PROBABILISTIC LANDSLIDE HAZARD ASSESSMENT: AN EXAMPLE IN THE COLLAZZONE AREA, CENTRAL ITALY

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ABSTRACT

We present a probabilistic model to determine landslide hazard. The model predicts where landslides will occur, how frequently they will occur, and how large they will be in a given area. We apply the model in the Collazzone area in central Umbria. For this area, we prepared a multi-temporal inventory map through the interpretation of multiple sets of aerial photographs and field surveys. We partitioned the study area into 894 slope units, and obtained the probability of spatial occurrence of landslides by discriminant analysis of thematic variables. For each slope unit, adopting a Poisson probability model for the temporal occurrence of landslides, we determined the probability of having one or more landslides in different periods. We obtained the probability of landslide size by analyzing the frequency-area statistics of landslides. Assuming independence, we determined landslide hazard as the joint probability of landslide size, of landslide temporal occurrence, and of landslide spatial occurrence.

1. INTRODUCTION

Assessment of landslide hazard involves determining "where" landslides are expected, "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. Different methods have been proposed to evaluate where landslides are expected (e.g., Carrara et al. 1995, Soeters and van Westen 1996, Chung and Fabbri 1999, Guzzetti et al. 1999). To predict the location of landslides, these methods use statistical classification techniques and exploit the known relationship between past landslides in an area and a set of geo-environmental thematic variables in the same area. Attempts have been made to predict "when" landslides will occur by establishing the probability of landslide occurrence in a given period (e.g., Keaton et al. 1988, Lips and Wieczorek 1990, Crovelli 2000, Guzzetti et al. 2002b, 2005). Most commonly, the temporal probability of landslide occurrence is obtained from catalogues of historical landslide events or multi-temporal landslide inventory maps. No single measure of landslide "magnitude" exists. For some landslide types, landslide size (i.e., area or volume) is a reasonable proxy for landslide magnitude. The frequency-area statistics of landslides can be obtained from landslide inventory maps (Stark and Hovius 2001, Guzzetti et al. 2002a, Malamud et al. 2004), and this information can be used as a proxy for the distribution of landslide magnitude in an area.

2. PROBABILISTIC MODEL OF LANDSLIDE HAZARD

Guzzetti et al. (1999) defined landslide hazard H_L as "the probability of occurrence within a specified period and within a given area of a potentially damaging landslide of a given magnitude". This definition can be written as:

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

where, A_L is the area of a landslide greater or equal than a minimum size, a_L. For any given area, proposition (1) is equivalent to:

$$H_L = P(A_L) \cdot P(N_L) \cdot P(S) \quad (2)$$

that expresses landslide hazard 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. From a geomorphological point of view, this assumption is severe and may not hold, always and everywhere (Guzzetti et al. 2005). 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.

2.1 Probability of landslide size

The probability that a landslide will have an area greater or equal than a_L is:

$$P(A_L) = P[A_L \geq a_L] \quad (3)$$

and can be estimated from the analysis of the frequency-area distribution of known landslides, obtained from landslide inventory maps. Malamud et al. (2004) proposed a truncated inverse Gamma probability distribution to approximate the probability density of landslide area. Using this distribution, the probability of landslide area $P(A_L)$ is given by:

$$P(A_L) = \int_{a_L}^{\infty} p(A_L;\rho,a,s)dA_L = \int_{a_L}^{\infty} \frac{1}{a\Gamma(\rho)}\left[\frac{a}{A_L - s}\right]^{\rho+1} exp\left[-\frac{a}{A_L - s}\right]dA_L \quad (4)$$

where: $\Gamma(\rho)$ is the gamma function of ρ, and $\rho > 0$, $a > 0$, and $s \leq A_L < \infty$ are parameters of the distribution. In equation (4), ρ controls the power-law decay for medium and large landslide areas, a primarily controls the location of the maximum of the probability distribution, and s primarily controls the exponential decay for small landslide areas.

In another study of frequency-area statistics of landslides, Stark and Hovius (2001) proposed the probability density function of landslide area to be in good agreement with a double Pareto probability distribution. Using this distribution, $P(A_L)$ is given by:

$$P(A_L)=\int_{a_L}^{\infty} p(A_L;\alpha,\beta,l,m,c)dA_L=\int_{a_L}^{\infty}\frac{\beta}{l(1-\delta)}\left[\frac{\left[1+(m/l)^{-\alpha}\right]^{\beta/\alpha}}{\left[1+(A_L/l)^{-\alpha}\right]^{1+(\beta/\alpha)}}\right](A_L/l)^{-(\alpha+1)}dA_L \quad (5)$$

where: $\alpha>0$, $\beta>0$, $0\leq c\leq l\leq m\leq\infty$, and with $\delta=y(c)=\left[\frac{1+(m/l)^{-\alpha}}{1+(A_L/l)^{-\alpha}}\right]^{\beta/\alpha}$. Note that α in equation (5) is the same as ρ in equations (4) and controls the power-law decay of landslide probability for large landslide areas. Also, β in equation (5) controls the power-law decays for small landslide areas.

2.2 Temporal probability of landslides

Landslides can be considered as independent random point-events in time (Crovelli 2000). In this framework, the exceedance probability of occurrence of landslide events during time t is:

$$P(N_L)=P[N_L(t)\geq 1] \quad (6)$$

where $N_L(t)$ is the number of landslides that occur during time t in a given area. Adopting a Poisson model for the temporal occurrence of landslides, the probability of experiencing one or more landslides during time t is:

$$P[N(t)\geq 1]=1-P[N(t)=0]=1-\exp(-\lambda t)=1-\exp(-t/\mu) \quad (7)$$

where λ is the estimated average rate of occurrence of landslides which corresponds to $1/\mu$, with μ the estimated mean recurrence interval between successive failure events. The variables λ and μ can be obtained from a historical catalogue of landslide events, or from a multi-temporal landslide inventory map. The Poisson model holds under the following assumptions (Crovelli 2000): (i) the number of landslide events that occur in disjoint time intervals are independent; (ii) the probability of an event occurring in a very short time is proportional to the length of the time interval; (iii) the probability of more than one event in a short time interval is negligible; (iv) the probability distribution of the number of events is the same for all time intervals of fixed length; and (v) the mean recurrence of events will remain the same in the future as it was observed in the past. The consequences of these assumptions, which may not always hold for landslide events, should be considered when interpreting the results of the probability model.

2.3 Spatial probability of landslide occurrence

The spatial probability of landslide occurrence, also known as landslide susceptibility, is the probability that any given region will be affected by landslides, given a set of environmental conditions. Defining L: "a given region will be affected by landslides", susceptibility, S, becomes:

$$S = P\,[L \text{ is true, given } \{ \text{ morphology, lithology, structure, land use, etc. } \}] \quad (8)$$

or,

$$S = P\,[L \mid v_1(r),\ v_2(r),\ \ldots,\ v_m(r)] \quad (9)$$

which is the joint conditional probability that a region r will be affected by future landslides given the m environmental variables $v_1, v_2, \ldots, v_m$ in the same region.

Susceptibility can be estimated using a variety of statistical techniques, which include discriminant analysis, logistic regression analysis, and conditional analysis based on a variety of favourability functions. Depending on the type of statistical technique, the meaning of the probability changes slightly. When using discriminant analysis or logistic regression analysis, the probability assigned to any given area (i.e., to each terrain or mapping unit) is the probability that the area pertains to one of two groups, namely: (i) the group of mapping units having landslides, G_1, or (ii) the group of mapping units free of landslides, G_0, given the set of environmental conditions used in the analysis. At the beginning of a study only past landslides in a region are known. Hence, classification of mapping units free or having landslides is made based on the known distribution of past slope failures. A straightforward deduction is to assume $S= P[r \in G_1] = 1-P[r \in G_0]$. In other words, if a region r pertains to the group of mapping units having known landslides because of the local environmental conditions, it is likely that the same region will experience slope failures again in the future. Equally, if a region pertains to the group of mapping units free of known landslides it is unlikely that the same region will experience mass movements. Chung and Fabbri (1999) proposed to estimate the probability of future landslides in any given region, S, from the probability of past landslides in the same region, given a set of environmental variables. Letting F: "a given region has been affected by landslides", the joint conditional probability of past landslides in a region r, given the m environmental variables $v_1, v_2, \ldots, v_m$ in the same region is:

$$D = P\,[F \mid v_1(r),\ v_2(r),\ \ldots,\ v_m(r)] \quad (10)$$

From equations (9) and (10) it follows that:

$$P\,[L \mid v_1(r),\ v_2(r),\ \ldots,\ v_m(r)] = P\,[F \mid v_1(r),\ v_2(r),\ \ldots,\ v_m(r)], \quad (11)$$

or $S = D$.

Quantitative susceptibility models can predict the spatial occurrence of future landslides under the general assumption that in any given area slope failures will occur in the future under the same circumstances and because of the same conditions that caused them in the past. This is a geomorphological rephrase of "the past is the key to the future", a direct consequence of the principle of uniformitarianism largely accepted in the Earth Sciences. However, the principle may not hold for landslides. New, first-time failures occur under conditions of peak resistance (friction and cohesion), whereas reactivations occur under intermediate or residual conditions. It is well know that terrain gradient is an important factor for the occurrence of landslides. An obvious effect of a slope failure is to change the morphology of the terrain where the failure occurs. In addition, when a landslide moves it may change the hydrological conditions of the slope. It is also well known that landslides can change their type of movement and velocity with time. Lastly, landslide occurrence and abundance are a function of environmental conditions that vary with time at different rates. Some of the environmental variables are affected by human actions (e.g., land use, deforestation, irrigation, etc.), which are also highly changeable. Because of these complications, each landslide occurs in a distinct environmental context, which may have been different in the past and that might be different in the future. Despite these limitations, we assume that the principle of uniformity hold "statistically", i.e., that in the investigated region future landslides will occur on average under the same circumstances and because of the same conditions that triggered them in the past. We further assume that our knowledge of the distribution of past failures is reasonably accurate and complete. We accept these simplifications to make the problem tractable.

3. HAZARD ASSESSMENT FOR THE COLLAZZONE AREA

The Collazzone area extends for 78.89 km^2 in Umbria, central Italy, with elevations ranging between 145 m and 634 m (Figure 1). Landscape is hilly, and lithology and structure control the morphology of the slopes. In the area crop out: (1) recent fluvial deposits along the valley bottoms, (2) continental gravel, sand and clay, Plio-Pleistocene in age, (3) travertine deposits, Pleistocene in age, (4) layered sandstone and marl in various percentages, Miocene in age, and (5) thinly layered limestone, Lias to Oligocene in age. Soils range in thickness from a few decimetres to more than one meter, and exhibit a xenic moisture regime, typical of the Mediterranean climate. Annual precipitation averages 885 mm, and rainfall is most abundant in the period from September to December. Landslides are abundant in the area, and range in type and volume from very old and partly eroded large deep-seated slides to shallow slides and flows.

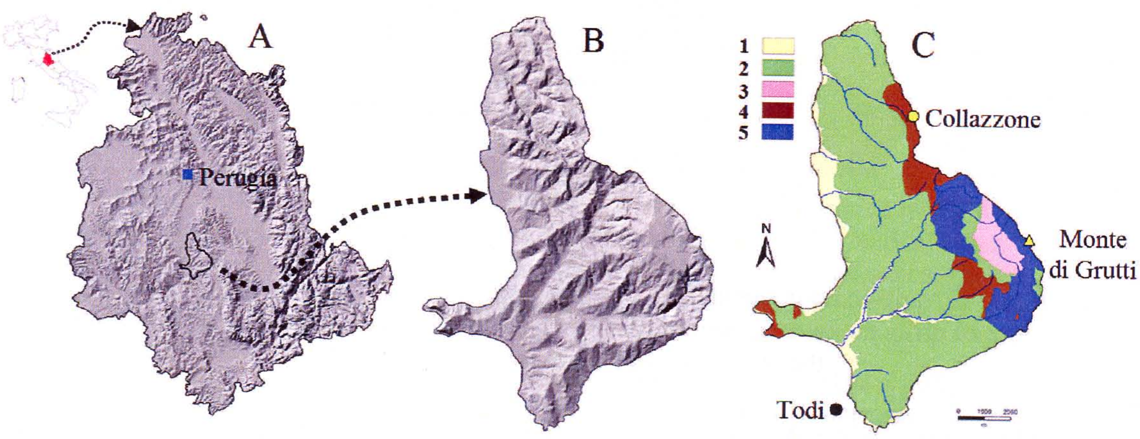

Figure 1. (A) Location of the study area in Umbria. (B) Shaded relief image showing morphology in the Collazzone area. (C) Lithological map for the Collazzone area: (1) Alluvial deposits, (2) Continental deposits, (3) Travertine, (4) Layered sandstone and marl, (5) Thinly layered limestone.

For the Collazzone area, a detailed multi-temporal landslide inventory map was obtained at 1:10,000 scale through the interpretation of multiple sets of aerial photographs and detailed geological and geomorphological field mapping (Figure 2). To prepare the landslide inventory, we used five sets of aerial photographs ranging in scale from 1:13,000 to 1:33,000, and covering unsystematically the period from 1941 to 1997. The inventory map obtained from the analysis of the aerial photographs was updated to cover the period from 1998 to 2004 through field surveys conducted following periods of prolonged rainfall. In the multi-temporal inventory, landslides are classified according to the type of movement, and the estimated age, activity and depth. Landslide type was defined according to Cruden and Varnes (1996) and the WP/WLI (1990).

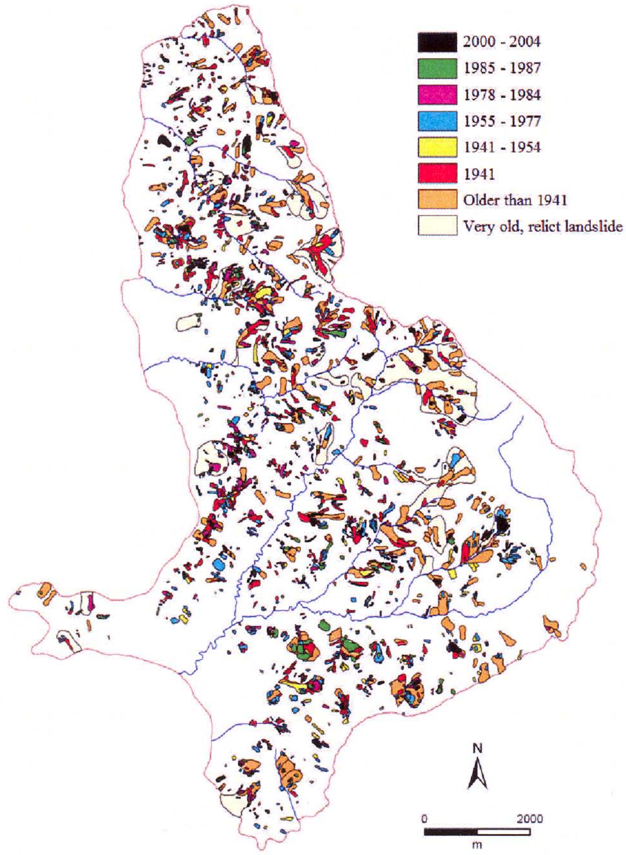

Figure 2. Multi-temporal landslide inventory map for the Collazzone area. Colors show landslides of different dates or periods, determined from the dates of the aerial photographs and the morphological appearance of the landslides.

Figure 3 summarises the data, models and products used to ascertain landslide hazard in the Collazzone area. The proposed probabilistic model requires an estimate of the probability of landslide area, a proxy for landslide magnitude. We obtained this estimate using the truncated inverse Gamma probability distribution of Malamud et al. (2004), and selecting the 2490 landslides shown in the multi-temporal inventory covering the 64-year period from 1941 to 2004. The hazard model requires an estimate of the temporal probability of slope failures. To obtain this estimate, we counted the number of landslides shown in the multi-temporal inventory in each slope unit. Considering only the recent landslides, we prepared a map of the total number of landslide events in the 64-year period between 1941 and 2004. For each slope unit, based on the past rate of landslide occurrence, we obtained the landslide recurrence, i.e., the expected time between successive failures. Knowing the mean recurrence interval of landslides in each mapping unit (from 1941 to 2004), assuming the rate of slope failures will remain the same for the future, and adopting a Poisson probability model, we computed the probability of having one or more landslides in each slope unit. The adopted hazard model requires a probabilistic estimate of the spatial occurrence of landslides. We obtained landslide susceptibility through discriminant analysis of 46 thematic variables, including morphology, lithology, structure, land use, and the presence of large relict landslide. As the dependent variable for the multivariate analysis, we selected the presence or absence of landslides in each slope unit, as shown by the multi-temporal inventory map (Figure 2).

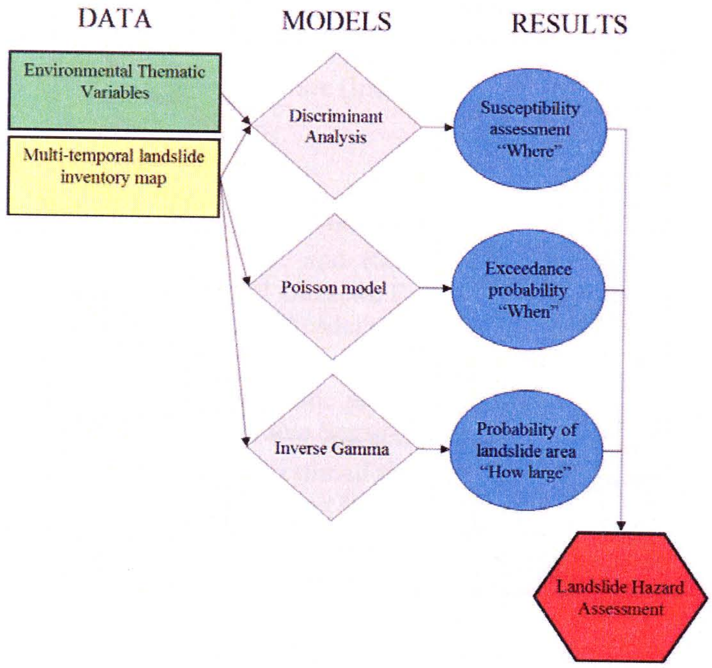

Figure 3. Block diagram exemplifying the work flow adopted to determine landslide hazard. Rectangles indicate input data. Diamonds indicate individual models, for landslide susceptibility, for the temporal probability of landslides, and for landslide size. Ellipses indicate intermediate results. Hexagon indicates the final result.

Assuming independence, we multiplied the probability of landslide size (eq. 4), the probability of landslide temporal occurrence (eq. 7), and the probability of spatial occurrence (eq. 11), and we obtained landslide hazard (eq. 2) i.e., the joint probability that a slope unit will be affected by future landslides that exceed a given size, in a given time, and because of the local environmental setting. Figure 4 shows examples of the landslide hazard assessment prepared for the Collazzone area. The Figure portrays landslide hazard for four periods (i.e., 5, 10, 25 and 50 years), and for two different landslide sizes, greater or equal than 1000 m^2, and greater or equal than 10,000 m^2.

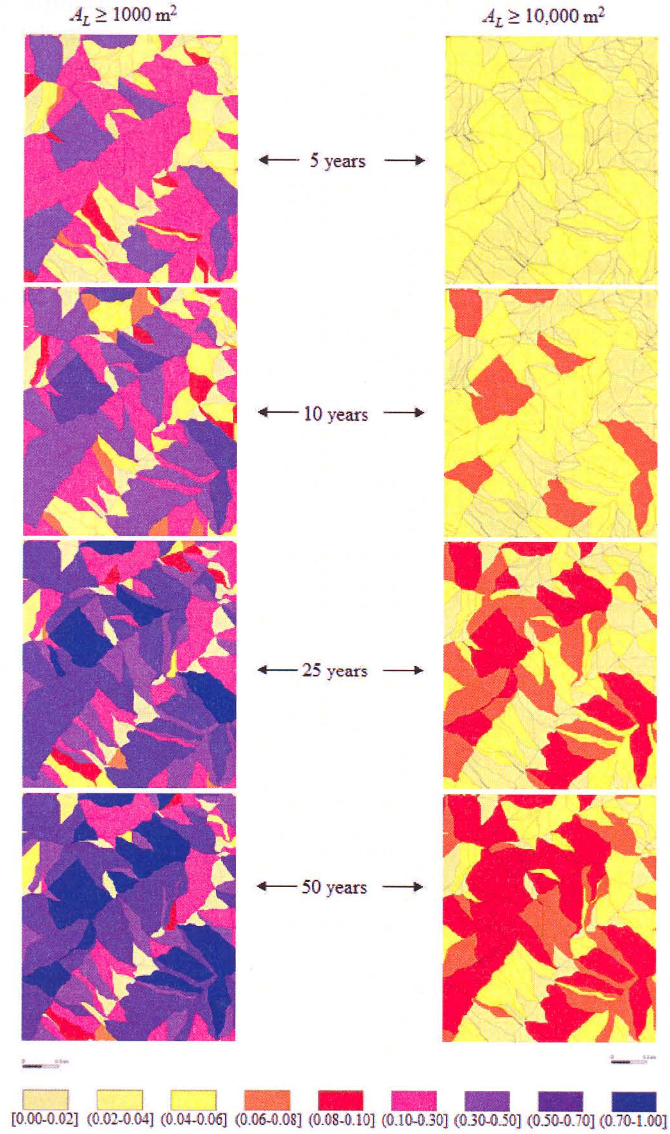

Figure 4. Examples of landslide hazard maps for four periods, from 5 to 50 years, and for two landslide sizes, $A_L \geq 1000$ m^2 and $A_L \geq 10{,}000$ m^2. Colors show different joint probabilities of landslide size, of landslide temporal occurrence, and of landslide spatial occurrence.

CONCLUSIONS

To ascertain landslide hazard in the Collazzone area we have adopted the probabilistic model proposed by Guzzetti et al. (2005). The adopted model expresses landslide hazard as the joint probability of landslide size, considered a proxy for landslide magnitude, of landslide occurrence in an established period, and of landslide spatial occurrence, given the local environmental setting. For the study area we have obtained most of the information used to determine landslide hazard from a detailed multi-temporal inventory map, prepared through the interpretation of five sets of aerial photographs and field surveys. The adopted model proved applicable in the test area. We judge the model appropriate in similar areas, and chiefly where a multi-temporal landslide inventory captures the types, sizes, and expected recurrence of slope failures. We conclude by pointing out that the main scope of a landslide hazard assessment is to provide probabilistic expertise on future slope failures to planners, decision makers, civil defence authorities, insurance companies, land developers, and individual landowners. The adopted method allowed us to prepare a large number of different hazard maps, depending on the adopted susceptibility model, the established period, and the minimum size of the expected landslide. How to combine such a large number of hazard scenarios efficiently, producing cartographic, digital, or thematic products useful for the large range of interested users, remains an open problem that needs further investigation.

ACKNOWLEDGMENTS

Work supported by CNR IRPI and Riskaware (Interreg III-C CADSES Program) grants.

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