10. CONCLUSION AND FINAL RECOMMENDATIONS

The player's attention is on the instrument,
a composer thinks to the whole opera.

We don't use good advice.
We just pass it to others.

In this last chapter, I draw the conclusions and I propose general recommendations for the preparation and use of landslide inventory maps, of landslide susceptibility and hazard assessments, and of landslide risk evaluations. I draw my conclusions on what I have presented and discussed in the previous chapters, and I propose the recommendations based on the experience gained in landslide studies carried out mostly in Central Italy in the last twenty years.

10.1. Landslide mapping

Landslide mapping (or "landslide inventory making") is a mandatory step for any rational and effective landslide investigation aimed at zoning a territory on landslide susceptibility, at ascertaining landslide hazards, or at determining landslide risk. In § 3, I have illustrated the characteristics, advantages and limitations of different types of landslide inventories, including archive inventories, geomorphological maps, event-inventory maps, and multi-temporal landslide maps. The latter represent the most advanced form of landslide inventory. In § 4, I have shown how to analyze the information portrayed in landslide inventories to: (i) ascertain the spatial distribution and abundance of landslides (through the construction of density maps), (ii) ascertain the temporal frequency of slope failures, (iii) compare different inventories quantitatively, and (iv) evaluate the completeness and reliability of the available landslide inventory maps. In the other chapters, I have demonstrated the use of landslide inventory maps to: (i) determine the frequency-size statistics of landslides, important information for erosion analysis, for landscape modelling, and for landslide hazards and risk evaluations (§ 5), (ii) prepare models for the appraisal and zoning of landslide susceptibility (§ 6), (iii) determine landslide hazards (§ 7), and (iv) to evaluate landslide risk (§ 8).

Good quality, reliable geomorphological landslide inventory maps provide knowledge on landslide distribution, abundance, types and patterns in a region. Geomorphological inventory maps: (i) are used to zone the landslide susceptibility in large and complex regions (e.g., § 6.4; Cardinali *et al*., 2001, 2002b), (ii) supply valuable data to study the relationships between the lithological and structural settings and the landslide types and pattern (Guzzetti *et al.*, 1996), and (iii) can be used to determine the possible impact of landslides on the structures, the infrastructure, or the agriculture (e.g., § 8.5.2; Guzzetti *et al*., 2003). Despite the fact that geomorphological inventory maps prove extremely valuable for susceptibility, hazard and risk studies – particularly over large areas – review of the literature shows that such products are rare. The reasons for this shortcoming are manifold, and include inability of environmental and planning agencies to understand the value of regional geomorphological inventories (Brabb, 1996), the difficulty of preparing landslide maps over large areas accurately and consistently (Guzzetti *et al*., 2000), and the complexity of building reliable geographical databases containing landslides, lithological, and structural information for large regions (Carrara *et al*., 1999). The experiments conducted in Umbria (§ 3.3.2.2; Antonini *et al*., 2002a; Guzzetti *et al*., 2003) and in the Upper Tiber River basin (Cardinali *et al*., 2001, 2002b) have demonstrated that a team of qualified geomorphologists can prepare reliable geomorphological inventory maps for large regions, at a cost comparable to – or lower than – the cost for the acquisition of other environmental information (e.g., geological, soil or land use mapping). Based on this experience, ***I recommend that geomorphological landslide inventory maps are prepared for large territories (e.g., a large river basin, a province, a region) and even for entire countries, using proper mapping methods and tools*** (e.g., photo-interpretation techniques aided by field surveys).

The experience gained in the Umbria Region, where detailed, large-scale (i.e., 10,000 scale) geomorphological landslide inventory maps were prepared for large areas (§ 3.3.2.2), has demonstrated that the landslide and the topographic information are strictly coupled, and that landslides should be shown only with the topographic maps used to prepare the inventory. Where this is not possible, information should be given to the user of the landslide inventory on the type, date and cartographic characteristics of the map used to identify and map the landslides, and of the base map used to portray or publish the landslide information. This cartographic recommendation is valid for all types of inventories, including the event and the multi-temporal maps, and applies particularly to landslide inventories shown or distributed in digital format, e.g. http://maps.irpi.cnr.it.

Event inventory maps prove extremely important for a variety of applications, including: (i) establishing the extent, abundance and types of slope failures triggered by a single event or by multiple events (e.g., § 3.3.3; Antonini *et al.*, 2002b; Cardinali *et al*., 2000, 2005; Guzzetti *et al*., 2004), (ii) determine the extent of damage caused by a triggering event on the population, the structures and the infrastructure (e.g., § 3.3.3.4; Guzzetti *et al*., 2003a; Cardinali *et al*., 2005), (iii) determine the frequency-size (i.e., area and volume) statistics of landslides in a region (§ 5; Guzzetti *et al.*, 2002b; Malamud *et al.*, 2004a), (iv) contribute to the production of multi-temporal inventory maps (e.g., § 3.3.4, § 7.3), and (v) to the verification of landslide susceptibility, hazard and risk assessments (e.g., 6.5.1.7). For these reasons, ***I recommend that accurate event inventory maps are prepared after each landslide triggering event*** (e.g., a rainstorm, a prolonged period of rain, an earthquake, or a rapid snowmelt event).

To prepare an event inventory map, recent (with respect to the event) stereoscopic aerial photographs taken from airplanes (or high-resolution, stereoscopic or pseudo-stereoscopic optical images of comparable resolution taken from satellites) must be available. ***I*** further ***recommend that such remotely-sensed images are systematically taken immediately 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 a fraction of any remedial effort. It is equally important that aerial photographs be obtained after large magnitude events, affecting a large territory, and moderate or slight magnitude events, affecting only a limited area.

Field surveys should also be conducted after an event, to: (i) obtain reliable landslide information (i.e., "ground truth") to guide the interpretation of the aerial photographs, (ii) obtain information not or poorly visible on the available aerial photographs, (e.g., to map landslides under a thick forest cover or landslides too small to be shown on the aerial photographs, or to determine the thickness of the failed material), (iii) estimate the completeness of an inventory obtained solely from the interpretation of the aerial photographs, and (iv) update an inventory prepared from the interpretation of aerial photographs. The event inventories should cover the entire territory affected by the event, and not only a part (often small) of the affected area. When this is not possible (e.g., for lack of resources), an estimate of the area affected by the landslides should be given, and a clear distinction should be made between areas where landslides were mapped systematically, areas where landslides were mapped un-systematically (e.g., only along the roads), and areas where slope failures were not searched.

Multi-temporal landslide inventory maps represent the most advanced and sophisticated form of a landslide inventory. They show landslides of different types and ages, allowing for the combined investigation of the spatial and temporal evolution of the slope failures in an area. The latter analysis provides very useful information for landslide hazard studies (§ 7.3, Guzzetti *et al*., 2005a) and for geomorphologically-based landslide risk assessments (§ 8.4; Cardinali *et al*., 2002a; Guzzetti *et al*., 2004; Reichenbach *et al*., 2005). In a good quality multi-temporal inventory map, landslides of different dates or periods are classified according to the type of movement, and the estimated age, activity, depth, and velocity – at the date of the aerial photographs or field investigations (e.g., 3.3.4.1; Galli *et al*., 2005). For many areas in the world, stereoscopic aerial photographs are available since about the mid 1950's, and in 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. ***I recommend that multi-temporal inventory mapping is pursued wherever information on the short-term*** (e.g., 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***.

The experience gained in the preparation of multi-temporal landslide maps in the Staffora River basin (§ 7.3, Guzzetti *et al*., 2005a), in the Collazzone area (§ 3.3.4.1, 6.5.1; Galli *et al*., 2005), and at other sites in Umbria (§ 8.4; Cardinali *et al*., 2002a; Guzzetti *et al*., 2004; Reichenbach *et al*., 2005), has demonstrated that obtaining a reliable multi-temporal inventory is a difficult and time consuming operation. In the production of a multi-temporal inventory, great care must be taken in the location of landslides of different dates or periods, and in identifying areas where local morphology has changed in response to mass movements, avoiding interpretation errors due to land use modifications or to the different views provided by aerial photographs taken at different dates. This is not an easy task (§ 3.3.4.1). For this reason, ***I recommend that multi-temporal inventories are prepared only where sufficient geomorphological competence and information exist, including the availability of multiple sets of aerial photographs. I*** further ***recommend that efforts are made to train personnel capable of preparing, maintaining and using multi-temporal landslide inventory maps***.

Multi-temporal inventories are expensive maps, when compared to other types of landslide inventories. In Umbria, an area for which inventory maps of different types are available (§ 3.4.1) the rate of photo-interpretation for a multi-temporal map was found 13-time higher than the rate for a detailed regional geomorphological map, and 60-time higher than the rate for a regional reconnaissance map. These figures indicate that multi-temporal inventory maps can effectively be prepared only for limited areas, where the added value of the combined analysis of spatial and temporal information is important (e.g., where landslide hazard or risk have to be determined).

Record of historical landslide events provide useful information, e.g. to: (i) determine the temporal frequency (or the recurrence) of landslide events in a region (§ 4.5, Guzzetti *et al.*, 2003a), (ii) ascertain landslide hazard at the national scale (§ 7.4), (iii) determine societal and individual risk levels at the regional or national scale (§ 8.3.1), or (iv) ascertaining the most common type of damage caused by slope failures in a region (§ 8.5). Regional and national Geological Surveys, environmental and planning agencies, civil defence offices, and other concerned organizations should keep records of the landslides and the landslide events that have occurred in historical times in any given area. 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, Guzzetti, 2000; Salvati *et al*., 2003), to the production of complex landslide databases, recording topographical, morphological, lithological, geotechnical, etc., information on individual and multiple slope failures. An ideal historical 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. ***I recommend that organizations and individuals interested in compiling landslide records tailor their efforts to the available resources and abilities, aiming at constructing longer catalogues rather than complex but less extended databases*** (Guzzetti *et al*., 2000).

Landslide inventory maps are very effective products that can – and should – be prepared for small and large areas (i.e., entire river basins, provinces or regions), and even for entire countries, for the benefit of many. To prepare landslide inventories, consistent and reproducible methods should be adopted, as the reliability and quality of the adopted methods influence the quality of the final product. Completeness, resolution and reliability of the landslide inventory maps (of all types) and of the landslide historical records, should always be ascertained. ***I recommend that***, 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, are clearly 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 susceptibility, hazard or risk.

A recognized limitation of landslide inventory maps refers to their intrinsic subjectivity, and to the difficulty of measuring their quality (Guzzetti *et al*., 2000; Malamud *et al*., 2004a). Absolute criteria to establish the quality of landslide inventory maps have not been established, and the quality of a landslide inventory is ascertained in relative terms, i.e., by comparison with other inventories (§ 3.4). In general, comparisons should be aimed at establishing how well the different inventories: (i) describe the location, type, and abundance of the landslides in the investigated region (§ 4.2, § 4.3), (ii) can be used to determine the statistics of landslide areas (§ 5), and (iii) provide reliable information to construct landslide susceptibility models (§ 6). ***Where two*** (or more) ***landslide inventory maps are available, I recommend that the maps are compared to assess: (i) the extent of the cartographic***

matching between the maps, (ii) the differences in the abundance and distribution of the mapped landslides, (iii) the frequency-size (i.e., area, volume) statistics of the mapped landslides, and (iv) the performance of the inventory maps as predictors of landslide susceptibility or landslide hazard. To reach these goals, specific tests are available. Pair-wise analysis of the mapped landslides in a GIS allows for testing the degree of cartographic agreement (or disagreement) between two maps (§ 4.2.2). To quantify the geographical correspondence, specific mapping error and map matching indexes can be computed. Drawing confidence belts of different sizes around the mapped landslides helps determining the proportion of the mismatch due to drafting and other cartographic errors, from map differences due to diverse geomorphological interpretations (§ 4.2.2). Simple geographical operations in a GIS allow for quantifying the differences in the abundance of the mapped landslides. For the purpose, a geomorphologically meaningful subdivision of the terrain is required. Slope units proved to be particularly suited for the scope, but other terrain subdivisions can be adopted. To summarize the differences, contingency tables and specific plots can be prepared. The frequency-area statistics of landslides can be obtained from digital catalogues of landslide areas (§ 5). In preparing the catalogues, care must be taken in defining the area of the individual landslides (Malamud *et al*., 2004a). Estimating the probability density or the frequency density of landslide area from an empirical distribution is not a trivial exercise. Care must be taken in the application of the obtained statistics, considering the errors (i.e., the levels of uncertainty) associated with the statistics (Guzzetti *et al*., 2002; Malamud *et al*., 2004a). Lastly, the significance of a landslide map as a source of information to assess landslide susceptibility can be established by comparing a susceptibility model prepared using the map to be tested against a second susceptibility model prepared using the same set of thematic data and different (more reliable) landslide information (Galli *et al*., 2005). Again, to summarize the differences between different susceptibility models, contingency tables and plots can be prepared.

10.2. Landslide susceptibility zoning

Landslide susceptibility is the likelihood of a landslide occurring in an area on the basis of the local terrain conditions (Brabb, 1984). It is the degree to which a terrain can be affected by slope movements, i.e., an estimate of “where” landslides are likely to occur in the future. In § 6, I have discussed the – numerous – methods proposed in the literature to ascertain landslide susceptibility, including a description of the applicable terrain subdivisions (i.e., the “mapping units”). I have then introduced a probabilistic model for landslide susceptibility, discussing problems and difficulties in its application, and presenting an example for the Upper Tiber River basin (§ 6.4). Lastly, I have discussed the problem of the verification of the performances and the prediction skills of a landslide susceptibility model. To illustrate the concepts and the proposed solutions, I have shown an example of a complete verification of a landslide susceptibility model prepared for the Collazzone area (§ 6.5.1).

The literature on landslide susceptibility assessment is vast (§ 6.1 and § 6.2), indicating a considerable interest for the topic worldwide. In Italy, several examples exist of landslide susceptibility assessments at various scales and in different physiographic regions. The Italian examples range from the pioneering work of Carrara (1983), who was essentially the first to introduce sound, classical statistical methods to determine landslide susceptibility, to modern examples exploiting GIS technology and large thematic databases, some of which cover areas extending for thousands of square kilometres (Cardinali *et al*., 2002b). The experience gained in preparing landslide susceptibility models and maps in Italy (e.g., Carrara, 1983; Carrara *et al.*, 1991, 1995, 1999, 2003; Guzzetti *et al.*, 1999a, 2000; Ardizzone *et al.*, 2002; Clerici *et al*., 2002; Donati and Turrini, 2002; Cardinali *et al.*, 2002b; Sorriso-Valvo, 2005; Guzzetti *et al*., 2005a,d) has shown that the quality and reliability of a landslide susceptibility assessment depend more on the quality, resolution, completeness and reliability of the thematic information used to ascertain the susceptibility, than on the classification method used to complete the susceptibility assessment. In order words, quality of the landslide and thematic information is more important than the type of modelling approach. Based on this result, ***I recommend that resources are invested in the acquisition of high-quality information that is relevant to the distribution and characteristics of landslides in a study area***. This is not a trivial or inexpensive task. In places, establishing what type of thematic information to collect to successfully ascertain landslide susceptibility is not obvious. The search for relevant parameters should be tailored to the complexity of the study area and the type of landslides to be investigated. Unreliable, badly formulated, low-quality data should not be used to ascertain landslide susceptibility, and investigators should refrain from using “whatever information is available” to construct a landslide susceptibility model. Unfortunately, review of the literature suggests that this is often the case. Many authors seem to be more interested in experimenting classification methods, often not even new, to estimate landslide susceptibility, rather than spending time and resources to obtain reliable landslide inventory maps and high quality thematic information. In addition, authors appear even less interested in obtaining data necessary for the verification of the obtained susceptibility models. If this practice can be tolerated (but certainly not applauded) in an academic environment, where results do not necessarily have a direct and immediate 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 landslide susceptibility zoning are (at least) as important as the methods used to obtain the zoning.

The work carried out in the central and northern Apennines has also shown that landslide susceptibility models and maps can be prepared at scales suitable for land planning and for areas extending from several tens to few thousands of square kilometres, using detailed geomorphological and thematic information at scales ranging from 1:10,000 to 1:25,000 (e.g., Cardinali *et al.,* 2001; 2002a). Based on this experience, ***I recommend that landslide susceptibility models and maps are 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 different physiographical environments in Italy and elsewhere have proved that these methods provide the most reliable, quantitative results.

Models for landslide susceptibility zoning are forecasts of the spatial occurrence of landslides that, like any other forecast, should always be verified. Inspection of the literature reveals that only recently a handful of authors have began considering the problem of the verification / validation of landslide susceptibility assessments, and have started publishing susceptibility models together with their quantitative verifications (§ 6.5). Lack of proper quantitative model validation may explain why planners, land developers and decision makers are reluctant to adopt landslide susceptibility zoning. ***I recommend that the quality, reliability and sensitivity of landslide susceptibility model and map are always carefully verified and tested***. This should be accomplished by checking the model results against good quality inventory maps. ***I*** further ***recommend that a landslide susceptibility model is tested to: (i) determine the degree of model fit, (ii) establish the aptitude of the thematic information to construct the model, including an assessment of the sensitivity of the model to changes in the landslide and the thematic information used to construct the model, (iii) determine the error associated with the probabilistic estimate obtained for each mapping unit, and (iv) verify the skill of the model prediction to forecast "future" landslides***. The latter, can only be accomplished using landslide information not available to construct the susceptibility model.

In § 6.5.2, I have discussed criteria for comparing and ranking the quality of landslide susceptibility assessments. ***I recommend that*** such ***criteria are adopted for evaluating the quality of all susceptibility models***. Based on the proposed criteria, when no information is available on the quality of a landslide susceptibility model (when no verification test is conducted) the obtained susceptibility product has the lowest possible level of quality (level 0). This level of quality should be considered unacceptable. When estimates of model fit – i.e., the ability of the model to replicate the known distribution of (past) landslides – are available, the susceptibility assessment has the least acceptable quality level (level 1). When a quantitative estimate of the error associated with the predicted susceptibility value for each mapping unit is available, the susceptibility assessment has a higher level of quality (level 2). Lastly, when the prediction skill of the model is known – i.e., the ability of the model to predict the location of new (future) landslides –, the susceptibility assessment has a still higher quality rank (level 4). The proposed scheme allows summing the individual quality levels, making available a flexible and comprehensive system for ranking the quality of landslide susceptibility predictions, provided acceptance thresholds are established. Defining acceptance thresholds for all the proposed verification tests which are valid for different study areas is not a trivial task. Much work needs to be done in this area.

I provide a last recommendation for landslide susceptibility assessments. ***Where landslide, geomorphological and environmental information is not available, or is not of adequate quality to prepare a reliable susceptibility model, or where the susceptibility model cannot be verified quantitatively, it is perhaps better to base land planning on a simpler form of landslide cartography*** (e.g., a landslide density map, or a simple landslide inventory) ***rather than using ill-formalized, unreliable, or unverified susceptibility models***.

10.3. Landslide hazard assessment

The largely accepted definition of landslide hazard given by Varnes and the IAEG Commission on Landslides and other Mass-Movements (1984) is now more than 20 years old. Amendments and modifications to this definition have been proposed by various researchers, including Guzzetti *et al*. (1999a) and Vandine *et al*. (2004), based on field and laboratory experiences. Despite the time and the extensive list of published papers – most of which, in spite of the title or the intention of the authors, deal with landslide susceptibility and not with landslide hazard (§ 6.1, 6.2, 7.1) – to the best of my knowledge only one example exists of a comprehensive (i.e., "complete") landslide hazard assessment at the basin scale (e.g., Guzzetti *et al*., 2005a; § 7.3). This is largely due to difficulties associated with the quantitative determination of landslide hazard.

In § 7.2 I have reviewed the relevant literature on landslide hazard assessment, and I have proposed a probabilistic model for the quantitative definition of landslide hazard. Following Varnes and his IAEG collaborators (1984) and Guzzetti *et al*. (1999a), the model defines landslide hazard as the probability of occurrence within a specified period and within a given area of a landslide of a given magnitude. Hence, for a complete landslide hazard assessment one must determine not only "where" landslide can occur, with a certain probability but also with what frequency ("when"), and "how large", destructive or intensive the landslides will be. Based on the proposed model, to determine landslide hazard one has to establish the probability of landslide spatial occurrence (i.e., susceptibility, § 6), the probability of temporal landslide occurrence (§ 4.5), and the probability of landslide area (§ 5), the latter is considered a proxy for landslide magnitude. When the three probabilities are known, and assuming independence, the investigator can successfully determine landslide hazard by multiplying the three individual probabilities.

As explained in § 7.2, the proposed probabilistic model is conceptually simple. The operational difficulty lays in the complexity of obtaining the required information. Despite the difficulty in data acquisition, Guzzetti *et al*. (2005a) successfully completed a landslide hazard assessment for the Staffora River basin, an area that extends for 275 square kilometres (§ 7.3). Based on the results obtained in the Staffora River basin, ***I recommend that landslide hazard is determined at the basin scale, using the proposed probabilistic model, or adopting a different model.*** In the latter case***, I recommend that the adopted model is well founded, mathematically and geomorphologically***.

Models for landslide hazard assessment are forecasts of the probability of the spatial and of the temporal occurrence of slope failures, and of the probability of landslide magnitude (e.g., area, volume, destructiveness, etc.). Like any other forecast, hazard assessments should be carefully verified. To verify a landslide hazard model, one has to verify the individual model components (i.e., the probabilities of spatial occurrence, of temporal occurrence, an of landslide size), and their ensemble (i.e., the joint probability). The latter involves establishing the validity for the condition of independence between the three individual probabilities, which may not be easy to prove. ***To verify the probability of spatial occurrence of landslides, I recommend that the same procedure and the same tests devised to verify a landslide susceptibility zoning are used*** (§ 6.5). The temporal aspect of landslide hazard (i.e., when or how frequently a landslide will occur in any given area) remains a crucial, poorly formalized problem. The difficulties encountered in the preparation of multi-temporal landslide inventory maps (§ 3.3.4, § 3.4.1), which are fundamental sources of information to establish landslide hazard (§ 7.3), may limit our ability to prepare landslide hazard assessments to areas of limited extent (e.g., from some tens to a few hundred square kilometres). ***I recommend that multi-temporal landslide inventory maps are prepared to obtain information on the temporal occurrence of landslides. I also recommend that efforts are made to better incorporate time into spatially distributed (statistical or deterministic) landslide hazard models*** (Guzzetti *et al.*, 2005a,d)***, and to establish quantitative tests to validate the landslide temporal predictions***. Where this is not possible (e.g., due to lack of relevant data), I suggest that an estimated time-frame for the validity of a hazard model (and the associated maps) is provided using external information (e.g., the age of the oldest landslides in a region, the known or inferred return period of the main landslide triggering events). ***I*** further ***recommend that tests are designed to verify and validate the estimates of the probability of landslide size used in the hazard models, and that the hypothesis that landslide size*** (e.g., area, volume) ***or landslide destructiveness are reasonable proxies for landslide magnitude is carefully tested***.

The latter can be established analysing historical records of landslides and their consequences, and by exploiting geomorphological reasoning.

A comprehensive set of criteria for ranking the quality of landslide hazard assessments is not available yet. ***I recommend that*** such ***criteria to evaluate the quality of hazard assessments are developed as an extension to the criteria used to rank the quality of landslide susceptibility zonings***. This will involve establishing appropriate acceptance thresholds for the proposed verification tests.

I conclude these remarks on landslide hazard modelling reminding that the proposed probabilistic method used to ascertain landslide hazard at the basin scale (e.g., in the Staffora River basin, Guzzetti *et al*., 2005a; § 7.3), and its variations adopted to assess landslide hazard to the population of Italy (at the national scale, § 7.4), or to determine rock fall hazard (e.g., along the Nera River and the Corno River valleys, Guzzetti *et al*., 2004b; § 7.5), all produced a considerable number of maps, i.e., a – potentially very large – number of predictions, one for each of several possible landslide scenarios. How to fully exploit this large amount of information needs further investigation. ***I recommend that studies are made to investigate methods and tools to make better products useful to the end users*** (e.g., civil defence managers, planners, decision makers, land developers, etc.). This includes investigations on how to treat multiple hazards, and how to properly transfer scientific information to key users and the public.

10.4. Landslide risk evaluation

The evaluation of the risk posed by individual slope failures or by multiple landslides on different assets, including the population, is the ultimate goal of all the investigations aimed at mitigating the consequences of the slope failures. In § 8, I have presented concepts and definitions useful for landslide risk assessment, including a discussion of the differences between quantitative (i.e., probabilistic) and qualitative (i.e., heuristic) approaches. In the same chapter, I have shown examples of probabilistic and heuristic (geomorphologically based) landslide risk assessments performed at several different scales, from the local scale (§ 8.4) to the national scale (§ 8.3.1). Based on the results obtained, ***I recommend that specific and total landslide risk evaluations be performed, quantitatively and qualitatively, at local, regional and national scales***.

The literature on landslide risk evaluation is expanding rapidly (e.g., Wise *et al*., eds. (2004a); Glade *et al*., eds. (2005); Hungr *et al*., eds. (2005)). Inspection of the recent literature reveals that not enough good quality examples are available to allow for a critical evaluation of the techniques and methods currently used to ascertain landslide risk, particularly where different types of slope failures pose multiple risks (Wise *et al*., 2004b). Both qualitative and quantitative risk assessments may prove useful, depending on the type, quality and abundance of the available data. ***I argue than more information should be collected, and renewed efforts should be made to critically compare the outcomes of different risk assessment procedures***.

Where a detailed and sufficiently complete catalogue of landslides and their human consequences is available, individual and societal risk levels can be established (§ 8.3.1; Guzzetti, 2000; Salvati *et al*., 2003; Guzzetti *et al*., 2005b,c). Such analyses should be encouraged, and the results should be compared with quantitative estimates available (or obtainable) for other natural (e.g., earthquakes, floods, volcanic eruption, snow avalanches, etc.), societal (e.g., homicides, workplace accidents, overdoses), and technological (e.g., car and airplane accidents) hazards, and for the leading medical causes of deaths (Salvati *et al*., 2003; Guzzetti *et al*., 2005b,c). This may also help defining acceptable risk criteria. ***I recommend the application of mathematically sound methods to define individual and societal risk levels***.

Where information to complete probabilistic risk assessments is not available, or is not sufficiently detailed or reliable, heuristic (e.g., geomorphological) assessments can be attempted. Based on the results obtained in Umbria, ***I recommend the experimentation of heuristic approaches that exploit geomorphological information and inference*** (§ 8.4). Such methods proved efficient, reliable and cost effective in Umbria (Cardinali *et al*., 2002b; Guzzetti *et al*., 2004; Reichenbach *et al*., 2005). ***Where information is not available even to attempt a heuristic analysis of landslide risk, I recommend that the possible impact of landslides on different assets is determined*** (§ 8.5.2). An estimate of the expected impact on slope failures on different types of elements at risk can be easily obtained by jointly analysing in a GIS the know distribution of landslides (i.e., a landslide inventory map) and the distribution of the elements at risk, including the population (8.5.2.2), the structures and infrastructure (8.5.2.1), and the agriculture (8.5.2.3) (Guzzetti *et al.,* 2003a). I encourage efforts aimed at ascertaining the possible (or expected) impact of slope failures on the population, the built-up environment, the transportation network and the other lifelines, at all scales, from the local to the national scale. When performing such exercises, ***I recommend that great care is taken in assessing the quality, reliability and consistency of the thematic data used for the analysis, including those showing the location and types of the vulnerable elements***. Apparently minor errors in the various thematic layers of a GIS database, and small cartographic mismatches between the different layers, may result in large errors in the obtained estimates of the expected landslide impact.

Serious attempts to ascertain landslide risk relay on the availability of reliable information on the frequency of landslide phenomena, and on the type and severity of the damage (i.e., the consequence) caused by the expected landslides (i.e., the vulnerability). Systematic records of historical landslide events and their consequences are rare, difficult to construct and expensive (§ 3.3.1). However, such catalogues provide fundamental (mandatory) information to determine landslide risk. ***I recommend that more resources are allocated to the construction of historical catalogues of landslide events and their consequences***. The catalogues should contain information on all types of landslide consequence (including damage to the population), important information for determining the vulnerability of the various elements at risk to slope failures.

Lastly, I like to stress that establishing landslide risk levels is a political as much as a technical decision-making process. Landslide experts should spend more time working in cooperation with economists, decision makers, land developers, civil defence managers, and concerned citizens in order 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 assessments with assessments for other natural and man-made hazards. Involvement of concerned or directly interested people (i.e., people whose life, assets or interests are potentially or directly at risk) is of paramount importance, and should be pursued – where possible – from the early stages of a landslide risk assessment effort. Informed people take sound, dependable decisions.

10.5. Concluding remarks

In the Introduction I gave myself nine major questions to answer (§ 1.2). These questions corresponded to ideas to verify and problems to solve. I can now say that I have answered all the questions, but I have not solved all the problems.

For most of the problems I was able to find a positive and satisfactory solution. I was able to demonstrate that landslide maps can be prepared consistently and reliably even for very large areas spanning across major physiographical boundaries, and that the quality, reliability and completeness of landslide maps can be determined and measured. I showed how the temporal information on slope failures can be obtained from archive and multi-temporal landslide inventories, and how this information can be exploited to determine landslide hazard and risk. I presented methods to obtain reliable statistics of landslide area and volume, and I have shown how to use the obtained statistics for probabilistic landslide hazard modelling. I have demonstrated that landslide susceptibility can be ascertained over large areas, allowing for large territories to be zoned based on their propensity to generate mass movements, and that the quality of the susceptibility forecasts can be measured and ranked. I have demonstrated that landslide hazard can be determined using simple probabilistic methods that exploit geomorphological information available from the interpretation of aerial photographs, and I have shown how landslide risk can be determined at different geographical scales. Lastly, I have proposed a method to best exploit the available landslide maps, models and forecasts to contribute to mitigate the risk posed by mass movements.

As I said, open problems remain. As an example, it is unclear how to obtain reliable multi-temporal landslide information with a spatial resolution suitable for probabilistic landslide hazard assessments over large areas. Also, it remains unclear to what extent probabilistic and heuristic (geomorphological) risk evaluations can be reconciled, and at what scale. Finally, I was not able to identify a single, unified framework for landslide cartography, i.e., for the science and art of mapping landslides, of determining landslide hazards, and of evaluating the associated risk. It is worth spending a few more words on this last open problem.

Landslides are the result of different geophysical (i.e., earthquakes, volcanic eruptions) and meteorological (i.e., intense rainfall, prolonged rain periods, rapid show melt) triggers, and of a variety of human actions, including topographical, morphological, hydrological and land use changes (Crozier, 1986; Turner and Schuster, 1996). The diversity of the triggers, and the large variety of morphological, geological, and climatic environments where landslides can develop, contribute to make slope failures extremely diversified phenomena that cover broad ranges in space (length, width, area, thickness and volume), time, velocity, energy, magnitude and destructiveness. Due to extraordinary breadth of the spectrum of landslide phenomena (§ 1.1), a single (unique) method to identify and map the landslides, to ascertain their hazards, and to evaluate the associated risk, is out of our reach at the present state of knowledge and technology. It remains unclear if such a "unified" method will be possible in the future, with improved knowledge and new technologies. This does not mean that similar approaches and comparable methods and techniques cannot be adopted. To the opposite, in this work I have demonstrated that a common set of tools (i.e., a "*toolbox*") can be used to map landslides, to zone their susceptibility, to ascertain the hazard levels, and to evaluate the risk posed by slope failures at different spatial and temporal scales.

The "*toolbox*" consists of an ensemble of scientific knowledge, case studies, reliable statistics, tested models, proven techniques, and verified procedures. With this respect, a similarity exists between a doctor (or a team of medical specialists) attempting to diagnose a complex illness and a geomorphologist (or a team of Earth scientists) investigating a landslide, or a population of landslides, and attempting to define the associated hazard and risk levels. In both cases, no single “tool” (i.e., procedure, method, technique, model, etc.) is available to solve the problem for all the people or for all the landslides, at all the times. Instead, both experts use a variety of tools, depending on the specific case and on the problem at hand. The type, number, precision and reliability of the available tools change with time, depending on the availability of new knowledge, additional or improved information, the available resources, and on technological advancements. What is also common to both experts is that availability of a large and efficient “toolbox” is meaningful only if the tools are used by well-trained and experienced professionals. Sophisticated tools in the hands of incompetent professionals are useless, or even dangerous.

Despite efforts, landslide phenomena are still poorly understood, particularly at the regional scale. Additionally, their interactions with the economic and human sphere remain a largely novel problem to geomorphologists and even more to social scientists. Geomorphology has only recently provided well-founded models (§ 6.3) and reliable and verified examples for landslide susceptibility assessment (§ 6.5). A model for landslide hazard assessment exists (§ 7.2), but applications remain limited, in extent and number. For landslide risk evaluation, models exist (§ 8.2) but no general agreement on their use has been reached among experts, and only a few reliable applications are available.

In this context, industrialised societies and developing countries face increasingly complex problems of civil defence, land use planning and environmental policy making (Plattner, 2005). These are different from the traditional problems of both pure and applied science (Funtowicz and Ravetz, 1995; Murck *et al.*, 1997). Environmental issues and policy decisions challenge geomorphologists with very difficult issues. Due to the uncertainties in data acquisition and handling, and in model selection and calibration, landslide hazard assessment, and risk evaluation are out of the reach of the traditional “puzzle-solving” scientific approach, based on controlled experiments. In general, predictive models of landslide hazard and risk cannot be readily tested by traditional scientific methods. Indeed, the only way a landslide prediction can be verified is through time (Hutchinson, 1995). Solutions to these challenging problems may come from a new scientific practice enabling to cope with large uncertainties, varying expert judgements, and societal issues raised by new hazard and risk evaluations. Within this framework, geomorphology may play a renewed role, particularly if geomorphologists will be able to better formalise and extend their knowledge on slope processes at different scales and in different physiographic environments. I hope this work has contributed to this ambitious goal.

Landslides are multivariate, multi-temporal, highly non linear phenomena with complex feedbacks varying in scale from the local to the regional. The geomorphological and economic impact of mass movements ranges from the very short to the very long term. Indeed, landslides represent a “complex” problem, and to a large extent a nightmare for modelling and forecasting. If the problem is “complex”, why there should be an easy solution? This work has demonstrated that there is no such easy solution. Landslide identification and mapping, landslide susceptibility zoning, landslide hazard assessment, and landslide risk evaluation, all require extensive work, and the collaborative efforts of skilful, well trained experts in several different fields.

10.6. Prospective thoughts

Problems remain to be solved in the realm of landslide cartography. It is perhaps useful to conclude this work with a look into the future, in an attempt to foresee (or to envision) strategies to solve the remaining problems and new problems that may arise.

Landslide inventory maps covering systematically entire nations, or even an entire continent, are not available, but methods to prepare such maps are available and have been successfully tested. It is not difficult to envision a landslide inventory map covering the whole of Europe, at a scale and with a resolution suitable for local decision making and land use planning. Such map will not only prove useful to obtain a continent-wide estimate of landslide susceptibility, it will also allow for, e.g., investigating the types, pattern and abundance of landslides in relation to agriculture, and in particular to changes induced to the landscape by agricultural policies of the European Union. This issue is relevant to many areas in Europe, and may become even more relevant in the near future. A detailed landslide inventory map of Europe will also contribute significantly to investigate the slope processes that shape the landscape of the continent, including soil erosion.

The assessment of landslide susceptibility is, in my opinion, a largely solved problem, at least for areas covering from a few tens to a few thousands of square kilometres. The challenge in this particular field is the preparation of landslide susceptibility zonings for very large territories, covering a large region, an entire country, or a whole continent. In this context the difficulty lays in the availability of the relevant information, and on the complexity and amount of the information. I envision the possibility of obtaining multiple landslide susceptibility zonings for entire nations, based on sound statistical modelling of detailed geo-environmental data, of the same or of higher quality and resolution than the information used to obtain, e.g., the landslide susceptibility map for the Upper Tiber River basin in Central Italy. I further envision the possibility to prepare susceptibility models at different spatial scales, nested one into the other like Russian dolls. Each model will exploit all the available thematic and landslide information at a given scale, will provide information relevant to different users, and will be linked to the other models obtained at smaller and larger scales.

In landslide susceptibility, the main issue today seems to be that of the validation of the obtained forecasts. On this topic, much can be learned from disciplines (e.g., meteorology and weather forecast) for which forecast verification has a long tradition and has become a daily practice. Schemes for susceptibility model validation are emerging, and criteria for acceptance or rejection of a susceptibility forecast have been proposed. I imagine the development and wide spread use of accepted, standardized criteria for the validation of the performances and the ranking of the quality of landslide susceptibility forecasts. This will provide much needed credibility to the landslide cartographic products.

To validate landslide susceptibility forecasts, information on new or reactivated landslides is compulsory. This type of information is not currently collected in a systematic fashion, using accepted, certified methods. I envision a system – a network of institutions, organizations, research groups, and individual investigators – capable of routinely and systematically collecting accurate and detailed information on slope failures, and particularly after each landslide triggering event. This system will exploit established mapping techniques (e.g., field surveys and the interpretation of aerial photographs) and innovative technologies, including very high resolution images obtained from satellite or high altitude airplanes. However, the remotely sensed images will have to allow for stereoscopic vision. Detailed spatial monitoring of landslides will also exploit innovative technologies capable of monitor subtle ground deformations, including networks of continuous GPS measuring stations, and the differential interferometric analysis of SAR images. The latter will require overcoming some of the limitations inherent in the existing satellites (e.g., short wavelength and consequent widespread loss of coherence, insufficient revisit time, etc.).

Probabilistic landslide hazard assessment is currently feasible only for relatively limited areas, extending at most for a few hundreds of square kilometres. However the proposed methods are – in principle – applicable to much larger areas. I envision the possibility of preparing multi-temporal landslide inventory maps (i.e., the basic building block for probabilistic landslide hazard assessment) for large and very large areas, extending for several thousands of square kilometres. This will require teams of well trained and motivated geomorphologists, and the wide spread utilization of new mapping techniques, including the exploitation of remote sensing technology and ground-based monitoring methods. To obtain landslide hazard, the frequency-size statistics of landslides must be determined as accurately as possible. Methods for obtaining reliable estimates of the probability distribution of landslide size from empirical data are available. However, only a handful of inventories – and only event inventories – are sufficiently complete to allow for a reliable estimate of the statistics of landslide size. I imagine the possibility of exploiting detailed nation-wide or continent-wide inventory maps, and of complete event inventories prepared after landslide triggering events of different magnitude and in different physiographical environments, to determine unequivocally the probability distribution of landslide area and volume.

For many applications, including the probabilistic definition of landslide hazard and the design of reliable and credible landslide risk scenarios, information on past slope failures is vital. For other natural hazards, and most prominently for earthquakes, large efforts have been made – and considerable resources have been invested – to collect historical information on past events and their consequences. Similar information is generally lacking for landslides. Where available, the historical information typically covers a comparatively short period of time (e.g., one or two centuries) or a small area (a single town, a valley or a group of valleys). Lack of historical data on the occurrence of landslides and their triggers hampers the definition of landslide hazard. I envision the systematic collection and analysis of historical information on landslides, and related natural hazards. This information will greatly contribute to the understanding of the landslide phenomena and to the design of better forecasting models and risk mitigation strategies. The historical information may also contribute to better determining the vulnerability to the different types of mass movements, which remains largely unknown.

To determine landslide susceptibility or landslide hazard, physically based methods are currently not applicable over very large areas, mostly due to the lack of relevant information and the simplifications required to make the models feasible (i.e., solvable). Availability of new thematic information (e.g., digital terrain models with sub-metric resolution prepared routinely, i.e., every year, every few months, or on demand, for entire nations, or information on soil thickness and water content obtained exploiting remote sensing technology) can foster the application of physically based methods for determining landslide hazard. I imagine the possibility of coupling physically-based and statistically-based methods for the better definition of landslide hazard at the national scale.

Methods and strategies to evaluate landslide risk are available. Better and more sophisticated methods can certainly be designed and implemented. However, in risk assessment the main issue seems to be the availability of relevant and reliable data to apply the available methods and models. Another issue is the possibility to – and again the availability of information for – the validation of the risk evaluations. In this context, multiple-risk analysis appears to be the next challenge. I foresee the possibility of completing complex risk analyses encompassing all hazards in area, including natural hazards and in particular landslide hazard.

Finally, I like to imagine a system – or a set of systems linked to form a network – that routinely (e.g. every day, or even every hour) ascertain the level of landslide hazard over very large areas or an entire nation, exploiting existing and new data and modelling facilities, real and near-real time measurements obtained from surface and sub-surface probes, networks of continuous GPS stations, and products obtained from remotely sensed observations. Coupled with reliable, quantitative weather forecasts, and detailed information on the type and location of the elements at risk, including information on the vulnerability of the different elements at risk, such system will contribute to mitigate landslide risk substantially, and chiefly by reducing the human consequences of potentially damaging landslide events. A measure of the success of such an idealized system will be the reduced number of lives lost due to mass movements.