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Landslide Mapping, Hazard Assessment and Risk Evaluation,Limits and Potential

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ABSTRACT:

In many areas 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, to ascertain landslide hazards and to estimate the risk. Examples and recommendations are given on the basis of the experience gained in studies conducted in central and northern Italy.

INTRODUCTION

Different phenomena cause landslides, including intense or prolonged rainfall, earthquakes, rapid snow melting, and a variety of human activities. On Earth, the volume of mass movements spans 15 orders of magnitude, from a single cobble falling from a rock cliff to gigantic submarine slides. 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 (Cruden and Varnes, 1996). The extraordinary breadth of the spectrum of landslide phenomena makes it difficult to define a single methodology to ascertain landslide hazards and 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 mass movements are larger than those produced by others damaging natural events, including floods, earthquakes and volcanic eruptions. In Italy, a Country for which the information is available, in the period from 1900 to 2003 (104 years) landslides have caused 7,555 casualties, including 5,216 deaths, 85 missing persons and 2,254 injured people. This represents an average of 51 fatalities each year. Fatal landslide events numbered 907, corresponding to a frequency of 8.72 fatal events every year. Limiting the analysis to the post War period (1950-2003), slope failures have caused at least 4,108 fatalities, in 637 landslide events. This figure is much larger than the estimated number of 1,221 deaths and missing persons caused by floods (in 524 events), and comparable to the number of 4,319 deaths and missing persons caused by earthquakes (in 17 events), during the same period (Guzzetti et al., 2004; Salvati et al., 2004).

The main causes and effects of landslides have long been known. Numerous 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 outline some of what I consider to be the inadequacies of the existing approaches to landslides recognition and mapping, hazard assessment, and risk evaluation, and I offer recommendations.

LANDSLIDE RECOGNITION AND MAPPING

Any landslide hazard or risk assessment begins with the collection of information on where landslides are located. This is the goal of landslide mapping. The simplest form of landslide mapping is landslide inventory, which 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 (Guzzetti et al., 2000). For convenience, landslide inventory maps can be classified based on their scale or the type of mapping, i.e., archive, geomorphological, event, or multi-temporal inventories.

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 (Cardinali et al., 1990). Medium-scale landslide inventories (1:25,000 to 1:200,000) are prepared through the systematic interpretation of aerial photographs at print scales ranging from 1:60,000 to 1:20,000 and by integrating local field checks with historical information (Cardinali et al., 2001). 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).

Archive inventories show the location of sites (or areas) affected by historical slope failures. They are a form of landslide database, and are produced by searching chronicles, journals, technical and scientific reports, local archives, or by interviewing experts. For Italy, a landslide archive inventory was compiled for the entire county (Guzzetti et al., 1994; Guzzetti and Tonelli, 2004), and synoptic maps showing the location of historical landslides (and inundations) were prepared at 1:1.200,000 scale (Guzzetti et al., 1996, Reichenbach et al., 1998).

Geomorphological inventory maps are usually prepared through the systematic interpretation of one or two sets of aerial photographs, and limited field checks. They show the cumulative effects of many events over a period of hundreds or even thousands of years. Depending on the extent and complexity of the study area, the abundance and diversity of the landslides, the scale of the aerial photographs, and the skill and experience of the photo-interpreters, they may also show the estimated type of movement (e.g., fall, slide, flow, complex, compound), depth (e.g., shallow, deep-seated), age (e.g., recent, old, very old), and degree of activity (active, dormant, inactive, stabilized) of the slope failures. Estimation of these characteristics requires geomorphological judgement, and introduces uncertainty in the maps. It should be noted that geomorphological inventories are never complete. They show the location of landslides that have left discernable traces in the study area. 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. Figure 1A 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 taken in 1954 and 1977 in the Umbria region, central Italy. The original map was prepared at 1:10,000 scale for an area of 8,456 km^2, and shows more than 45,000 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.

Event inventory maps show the slope failures triggered by a single event, such as an earthquake, rainstorm or snowmelt. They are commonly prepared by interpreting large or medium scale aerial photographs taken shortly after an event, supplemented by field surveys, often very extensive. 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. Figure 1B is an example of an event landslide inventory map. It portrays, for the same area shown in Figure 1A, landslides triggered by prolonged rainfall in the period from 1937 to 1940. The map was prepared by interpreting aerial photographs taken in 1941 at 1:25,000 scale.

Multi-temporal inventory maps are prepared by interpreting multiple sets of aerial photographs of different ages. A multi-temporal inventory not only shows the location and types of failures in an area, but it also portrays their evolution in time. An important information for landslide hazard assessment. Difficulties in preparing a multi-temporal inventory map include: (a) the availability of multiple sets of aerial photographs for the same area, that locally limits the possibility of producing the multi-temporal inventory, (b) the ability to recognize, interpret, and map subtle morphological changes as slope movements, (c) the possibility of mapping landslides of different age (obtained from different flights) on the same topographic maps, which may not portray the topography present on the aerial photographs (every time a landslide occurs it changes topography, locally significantly, but this is not shown in the base map), and (d) be consistent when transferring the information on landslides from the aerial photographs to the base maps and in the GIS, without loosing information or introducing errors (where morphological changes are subtle it may be difficult to map and digitize the changes). To overcome these limitations, multi-temporal inventory maps must be prepared by teams of well-trained, experienced and motivated geomorphologists. Figure 1C is an example of a multi-temporal landslide inventory map. It portrays, for the same area shown in Figures 1A and 1B, landslides identified by interpreting five sets of aerial photographs, taken in the period 1941-1997 at scales ranging from 1:13,000 to 1:70,000, and by field surveys carried out in the period from 2000 and 2004.

The main limitations of all landslide inventory maps refer to their intrinsic subjectivity and to the difficulty of measuring their reliability. 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. 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 inventory maps compiled through the interpretation of aerial photographs, 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 these inventories (geomorphological, event, multi-temporal) depends on many factors, including: (a) landslide freshness and age, (b) the persistence of landslide morphology within the landscape, (c) the type, quality and scale of aerial photographs and base maps, including the scale of the final map, (d) the morphological and geological complexity of the study area, (e) land use types and alterations, (f) the quality of the stereoscopes used to analyse the aerial photographs, and (g) the degree of experience of the interpreter who completes the inventory (Carrara et al., 1992; Fookes et al., 1991, Hansen, 1984).

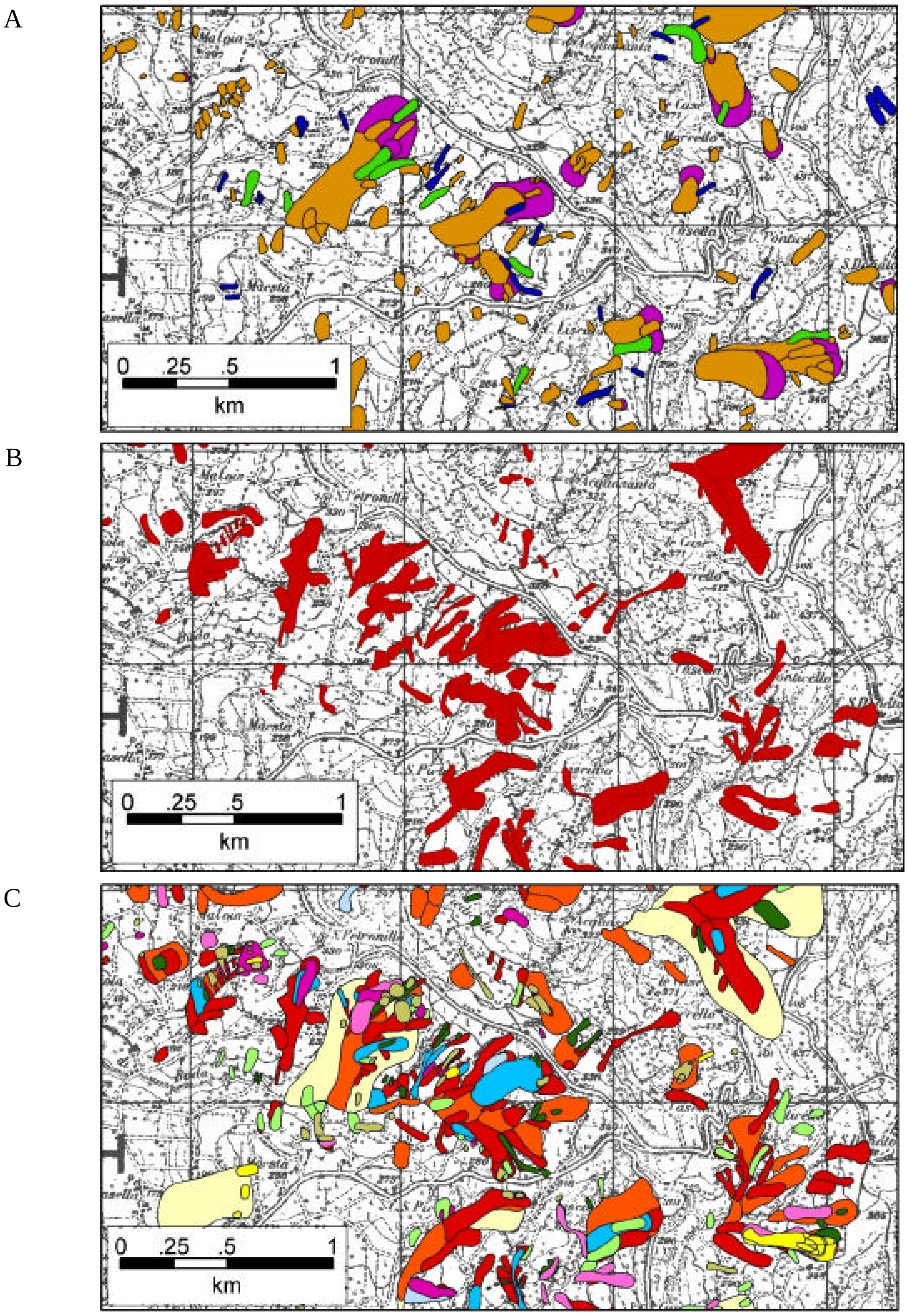

Figure 1. Landslide inventory maps for the Umbria region, central Italy. A) geomorphological inventory; colours indicate landslides of different types. B) event inventory showing landslides triggered by prolonged rainfall in the period 1937-40. C) multi-temporal inventory map prepared by interpreting 5 sets of aerial photographs and extensive filed surveys. Colours indicate landslides of different ages. Original maps at 1:10,000 scale.

Despite the numerous published works dealing with landslide recognition and the production of inventory maps, only a few attempts have been made to assess their reliability and completeness quantitatively (Roth, 1983; Carrara et al., 1992; Ardizzone et al., 2002; van Westen et al., 1999). 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.

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).

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) amended the definition to include the magnitude of the event, i.e. the area, volume, velocity or momentum of the expected landslide. The new definition incorporates the concepts of location, time and magnitude. To fulfil this definition, one has to predict (quantitatively) where a landslide will occur, when, or how frequently it will occur, and how large, fast or destructive the landslide will be.

The definition of landslide hazard is largely accepted, but poses severe 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 trigger (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. At the basin scale, landslides are mostly localised ("point") events controlled by the intensity, duration and extent of the triggering mechanism. At the local (site) scale, landslides are area features controlled by the local morphological, lithological, hydrological, structural and land-use settings. To complicate matters further, these factors vary with time at different rates. Meteorological conditions vary at every events; climate, hydrology and land use change seasonally or over a period of decades; morphology varies rapidly or over a period of centuries; lithology and structure change over periods of thousands to millions of years.

Many methods have been proposed to evaluate landslide hazard spatially (Chung and Fabbri, 1999; Guzzetti et al., 1999; Soeters and van Westen, 1996; Carrara et al., 1995; van Westen, 1994). Two approaches are the most promising: (a) methods based on the statistical analysis of geo-environmental factors related to the occurrence of landslides; and (b) 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 slope movements whose behaviour is easily predicted by simple mechanical laws (e.g., soil slips or rock falls), but they too lack consideration of the temporal aspect of landslides. Models lacking the temporal aspect do not satisfy the definition of landslide hazard adopted by Varnes and the IAEG (1984) or the definition proposed by Guzzetti and co-workers (1999), and should be classified as susceptibility models (Brabb, 1984).

Figure 2 shows an example of a landslide spatial hazard (susceptibility) assessment for the Upper Tiber River basin, in central Italy. Landslide hazard was defined 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 of a 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). 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 spatial hazard map provides the basis for establishing planning regulations aimed at defending the land and the population against landslide hazards.

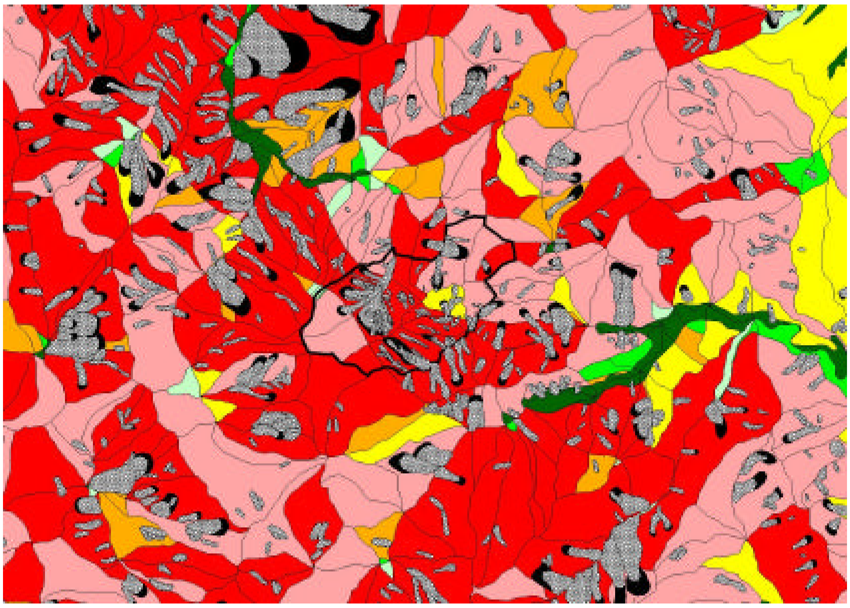

Figure 2. Portion of a statistically-based landslide hazard map for the Umbria region, central Italy (Cardinali et al., 2002a). Hazard levels are shown by five colours, from stable (dark green) to unstable (dark red) slopes. Grey, landslide deposit; Black, landslide crown areas. Original publication scale 1:100,000.

A few attempts have been made to consider time when assessing landslide hazards. Coe et al. (2000) proposed a probabilistic model of landslide occurrence based on a catalogue of historical landslides. Based on the average recurrence interval between successive failures, the model provides the exceedance probability of having one or more landslides in any given area and for any given year. Landslides are considered independent (uncorrelated) events, and a Poisson or a Binomial probability model is adopted to estimate the probability, assuming the mean recurrence interval of landslides will remain the same in the future as it was observed in the past. As an alternative, Guzzetti et al. (2003b), who used a physical model to study rock fall hazard (Guzzetti et al., 2002a), simulated the time effect by launching a large number of boulders from each rock fall source area.

Recently, attempts have been made to prepare landslide hazard assessments that fully complies with the definition of hazards adopted by Varnes and the IAEG (1984) and by Guzzetti and co-workers (1999). At the basin scale, the attempts are based on: (a) the assessment of the spatial hazard (susceptibility) through the multivariate analysis of a set of thematic variables, including morphology, lithology, and land-use; (b) the assessment of the exceedance probability of having one or more landslides for different return periods, based on the observed mean recurrence of landslides obtained by interpreting multiple sets of aerial phorographs; and (c) the determination of probability of experiencing landslides of any given size, through the analysis of the frequency-area statistics of landslides (Guzzetti et al. 2002b; Malamud et al., 2004). At the national scale the efforts relay on: (a) the assessment of the susceptibility through the multivariate analysis of a set of thematic variables, including morphology, lithology, and soil types; (b) the assessment of the exceedance probability of having one or more landslides for different return periods, based on a historical catalogue of landslide events; and (c) an estimate of the event destructiveness, measured by the expected fatalities. The probabilities of: (a) having a landslides given the landscape susceptibility (spatial hazard), (b) occurrence of a slope failures in any give year (time), and (c) of landslide magnitude (size or destructiveness), are taken as independent, and multiplied to obtain the landslide hazard.

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 are 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 Guzzetti et al., 2000).

LANDSLIDE RISK EVALUATION

Risk analysis aims to determine the probability that a specific hazard will cause harm, and it investigates the relationships between the frequency of damaging events and the intensity of their consequences. It seeks to establish thresholds for the individual risk (i.e., the risk imposed by a hazard to any identified individual), and the societal risk (i.e., the risk imposed by a hazard on society). According to Varnes and the IAEG (1984) landslide risk evaluation aims to determine the "expected degree of loss due to a landslide (specific risk) and the expected number of live lost, people injured, damage to property and disruption of economic activity (total risk)".

Quantitative (probabilistic) and qualitative (heuristic) approaches are possible to determine landslide risk. Quantitative landslide risk assessment aims to establish the probability of occurrence of a catastrophic event, the probability of live losses (Fell and Hartford, 1997; Evans, 1997; Guzzetti, 2000; Kong, 2002; Guzzetti et al., 2004b), or the expected damage due to a slope failure (Brunce et al., 1997; Hungr et al., 1999; Budetta, 2002; Guzzetti et al., 2004a). Establishing the probability of a loss requires a catalogue of landslides and their consequences. A few of such lists have been prepared for damage to the population, i.e., deaths, missing persons, injuries, homeless and evacuees (Evans, 1997;

Guzzetti, 2000; Kong, 2002; Guzzetti et al., 2004b). 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-consequences plots showing the number of fatalities in each event versus the frequency of the event, on a log-log scale, can be prepared and the frequency or probability of the event can be estimated (societal risk). Alternatively, mortality rates (i.e., the number, or the average number, of deaths per 100,000 of any given population over a pre-defined period) can be established (individual risk). Acceptable levels of societal and individual risk can be determined by comparison with other natural or human-induced hazards, including societal (e.g., homicides, workplace accidents, overdoses), and technological (e.g., car, train and airplane accidents) hazards and the leading medical causes of deaths for which risk levels have been established (Fell and Hartford, 1997; Salvati et al., 2003; Guzzetti et al., 2004b). The completeness and time span of the landslide catalogue greatly affect the reliability of such quantitative risk assessments.

Attempts have also been made to evaluate quantitatively the risk to vehicles or to people travelling along roads subject to landslide hazards (Pierson et al., 1990, Bunce et al., 1997, Hungr and Beckie 1998, Hungr et al., 1999, Budetta 2002). The “Rockfall Hazard Rating System”, developed by the Oregon Highway Division (Pierson et al., 1990), uses a simple approach to estimate rock fall risk based on the calculation of the Average Vehicle Risk (AVR). The AVR measures the percentage of time a vehicle will be present in a rock fall hazard zone. The measure is based on the length of the hazard zone, the percentage of a vehicle that at any time can be expected to be within the hazard zone, the average daily traffic, and the posted speed limit.

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 (uneconomical or impossible). 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 and their consequences 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. (2002b) described an attempt to determine qualitative risk levels based on the geomorphological interpretation of multiple 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. The method involves: (a) the definition of the extent of the study area; (b) the production of a multi-temporal landslide inventory map; (c) the definition of landslide hazard zones; (d) the landslide hazard assessment; (e) the identification and mapping of the elements at risk and of their vulnerability; and, (f) the evaluation of landslide risk. Levels of specific landslide risk are shown using a three-digit positional index. The right digit shows the landslide intensity, the left digit shows the landslide frequency, and the left digit shows the expected damage. The positional index expresses landslide hazard and risk by keeping the components of the hazard and risk separate. This facilitates landslide hazard and risk zoning by allowing the user to understand whether the risk is due to a high frequency of landslides (i.e., high recurrence), a large intensity (i.e., large volume and high velocity), or a large vulnerability (i.e., total destruction expected). Figure 3 shows an example of specific risk assessment for the village of Collevalenza (Umbria region). Landslide risk was determined for deep-seated (Figures 3A and C), and for shallow (Figures B and D) landslides.

An alternative to qualitative risk assessment is the analysis of the impact that slope failures may have (or have had) in a given area. This can be accomplished in two ways.

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; Salvati et al., 2003). 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 (Garberi et al., 1999; Brabb et al., 2000; Guzzetti et al., 2003a).

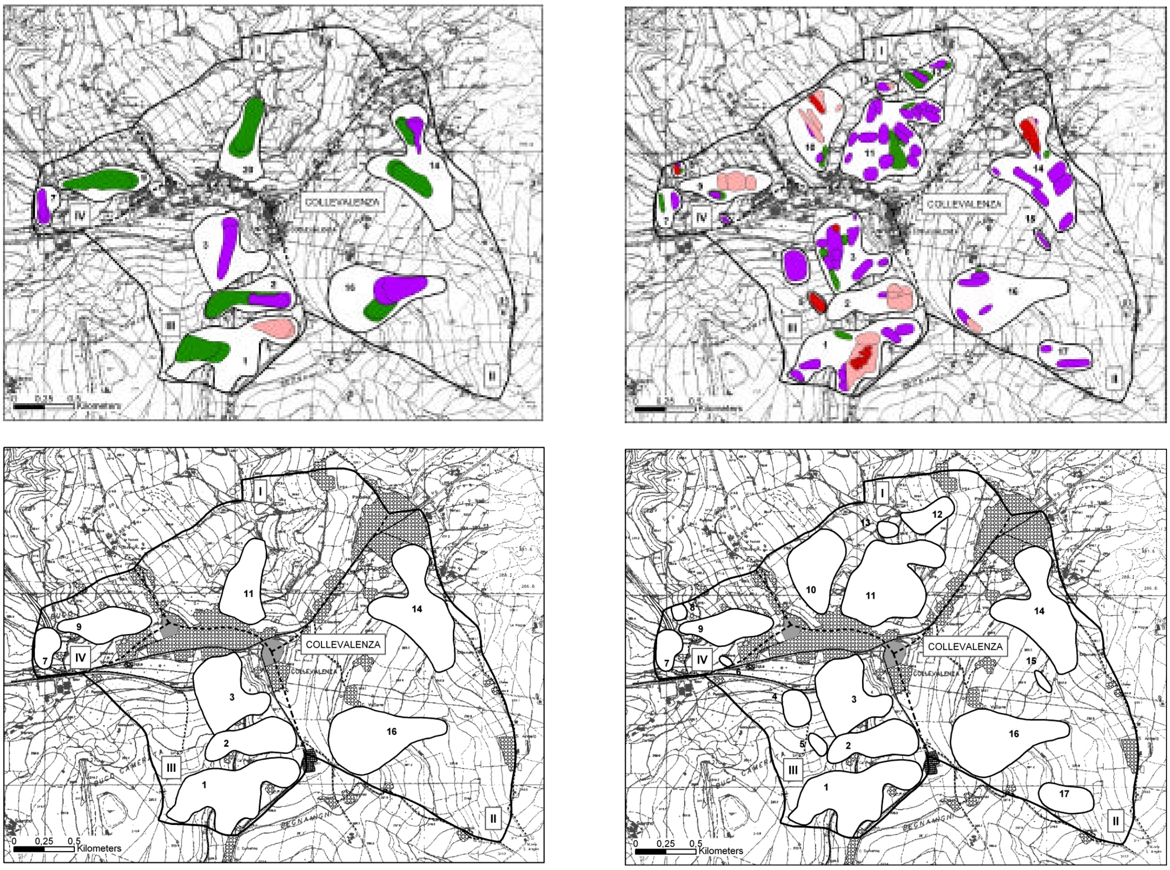

Figure 3. Collevalenza, Umbria region. Maps A and B are multi-temporal inventories for deep-seated and shallow landslides, respectively. Colours indicate landslides of different ages. Maps C and D show landslide hazard zones (LHZ) for deep seated and shallow landslides, respectively. Vulnerable elements within a LHZ are at risk. For each vulnerable element specific landslide risk is expressed using a three-digit positional index (not shown).

Figure 4 and 5 show the results of an attempt aimed at ascertaining the possible impact of landslides on the built-up areas and the transportation network in the Umbria region of central Italy (Guzzetti et al., 2003a). The intersection in a GIS of a detailed geomorphological landslide inventory map compiled at 1:10,000 scale and showing more than 45,000 landslides, 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

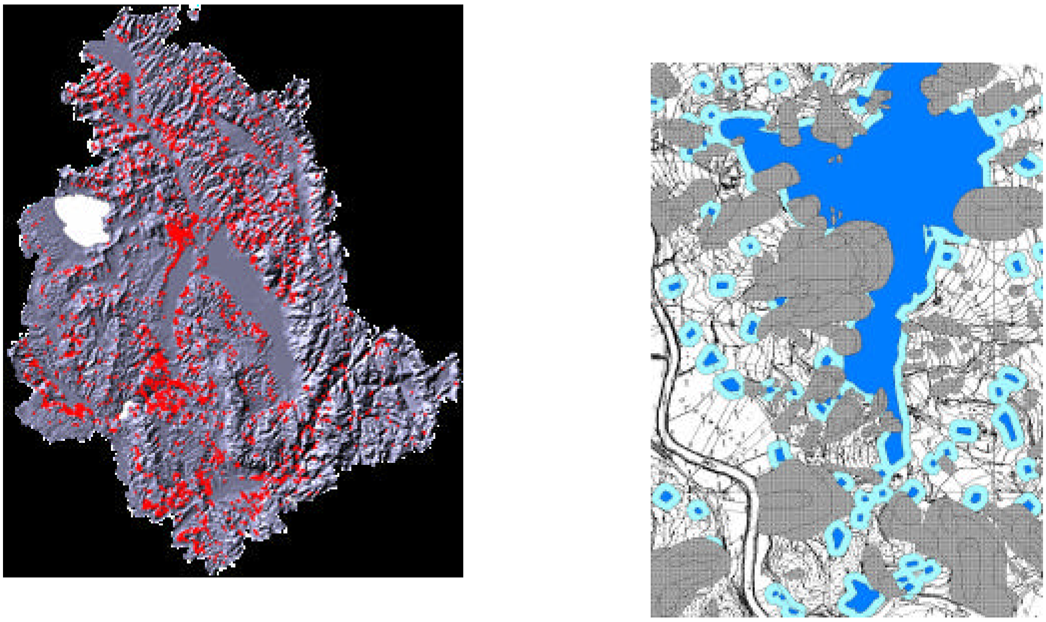

Figure 4. Umbria region, central Italy. Expected impact of landslides on the built-up areas. Left: location of 6,119 sites (red dots) where landslides intersect built-up areas. Right: enlargement showing GIS analysis. Grey areas are landslide source and deposition areas. Blue shows built-up areas. Light blue shows buffer zone around built-up areas. Original map scale 1:10,000.

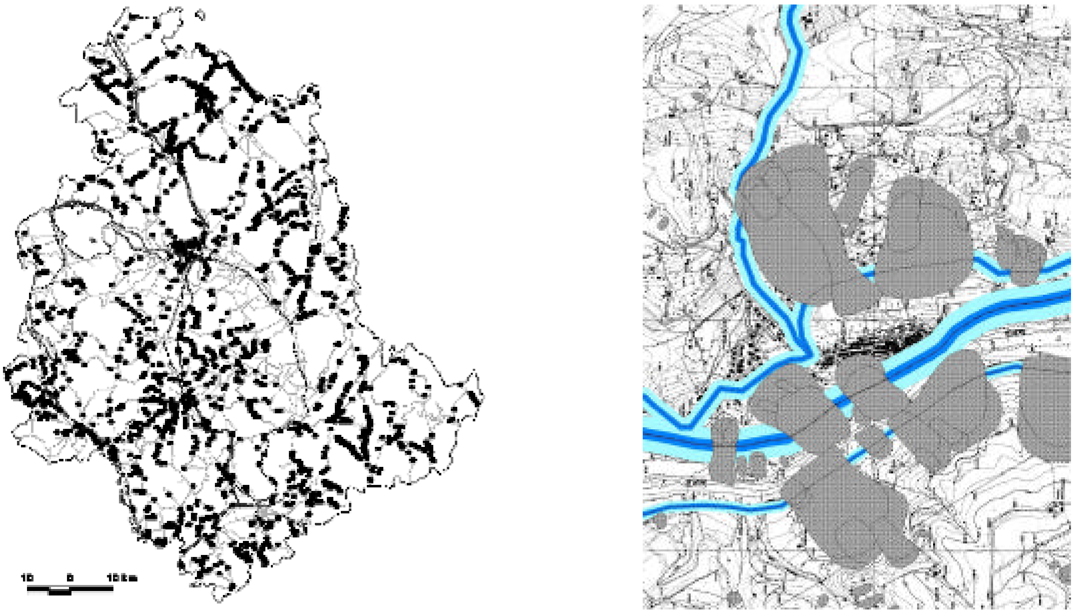

Figure 5. Umbria region, central Italy. Expected impact of landslides on the transportation network. Left: location of 4,115 sites (black dots) where landslides intersect roads or railways. Right: enlargement showing GIS analysis. Grey areas are landslides (crown and depositional areas). Blue shows roads of various categories. Light blue shows buffer zone around the roads. The extent of the buffer varies with the type of road. Original map scale 1:10,000.

(Figure 4), and 4,115 sites where landslide intersect roads or railways (Figure 5). Intersection between the geographical information on landslides and on the vulnerable elements was performed in two ways: (a) considering the know (mapped) area extent of the landslides and the vulnerable elements, and (b) considering a buffer of variable width around the vulnerable elements. Where landslides intersect, or are very close to structures and infrastructure damage due to slope failures can be expected, particularly during major landslide triggering events (e.g., prolonged or intense rainfall, snowmelt events, earthquake, etc.).

RECOMMENDATIONS

In this section, I propose recommendations for the preparation and use of landslide inventory maps, landslide hazard assessments and landslide risk evaluations. I base the recommendations on the experience gained in landslide studies carried out in Italy in the last fifteen years.

LANDSLIDE MAPPING

Landslide cartography is a mandatory step for any hazard or risk investigation. Landslide inventory maps should be prepared for large areas (i.e., entire river basins, provinces or regions), or even for entire countries, using consistent and reproducible methods. Good quality, geomorphological inventory maps provide unique information on the distribution and abundance of landslides, and supply valuable data 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 and risk assessments, 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, and are difficult to prepare consistently.

Stereoscopic aerial photographs taken from airplanes (or high-resolution, stereoscopic or pseudo-stereoscopic optical images of comparable resolution taken form satellites) should systematically be acquired after a landslide-triggering event. Images taken immediately after an event provide unique information on the type and extent of damage, including landslides, caused by the event, at a cost that is usually a fraction of any ground based investigation or remedial effort. It is equally important that aerial photographs or satellite images of similar quality be obtained after large magnitude events, affecting a large territory, and moderate or slight magnitude events, affecting only a limited area. Where such information is available, accurate landslide inventory maps should be prepared after each landslide-triggering event (e.g., a rainstorm, a prolonged period of rain, an earthquake, or a snowmelt event). The event inventory should cover the entire territory affected by the event, and should be prepared thought the careful scrutiny of stereoscopic aerial photographs (or satellite imagery of comparable ground resolution) taken immediately after an event, aided by field surveys. 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. The extent and magnitude of the landslides triggered by the extreme events can be described quantitatively using frequency-size (i.e., area, volume) statistics of the triggered landslides (Guzzetti et al., 2002b; Malamud et al., 2004). This information allows comparing the ground effects produced by different triggers.

For many areas in the world, stereoscopic aerial photographs are available since about the mid 1950's, and in a few places earlier than that. Where multiple sets of aerial photographs taken at different dates are available, multi-temporal landslide inventory maps can be completed to estimate the local landslide recurrence, and to investigate the spatial relationships between failures of different ages and types. Multi-temporal inventory mapping should be pursued wherever information on the short-term

(25-50 years) evolution of slopes is important (or mandatory) to correctly map the landslides, to evaluate the hazards, and to ascertain the associated risk. However, preparing multi-temporal maps is a difficult and time consuming operation, that requires well trained, motivated geomorphologists. For this reason, efforts should be made to train personnel capable of preparing, maintaining and using multi-temporal landslide inventory maps.

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 (Coe et al., 2000; Guzzetti et al., 2003a), mandatory information to properly assess landslide hazards and risk. Maintaining information on landslides and their consequences can be done at different levels of completeness, ranging form the compilation of simple lists showing the date of occurrence of an event and the consequences (e.g., the number of casualties), to the production of complex landslide databases, recording topographical, morphological, lithological, geotechnical, etc., information on individual and multiple slope failures. An ideal landslide record should be "long" and "comprehensive", i.e., it should span many years and it should contain information on all aspects of the landslide phenomenon. However, due to time, financial and other constrains this is rarely (or never) possible. Organizations and individuals interested in compiling landslide records should tailor their efforts to the available resources and abilities, aiming at constructing longer catalogues rather than complex but less extended databases.

Completeness, resolution and reliability (i.e., quality) of the landslide inventory maps and of the landslide records should always 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, level of experience of the investigators, time required, and extent of field checking, 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. Knowing the characteristics of a landslide catalogue, including completeness, sources and methods used to compile the information, is important when using the landslide record to estimate landslide hazards or risk.

LANDSLIDE HAZARD ASSESSMENT

The experience gained in preparing landslide susceptibility and hazard maps in Italy has shown that 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. Authors seem to be more interested in experimenting methods, often not even new, to estimate landslide hazards, rather than spending time and resources to obtain reliable landslide maps and high quality thematic information, or to validate the results of the hazard models scientifically. If the practice can be tolerated in an academic environment, where results do not necessarily have an impact on society, it cannot be accepted for regional and national Geological Surveys or for planning agencies, whose task is to provide reliable information to the planners and decision makers, with the aim of establishing policies that may directly effect the life of individuals or the economy of a region. For these Institutions and Organizations the quality and reliability of the results of a hazard assessment are (at least) as important as the methods used to obtain them.

The work carried out in Umbria has shown that landslide hazard models and maps can be prepared at scales suitable for land planning for areas extending thousands of square kilometres, using detailed geomorphological information, and at scales ranging from 1:10.000 to 1:25.000 (Cardinali et al., 2001; 2002a). Based on this experience, I recommend landslide hazard models and maps 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 records 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, poorly formalized 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, using external information (e.g., the age of the oldest landslides in a region). Where geomorphological and thematic information is not adequate to prepare a hazard model, or where the model cannot be verified quantitatively (scientifically), it is better to base land planning on a simpler form of landslide cartography (e.g., landslide density maps) rather than using ill-formalized, unreliable models (Guzzetti et al., 2000).

LANDSLIDE RISK ASSESSMENT

Landslide risk assessment is the ultimate goal of any landslide investigation aimed at reducing the negative consequences of slope failures. Specific and total landslide risk studies should be performed, quantitatively and qualitatively, at local, regional and national scales. Not enough examples of 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. Application of established methods to define individual and societal risk levels should be encouraged, and results should be compared with quantitative estimates available for other natural (e.g., earthquakes, floods, volcanic eruption, snow avalanches, etc.), societal (homicides, workplace accidents, overdoses), and technological (car and airplane accidents) hazards and for the leading medical causes of deaths.

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 (the consequences) caused by landslides (i.e., the vulnerability). Systematic records of historical landslide events and their consequences 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 damage to 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 and thematic databases containing geomorphological, lithological, structural, land-use information, facilitates the attempts at determining the impact of landslide phenomena (Guzzetti et al., 2003a). 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.

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.

DISSEMINATION

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 (Guzzetti and Tonelli, 2004). In this context, Web-GIS technology appears promising (Brabb et al., 2000, http://maps.irpi.cnr.it). 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.

CONCLUDING REMARKS

The growing population and the expansion of settlements and life-lines over hazardous areas have increased the impact of natural hazards, including landslides, worldwide. In industrialized countries, the generalized shortage of economic resources hampers systematic, long term investments in structural measures to substantially reduce the risk posed by natural hazards. For landslides the problem is especially difficult. Individual remedial measures can be very expensive, and most commonly mitigate the risk only in limited areas, often a single slope, making it economically impossible to lessen the hazards over large areas. In developing countries societal and economic problems are often so large and serious that little attention is posed to the negative effects of natural hazards in general and of landslides in particular. In these countries, the limited resources are invested primarily to improve health and education or to promote the economy, and little remains available to mitigate the catastrophic effects of natural hazards, including slope failures. In many areas the new issue seems to be the implementation of warning systems, and new regulation for land utilisation 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 hazards assessments and risk evaluations are a great challenge for scientists, planners, decision makers and land developers.

Many countries face increasingly complex problems of planning and land-use policy making. These are different from the traditional problems of both pure and applied science (Guzzetti et al., 1999). As regards to landslide hazards assessment and risk evaluation, on one side geomorphology is unable to provide well-founded theories for hazard evaluation, and on the other side environmental issues and policy decisions challenge geomorphologists with very difficult questions. Due to the large spectrum of landslide phenomena, and 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 additional resources are needed to transfer the scientific information on landslide hazards and risk into planning regulations, building codes and civil defence plans. Increasing the awareness of the hazards posed by landslides, including their potential consequences, is the first step in risk mitigation.

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