**Mediterranean Storms**
*(Proceedings of the 4th EGS Plinius Conference held at Mallorca, Spain, October 2002)*


# LANDSLIDE HAZARD ASSESSMENT AND RISK EVALUATION: LIMITS AND PROSPECTIVES

*Fausto Guzzetti*

CNR – IRPI, via della Madonna Alta 126, 06128 Perugia, Italy, F.Guzzetti@irpi.cnr.it

## ABSTRACT

*In the Mediterranean region landslides occur every year, causing casualties and large economic damage. Landslide mapping, hazard assessment and risk evaluation are important goals for scientists, planners, decision makers and land developers. In this short report I outline the main characteristics and principal limitations of the methods and techniques currently used to map slope failures, ascertain landslide hazards and estimate the associated risks. Recommendations are given on the basis of experience gained in studies conducted in central and northern Italy.*

## 1 INTRODUCTION

Many different triggers cause landslides. They include intense or prolonged rainfall, earthquakes and snow melting. On Earth the volume of mass movements spans 15 orders of magnitude; and landslide velocity extends over 14 orders of magnitude, from millimetres per year to hundreds of kilometres per hour. Mass movements can occur singularly or in groups of up to several thousands. Multiple landslides occur simultaneously (e.g., when slopes are shaken by an earthquake) or over a period of hours or days (e.g., when failures are triggered by intense rainfall or rapid snow melting). Slope failures can involve flowing, sliding, toppling or falling movements, and many landslides exhibit a combination of these types of movements (*Varnes*, 1978). The extraordinary breadth of the spectrum of mass-movement phenomena makes it difficult to define a single methodology to ascertain landslide hazards and to evaluate the associated risk.

The main causes and effects of landslides have long been known. Moreover, several different methods and techniques have been proposed to identify and map slope failures (*Rib and Liang*, 1978), to evaluate landslide hazards (*Guzzetti et al.*, 1999; *van Westen*, 1994) and to ascertain landslide risk (*Cruden and Fell*, 1997). However, no general agreement has been reached on how to accomplish these tasks effectively. In this short report I will briefly outline some of what I consider to be the inadequacies of the existing approaches to landslides mapping, hazard assessment and risk evaluation. I will offer some recommendations on the basis of experience gained in landslide studies carried out in Central and Northern Italy.

## 2 LANDSLIDE IDENTIFICATION AND MAPPING

Any landslide hazard or risk assessment must begin with the collection of information on where landslides are located. This is the goal of landslide mapping. A landslide inventory is the simplest form of landslide map. It records the location and, where known, the date of occurrence and types of landslides that have left discernable traces in an area (Hansen, 1984). Inventory maps can be prepared by different techniques, depending on their scope, the extent of the study area, the scales of base maps and aerial photographs, and the resources available to carry out the work. Landslide inventory maps may show all the slope failures triggered by a single event, such as an earthquake, rainstorm or snowmelt (event inventories), or they may show the cumulative effects of many events over a period of hundreds or even thousands of years (historical inventories) (*Guzzetti et al.*, 2000). By interpreting multiple sets of aerial photographs of different ages, multi-temporal inventory maps can be prepared.

As they are prepared by interpreting one or more sets of aerial photographs and correcting the results by field mapping, landslide inventory maps tend to be subjective. Reliability, completeness and resolution are issues to consider when preparing and using an inventory map. An incomplete or unreliable inventory may result in erroneous hazard or risk assessments. Many factors affect the reliability, completeness and resolution of an inventory map, including: (a) landslide freshness and age, (b) the quality and scale of aerial photographs and base maps, (c) the morphological and geological complexity of the study area, (d) land use types and alterations, and (e) the degree of experience of the geomorphologist who completes the inventory. Good quality event inventories should be reasonably complete, at least in the areas for which aerial photographs were available and where it was possible to perform fieldwork. As a drawback, event inventories often cover only a part of the total geographic area associated with a landslide triggering event. Historical inventories are never complete. Evidence for the existence of landslides is rapidly removed by erosion, growth of vegetation and human activity, and with time landslide boundaries become fuzzy, making it difficult to map the landslide precisely. Multi-temporal inventory maps can be prepared only where multiple sets of aerial photographs are available, i.e., only for the last 50 to 60 years in Europe. Despite the numerous published works dealing with landslide inventory maps, very few attempts have been made to assess their reliability and completeness quantitatively (*Carrara et al*., 1992; *van Westen et al*., 1994; Ardizzone et al., 2002). Where this has been accomplished, results have shown that landslide identification needs to be carried out by experienced geomorphologists, but that landslide mapping lacks clearly defined standards. The latter is both a science and an art, and efforts should be made to make it more objective, reproducible and scientific.

Landslide inventories are easy for both experts (e.g., geomorphologists) and non-experts (planners and policy-makers) to understand. Trained geomorphologists can easily prepare such maps without the need for large investments in costly equipment. Despite the ease with which they can be prepared, their immediateness and their low cost, landslide inventories are still not very popular, particularly among regional and national agencies. The reasons for this include: (a) inability to understand the value of regional inventories for planning purposes, (b) lack of resolve in preparing such maps for large regions, (c) unwillingness to know where landslides are located (lack of knowledge represents more freedom), and (d) the intrinsic subjectivity of landslide inventory maps (*Guzzetti et al*., 2000).

### 2.1 Recommendations

I propose the following recommendations for the preparation and use of landslide inventories maps:

- Prepare inventory maps for large areas (entire provinces or regions) using consistent, reproducible methods. Study the relationships between the lithological and structural settings and the landslide types and pattern.
- Prepare inventory maps after each landslide-triggering event, covering the entire territory affected by the event. Use frequency-size statistics to describe landslides triggered by extreme events.
- Keep a record of the landslides and of the landslide events that have occurred in historical times. Prepare multi-temporal inventory maps. Study the spatial relationships between failures of different ages and types.
- Ascertain the quality (in terms of completeness, resolution and reliability) of the inventory maps. Specify the techniques, methods and tools used to complete the inventory, including type of stereoscope, type and scale of aerial photographs and base maps, and level of experience of the investigators

## 3 LANDSLIDE HAZARD ASSESSMENT

In a very well-known report, *Varnes and the IAEG Commission on Landslides and other Mass–Movements* (1984) proposed that the definition adopted by UNDRO (1982) for all natural hazards be applied to landslide hazards. Landslide hazard is therefore “the probability of occurrence within a specified period of time and within a given area of a potentially damaging phenomenon”. *Guzzetti et al*. (1999) preferred the definition to include the magnitude of the event, i.e. the area, volume and velocity or momentum of the expected landslide.

This definition of landslide hazard is widely accepted. However it poses problems, largely as a result of the peculiarities of landslides when compared to other natural hazards, chiefly earthquakes, for which the UNDRO definition is best adapted. Even when they are caused by a single triggering event (e.g., intense rainfall, earthquake or rapid snowmelt), landslides affect any given geographical area in a way that differs from that of other natural hazards. Landslides are localised (“point”) events controlled by the intensity, duration and extent of the triggering mechanism, and by the local morphological, lithological, hydrological, structural and land-use settings. Moreover, some of these factors vary with time. The definition of landslide hazard incorporates the concepts of location (where a landslide will occur), time (when, or how frequently a landslide will occur) and magnitude (how large, or how fast the landslide will be). In conceptual terms, confusion may arise from the use of the term landslide to address both the landslide deposit and the movement of slope material or remobilisation of an existing mass movement deposit. Thus, hazard models cannot predict when a landslide will occur based on where landslides have occurred in the past. Information on frequency is evaluated by studying historical records or through a multi-temporal analysis of various sets of aerial photographs. This information is difficult to obtain. In addition, each time a landslide occurs, the topographical, geological and hydrological settings of the slope change, giving rise to different conditions of instability. Due to the variety of landslide types and the possibility that the landslide will evolve abruptly from one type of movement to another (e.g., when a soil slip is transformed into a debris flow), the magnitude of the expected mass movement is also difficult to predict.

Many methods have been proposed to evaluate landslide hazard spatially (*Guzzetti et al*., 1999). Two approaches are the most promising: methods based on the statistical analysis of geo-environmental factors related to the occurrence of landslides; and deterministic modelling based on simple 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 in a quantitative, objective and reproducible way of ascertaining the spatial pattern of landslides. Good multivariate models usually perform better than the original inventory map in predicting the occurrence of landslides (*Ardizzone et al*., 2002) but do not explicitly incorporate the temporal aspect of movement. Physically-based models perform well for landslides whose behaviour is easily predicted by simple mechanical laws (e.g., soil slips and rock falls), but they too lack consideration of the temporal aspect of landslides. Attempts to introduce the time component into hazard models have been proposed by *Agostoni et al.* (2000), who incorporated historical landslide events in a multivariate discriminant model. Moreover, *Coe et al*. (2000) proposed a probabilistic model of landslide occurrence based on a catalogue of historical landslides. *Guzzetti et al*. (2002), who used a physical model to study rockfall hazard, simulated the time effect by launching a large number of boulders from each rockfall source area.

The experience gained in numerous hazard investigations has shown that, although quantitative, indirect methods of assessing landslide hazards are preferable, no single method has proved to be superior in every area and for all types of landslide. Selection of the statistical technique and the type of deterministic model appears less important than the availability, quality, resolution and abundance of input data, including those derived from inventory maps. Equally important is the ability of the geomorphologist to interpret the model results and to design appropriate forms of protection for the different hazard zones.

### 3.1 Recommendations

On the basis of these considerations, I propose the following recommendations concerning the procedures for landslide hazard assessment:

- Invest in the acquisition of high-quality information that is relevant to the distribution and characteristics of landslides in the study area. When seeking to ascertain the magnitude of landslide hazard, do not use unreliable, badly formulated, low-quality data.
- Prepare landslide hazard maps for large areas (an entire province or region) using consistent, scientifically-based, and reproducible methods. Choose the modelling technique that is more suited to the type of landslides to be investigated. Make preferential use of statistical (functional) and deterministic (physically-based) methods that provide quantitative results.
- Verify the quality, reliability and sensitivity of landslide hazard models and maps using good quality inventory maps and reliable historical catalogues.
- Incorporate the time component (i.e., the frequency or occurrence of landslides) into the hazard models. If this is not possible, provide a time-frame for the validity of hazard models and maps.
- Investigate new approaches to the portrayal of landslide hazards, and new means of transferring scientific and quantitative information on landslide hazards to decision makers, land-use planners, consultants and concerned citizens. Help design land-use regulations and policies that incorporate landslide hazard zoning.

## 4 LANDSLIDE RISK ASSESSEMENT

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)” (*Varnes et al*., 1984). Quantitative (probabilistic) and qualitative approaches are possible. Quantitative risk assessment aims to establish the probability of occurrence of a catastrophic event, e.g., the probability of live losses, or the probability of a landslide causing N or more casualties (*Fell and Hartford*, 1997). The method requires a catalogue of landslides and their consequences. Such lists have been prepared for landslides with human consequences, i.e., deaths, missing people, and injuries (*Evans*, 1997; *Guzzetti et al*., 2000; *Kong*, 2002), but are more difficult to compile for other types of damage due o the lack of relevant information. With this information, frequency vs. consequences (F-n or F-N) plots can be prepared and the probability estimated. Acceptable risk levels are determined by comparison with natural or human-induced hazards for which acceptable risk levels have already been established (*Fell and Hartford*, 1997). The completeness and timespan of the landslide catalogue greatly affect the reliability of risk assessments.

When attempting to evaluate specific and total risk for a site or region where landslides are likely to take various forms or pose various types of threat, the quantitative approach often becomes impracticable. It may not be easy to ascertain the magnitude, frequency and forms of evolution of landslides in the area, and a detailed and reasonably complete catalogue of historical events may not be available. In some areas a qualitative approached can be pursued in such a way as to establish qualitative levels of landslide risk. This involves designing landslide scenarios. *Guzzetti et al*. (2002) described an attempt to determine qualitative risk levels based on the geomorphological interpretation of several sets of aerial photographs of different ages (a process of multi-temporal landslide mapping).

A reasonable alternative to qualitative risk assessment is analysis of the impact that slope failures have had, or may have, in a given area. This can be accomplished in two ways. First, where a historical catalogue of landslides and their consequences is available, the sites repeatedly affected by catastrophic events can be determined and the vulnerability of the elements at risk ascertained (*Kong*, 2002). Alternatively, where a detailed landslide inventory map and a map of structures (houses, buildings, etc.) and infrastructure (roads, railways, lifelines, etc.) at risk are available in GIS form, simple geographical operations allow one to determine where landslides may interfere with the elements at risk. Despite the relative simplicity--and effectiveness--of such analyses, they are not commonly performed.

### 4.1 Recommendations

The following recommendations are intended to help improve the quality of landslide risk assessments:

- Assess landslide risk quantitatively and qualitatively at local and regional scales.

- Build catalogues of landslide events and their consequences. This information is essential to any quantitative risk assessment.
- Collect and analyse information on vulnerability to landslides. Such information is usually lacking.
- Use GIS-based landslide maps and maps that show population density and the location of structures and infrastructure to ascertain the potential impact of landslides.
- In cooperation with economists, decision makers, land developers and concerned citizens, perform risk analyses. Establishing risk levels is a political as much as a technical decision-making process.
- Compare and integrate landslide risk assessments with assessments for other natural and man-made hazards.

## 5 CONCLUSIONS

Landslide mapping exercises, hazard assessments and risk evaluations are a great challenge for scientists, planners, decision makers and land developers. Despite numerous efforts reported in the literature, most of the methods and techniques proposed and tested to accomplish these tasks are still badly defined and poorly documented. More effort should be made to make these methods more quantitative, better documented and more reproducible. More effort is needed to transfer the scientific information on landslide hazards and risk into building codes and civil protection plans.

**Acknowledgements.** This is CNR – GNDCI publication n. 2461. David Alexander reviewed the text.

## REFERENCES

Agostoni S., Cardinali M., Carrara A., Crosta G., Fossati D., Frattini P., Guzzetti F., Laffi R. & Reichenbach P., Assessment of landslide hazard of the Staffora basin (northern Italy) by integrating geomorphological and historical data within a multivariate model. XXV EGS General Assembly, Nice, 2000, abstract.

Ardizzone F., Cardinali M., Carrara A., Guzzetti F. & Reichenbach P., Uncertainty and errors in landslide mapping and landslide hazard assessment. *NHESS*, **2**:1-2, 2002, 3-14.

Cardinali M., Reichenbach P., Guzzetti F., Ardizzone F., Antonini G., Galli M., Cacciano M., Castellani M. & Salvati P. A geomorphological approach to estimate landslide hazard and risk in urban and rural areas in Umbria, central Italy. *NHESS*, **2**:1-2, 2002, 57-72.

Carrara A., Cardinali M. & Guzzetti F., Uncertainty in assessing landslide hazard and risk. *ITC Journal*, The Netherlands, **2**, 1992, 172–183.

Coe J.A., Michael J.A., Crovelli R.A. & Savage W.Z., Preliminary map showing landslide densities, mean recurrence intervals, and exceedance probabilities as determined from historic records, Seattle, Washington. U.S. Geological Survey Open File Report 00-303, 2000, http://greenwood.cr.usgs.gov/pub/open-file-reports/ofr-00-0303/

Cruden D.M. & Fell R. (eds.), Landslide risk assessment. *Proc. Int. Workshop on Landslide Risk Assessment*, Balkema, 1997, 371 p.

Evans S.G., Fatal landslide and landslide risk in Canada. In: Cruden D.M. & Fell R. (eds.), Landslide risk assessment. *Proc. Int. Workshop on Landslide Risk Assessment*, Balkema, 1997, 185-196.

Fell R., & Hartford D., Landslide risk management. In: Cruden D.M. & Fell R. (eds.) Landslide Risk Assessment. *Proc. Int. Workshop Landslide Risk Assessment*, Balkema, 1997, 51-109.

Guzzetti F., Landslide fatalities and evaluation of landslide risk in Italy. *Engineering Geology*, **58**, 2000, 89-107.

Guzzetti F., Cardinali M., Reichenbach P. & Carrara A., Comparing landslide maps: A case study in the upper Tiber River Basin, central Italy. *Environmental Management*, **25**:3, 2000, 247-363.

Guzzetti F., Carrara A., Cardinali M. & Reichenbach P., Landslide hazard evaluation: an aid to a sustainable development. *Geomorphology*, **31**, 1999, 181-216.

Guzzetti F., Crosta G., Detti R. & Agliardi F., STONE: a computer program for the three-dimensional simulation of rock-falls. *Computers & Geosciences*, **28**: 9, 2002, 1079-1093.

Hansen A. Landslide hazard analysis. In: Brunsden D. & Prior D.B. (eds.), Slope Instability, John Wiley and Sons, New York, 1984, 523–602.

Kong W.K., Risk assessment of slopes. Quarterly Journal Engineering Geology and Hydrogeology, 35; 2002, 213-222.

Rib H.T. & Liang T., Recognition and identification. In: Schuster R.L. & Krizek R.J. (eds.), *Landslide analysis and control*. Washington Transportation Research Board, Special Report 176, NAS, Washington, 1978, 34-80.

van Westen C.J., GIS in landslide hazard zonation: A review with examples from the Colombian Andes. In: Price M.F. & Heywood D.I. (eds.), Taylor and Francis, London, 1994, 135-165.

van Westen C.J, Seijmonsbergen A.C. & Mantovani F., Comparing landslide hazard maps. *Natural Hazards*, **20**:2-3, 1999, 137-158.

Varnes D.J. Slope movements, type and processes. In: Schuster R.L. & Krizek R.J. (eds.), *Landslide analysis and control*. Washington Transportation Research Board, Special Report 176, NAS, Washington, 1978, 11-33.

Varnes D.J., and IAEG Commission on Landslides and other Mass–Movements, Landslide hazard zonation: a review of principles and practice. UNESCO Press, Paris, 1984, 63 p.