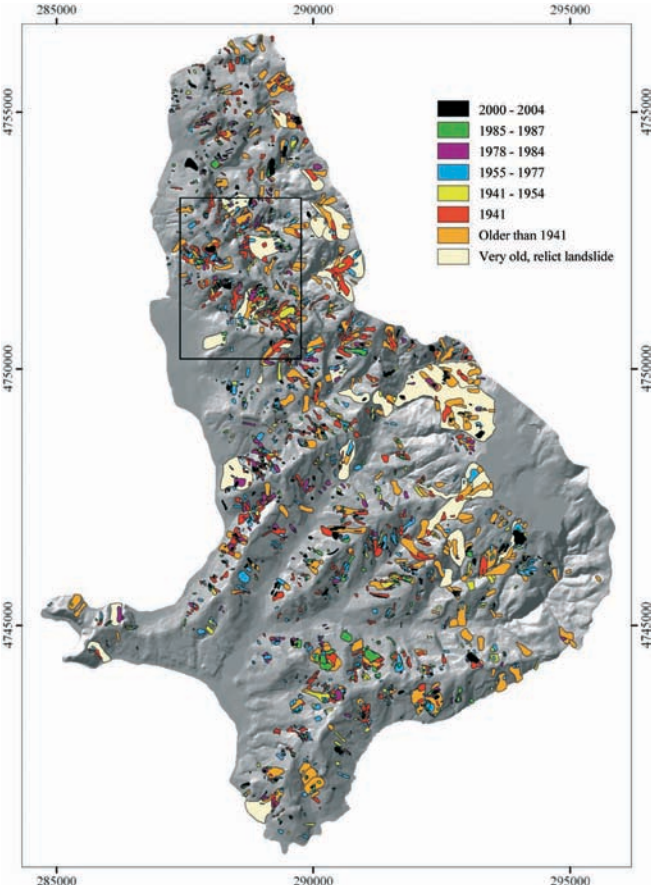

FIG. 2 - Multi-temporal landslide inventory map for the Collazzone area. Colors show landslides of different dates or periods, determined from the dates of five sets of aerial photographs and field surveys. Rectangle shows location of figure 9.

failures. To achieve this goal, information on landslide hazard and vulnerability to landslides is required (Varnes & IAEG Commission on Landslides and other Mass-Movements, 1984). Several different techniques have been proposed to evaluate landslide hazard, and the literature on the topic is extensive (for general concepts and reviews see, e.g., Aleotti & Chowdhury, 1999; Carrara & *alii*, 1995; Chung & Fabbri, 1999; Glade & Crozier, 2005; Fuchs & *alii*, 2007; Guzzetti & *alii*, 2005a, 2006b; Papathoma-Köhle & *alii*, 2007; Vandine & *alii*, 2004; van Westen & *alii*, 1997). Assessment of landslide hazard involves determining «where» landslides are expected (i.e. landslide susceptibility), «when» or how frequently they will occur, and how large or destructive the slope failures will be, i.e. the «magnitude» of the expected landslides (Guzzetti & *alii*, 1999).

Studies of the vulnerability to landslides, including methods to determine vulnerability and examples of damage assessments, are less abundant (Alexander 1999, 2000, 2005; Cascini & *alii*, 2005; Copons & *alii*, 2005; Düzgün & Lacasse, 2005; Fell & Hartford, 1997; Fell & *alii*, 2005; Lee & Jones, 2004; Leone & *alii*, 1996; Glade, 2004; Glade & Crozier, 2005; Msilimba & Holmes, 2005; Reichenbach & *alii*, 2005; Roberds, 2005; Wen & *alii*, 2005; Wong, 2005). Investigators do not agree on methods and scales for determining landslide damage, and accepted standards for measuring landslide vulnerability are lacking. This is particularly the case where vulnerability has to be determined over large areas (Reichenbach & *alii*, 2005). Lack of established methods to assess the damage and of reliable information on vulnerability hampers our ability to properly determine landslide risk (Galli & Guzzetti, 2007).

For the Collazzone area, central Umbria, a probabilistic landslide hazard model was prepared combining the probability of landslide size, the probability of landslide occurrence in an established period, and the probability of landslide spatial occurrence. For the same area, the spatial distribution of the vulnerability to landslides was mapped. Exploiting the hazard assessment and the vulnerability information, landslide risk to roads in the area was ascertained. Results indicate that landslide risk can be determined over large areas, provided adequate forecasting models are adopted and reliable landslide and thematic information is available.

STUDY AREA

Settings

The Collazzone area extends for about 79 km^2 in central Umbria, Italy (fig. 1). Elevation in the area ranges from 145 m to 634 m above sea level, with an average value of 273 m. Terrain gradient ranges from 0° to more than 60°, with a mean value of about 10°. In the area the terrain is hilly, valleys are asymmetrical, and the lithology and attitude of bedding control the morphology of the slopes. In the area crop out sedimentary rocks, including recent fluvial deposits, continental gravel, sand and clay, Plio-Pleistocene in age, travertine deposits, Pleistocene in age, layered sandstone and marl in various percentages, Miocene in age, and thinly layered limestone, Lias to Oligocene in age. Soils range in thickness from a few decimeters to more than one meter; they have a fine or medium texture and exhibit a xenic moisture regime, typical of the Mediterranean climate. Precipitation is most abundant in October and November with a mean annual rainfall in the period from 1921 to 2001 of 884 mm. Snow falls on the area on average every 2-3 years. Landslides are abundant in the area, and range in age, type, morphology and volume from very old, partly eroded, large and deep-seated slides to young shallow slides. Slope failures are triggered chiefly by meteorological events, including intense and prolonged rainfalls and rapid snow melting (Guzzetti & *alii*, 2006a).

Landslide inventory map

A multi-temporal landslide inventory map for the study area (fig. 2) was prepared through the interpretation of five sets of aerial photographs covering unsystematically the period from 1941 to 1997, and ranging in scale from 1:13,000 to 1:33,000 (Guzzetti & *alii*, 2006a). The map was updated through field surveys carried out in the period from 1998 to 2004. In the multi-temporal map, landslides were classified according to the type of movement, and the estimated age, activity, depth, and velocity. Landslide type was defined according to Cruden & Varnes (1996). Landslide age, activity, depth, and velocity were determined based on the type of movement, the morphological characteristics and appearance of the landslides on the aerial photographs or in the field, the local lithological and structural setting, and the date of the aerial photographs or the field surveys.

Thematic information

For the study area, a 10 m x 10 m digital elevation model (DEM) was prepared by interpolating 5 m and 10 m contour lines shown on 1:10,000 scale topographic maps. The DEM was used to partition the study area into 894 slope units, using specialized software (Carrara & *alii*, 1991) that also computed 26 morphological and hydrological variables. Hydrological variables included slope unit drainage channel length, gradient, order and magnitude, and slope unit area and upstream contributing area. Morphological variables included slope unit mean elevation, standard deviation of elevation, mean length, mean terrain gradient and standard deviation of terrain gradient, slope unit aspect, slope unit terrain roughness, and mean terrain gradient for the upper, intermediate and lower portions of the slope unit. From the latter three statistics, derivative variables describing the shape of the slope unit profile (concave, convex, irregular, etc.) were obtained.

A geological map for the study area was prepared at 1:10,000 scale through field surveys aided by the interpretation of aerial photographs (Guzzetti & *alii*, 2006a). The map shows lithological and structural data, including the attitude of bedding. Information on land use, at 1:10,000 scale, was obtained from a map compiled in 1977 by the Umbria Regional Government, revised and updated by interpreting the most recent aerial photographs.

METHODS

Landslide hazard

Varnes and the IAEG Commission on Landslides and other Mass-Movements (1984) proposed landslide hazard to be «the probability of occurrence within a specified period of time and within a given area of a potentially damaging phenomenon». Guzzetti & *alii* (1999) amended the definition to include the magnitude of the event, i.e. the area, volume, velocity or momentum of the expected landslide. The later definition incorporates the concepts of location, time and magnitude. To fulfil this definition, one has to predict (quantitatively) where a landslide will occur, when or how frequently it will occur, and how large, fast or destructive the landslide will be.

Many methods have been proposed to evaluate landslide hazard spatially (Chung & Fabbri, 1999; Guzzetti & *alii*, 1999; Carrara & *alii*, 1995). Two approaches are the most promising, namely: (i) methods based on the statistical analysis of geo-environmental factors related to the occurrence of landslides, and (ii) deterministic modelling based on mechanical laws that control slope instability. Multivariate statistical models provide the best results for large areas and where the relationships between determining factors and landslide occurrence are complex. These models provide a quantitative, objective and reproducible way of ascertaining the spatial pattern of landslides.

Recently, attempts have been made to prepare landslide hazard assessments that fully comply with the definition of hazard adopted by Guzzetti & *alii* (1999). At the basin scale, the attempts are based on (i) the assessment of the spatial hazard (susceptibility) through the multivariate analysis of a set of thematic variables, including morphology, lithology and land use (Chung & Fabbri, 1999; Guzzetti & *alii*, 1999, 2005a, 2006b), (ii) the assessment of the exceedance probability of having one or more landslides for different return periods, based on the observed mean recurrence of landslides obtained by interpreting multiple sets of aerial photographs (Crovelli, 2000; Coe & *alii*, 2000; Guzzetti & *alii*, 2003, 2005a); and (iii) the determination of the probability of experiencing landslides of any given size, through the analysis of the frequency-area statistics of landslides (Guzzetti & *alii*, 2002; Malamud & *alii*, 2004). In mathematical terms, the adopted definition of landslide hazard can be written:

$$H_L = P\,[A_L \geq a_L \textit{ in a time interval } t\textit{, given } \{\textit{morphology, lithology, structure, land use, …}\}] \qquad (1)$$

where, A_L is the area of a landslide greater or equal than a minimum size, a_L, measured e.g., in square meters. For any given area, proposition (1) can be written as (Guzzetti & *alii*, 2005a):

$$H_L = P(A_L) \times P(N_L) \times P(S) \qquad (2)$$

that expresses landslide hazard H_L as the conditional probability of landslide size $P(A_L)$, of landslide occurrence in an established period $P(N_L)$, and of landslide spatial occurrence $P(S)$, given the local environmental setting.

Equation (2) assumes independence of the three individual probabilities i.e., of the three components of landslide hazard. From a geomorphologic point of view, this assumption is severe and may not hold, always and everywhere (Guzzetti & *alii*, 2005a). In many areas one expects slope failures to be more frequent (time component) where landslides are more abundant and landslide area is large (spatial component). However, given the lack of understanding of the landslide phenomena, independence is an acceptable approximation that makes the problem mathematically tractable and easier to work with.

Landslide vulnerability

Vulnerability is the potential to experience an adverse impact (Alexander, 1999), a measure of the damage suffered by an element at risk when affected by a hazardous process or event (Blaikie & *alii*, 1994; Dooge, 2004; Wisner & *alii*, 2005). Elements at risk comprise the population, properties, economic activities, and public services (Alexander, 2005). According to Varnes and the IAEG Commission on Landslides and other Mass-Movements (1984), landslide vulnerability is the degree of loss to a given element, or a set of elements, at risk resulting from the occurrence of a landslide of a given magnitude in an area. This can be expressed as (Einstein, 1998)

$$W_L = P[D_L \geq 0 | L] \; (0 \leq D_L \leq 1) \qquad (3)$$

where W_L is landslide vulnerability, and D_L is the assessed (definite) or the expected (forecasted) damage to an element given the occurrence of a hazardous landslide (L). In equation (3), vulnerability is the probability of total loss to a specific element, or the proportion of damage to an element, given the occurrence of a landslide (Vandine & *alii*, 2004). In both cases, vulnerability is expressed on a scale from 0 to 1, 0 meaning no damage and 1 expressing complete loss or destruction.

Landslide risk

Risk analysis aims to determine the probability that a specific hazard will cause harm, and it investigates the relationships between the frequency of damaging events and the intensity of the consequences. It seeks to establish thresholds for individual risk (i.e., the risk imposed by a hazard to an individual), and for societal risk (i.e., the risk imposed by a hazard on society). According to Varnes and the IAEG Commission on landslides and other mass-movements (1984), landslide risk evaluation aims to determine the «expected degree of loss due to a landslide (specific risk) and the expected number of live lost, people injured, damage to property and disruption of economic activity (total risk)». Specific landslide risk, R_S, is commonly expressed by the product of landslide hazard, H_L, and landslide vulnerability, W_L, or:

$$R_S = H_L \times W_L \qquad (4)$$

In equation (4), landslide hazard, H_L, and landslide vulnerability, W_L, are probabilities.

Quantitative (probabilistic) and qualitative (heuristic) approaches are possible to determine landslide risk. Quantitative landslide risk assessment aims to establish the probability of occurrence of a catastrophic event, the probability of live losses (Fell & Hartford, 1997; Evans, 1997; Guzzetti, 2000; Kong, 2002; Guzzetti & *alii*, 2005b), or the expected damage due to a slope failure (Bunce & *alii*, 1997; Budetta, 2002; Guzzetti & *alii*, 2004). Establishing the probability of a loss requires a catalogue of landslides and their consequences. A few of such lists have been prepared for damage to the population i.e., deaths, missing persons, injuries, homeless and evacuees (Evans, 1997; Guzzetti, 2000; Kong, 2002; Guzzetti & *alii*, 2005b; Salvati & *alii*, 2003).

LANDSLIDE HAZARD ASSESSMENT

To determine landslide hazard in the Collazzone area, the probabilistic model proposed by Guzzetti & *alii* (2005a) and presented before was used. The model predicts where landslides will occur, how frequently they will occur, and how large they will be in a given area. Figure 3 summarises the data, models, and products used to ascertain landslide hazard.

First, the probability of landslide area, considered a proxy for landslide magnitude, was determined. To determine the probability of landslide size, the truncated inverse Gamma probability distribution of Malamud & *alii* (2004) was applied to 2760 landslides shown in the multi-temporal inventory in the period from 1941 to 2004. Figure 4 shows the obtained result, which can be used to predict the probability that an individual landslide in the Collazzone area exceeds a given size.

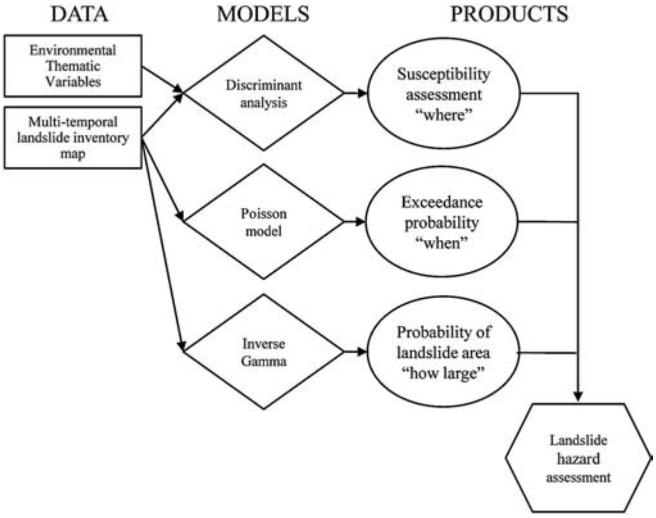

FIG. 3 - Block diagram exemplifying the work flow adopted to determine landslide hazard. Rectangles indicate input data. Diamonds indicate individual models, for the landslide susceptibility, for the temporal probability of landslides, and for the landslide size. Ellipses indicate intermediate results. Hexagon indicates final result (after Guzzetti & *alii*, 2005a).

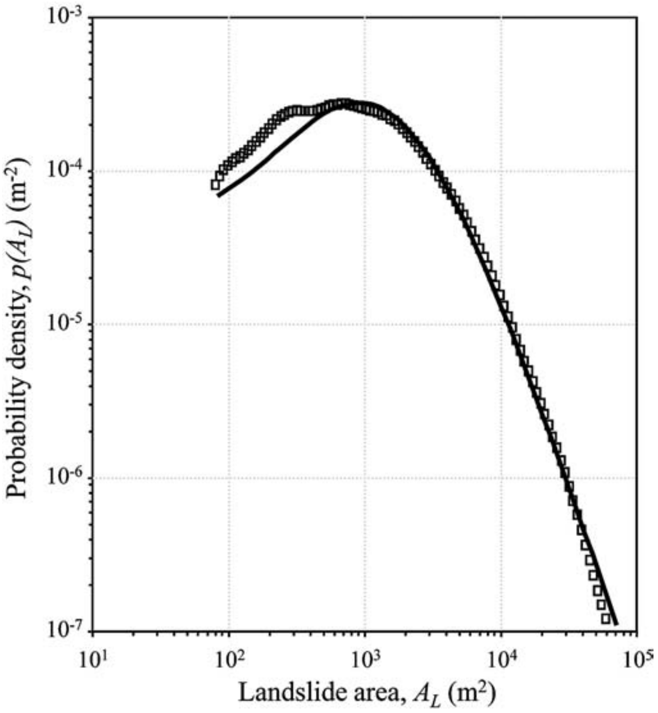

FIG. 4 - Probability density of landslide area for landslides in the period from 1941 to 2004, in the Collazzone area. Squares show empirical data, black line shows inverse Gamma probability distribution of Malamud & *alii* (2004).

Next, the temporal probability of landslides was ascertained. To obtain this estimate, the number of landslides occurred in the 64-year period from 1941 to 2004 in each slope unit was counted, and the average rate of landslide occurrence in the slope units was calculated. Knowing the mean recurrence interval of landslides in each slope unit (from 1941 to 2004), assuming the rate of slope failures will remain the same for the future, and adopting a Poisson probability model (Crovelli, 2000; Coe & *alii*, 2000; Guzzetti & *alii*, 2005a), the probability of having one or more landslides in each slope unit was determined (fig. 5).

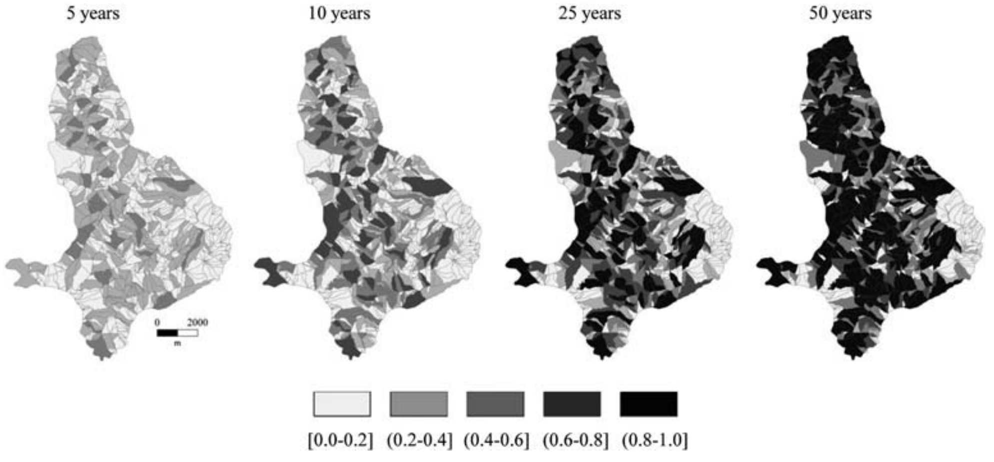

FIG. 5 - Exceedance probability of landslide temporal occurrence obtained adopting a Poisson probability model. Exceedance probability shown for four periods from 5 to 50 years. Square bracket indicates class limit is included, round bracket indicates class limit is not included.

Next, a probabilistic estimate of the spatial landslide occurrence (i.e., of landslide susceptibility) was ascertained. Landslide susceptibility was obtained through discriminant analysis of 46 thematic variables, including morphology, lithology, structure, land use, and the presence of large relict landslides. As the dependent variable for the multivariate analysis, the presence or absence of landslides in the 894 slope units was selected. Results of the susceptibility assessment are shown in figure 6. The obtained susceptibility zonation correctly classifies 83.0% of the slope units. The model performs better in classifying unstable areas (i.e., slope units that contain known landslides, 89.8%), and is poorer in the classification of stable areas (i.e., slope units that are free of recognized landslides, 67.6%).

Assuming independence of the three computed probabilities, the probability of landslide size, the probability of landslide temporal occurrence, and the probability of spatial occurrence, were multiplied to obtain landslide hazard i.e., the joint probability that a slope unit will be affected by future landslides that exceed a given size, in a given time. Figure 7 shows examples of the landslide hazard assessment prepared for the Collazzone area. The figure portrays landslide hazard for four different periods (i.e., 5, 10, 25 and 50 years), and for landslides of two size classes, greater or equal than 1000 m^2 and greater or equal than 10,000 m^2.

Model validation

The individual components of the probability model were evaluated independently, exploiting landslide infor-

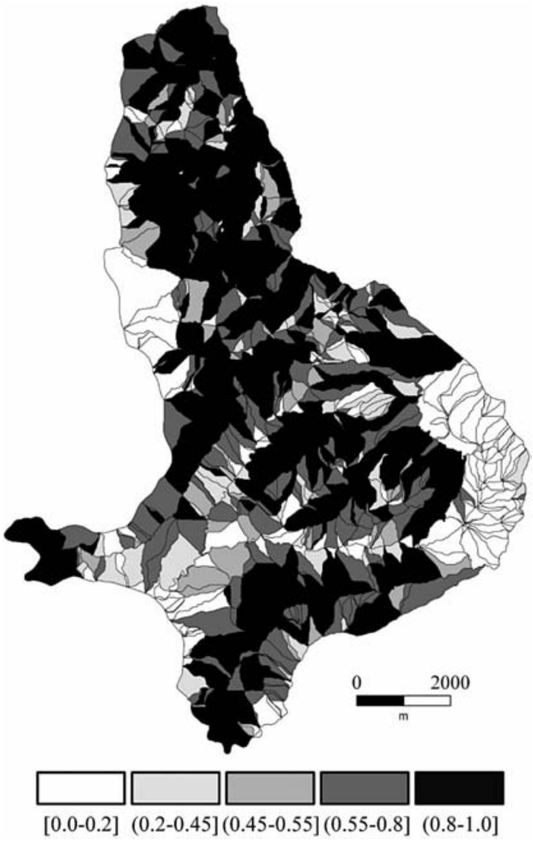

FIG. 6 - Map showing spatial probability of landslide occurrence (landslide susceptibility) in five classes, obtained through discriminant analysis of 46 thematic variables. Square bracket indicates class limit is included, round bracket indicates class limit is not included.

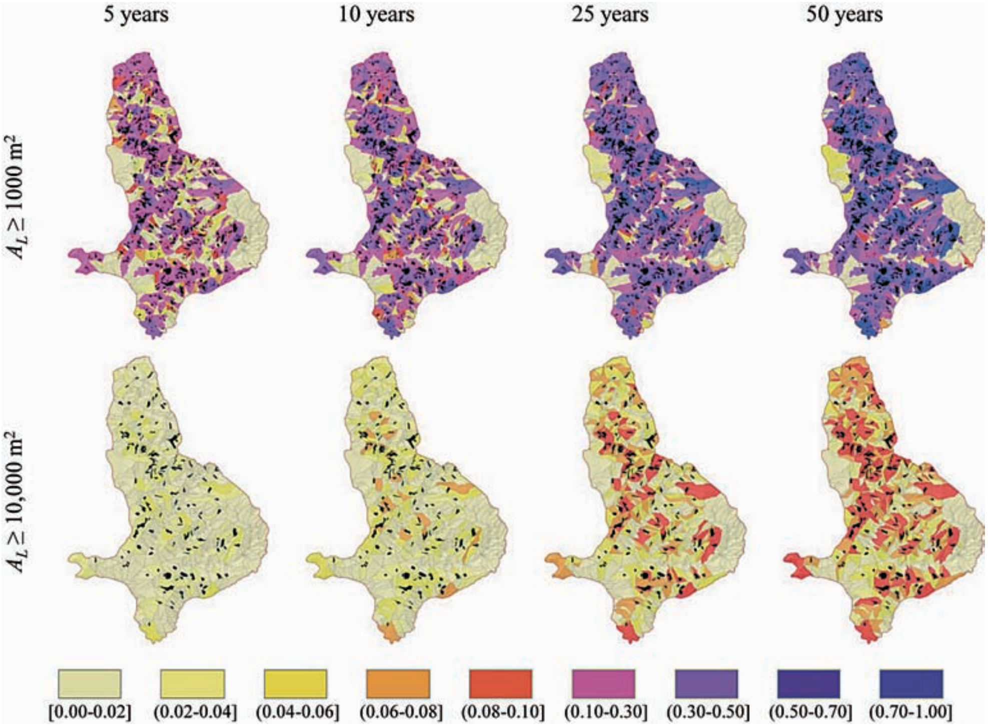

FIG. 7 - Landslide hazard scenarios for four periods, from 5 to 50 years, and for two classes of landslide size, $A_L \geq 1000$ m^2 and $A_L \geq 10,000$ m^2. Colours show different joint probabilities of landslide size, of landslide temporal occurrence, and of landslide spatial occurrence.

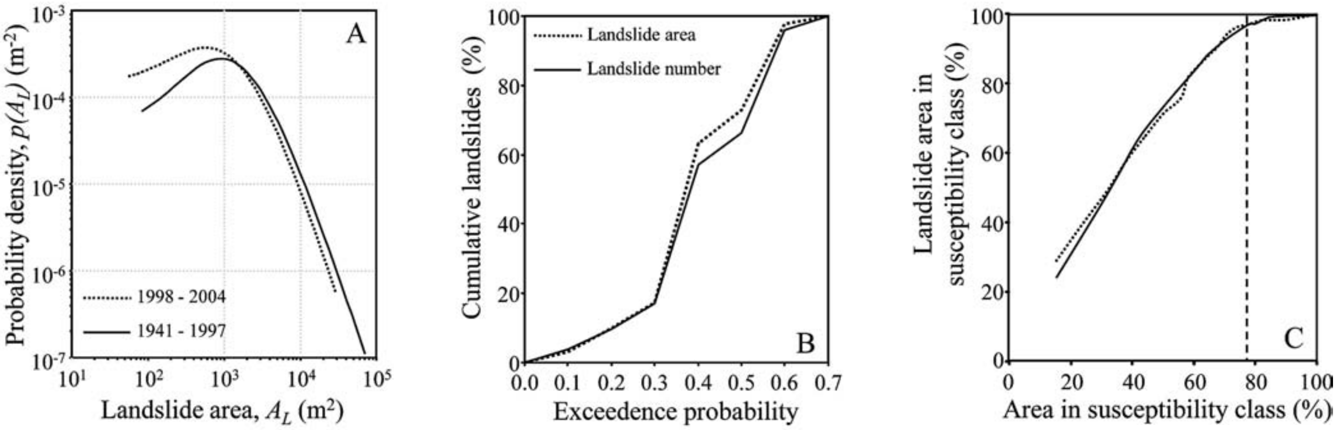

FIG. 8 - Model validation. (A) Comparison between the probability density of landslide area for the modeling set (1941 to 1997) and the validation set (1998 to 2004). (B) Estimate of the temporal forecast prediction skill. x-axis shows classes of the temporal probability obtained considering the modeling set, y-axis shows cumulative percentage of landslide area (dotted line) and landslide number (black line) in the validation set. (C) Comparison of the susceptibility model fit and prediction performance. x-axis shows the percentage of study area in each susceptibility class, ranked from most (left) to least (right) susceptible, and y-axis shows the percentage of landslide area in each susceptibility class. Black line measures the degree of model fit and dotted line measures the prediction skill of the susceptibility models. Vertical dashed line shows 0.5 probability threshold, separating unstable ($P(S) \leq 0.5$) and stable ($P(S) > 0.5$) slope units.

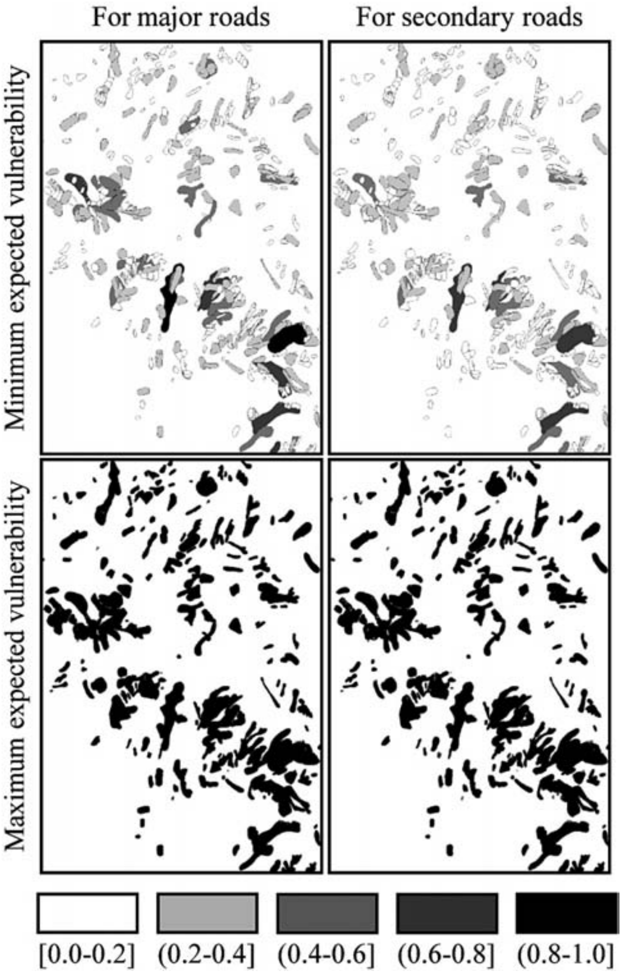

FIG. 9 - Minimum and maximum expected vulnerability to landslides in five classes for a portion of the Collazzone area (see figure 2 for location). Square bracket indicates class limit is included, round bracket indicates class limit is not included.

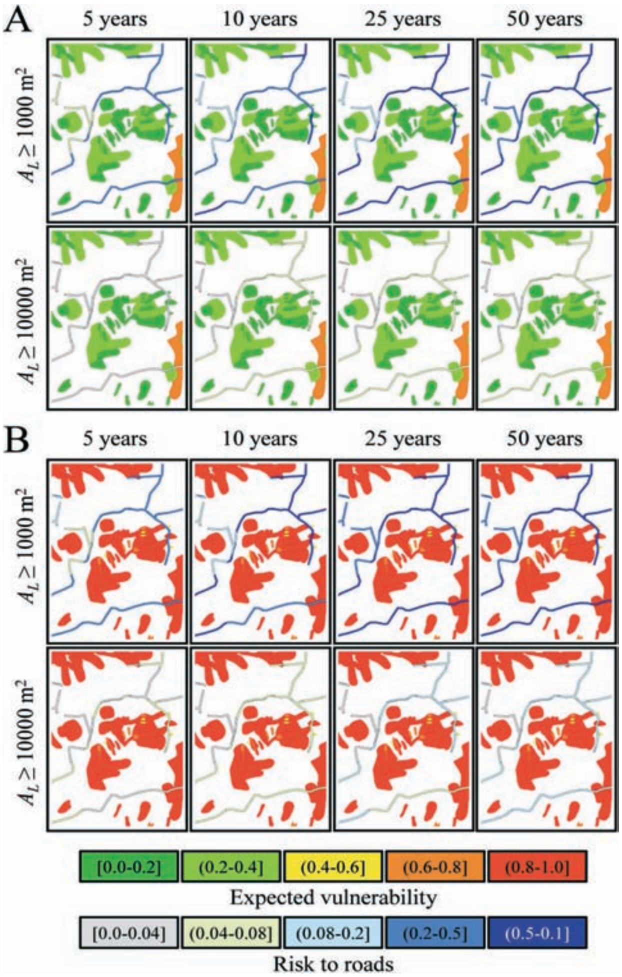

FIG. 10 - Scenarios for landslide risk to roads for four periods, from 5 to 50 years, and for two classes of landslide size, $A_L \geq 1000$ m^2 and $A_L \geq 10{,}000$ m^2. Maps prepared assuming the minimum (A) and the maximum (B) expected vulnerabilities.

mation not used to construct the model (Chung & Fabbri, 2003; Guzzetti & *alii*, 2006b). For the purpose, the multi-temporal inventory covering the period from 1941 to 2004 was split in two sub-sets: (i) the 2250 landslides (90.4%) in the 57-year period from 1941 to 1997 (modeling set), and (ii) the 240 landslides (9.6%) in the 7-year period from 1998 to 2004 (validation set).

To validate the forecast of landslide size, the probability density of landslide area for the modeling and the validation sets were obtained (fig. 8A). Visual inspection of figure 8A reveals a reasonably good agreement between the two probability curves. We take this as indication of the ability of the forecast model to predict the size of future landslides.

To evaluate the temporal forecast, the modeling set was used to establish the exceedance probability of landslide occurrence in the 7-year validation period (from 1998 to 2004). The forecast was then compared with the location of landslides occurred during the validation period (fig. 8B). In the 7-year validation period, the largest expected probability of landslide occurrence is 0.7, indicating that nowhere in the study area landslides were expected to be «certain». Most of the mapped landslides (~ 79%) and most of the mapped landslide area (~ 81%) occurred in slope units with an expected probability of experiencing landslides ranging between 0.3 and 0.6. This is a reasonable result, given (i) the difficulty of the task, (ii) the comparatively limited number of landslides occurred in the short validation period, (iii) the simplicity of the adopted Poisson model, and (iv) the temporal variability of landslide phenomena.

To validate the spatial landslide prediction, the total area of landslides occurred during the validation period in each slope unit was calculated, and compared with a susceptibility zoning obtained through discriminant analysis on the modeling set. Figure 8C shows on the x-axis the percentage of the study area in each susceptibility class, ranked from most (left) to least (right) susceptible, and on the y-axis the percentage of landslide area (validation set) in each susceptibility class. In the graph, the filled squares show the proportion of landslides used to construct the susceptibility model, and the open squares show the proportion of recent landslides i.e., the slope failures that occurred after the date of the landslides used to construct the model. The dotted line shows the 0.5 probability threshold i.e., the limit between slope units classified as unstable ($P(S) \leq 0.5$) or stable ($P(S) > 0.5$) by the discriminant model. The graph shows that the forecast obtained using landslides of the modeling set was capable of correctly predicting 92.9% of the landslides shown in the validations set. The graph is a quantitative measure of the model forecasting skills (Guzzetti & *alii*, 2006b)

VULNERABILITY EVALUATION AND RISK ESTIMATION

Information on the damage caused by individual landslides in Umbria was recently used to establish dependencies between the area of the landslide and the amount of damage caused by the slope failure to built-up areas and roads (Galli & Guzzetti, 2007). The attempt was based on the empirical observation that, in Umbria, the proportion of direct damage caused to buildings and roads by slides and slide-earth flows depends on the area of the damaging landslide. As a first approximation, the direct damage caused by a slope failure increases with the area of the hazardous landslide. However, the proportion of the damage does not scale linearly with the area, complicating the assessment of landslide vulnerability. The minimum and maximum vulnerability curves established for roads in Umbria (Galli & Guzzetti, 2007) were used to map the expected vulnerability of the road network to landslides in the Collazzone area (fig. 9).

Analysis of the vulnerability maps (fig. 9) allowed quantitative information to be obtained for the evaluation of the expected landslide risk to the road network in the study area. In a geographical information system, the size of individual landslides in each slope unit was computed, and an empirical relationship to link the area of the slope unit and the size of the landslides was established. Using this relationship, together with the available vulnerability curves (Galli & Guzzetti, 2007), the minimum and the maximum expected vulnerability to landslides in each slope unit were established and mapped. In most of the slope units the maximum expected vulnerability is very large (close to 1). This was expected, given the size of the landslides in the study area.

By combining the probability of landslide hazard and the probability of expected damage to roads (i.e., the minimum and the maximum vulnerability to landslides), specific landslide risk for the road network was ascertained. This involved preparing multiple scenarios. Figure 10 portrays landslide risk for four periods (i.e., 5, 10, 25 and 50 years), and for landslides of two classes of landslide size (greater or equal than 1000 m^2, and greater or equal than 10,000 m^2), assuming the minimum (fig. 10A) and the maximum (fig. 10B) expected vulnerabilities. Two legends are shown in figure 10. The upper legend shows vulnerability to landslides, in five classes; the lower legend shows landslide risk classes to roads, in five classes. The minimum and the maximum expected vulnerabilities remain constant throughout the considered period since they dependent only on landslide size and the expected damage. Inspection of figure 10 reveals that risk to roads increases with time.

DISCUSSION AND CONCLUSIONS

For the Collazzone area, landslide hazard was ascertained, landslide vulnerability was estimated, and landslide risk was evaluated. Results of this exercise indicate that landslide risk can be determined quantitatively over large areas, provided a set of adequate forecasting models are adopted, and reliable landslide and thematic information is available.

The adopted models hold under assumptions that must be considered when using the hazard, vulnerability, and risk forecasts. For landslide hazard, assumptions include the following (Guzzetti & *alii*, 2005a): (i) landslides will occur in the future under the same circumstances and because of the same factors that produced them in the past, (ii) landslide events are independent (uncorrelated) random events in time, (iii) the mean recurrence of slope failures will remain the same in the future as it was observed in the past, (iv) the statistics of landslide area do not change in time, (v) landslide area is a reasonable proxy for landslide magnitude, and (vi) the probability of landslide size, the probability of landslide occurrence for established periods, and the spatial probability of slope failures, are independent. For landslide vulnerability, relevant assumptions are the following (Galli & Guzzetti, 2007): (i) no relationship exists between the amount of displacement, the type and extent of the damage, and the engineering characteristics of the affected elements, (ii) the time required for repairing the damage or to replace a lost (destroyed) road section, and the importance of the road to the population were considered heuristically, (iii) to rank damage to roads, indirect damage to the population and the economy was considered locally, (iv) only damage caused by landslides of the slide type, or prevalently of the slide type, were considered, and (v) the type and proportion of the damage caused by past landslides in Umbria was considered comparable to the expected damage caused by similar, future slope failures in the Collazzone area. Lastly, for the evaluation of landslide risk, the key assumption was made that landslide hazard and landslide vulnerability are independent (Alexander, 2000). Most of the listed assumptions were adopted in the attempt to simplify the problem, and make it mathematically and geomorphologically tractable. Determining the validity of the adopted assumptions proves difficult (Guzzetti *& alii*, 2005a). The relevance and legitimacy of the assumptions may vary in different areas, and should always be tested using independent (i.e., external) information and geomorphological inference.

We conclude by pointing out that the main scope of a landslide risk assessment is to provide probabilistic expertise on future slope failures to planners, decision makers, civil defense authorities, insurance companies, land developers, and individual landowners. The proposed method and the associated models allowed to prepare a large number of different maps, depending on the adopted susceptibility model, the established period, the minimum size of the expected landslide, the available vulnerability estimates, and the adopted risk scenarios. How to combine such a large number of forecasts efficiently, producing cartographic, digital, or thematic products useful for the large range of interested users, remains an open problem that needs further investigation.

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