Landslide Cartography, Hazard Assessment and Risk Evaluation: Overview, Limits and Prospective

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ABSTRACT: Landslides occur every year, causing casualties and large economic damage. Landslide cartography, including landslide inventory, density and hazards maps, and landslide hazards assessment and risk evaluation are important goals for scientists, planners, decision makers and land developers. In this 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. Examples and recommendations are given on the basis of the experience gained in studies conducted mostly in central and northern Italy.

1 INTRODUCTION

Many different triggers cause landslides, including intense or prolonged rainfall, earthquakes and rapid 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 almost simultaneously when slopes are shaken by an earthquake, or over a period of hours or days when failures are triggered by intense rainfall or snow melting. Landslides 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 landslide phenomena makes it difficult to define a single methodology to ascertain landslide hazards and to evaluate the associated risk.

Landslides are reported in all continents and their economical and societal impact can be tremendous and widespread. In many Countries casualties and economic losses caused by landslides are larger than those produced by others damaging natural events, including floods and earthquakes. In Italy, a Country for which the information is available, in the 20th century landslides have caused 7,799 casualties, comprising 5,831 deaths, 108 missing persons and 1,860 injured people. This represents an average of 59.4 deaths or missing persons each year. Limiting the analysis to the post War period (1950-2000), slope failures have caused at least 4,408 deaths or missing persons, in 521 landslide events. This figure is much larger than the estimated number of 1,040 deaths and missing persons caused by floods, and larger than the number of 4,160 deaths and missing persons caused by earthquakes, during the same period (*Guzzetti*, 2000).

The main causes and effects of landslides have long been known and several different methods and techniques have been proposed to identify and map slope failures (*Rib and Liang*, 1978; *Turner and Schuster*, 1996), to evaluate landslide hazards (*Guzzetti et al.*, 1999; *Soeters and van Westen*, 1996; *Carrara et al.*, 1995, *van Westen*, 1994) and to ascertain landslide risk (*Cruden and Fell*, 1997; *Einstein*, 1988). However, no general agreement has been reached on how to accomplish these tasks effectively.

In this report I will outline some of what I consider to be the inadequacies of the existing approaches to landslides mapping, hazard assessment and risk evaluation, and 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; *Wieczorek*, 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.

Small-scale inventories (<1:200,000) are compiled mostly from data captured from the literature, through inquires to public organisations and private consultants, by searching chronicles, journals, technical and scientific reports, or by interviewing landslide experts (archive inventories). Small-scale landslide maps can also be obtained through the analysis of aerial photographs. Medium-scale landslide inventories (1:25,000 to 1:200,000) are prepared through the systematic interpretation of aerial photographs at print scales which range from 1:60,000 to 1:20,000 and by integrating local field checks with historical information. Large-scale inventories (>1:25,000) are prepared, usually for limited areas, using both the interpretation of aerial photographs at scales greater than 1:20,000 and extensive field investigations, which make use of a variety of techniques and tools that pertain to geomorphology, engineering geology and geotechnical engineering (*Guzzetti et al*., 2000).

Figure 1 shows a portion of a large scale geomorphological landslide inventory map prepared through the interpretation of two sets of medium- and large-scale aerial photographs in the Umbria Region, in central Italy. The original map was prepared at 1:10,000 scale for an area of 8,456 km^2, and shows more than 47,000 landslides, for a total landslide area of 712 km^2. Landslides are classified based on the type of movement, the estimated depth, velocity, and age, and the degree of certainty (*AA.VV.*, 2002).

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 (geomorphological inventories). 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. Geomorphological 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; *Ardizzone et al.*, 2002). Where this has been accomplished, results have shown that landslide identification needs to be carried out by experienced geomorphologists, and that landslide mapping still lacks clearly defined standards. Landslide identification and mapping is both a science and an art, and efforts should be made to make it more objective, reproducible and scientific.

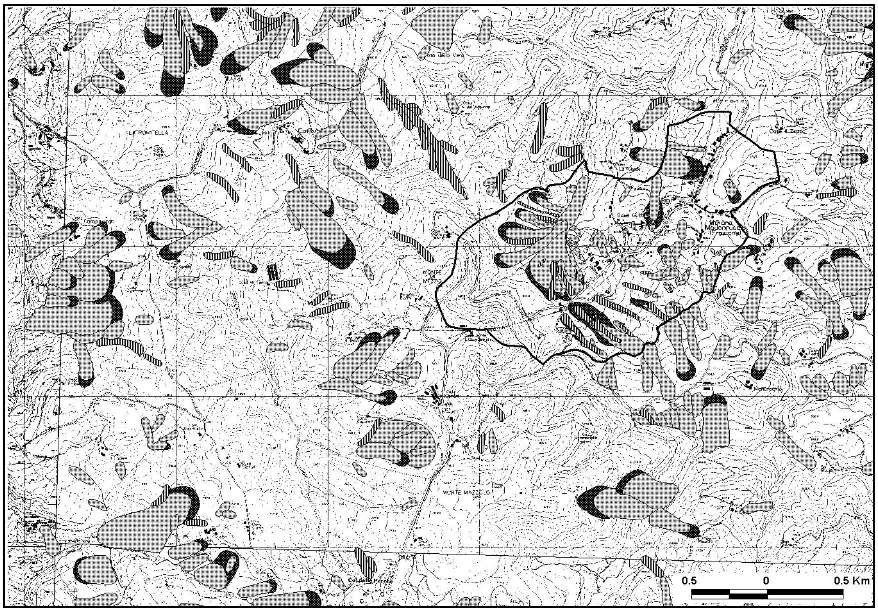

Figure 1. Umbria region, central Italy. Portion of a geomorphological landslide inventory map. Legend: Grey, landslide deposits of slide, slide earth-flow and complex failures; vertical pattern, deposits of flow slides; dark grey, crown area of deep-seated landslides. Thick black line shows an area where landslide risk was determined (see Figure 3). Original map scale is 1:10,000.

The limitations of landslide inventories refer to their subjectivity and to the difficulty of measuring their reliability. The reliability of archive inventories depends largely on the quality and abundance of the information sources (*Glade*, 1998; *Cruden*, 1997; *Guzzetti et al.*, 1994). For geomorphological maps, the experience gained from surveys carried out in different parts of the world has shown that trained investigators can reliably detect landslides by standard photo-interpretation techniques coupled with systematic checks in the field (*Turner and Schuster*, 1996; *Rib and Liang*, 1978). However, the reliability of geomorphological inventories depends on the type and scale of the aerial photographs used, the experience and skill of the interpreter, the scale of the final map, the complexity of the geological, morphological and land-use setting, and the persistence of landslide morphology within the landscape (*Carrara et al.*, 1992; *Fookes et al.*, 1991, *Hansen*, 1984).

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) lack of resolve in preparing such maps for large regions, (b) unwillingness to know where landslides are located (often lack of knowledge represents more freedom), (c) inability to understand the value of regional inventories for planning purposes, and (d) the subjectivity of landslide inventory maps (*Guzzetti et al*., 2000).

2.1 Recommendations

I propose the following recommendations for the preparation and use of landslide inventory maps. Landslide cartography should be increasingly pursued, and landslide inventory maps should be prepared for large areas (i.e., entire provinces or regions) using consistent and reproducible methods. Geomorphological inventory maps can be used to study the relationships between the lithological and structural settings and the landslide types and pattern. Despite the fact that this information can prove extremely valuable for landslide hazards assessment, review of the literature shows that such studies are rare, mostly because geographical databases containing landslides, lithological, and structural information with the required accuracy are not readily available.

Landslide inventory maps should be prepared after each landslide-triggering event (e.g., a rainstorm, a snowmelt event, or an earthquake), covering the entire territory affected by the event. Such maps allow determining the full extent of landslide events on the structures and the infrastructure. They can also provide valuable information for evaluating the types, extent and severity of damage caused by slope failures. Frequency-size (i.e., area, volume) statistics of landslides can be used to describe quantitatively the extent and magnitude of the landslides triggered by the extreme events. This information may be used to compare the ground effects produced by different triggers and by preparing regional landslide scenarios.

Regional and national Geological Surveys, planning agencies, and other concerned organizations should keep records of the landslides and the landslide events that have occurred in historical times in any given area. This information can be used to determine the frequency of landslide phenomena, mandatory information to properly assess landslide hazards. Where multiple sets of aerial photographs are available, multi-temporal landslide inventory maps should be completed to estimate the local landslide recurrence and to investigate the spatial relationships between failures of different ages and types.

Completeness, resolution and reliability (i.e., quality) of the landslide inventory maps should be ascertained. When preparing a landslide inventory map, 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, should always be specified. Without this information an inventory map may be used by others for scopes for which the map was not originally prepared.

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 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, costly and time consuming 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; *Soeters and van Westen*, 1996; *Carrara et al.*, 1995; van Westen, 1994). 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 a quantitative, objective and reproducible way of ascertaining the spatial pattern of landslides. Good multivariate models perform better than the original inventory map in predicting the occurrence of landslides but do not explicitly incorporate the temporal aspect of movement (*Ardizzone et al.*, 2002). 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. *Coe et al*. (2000) proposed a probabilistic model of landslide occurrence based on a catalogue of historical landslides. *Guzzetti et al*. (2002a), 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.

Figure 2 shows an example of a landslide hazard map for the same area portrayed in Figure 1. Landslide hazard was defined for the Upper Tiber River basin, in central Italy, as the probability of spatial occurrence of landslides in the terrain units into which the study area is partitioned (*Cardinali et al.*, 2002a). The probability of occurrence was ascertained through a multivariate statistical analysis (discriminant analysis) of a large set of lithological, structural, morphological and land use information. The geo-environmental information was obtained through photo-geological interpretation of aerial photographs, field surveys, bibliographical and historical studies, and spatial information analysis using GIS technology. The study area was partitioned into hydro-morpho-lithological terrain units. These are areas bounded by hydrological (drainage line), morphological (divide line) or lithological boundaries (*Cardinali et al.*, 2002a).

The map can be used to assess landslide hazards and to evaluate landslide risk at the basin scale. Combined with a landslide inventory map (*Cardinali et al.*, 2001) and with the results of recent investigations aimed at determining landslide risk in the Umbria region (*Cardinali et al.*, 2002b), the hazard map provides the basis for establishing planning regulations aimed at defending the land and the population against landslide hazards.

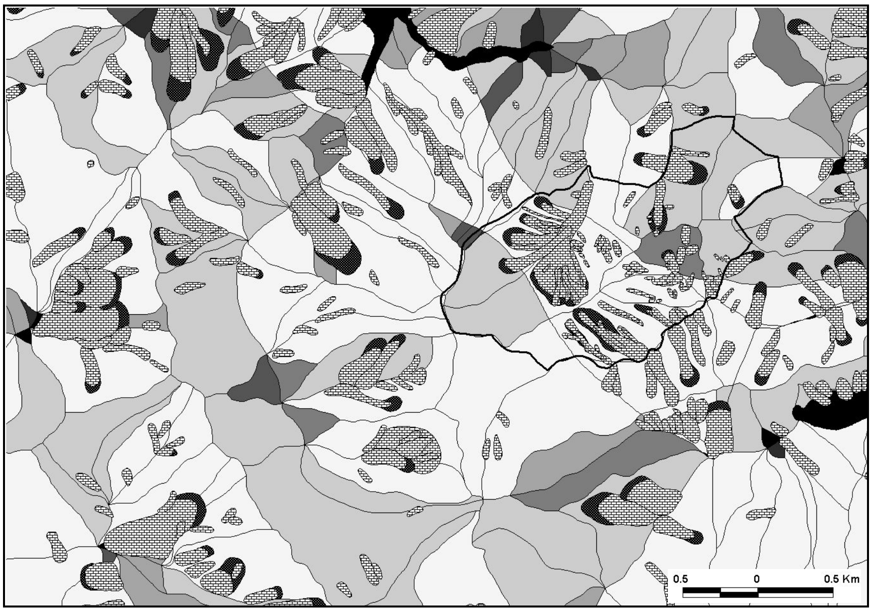

Figure 2. Umbria region, central Italy. Portion of a statistically-based landslide hazard map (*Cardinali et al.*, 2002a), for the same area shown in Figure 1. Hazard levels are shown by shades of grey, from stable (light grey) to unstable (dark grey) slopes. Light brick pattern, landslide deposits; dark pattern, landslide crown areas.

The experience gained in numerous hazard investigations completed by various teams in different areas of the World 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 (*Guzzetti et al.*, 1999; *van Westen et al.*, 1999). 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

The quality and reliability of a landslide hazard assessment depend more on the quality, resolution, completeness and reliability of the thematic information used to ascertain the hazards, than the type or method used to complete the hazard assessment. More resources should be invested in the acquisition of high-quality information that is relevant to the distribution and characteristics of landslides in the study area. Unreliable, badly formulated, low-quality data should not be used to ascertain the magnitude of landslide hazards. Unfortunately, review of the literature suggests that this is often the case.

Landslide hazard models and maps should be prepared for large areas (i.e., entire provinces or regions) using consistent, scientifically-based, and reproducible methods. Selection of the modelling techniques should be aided by the type of landslides to be investigated and the availability of relevant thematic information, and not by the GIS, statistical or modelling software at hand. Statistical (i.e., functional) and deterministic (i.e., physically-based) methods should be preferred. Experiences obtained by different teams in many physiographical environments proved that these methods provide the most reliable, quantitative results.

The quality, reliability and sensitivity of landslide hazard models and maps should always be carefully verified. This should be accomplished by checking the model results against good quality inventory maps and reliable historical catalogues of landslide events. Since the main goal of landslide hazard maps is to provide planners, decision makers and land developers with information aimed at defending the land and the population against landslide hazards, the maps should be reliable and robust, both spatially and in time. The time aspect of hazard assessment (i.e., *when* or *how frequently* a landslide will occur in any given area) remains a crucial, still largely unresolved problem. Efforts should be made to incorporate time into spatially distributed (statistical or deterministic) hazard models. Where this is not possible, the estimated time-frame for the validity of hazard models and maps should be provided.

Lastly, new approaches should be attempted 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 should be experimented. Geomorphologists interested in the application of landslide hazard assessments should help decision makers design land-use regulations and policies that properly incorporate landslide hazard zoning, fully exploiting the available knowledge on landslide phenomena and the associated hazards.

4 LANDSLIDE RISK ASSESSMENT

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 and the IAEG Commission on Landslides and other Mass–Movements*, 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. A few of such lists have been prepared for landslides with human consequences, i.e., deaths, missing people, and injuries (*Evans*, 1997; *Guzzetti*, 2000; *Kong*, 2002). To compile accurate and complete lists of landslides that have caused other types of damage is more difficult, due to the lack of relevant information. When this information is available, 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 time span of the landslide catalogue greatly affect the reliability of such quantitative 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 readily 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. *Cardinali 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), combined with the analysis of historical information on past landslide events. **Figure 3** shows an example for the village of Moranno Madonnuccia (Perugia province), where total landslide risk was determined for deep-seated and shallow landslides.

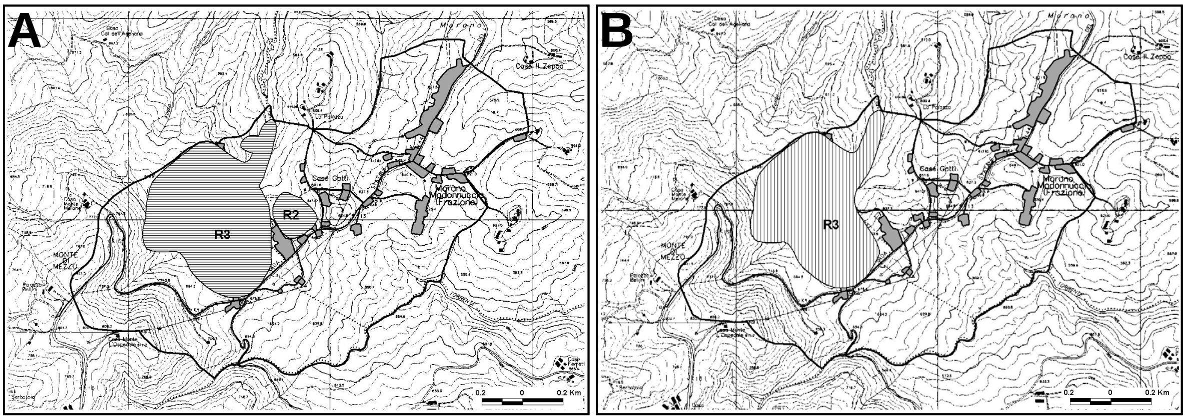

Figure 3. Umbria region, central Italy. Maps showing total landslide risk near the village of Morano Madonnuccia, Perugia province. Total landslide risk is ranked in four classes, two of which are shown here: R2, where landslide risk is moderate, and R3, where landslide risk is high. A) Risk for shallow landslides; B) Risk for deep-seated landslides. See also Figure 1.

A reasonable alternative to qualitative risk assessment is the 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. **Figure 4** shows an example of a recent attempt aimed at ascertain the possible impact of landslide phenomena on the built-up areas and the transportation network in the Umbria region. The intersection in a GIS of the geomorphological landslide inventory map (*Guzzetti et al.,* 2002b) with maps of the built-up areas and of the transportation network, revealed 6,119 sites where known landslides intersect (i.e., may interfere) with built-up areas, and 4,115 sites where landslide intersect roads or railways. At these localities damage due to landslides can be expected, particularly during major landslide triggering events (e.g., prolonged rainfall, snowmelt events, etc.).

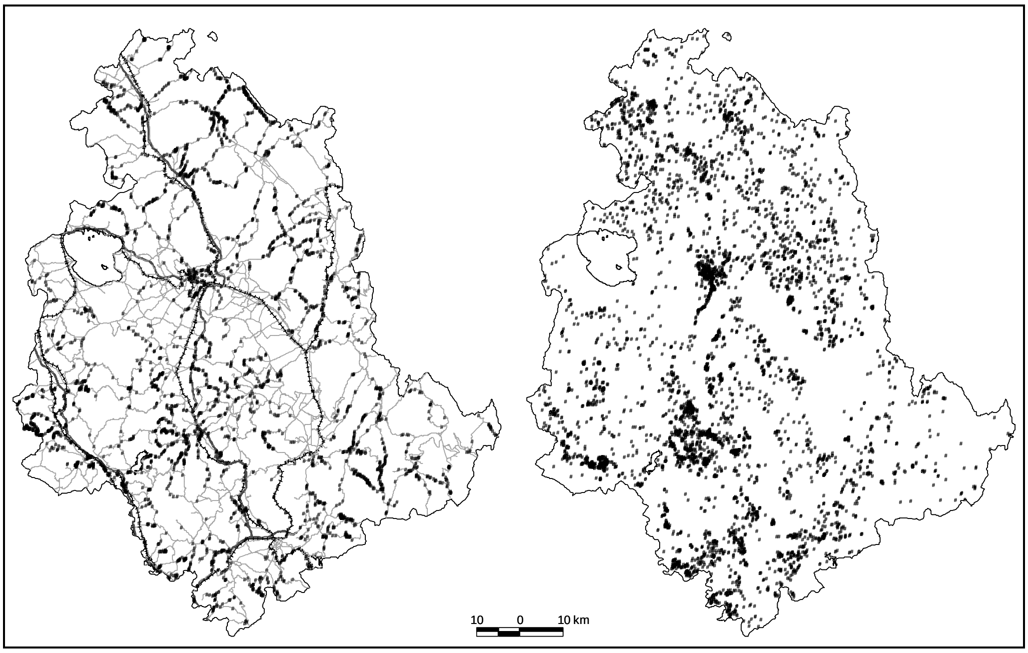

Figure 4. Umbria region, central Italy. Expected impact of landslides on the built-up areas and the transportation network. Left: location of 4,115 sites where landslides intersect roads or railways. Right: location of 6,119 sites where landslides intersect built-up areas.

4.1 Recommendations

The following recommendations are intended to help improve the quality of landslide risk assessments. Specific and total landslide risk assessments should be increasingly performed quantitatively and qualitatively at local and regional scales. Not enough examples of regional and local landslide risk assessments are available to perform a critical evaluation of the techniques and methods currently used to ascertain landslide risk. Data should be collected and efforts should be made to critically compare the outcomes of qualitative and quantitative risk assessment procedures.

Any serious attempt to ascertain landslide risk relays on the availability of reliable information on the frequency of landslide phenomena, and the type and severity of the damage caused by landslides (i.e., the vulnerability). Catalogues and archives of historical landslide events are rare, difficult to construct and expensive. More resources should be allocated to the construction of historical catalogues of landslide events. The catalogues should contain information on all types of landslide consequence (including the population), an important information for determining the vulnerability of the various elements at risk to slope failures.

The general accessibility to GIS software and the increasing availability of geo-environmental databases containing geomorphological, lithological, structural, land-use information, facilitates the attempts at determining the impact of landslide phenomena. Efforts to ascertain quantitatively the impact of slope failures on the population, the built-up environment, the transportation network and the other lifelines should be encouraged at the regional and local scale. When performing such exercises care must be taken in assessing the quality, reliability and consistency of all the thematic datasets, including those showing the location and types of vulnerable elements.

Geomorphologists and other landslide experts should spend more time working in cooperation with economists, decision makers, land developers and concerned citizens to perform landslide risk analyses. This is most important when attempting to determine total risk, a process that includes the comparison and integration of landslide risk assessment with assessments for other natural and man-made hazards. It should be understood that establishing risk levels is a political as much as a technical decision-making process.

5 FINAL REMARKS

The growing population and the expansion of settlements and life–lines over hazardous areas have largely increased the impact of landslides (and other natural hazards) in Europe. Due to the generalized scarcity of economic resources, European Countries are reluctant to invest money in structural measures that can reduce natural risks. Hence, the new issue is to implement warning systems and land utilisation regulations aimed at minimising the loss of lives and property without investing in long–term, costly projects of ground stabilisation. In this framework, landslide identification and mapping, landslide hazard assessments and risk evaluations are a great challenge for scientists, planners, decision makers and land developers.

The European Union faces increasingly complex problems of planning and policy making. These are different from the traditional problems of both pure and applied science. As regards to landslide hazards evaluation and risk determination, on one side geomorphology is unable to provide well-founded theories for hazard assessment, and on the other side environmental issues and policy decisions challenge geomorphologists with very difficult questions. Due to the uncertainties in data acquisition and handling, and in model selection and calibration, landslide hazard evaluation and risk-zoning appear out of the reach of the traditional puzzle-solving scientific approach, based on experiments and on a generalised consensus among experts. Solutions to these challenging problems may come from a new scientific practice capable to cope with large uncertainties, varying expert judgements, and societal issues raised by hazard and risk evaluations. Increasing efforts are needed to make methods for landslide hazards assessment and risk determination more quantitative, better documented and more reproducible, and more resources are required to transfer the scientific information on landslide hazards and risk into planning regulations, building codes and civil defence plans.

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6 REFERENCES

AA.VV. (2002) “Rapporto Conclusivo. Protocollo d’Intesa fra la Regione dell'Umbria ed il CNR-IRPI di Perugia per l'acquisizione di nuove informazioni sui fenomeni franosi nella regione dell'Umbria, la realizzazione di una nuova carta inventario dei movimenti franosi e dei siti colpiti da dissesto, l'individuazione e la perimetrazione delle aree a rischio da frana di particolare rilevanza, e l'aggiornamento delle stime sull’incidenza dei fenomeni di dissesto sul tessuto insediativo, infrastrutturale e produttivo regionale”. CNR-IRPI, Perugia, May 2002, 140 pp., (in Italian).

Agostoni, S., Cardinali, M., Carrara, A., Crosta, G., Fossati, D., Frattini, P., Guzzetti, F., Laffi, R. and Reichenbach, P., (2000) “Assessment of landslide hazard of the Staffora basin (northern Italy) by integrating geomorphological and historical data within a multivariate model”. *25th EGS General Assembly Abstract Volume*, April 2000, Nice (abstract).

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

Cardinali, M., Antonini, G., Reichenbach, P. and Guzzetti, F. (2001) “Photo geological and landslide inventory map for the Upper Tiber River basin”. *CNR-GNDCI Pub. N. 2154,* map at 1:100,000 scale.

Cardinali, M., Carrara, A., Guzzetti, F. and Reichenbach, P. (2002a) “Landslide hazard map for the Upper Tiber River basin”. *CNR-GNDCI Pub. N. 2116*, map at 1:100,000 scale.

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

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

Carrara, A., Cardinali, M., Guzzetti, F. and Reichenbach, P. (1995) “GIS technology in mapping landslide hazard”. In: Carrara, A. and Guzzetti, F. (eds.), *Geographycal Information Systems in Assessing Natural Hazards*. Kluwer Ac. Pub., Dordrecht, The Netherlands, 135-175.

Coe, J.A., Michael, J.A., Crovelli, R.A. and Savage, W.Z. (2000) “Preliminary map showing landslide densities, mean recurrence intervals, and exceedance probabilities as determined from historic records, Seattle, Washington”. *U.S.G.S. Open File Report 00-303*.

Cruden, D.M. (1997) “Estimating the risks from landslides using historical data”. In: Cruden, D.M. and Fell, R. (eds.), *Landslide risk assessment*, Balkema Pub., Rotterdam, 177-184.

Cruden, D.M. and Fell, R., eds. (1997) “Landslide risk assessment”. *Proc. Int. Workshop on Landslide Risk Assessment*, Honolulu, February 1997, Balkema Pub., Rotterdam, 371 p.

Einstein, H.H. (1988) “Landslide risk assessment procedure”. *Proc. 5th Int. Symp. Landslides,* Lausanne, Vol. 2, 1075-1090.

Evans, S.G. (1997) “Fatal landslide and landslide risk in Canada”. In: Cruden, D.M. and Fell, R. (eds.), *Landslide risk assessment,* Balkema Pub., Rotterdam, 185-196.

Fell, R., and Hartford, D. (1997) “Landslide risk management”. In: Cruden, D.M. and Fell, R. (eds.), *Landslide Risk Assessment,* Balkema Pub., Rotterdam, 51-109.

Fookes, P.G., Dale, S.G. and Land, J.M. (1991) “Some observations on a comparative aerial photography interpretation of a landslipped area”. *Quart. J. Eng. Geology*, 24, 249-265

Glade, T. (1998) “Establishing the frequency and magnitude of landslide-triggering rainstorm events in New Zealand”. *Environ. Geology,* 35:2-3, 160-174.

Guzzetti, F. (2000) “Landslide fatalities and evaluation of landslide risk in Italy”. *Eng. Geology*, 58, 89-107.

Guzzetti, F., Cardinali, M. and Reichenbach, P. (1994) “The AVI Project: A bibliographical and archive inventory of landslides and floods in Italy”. *Env. Management*, 18:4, 623-633.

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

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

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

Guzzetti, F., Reichenbach, P., Cardinali, M., Ardizzone, F. and Galli, M. (2002b) “Impact of landslides in the Umbria Region, Central Italy”. Submitted to NHESS.

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

Kong, W.K. (2002) “Risk assessment of slopes”. *Quart. J. Engin. Geol. Hydrogeol.*, 35: 213-222.

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

Soeters, R. and van Westen, C.J., (1996) “Slope instability recognition, analysis and zonation”. In: Turner, A.K. and Schuster, R.L. (eds.), *Landslide investigation and mitigation*. NRC, Transportation Research Board Special Report 247, Washington, 129-177.

Turner, A.K., and Schuster, R.L., eds., (1996) “Landslides: Investigation and Mitigation”. Washington, D.C., NRC, *Transportation Research Board Special Report 247*, 675 pp.

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

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

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

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

Wieczorek, G.F. (1984) “Preparing a detailed landslide-inventory map for hazard evaluation and reduction”. *Bull. Assoc. Eng. Geologists*, 21:3, 337-342.