Landslide Hazard Assessment, Vulnerability Estimation, and Risk Evaluation at the Basin Scale

Francesca Ardizzone, Mauro Cardinali, Fausto Guzzetti, Paola Reichenbach (CNR – IRPI, Italy)

Abstract. For one area in central Italy, landslide hazard was ascertained, landslide vulnerability was estimated, and landslide risk was evaluated, for different scenarios. To ascertain landslide hazard, a specific probabilistic model was adopted to predict where landslides will likely occur, how frequently they will occur, and how large they will be in a given area and period. For the study area, a multi-temporal landslide inventory map was prepared through the interpretation of five sets of aerial photographs covering the period from 1941 to 1997, and field surveys in the period from 1997 to 2004. For each mapping unit: (i) the probability of spatial landslide occurrence was obtained through discriminant analysis of a large set of thematic and environmental variables; (ii) the probability of experiencing one or more landslides in different periods was determined adopting a Poisson probability distribution model for the temporal occurrence of landslides, and (iii) the probability of landslide size was obtained by analyzing the frequency-area statistics of known landslides. Assuming independence of the three computed probabilities, landslide hazard was determined as the joint probability of landslide size, of landslide temporal occurrence, and of landslide spatial occurrence. Landslide vulnerability curves established for the Umbria Region using information on landslide damage to buildings and roads caused by individual landslides based on slide type were adopted. 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.

Keywords. Landslide, hazard, vulnerability, risk, model, Italy.

1. Introduction

The ultimate goal of many landslide studies is the determination of the risk posed by existing or future slope failures to either the population and/or the infrastructure. To achieve this goal, information on landslide hazard (Guzzetti et al. 1999, 2005, 2006a) and vulnerability (Galli and Guzzetti 2007) to landslides is required. Several different techniques have been proposed to evaluate landslide hazard, and the literature on the topic is extensive. 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 et al. 1999, 2005, 2006b).

Studies of the vulnerability to landslides, including methods to determine vulnerability and examples of damage assessments have been proposed by several authors (for a review see Galli and Guzzetti 2007). 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 (Cardinali et al. 2002; Reichenbach et al. 2005). Lack of established methods to assess the damage and of reliable information on vulnerability, hampers our ability to properly determine landslide risk (Galli and Guzzetti 2007).

In this paper, we report the results of an attempt to ascertain landslide risk in the Collazzone area, central Umbria, Italy.

2. Study area

The Collazzone area extends for about 79 km^2 in central Umbria, with elevations ranging between 145 m and 634 m. The landscape is hilly, and lithology and bedding attitude control the morphology of the slopes. In this area sedimentary rocks are mantled by soils that range in thickness from a few decimeters to more than one meter. Precipitation is most abundant in the period from September to December; with a mean annual rainfall between 1921 and 2001 of 885 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 and flows. Slope failures are triggered chiefly by meteorological events, including intense and prolonged rainfall and rapid snow melt. Although the area is seismically active, no information is available on earthquake induced slope failures in the area.

Fig. 1 Multi-temporal landslide inventory map for the Collazzone area

Landslide and thematic information is available for the

Collazzone area. A multi-temporal landslide inventory map, at 1:10,000 scale shows 2760 landslides in the study area (Fig. 1). The inventory was prepared through the systematic interpretation of five sets of aerial photographs covering the period from 1941 to 1997, supplemented by field surveys conducted in the period from January 1998 to December 2004 (Galli et al. 2008). A 10 m × 10 m digital representation of the topography (DEM) is available for the area, and was used to partition the study area into 894 slope units (Carrara et al. 1991), a terrain subdivision that has proven reliable to determine landslide susceptibility and hazard in Umbria (Carrara et al. 1991; Cardinali et al. 2002; Guzzetti et al. 2006a). Geological information, including lithology and bedding attitude, is available from a geological map at the 1:10,000 scale, prepared through field mapping aided by the interpretation of medium and large-scale aerial photographs. Information on land use types, including the presence of roads, was obtained from a land use map compiled in 1977 by the Umbria Regional Government, largely revised and updated by interpreting the most recent aerial photographs and by inspection of detailed topographic maps at 1:10,000 scale, and limited field checks.

3. Landslide hazard assessment

To determine landslide hazard in the Collazzone area, the probabilistic model proposed by Guzzetti et al. (2005) was used. The model predicts where landslides will occur, how frequently they will occur, and how large they will be in a given area.

Fig. 2 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

First, 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. The result of the susceptibility assessment is shown in Fig. 2. 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%).

Next, the temporal probability of slope failures was ascertained. To obtain this estimate, the number of landslides that 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 individual 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 for the temporal occurrence of the events (Crovelli 2000; Coe et al. 2000; Guzzetti et al. 2005, 2006a), the probability of having one or more landslides in each slope unit was determined for different periods.

Next, the probability of landslide size (area), considered a proxy for landslide magnitude was determined. To determine the probability of landslide size, the truncated inverse Gamma probability distribution of Malamud et al. (2004) was applied to the landslides shown in the multi-temporal inventory in the period from 1941 to 2004. The obtained result can be used to predict the probability that an individual landslide in the Collazzone area exceeds a given size.

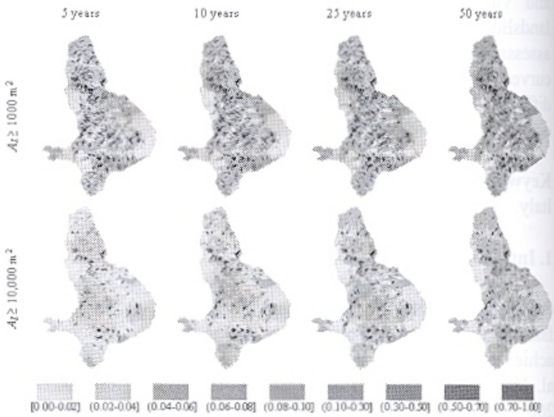

Fig. 3 Landslide hazard scenarios for four periods, from 5 to 50 years, and for two classes of landslide size, $A_L \geq 1000$ m^2 and $A_L \geq 10{,}000$ m^2. Shades of gray show landslide hazard, i.e., the joint probability of landslide size, of landslide temporal occurrence, and of landslide spatial occurrence. Black polygons denote landslides

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 estimates of landslide hazard, i.e., the joint probability that a slope unit will be affected by future landslides that exceed a given size, in an established period. Fig. 3 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.

4. Landslide vulnerability and risk evaluation

Information on the vulnerability to landslides is lacking almost everywhere in the World (Alexander 2000; Glade et al. 2005; Hungr et al. 2005), hampering our ability to evaluate risk. For the Umbria region, landslide vulnerability curves were established exploiting information on landslide damage to buildings and roads caused by individual landslides of the slide type in the 24-year period between 1982 and 2005 (Galli and Guzzetti 2007). Empirical observations revealed 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. Minimum and maximum vulnerability curves were established for roads in Umbria and were used to map the expected vulnerability of the road network to landslides in the Collazzone area.

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 in the Collazzone area, for different scenarios.

5. 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 et al. 2005): (i) landslides will occur in the future under similar circumstances and due to the same factors that triggered 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 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 include the following (Galli and 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; Galli and Guzzetti 2007). 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 et al. 2005; Galli and Guzzetti 2007). 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.

Acknowledgments

We dedicate this work to Mirco Galli, a friend and colleague who passed away suddenly on 29 November 2007. His contribution was instrumental to the outcome of this research.

References

Alexander DE (2000) Confronting catastrophe. Terra Publishing, Harpenden, 282 p

Cardinali M, Reichenbach P, Guzzetti F, Ardizzone F, Antonini G, Galli M, Cacciano M, Castellani M, Salvati P (2002) A geomorphological approach to estimate landslide hazard and risk in urban and rural areas in Umbria, central Italy. Natural Hazards and Earth System Sciences 2(1-2): 57-72

Carrara A, Cardinali M, Detti R, Guzzetti F, Pasqui V, Reichenbach P (1991). GIS Techniques and statistical models in evaluating landslide hazard. Earth Surface Processes and Landform, 16(5): 427-445

Coe JA, Michael JA, Crovelli RA, Savage WZ (2000) Preliminary map showing landslide densities, mean recurrence intervals, and exceedance probabilities as determined from historic records, Seattle, Washington. United States Geological Survey Open File Report 00-303

Crovelli RA (2000) Probability models for estimation of number and costs of landslides. United States Geological Survey Open File Report 00-249

Galli M, Ardizzone F, Cardinali M, Guzzetti F, Reichenbach P (2008) Comparison of landslide inventory maps. Geomorphology 94: 268–289

Galli M, Guzzetti F (2007) Landslide vulnerability criteria: a case study from Umbria, Central Italy. Environmental Management 40: 649-664

Glade T, Anderson MG, Crozier MJ (2005) Landslide hazard and risk. John Wiley, Chichester, 802 p

Guzzetti F, Carrara A, Cardinali M, Reichenbach P (1999) Landslide hazard evaluation: a review of current techniques and their application in a multi-scale study, Central Italy. Geomorphology 31, 181-216

Guzzetti F, Galli M, Reichenbach P, Ardizzone F, Cardinali M (2006a) Landslide hazard assessment in the Collazzone area, Umbria, central Italy. Natural Hazards and Earth System Sciences 6: 115-131

Guzzetti F, Reichenbach P, Ardizzone F., Cardinali M, Galli M (2006b) Estimating the quality of landslide susceptibility models. Geomorphology 81: 166-184.

Guzzetti F, Reichenbach P, Cardinali M, Galli M, Ardizzone F (2005) Probabilistic landslide hazard assessment at the basin scale. Geomorphology 72: 272-299

Hungr O, Fell R, Couture R, Eberhardt E (2005) Landslide Risk Management. Taylor & Francis Group, London, ISBN 041538043X, 761 p

Malamud BD, Turcotte DL, Guzzetti F, Reichenbach P (2004) Landslide inventories and their statistical properties. Earth Surface Processes and Landforms 29(6): 687-711

Reichenbach P, Galli M, Cardinali M, Guzzetti F, Ardizzone F (2005) Geomorphologic mapping to assess landslide risk: concepts, methods and applications in the Umbria Region of central Italy. In: Glade T, Anderson MG, Crozier MJ (eds) Landslide hazard and risk. John Wiley, Chichester, 429-468

Proceedings of

The First World Landslide Forum

18-21 November 2008

United Nations University, Tokyo, Japan

Parallel Session Volume

Global Promotion Committee of

The International Programme on Landslides (IPL)