9. USE OF LANDSLIDE MAPS AND MODELS

It's good to have a map,
if you know how to use it.

A good strategy consists in sticking
to the facts and in telling the truth.

The value of a map refers to its information content, which depends on the type of data shown, their quality and the extent to which the information is new and essential. A map is valuable when the data shown are useful to the user, i.e., when the map is both relevant and understood by the user (Guzzetti *et al*., 2000).

A carefully designed inventory map that shows landslides as recognised by the interpreter, without any modification apart from scale or graphical constrains, is a basic map. A landslide density map obtained by interpolating an inventory map without any additional information is a derivative map. Landslide susceptibility and hazard maps obtained from an inventory are also derivative maps but, since they include additional information on factors such as lithology and morphology that are used to build the susceptibility or hazard models, they have an information content which is superior to that of the input maps, including the inventory. Risk assessments are complex, high level products that exploit basic, derivative and other thematic information and maps (Guzzetti *et al*., 2000).

In this chapter, I first describe and compare the information content of different landslide cartographic products, including inventory, density, susceptibility and hazard maps, and risk evaluations. Next, I introduce and discuss the concept of a "*landslide protocol*", i.e., a set of regulations established to link terrain domains shown on the different landslide maps to proper land use rules.

9.1. Landslide inventory maps

In § 3, I have shown that landslide inventory maps can be prepared using different techniques, depending on their purpose, the extent of the study area, the scales of base maps and aerial photographs, and the resources available to carry out the work. Regardless of the adopted techniques and of the sources of information used to prepare or compile the inventories, landslide inventory maps show the location and, where known, additional characteristics of the slope movements (e.g., type of movement, depth, date, age, degree of activity, etc.) that left discernable features in an area, or that are known to have occurred in an area (Hansen, 1994; Wieczorek, 1984; Guzzetti *et al.*, 2000). In other chapters, I have shown how the information portrayed in a landslide inventory can be exploited to determine the abundance of landslides (§ 4.1), to determine the frequency-area statistics of landslides in an area (§ 5), to ascertaining landslide susceptibility (§ 6) or hazard (§ 7), and to evaluate landslide risk (§ 8). Hence, the usefulness of landslide inventories should now be clear.

Landslide inventory maps are easy to understand (i.e., straightforward, direct) for experts, such as geomorphologists, and non-experts, such as decision makers, planners and civil defence managers. Inventory maps are easily prepared by well trained geomorphologists and do not require large investments, particularly when compared to other thematic maps showing environmental data, including geological and soil maps. Only limited resources are required for the completion of landslide inventory maps, namely aerial photographs, base maps, and a good quality stereoscope. Experiments conducted in northern and central Apennines of Italy have demonstrated that, with the resources commonly available to complete a landslide mapping project, accurate multi-temporal inventory maps can be successfully prepared for areas extending from a few tens to a few hundreds of square kilometres (e.g., Galli *et al*., 2005; Guzzetti *et al*., 2005a), whereas good quality, geomorphological inventory maps can be prepared for larger areas, extending for thousands of square kilometres (e.g., Antonini *et al*., 1993, 2000, 2002a; Cardinali *et al*., 2001).

Despite the ease with which they are prepared and their immediateness, landslide inventories are not yet very common. Inventory maps are available for only a few countries and mostly for limited areas (Brabb and Harrod, 1989; Brabb, 1991, 1993, 1995). This is surprising because inventory maps provide fundamental information on location and size of landslides that is necessary in the assessment of slope stability at any scale, and in any physiographical environment. The reasons for this shortcoming are manifold and depend on general and local conditions (Brabb, 1991, 1993; Guzzetti *et al.*, 2000).

There is a certain inability of environmental and planning agencies, and of national and regional geological surveys, to understand the value of regional inventories for planning purposes (Brabb, 1991, 1996). This is often coupled with inability or lack of resolve in preparing landslide inventories for large regions, which has the effect of limiting knowledge of landslide distributions, types and patterns. Indeed, some planning agencies prefer to ignore where landslides are located: lack of knowledge in this case represents a degree of freedom (Guzzetti *et al.,* 2000). The opinion that landslide mapping, and in particular inventory making, is not "scientific" finds advocates even among earth scientists (Sassi *et al.,* 1998). I believe that landslide mapping is an important, scientific operation, but I am conscious of the fact that preparing a landslide inventory, particularly from aerial photographs with or without field surveys, is a subjective operation that requires skills and training. Maps prepared by personnel not sufficiently trained or experienced, or lacking the proper resources may be wrong and unreliable. The subjectivity and the difficulty in assessing quantitatively its reliability, makes landslide inventory maps somewhat unreliable in the eyes of some potential user. The fact that most published inventories are not accompanied by clear documentation on the tools, methods and techniques used to prepare or to compile them, and lack sufficient specifications on the estimated degree of completeness and reliability, add to the difficulty of using landslide inventories. Lastly, in the recent years there has been a general, largely unjustified, preference for "high-tech" remote sensing techniques, which are not yet capable of mapping landslides efficiently over even small areas (Soaters *et al.,* 1991).

Landslide inventory maps are important and useful products but suffer from limitations, which is important to know and expose clearly. Even if it is very accurate and precise, a landslide inventory map cannot portray all slope failures that have occurred in an area. Geomorphological inventories portray only a reduced fraction of the total number or the total area of landslides that have occurred in a region over time (Malamud *et al*., 2004a). A landslide map will show only slope failures that have (presumably) left discernible morphological signs on the date and at the scale of the investigation. If aerial photographs are used to complete the investigation, the inventory map will portray only landslides visible on the aerial photographs. Thus, the quality of a landslide inventory depends: (i) on the persistence of landslide morphology within the landscape, (ii) the skill of the interpreter to capture the morphological features typical of a landslide, and (iii) the ability of the interpreter to properly understand the geomorphic evolution of the slopes. In the areas that are shown as having landslides in an inventory map, interpreters are (usually) confident that landslide scars and or deposits exist, but nothing is said about the reliability of such statement – i.e., the veracity of the map. Additionally, where landslides are not shown, most commonly nothing is said about the potential presence or absence of slope failures. Indeed, authors of inventory maps often state that areas not mapped as landslides cannot be considered free of mass movements, but rather represent domains where the interpreter was not able to identify a slope failure (e.g., Guzzetti and Cardinali, 1989, 1990; Antonini *et al*., 1993; Cardinali *et al*., 1990, 2001). For most potential users of landslide inventory maps the difference is significant.

In landslide inventory maps, no effort is made to distinguish areas that are landslide-free (such as large alluvial plains, valley bottoms, flat ridge tops, and recognized stable ground) from areas where landslides could exist but either are not present at the date of the investigation or were not recognised (Guzzetti *et al*., 2000). The imprecision limits the value of landslide inventory maps, and may jeopardise their usefulness for planning, land development and decision making. Indeed, where landslides are recognised, actions can be taken and proper regulations can be established before planning or land development takes place. Much less clear is what to do where landslides are not recognised, particularly in the vicinity of existing mass movements or in terrain that is prone to slope failures. As an example, on 5 May 1998 rainfall induced shallow failures were triggered on the steep slopes mantled by volcanic deposits of the Pizzo d'Alvano area (Campania Region, Italy) (Guadagno *et al*., 1999; Guadagno and Periello Zampelli, 2000; Crosta and Dal Negro, 2003). The resulting debris flows killed 137 people in the village of Episcopio (Sarno). Twenty-three additional casualties were reported at Quindici, Siano, Braciliano and San Felice a Cancello (Guzzetti, 2000). Inspection of medium-scale (1:33,000) aerial photographs flown in 1955 showed that prior to the event little could be said about the exact location of the source areas of the individual debris flows. However, on the basis of the overall geological and geomorphological settings, slopes could be interpreted to be highly susceptible to failures. Archive data confirmed that the area suffered similar catastrophic landslides in historical and recent time. Thus, a reconnaissance landslide inventory – which was not available for the area at the time of the catastrophic event – may have failed to predict the exact location of the individual landslides, but a detailed geomorphological inventory map would have quite certainly identified the areas potentially subject to debris flow hazards, e.g., mapping the fans where debris flow deposited.

9.2. Landslide density maps

To improve the accuracy with which future landslides are predicted (in space), the density of slope failures (§ 4.1) can be determined within pre-defined terrain domains, or mapping units (§ 6.2.2). Geomorphological terrain subdivisions, such as slope units, have proven particularly adequate for computing and displaying landslide density, at the local and the regional scales. Density is a clearly definable and easily comprehended quantitative measure of the spatial distribution of slope failures (§ 4.1). Regardless of the geological or morphological setting, where landslides are abundant, density is high and, conversely, where landslides are sparse, density is low. This is an advantage of density maps over more complicated forms of mapping, such as susceptibility and hazard maps. The advantage may be particularly significant for non-expert users, such as decision and policy makers.

As an improvement to landslide inventories, landslide density maps are fillers of space. Such maps provide insight on the expected (or inferred) occurrence of landslides in any part of the investigated area without leaving unclassified areas. A density map does not show where landslides are located but this (apparent) loss in resolution is compensated for by improved map readability and reduced cartographic errors (Carrara *et al.*, 1992; Guzzetti *et al.*, 2000; Ardizzone *et al.*, 2002; Galli *et al*., 2005). Additionally, landslide density is independent of the extent of the study area, which makes comparison between different regions straightforward. Such characteristics contribute to making density maps appealing to decision makers and land developers.

Landslide density maps can be conveniently combined with the inventory maps from which they were obtained (Guzzetti *et al*., 2000). This can be easily achieved in a GIS, by overlying a geomorphological landslide inventory on top of the corresponding density map. This was demonstrated in § 4.1.2 for the Upper Tiber River basin, in central Italy. The resulting map, shown in Figure 4.1, is based on slope units and retains the advantages of a landslide inventory map (i.e., it shows where failures were recognised by the investigator) and fills spaces, thus providing insight into the geographical distribution and abundance of slope failures. The use of an appropriate terrain unit (i.e., the slope unit) guarantees a match with the local morphological setting. The map shown in Figure 4.1 was further improved by clipping out of the frequency count the areas that are known to be landslide free (e.g., large valley bottoms). The combined inventory and density map gains in readability and applicability to decision making and land use planning.

Density maps represent an improvement over landslide inventories, but have limitations. These maps are based on the assumption that landslide density is continuous in space, which may not be the case everywhere (§ 4.1). If the original landslide inventory is incorrect, i.e., if the original landslide map does not show some of the slope failures present in an area, or if it overestimates the extent of the slope failures, the density map will inherit the errors and will be incorrect or imprecise. A level of uncertainty cannot be easily associated to the density estimate, further limiting the applicability of landslide density maps for planning and decision making. Also, despite improvements, landslide density maps do not incorporate any physical relation between slope failures and the landscape. Thus, they cannot be used to establish and investigate the factors that control landslide occurrence. Indeed, density maps can be used to decide where landslides are more abundant but not why this is so. They can be of help in specifying where subsequent studies have to be made, but not to model the effects of remedial works. This is the goal of landslide susceptibility modelling.

9.3. Landslide susceptibility zoning

In § 6, I have shown that good quality landslide susceptibility maps can be obtained from deterministic or statistical models. The latter, usually incorporate several instability factors and use a variety of classification methods (Michie *et al.*, 1994). Reliable susceptibility models are capable of explaining why the known (i.e., past) landslides are abundant or sparse. Under assumptions (e.g., § 6.2.1, § 6.4.1), this information can be used to predict where new or reactivated landslides will be abundant or sparse in the future. Given that landslides take many different forms and are the result of the interplay of a variety of causes (§ 1.1, Schuster and Krizek, 1978; Crozier, 1986; Dikau *et al.,* 1996; Turner and Schuster, 1996), different susceptibility models can be prepared that take into account the main instability factors (slope morphology, rock composition, structure, hydrological conditions, land use types, etc.) and the various landslide types (deep-seated slides, shallow failures, debris flows, rock falls, etc.).

The availability of different methods (§ 6.2.3) and the numerous published examples (§ 6.1), indicate that landslide susceptibility maps are relatively simple to prepare. The experience gained in Italy has shown that for the production of reliable landslide susceptibility maps, quality and abundance of the available landslide and thematic information is more important than selection of a "best" statistical classification method (Carrara *et al*., 1992, 1995, 1999; Guzzetti *et al*., 1999a). Others authors have expressed a different opinion, supported by field data and statistical analyses (e.g., Chung and Fabbri, 2004), but it is unquestionable that where sufficient information exists landslide susceptibility can be ascertained, and maps showing its spatial distribution can be prepared. Indeed, susceptibility models and maps of different forms and reliability can be obtained for the same area depending on the type and quality of the available information.

By incorporating information on the instability factors that are known or supposed to control landslide spatial occurrence and abundance, susceptibility maps are capable of predicting the location of landslides even in the areas where landslides were not recognized or mapped. As a result, errors in the landslide inventory maps are compensated for by a reliable susceptibility model. This is a marked improvement over inventory and density maps. Susceptibility maps are also filler in space and, if combined with the corresponding landslide inventory (e.g., Cardinali *et al.*, 2002b), they retain the advantages of the inventory, e.g. they show where landslides were recognized and mapped, and they provide a quantitative assessment of the probability of spatial occurrence of future landslides for the entire territory.

Landslide susceptibility models – and the resulting maps – represent a marked improvement over inventories and density maps, but have limitations. In a landslide susceptibility map only the presence (and not the extent or the number) of landslides is predicted. Within each mapping unit (and regardless of the type of the adopted mapping unit) no distinction is made between a small slope failure and a large landslide, or between several small failures and a single large mass movement. The problem is less severe when using grid cells as the mapping unit of reference, and is more severe when adopting one of the other types of terrain subdivisions (§ 6.2.2). Most commonly, the degree of activity of the known landslides is not accounted for by a susceptibility assessment. A further limitation of a landslide susceptibility map lays in the fact that such map does not provide any insight on the temporal frequency of occurrence, or the magnitude (i.e., the size or destructiveness) of the expected slope failures. In a susceptibility map, no distinction is made between mapping units where landslides are expected with a high temporal frequency (e.g., every rainy season), from those where slope failures are expected only every tens, hundreds or even thousands of years. Also, no distinction is made on the size (e.g., length, area, volume) of the expected landslides, which in many cases directly affects their destructive power. In addition, statistically-based susceptibility models are negatively influenced by the extent of the investigated area, which makes it difficult to compare susceptibility classes from different locations (Carrara *et al.,* 1991, 1995; Guzzetti *et al.,* 1999a; 2000). These limitations jeopardize the potential use of landslide susceptibility maps for civil defence, for applications in landslide warning systems, and to some extent even for land use planning. In a pristine area, where elements at risk are not yet present, a susceptibility map can be applied, and more detailed studies can be made to determine the temporal occurrence of landslides. In an area where elements are risk are already present (e.g., houses, roads, the population, etc.), and decisions have to be made on remedial or relocation measures, it is difficult to establish a policy without knowing when (or at least how frequently) a landslide will occur, and how large or destructive the mass movement is expected to be.

Although they are diagnostically powerful and superior to more simple approaches, such as inventory and density maps, landslide susceptibility models are complex tools that can be difficult to master and exploit. They need to be applied with care to planning and land development, and only by experienced geomorphologists, who will often be the same people who helped build them. This is particularly relevant for areas that were either misclassified by the susceptibility model, or where the model was unable to classify the terrain. In these places, it is essential to understand how a model behaves before it can be put to any practical use. A landslide susceptibility model should always be used in combination with all the information that was used to build it. The operation is simplified if the information is available in digital format in a properly organised GIS database.

Lastly, it should be understood that landslide susceptibility models – and the resulting associated maps – are nothing more than geomorphological spatial predictions. Like any other scientific prediction, they should be accompanied by a quantitative estimate of the error associated with the prediction (Jolliffe and Stephenson, 2003). Susceptibility maps should be further quantitatively tested to evaluate their prediction skills (§ 6.5). To those embarking in the preparation a landslide susceptibility assessment, it should be clear that a policy maker interested in incorporating their landslide susceptibility prediction into a land use regulation or a building code is most probably more concerned in the performance of the susceptibility model with time (i.e., in the aptitude of the model of predicting new landslides) and less interested by how well the same model fits the known distribution of past slope failures. Lack of proper model verification and of relevant information on the error associated with the susceptibility estimate, is a primary reason for the limited application of landslide susceptibility models and maps in building codes, civil defence scenarios, and land development and exploitation plans.

9.4. Landslide hazard assessments

Landslide hazard assessments are the most sophisticated and complex form of landslide cartography currently available (e.g., Guzzetti *et al.*, 2005a). As they are derived from the analysis of many instability/environmental factors, landslide hazard models are capable of explaining why landslides are abundant or sparse (through their landslide spatial probability component), to provide estimates of the frequency of landslide occurrence, and of the magnitude (e.g., size, or destructiveness) of the expected slope failures (§ 7). These are considerable enhancements over susceptibility zonations, which make hazard models and maps particularly appealing to decision makers, land use planners, and civil defence managers.

Like density and susceptibility maps, landslide hazard maps are filler of space. If combined with the corresponding (multi-temporal) inventory maps, they retain the advantages of the inventories, e.g. they can show where landslides were recognized and mapped, including information on the age of the landslides inferred from the date of the aerial photographs or of the field surveys. Hazard models incorporate a susceptibility component, i.e., the spatial probability of landslide occurrence. For this reason, many of the advantages and the limitations discussed for susceptibility models and maps also apply to hazard models and maps, including the need for proper model verification and for a quantitative estimate of the error associated with the hazard prediction.

Landslide hazard models are indubitably the most powerful analytical and diagnostic tool currently available to geomorphologists and decision makers to predict the spatial and temporal occurrence of mass movements, and the evolution of landslide hazards in a region. However, models of landslide hazard are more difficult to prepare than susceptibility models or density maps (§ 7). Hazard modelling requires considerable efforts to collect and validate input data that are often not readily available (e.g., multi-temporal landslide inventory maps). Being dependent on information on the temporal occurrence of landslides, which can be currently effectively colleted only for relatively small areas, hazard models are also negatively influenced by the extent of the investigated area. Lastly, hazard models needs interaction between expert geomorphologists and statisticians in order to process the available data in such a way as to avoid statistically sound but geomorphologically unrealistic results.

More than any other landslide cartographic product, hazard models need to be applied with great care to planning and land development, and only by the same team of experienced geomorphologists and statisticians who helped prepare them. The problem is particularly relevant for the areas that were either misclassified by the susceptibility component of the hazard model, or where the susceptibility assessment was unable to classify the terrain. The problem is also significant where the temporal component of the hazard model was unable to provide reliable estimates of landslide occurrence (or recurrence), or where the model component for landslide magnitude was unable to provide reliable estimates of the expected landslide size or destructiveness. In these places, it is essential (mandatory) to understand how a hazard model behaves before it can be put to any practical use.

Like the other previously discussed landslide cartographic products, a landslide hazard model must always be used in combination with all the geomorphological and the thematic information used to construct it. However, there is a significant difference between hazard models and the other cartographic products (i.e., landslide inventory, density and susceptibility maps). The probabilistic model adopted to ascertain landslide hazard at the basin scale (§ 7.3), and its variations used to determine landslide hazard at the national scale (§ 7.4), or to determine rock fall hazard along roads (§ 7.5), all generate a very large number of predictions (i.e., of hazard assessments). Each prediction represents a possible landslide scenario, i.e., a combination of landslide spatial occurrence, of expected landslide size or destructiveness, and of landslide temporal probability for a different period. Individual landslide scenarios can be shown by separate hazard maps, each portraying different levels of landslide hazard. Efficient display of multiple hazard scenarios cannot be obtained using traditional (paper) maps. A large ensemble of landslide hazard maps and of the geomorphological and thematic information used to prepare them can be accomplished efficiently by exploiting GIS technology, provided the information is stored in a properly organized database.

Even an efficient GIS system that operates on a well organized geographical database cannot solve two problems typical of (i.e., inherent to) landslide hazard assessments. The first problem concerns the development and use of methods and techniques to synthesize the large number of predictions produced by a single hazard assessment in a reduced number of maps or charts. This involves establishing criteria and defining thresholds to efficiently cluster hazard scenarios in a reduced set manageable by decision makers, land developers, civil defence managers, and concerned citizens. The second problem concerns the comprehensive assessment of the level of hazard posed by different threats, e.g., by different landslide types, or by different natural hazards (e.g., landslides, floods, show avalanches, etc.) present in the same area at the same or at different times. This includes investigations on methods and techniques for the appropriate analysis of multiple hazards.

9.5. Landslide risk evaluations

A significant difference exists between the information provided by landslide risk evaluations (as discussed in § 8) and the information supplied by the other landslide cartographic products (§ 9.1 to § 9.4). The goal of a landslide inventory map consists in showing the location of slope failures. The purpose of landslide density, susceptibility and hazard maps is to zone (rank) the territory, based upon the abundance of landslides, the levels of landslide susceptibility, or the levels of landslide hazard. Thus, the focus of landslide inventory, density, susceptibility, and hazard maps is the territory. Conversely, landslide risk assessment aims at determining the loss or the expected damage to a specific element (e.g., a person, house, road, or asset), resulting from a hazardous affecting landslide (§ 8.2, Varnes and IAEG Commission on Landslides and other Mass-Movements, 1984; Vandine *et al.*, 2004). Hence, the focus of a landslide risk assessment is the element at risk (and not the territory). The difference is significant and should be made clear to the potential users of landslide risk evaluations.

Establishing heuristic or probabilistic levels of landslide risk is a complex operation that most commonly involves designing multiple landslide scenarios. From what I have presented in § 8, it should be clear that preparing a single landslide risk assessment does not make much sense. Risk depends on hazard (i.e., on the state of nature, § 7) as much as on the type, distribution, abundance and vulnerability of the elements at risk (§ 8.2.1). The latter varies for the different types of mass movements. As an example, a person travelling along a road may be highly vulnerable to small rock falls, which may cause only minor, aesthetic damage to the road. Conversely, a large but slow moving landslide may not cause direct harm to the people leaving or working on the landslide, whose houses however may be severely damaged or destroyed by the movement of the landslide.

Difficulties in preparing and using risk assessments include: (i) the difficulty in determining all the relevant information needed to establish levels of landslide risk (lack of information), (ii) problems in selecting meaningful and realistic landslide scenarios, (iii) the fact that establishing risk levels is a political and economical as much as a technical, scientific and logical decision (see below), (iv) the difficulty in combining in a meaningful and useful form the results obtained for different scenarios (multiple risk), and the results obtained by different experts (lack of consensus), and (v) the fact that even minor changes, e.g., in the number, position or type of the elements at risk can affect significantly the result of the risk assessment effort (large uncertainty). For these reasons, even more than for the susceptibility and hazard assessments presented before, risk evaluations should always be used in conjunction with all the information used to obtain them. The user of a risk assessment should always be aware of the information, data, assumptions, logics and constrains used or assumed to perform the risk evaluation. If the information changes, the assumptions don’t hold true, or constrains are modified, the risk evaluation should be reconsidered, updated or rejected. Risk evaluations need to be applied with extreme care to planning, land development, civil defence and warning systems, and only by experienced scientists in combination with decision and policy makers and qualified risk managers.

Establishing landslide risk levels is a political and economical as much as a technical decision-making process, which depends on the interests and the assets of the person, institution, company, etc. (i.e., of the "stakeholder") potentially bearing the physical, economical and political consequences of the landslide(s). For the manger of a mountain road network, rock falls endangering a highly trafficked road used daily by local inhabitants and tourists, may represent a severe hazard. For this manager, the road and the people travelling along it may be at high risk, requiring first-priority mitigation efforts. For the manager of a gas duct laid along the same mountain road, rock falls may not represent a significant threat to the pipeline. The second manager may be more concerned about debris flows destroying a bridge and severing the pipeline; a condition of high economical and technological risk for the gas duct. The Maier of a town may have to decide how to invest finite economic resources to mitigate the hazard posed by a large magnitude but low frequency landslide event (a large rock slide), with potential catastrophic consequences to private properties of high economic value to the community (e.g., hotels in a mountain resort), or to reduce the risk posed by frequent, but small rock falls and by recurrent, minor debris flows along the access road to the town. The Maier decision will – quite certainly – be taken not solely on a technical (e.g., geomorphological) background, but will require the analysis of several – probably conflicting – information, interests, constraints and obligations.

9.6. Establishing a landslide protocol

For civil defence purposes, land use planning and policy making, a single landslide map (whether it be an inventory, density, susceptibility or hazard map), or even a combination of two or more types of landslide maps, is seldom considered adequate (Godefroy and Humbert, 1983; Ahlberg *et al.*, 1988; Swanston and Schuster, 1989; Brabb, 1991, 1995, 1996, 2002; Guzzetti *et al.*, 1999, 2000; Raetzo *et al*., 2002). To exploit the map(s) potential to the full, a "protocol" must be established. A "*landslide protocol*" consists in a coherent and organized set of regulations that links terrain domains to proper rules for best exploitation of the terrain and maximum acceptable safety to human beings and the assets. This is comparable to a protocol in the medical science and practice, which is followed (adopted) by researchers and doctors to cure a specific illness based on scientific knowledge, verified statistics, available information, and the results of specific laboratory tests.

A landslide protocol should exploit all the available knowledge on landslides in a given area – including maps and predictive models – to allow decision and policy makers to make the best possible choice on the use of the land, given the existing constrains and the available information. A landslide protocol: (i) should fit the local morphological, geological, meteorological, and land use setting, including the different types of mass movements that may be present in an area, and their most common triggers; (ii) it should be tailored to respond to specific and general user needs. More than one protocol may be established on the same area by different users (e.g., the two managers of the mountain road network and of the gas duct discussed in § 9.5 may adopt different landslide protocols); (iii) it should be "scalable", i.e., it should be able to use additional or new information when it becomes available (e.g., it should be able to exploit the information provided by a new susceptibility map prepared for an area for which an inventory and a density map are already available and used by the protocol); (iv) it should comply with the existing local and national legislation – or it should be able to modify it; and (v) it should conform to the social and economic structure of the territory for which it is designed. Finally, the "performance" of a landslide protocol should be monitored, in space and time. Procedures for monitoring of the entire protocol and of specific rules must be built-in in the protocol, and must be put into action in the early stage of implementation of the protocol.

Here, I do not intend to design – or explain how to design – a specific landslide protocol, or to establish general (i.e., all-purpose, wide-ranging, regional) or specific (i.e., local) rules for the proper and effective management of single or multiple landslides or landslide areas. On the one side, this is beyond the scope of this work (§ 1.2). On the other side, rules and regulations to manage landslide hazards and to mitigate the associated risk are largely site specific and problem oriented. Such rules must be established to solve local and regional instability problems, considering all the existing technological, economical, societal, legislative, and political constrains. Instead, I intend to outline a framework for the design of an effective landslide protocol. The proposed framework: (i) is deliberately very general, (ii) it is based on landslide cartographic products discussed in this work, including inventory, density, susceptibility and hazard maps, (iii) it is independent from the techniques, methods and tools used to obtain the different types of landslide maps and models, (iv) it is capable of using information of different completeness and complexity, from inventory maps to hazard models, and (v) it assumes that land use regulations are established – and applied – in landslide areas, in the vicinity of landslide areas, and in the mapping units used to partition (i.e., zone) the territory.

Where no landslide information is available, i.e., where not even an inventory map was prepared, land use regulations based on landslide information cannot be established. For areas where a landslide inventory was prepared (Figure 9.1.A) only one set of regulations can be established, i.e., for the areas mapped as landslides. Little can be said about the remaining territory, unless a distinction is made between the areas that are free of landslides and those where landslides were not recognised (e.g., Cardinali *et al.*, 1990); a distinction that is usually not made in landslide inventory maps. For landslide areas, regulations may change depending on the type, age, degree of activity, and certainty of the landslide, where this information is available. Separate rules, e.g. calling for more specific investigations, can be established in the vicinity of an existing (i.e., known, mapped) landslide, or in the area of the possible expansion of a landslide (e.g., down slope from the toe of a complex slide). The extent of the warning zone may be fixed, or may vary depending on landslide size, type, and expected evolution (Felicioni *et al*., 1994; Cardinali *et al.*, 2003; Guzzetti, 2004; Reichenbach *et al*., 2005).

Designing regulations for density maps may be somewhat easier (Figure 9.1.B). In these maps, the land area that is potentially hazardous is not classified as totally free of landslides. A single rule, either loosely or tightly enforced, or a set of rules of escalating complexity can be designed to depict increasing spatial density of landslides. The combination of landslide and density maps shows information of different utility and requires two sets of rules: one for the areas mapped as having landslides and one for the remaining land area. The latter will be based on the abundance of landslides. For the San Mateo County in the San Francisco Bay Region (California), the number of landslides per square acre was used to control (i.e., limit) the building of new developments (Brabb, 1995). For the purpose, a landslide inventory map prepared by the U.S. Geological Survey was used (Brabb and Pampeyan, 1972). This is an example of a simple and effective land use regulation established based upon landslide density.

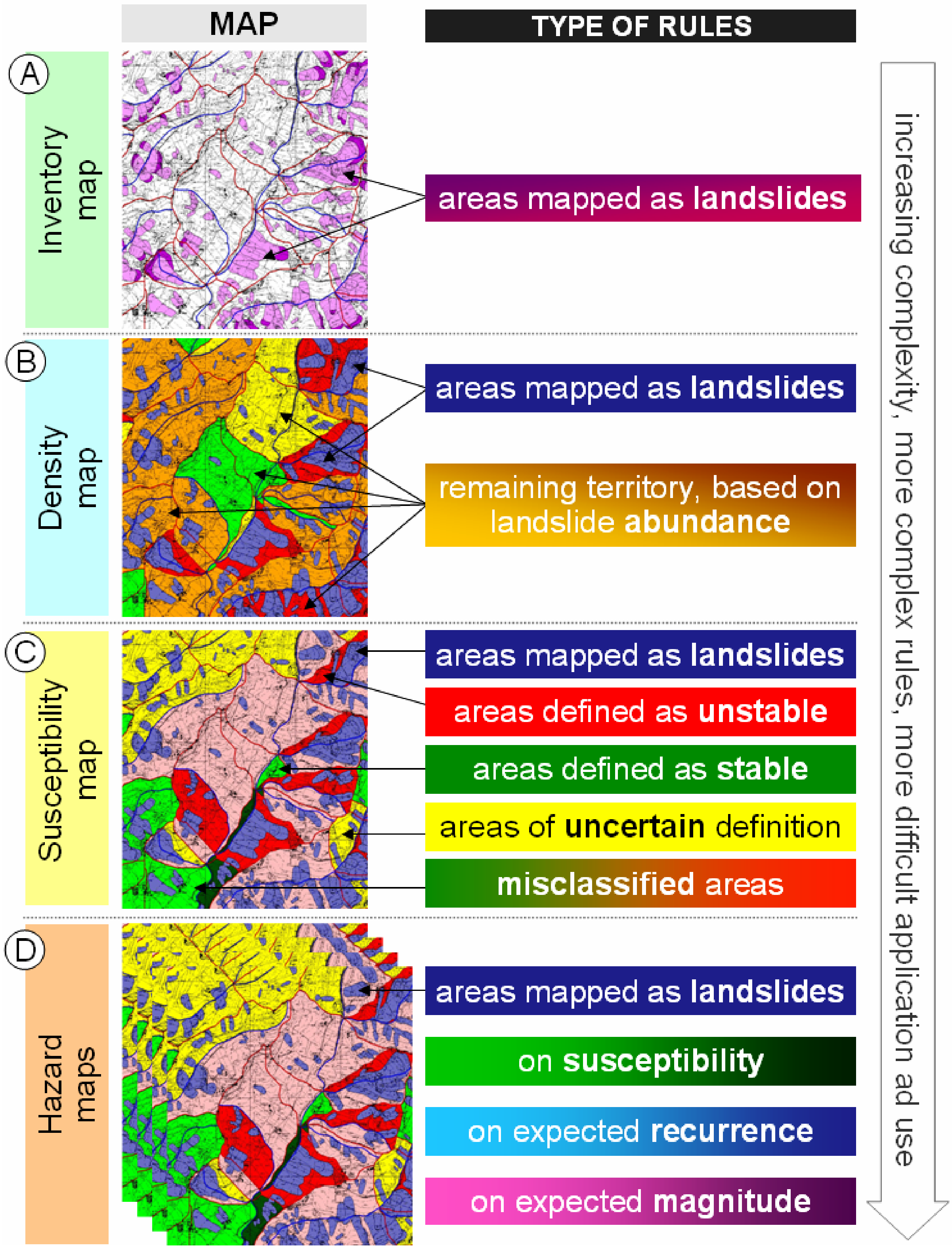

Figure 9.1 – Conceptual example for the design of a landslide protocol. Rules are based on the type of landslide map, and the type and abundance of the available landslide information.

It can be difficult to design a protocol for a landslide susceptibility map (Figure 9.1.C). Rules can be made that take model output and reliability into consideration, and deal differently with terrain domains classified as unconditionally stable or unstable, and those for which further investigation is required. A complex set of regulations based on a susceptibility model would cover areas mapped as having landslides, those that the model defines as landslide-prone or stable, those of uncertain definition, and even the areas that were mapped erroneously (i.e., misclassified) by the susceptibility model. Where the quality of the susceptibility model was quantitatively verified, and the error (i.e., a measure of the uncertainty) associated with the probability estimate was determined, the information can be used to modify individual rules, e.g., by calling for more specific investigations in areas where the uncertainty is large. Development of a thorough protocol based on landslide susceptibility may be greatly aided by GIS technology.

Design of a landslide protocol that fully exploits the information provided by a complete landslide hazard assessment (Figure 9.1.D) can be extremely complex, but may also prove very effective (advantageous) for the end user , allowing for the optimal development of a territory, given the physiographical setting and the social, economical and political constrains. Where a landslide hazard assessment exists, rules can be made that: (i) cover areas mapped as having landslides, (ii) consider the spatial probability of landslide occurrence (i.e., susceptibility), (iii) consider the expected recurrence of landslides, for different time periods, and (iv) consider the magnitude (e.g., area, volume, destructiveness) of the expected slope failures. For landslide areas, the same considerations made for landslide inventories apply, i.e., regulations may change depending on the type, age, degree of activity, and certainty of the landslide, where this information is available. Separate rules can be established in the vicinity of an existing landslide, or in the area of the possible or probable expansion of a landslide. For the spatial probability of landslide occurrence the same considerations made for susceptibility maps apply, i.e., rules can be established for areas defined as stable or unstable by the model, for unclassified areas, and for areas misclassified by the model. In addition, specific rules can be established – or the existing rules can be modified – based on the expected magnitude or the expected recurrence of the slope failures. As a complete hazard assessment results in a large set of scenarios, a comprehensive protocol exploiting all the available hazard information would probably be linked to different landslide scenarios. For the purpose, GIS technology becomes essential. Within a GIS environment encompassing all the information used to build the hazard model, rules can be defined that consider information such as topography, morphology, lithology, urban expansion, and land use, which is not readily available from landslide inventory, density or susceptibility maps.

Establishing general land use regulations based on the results of a landslide risk evaluation is problematic, and to some extent controversial. For this reason, I have not considered landslide risk in Figure 9.1. As I have explained before (§ 9.5), the focus of a landslide risk evaluation differs from that of the other types of landslide investigations. The focus of a risk assessment is an individual element at risk (e.g., a single house), a group of elements at risk (e.g., a group of houses, or a village), or a class of elements at risk (e.g., all residential buildings in a village). Thus, focus of a risk assessment are the elements at risk present or anticipated in an area, and not the area *per se* (i.e., the territory) – unless the area is considered an asset. Since the rules of a landslide protocol apply to terrain domains (i.e., to clearly defined land areas), establishing rules based on risk evaluations is difficult. Further, landslide risk results from the complex interaction between hazards (i.e., the “state of nature”, Cardinali *et al*., 2003), the presence of the elements at risk, and their individual and cumulative vulnerability to the expected hazards (§ 8.2). Thus, regulations should take into account all the three mentioned aspects, including hazards, elements at risk, and vulnerability. Such regulations may be very difficult to establish, and controversial in places. This is not to say that the results of a landslide risk evaluation cannot be used to mitigate the negative effects of landslide hazards. Landslide risk evaluations can be used to determine the levels of risk of single or multiple elements at risk. Based on this information, actions to reduce the risk to the vulnerable elements can be selected and implemented, including structural and non-structural measurements aimed at mitigating the hazards.

It is worth pointing out that the design of a landslide protocol – as such – does not guarantee that landslide hazards are reduced, and that landslide risk is mitigated or avoided. To mitigate the hazards and reduce the associated risk, a protocol must be: (i) adopted, (ii) implemented, (iii) monitored, and (iv) modified and updated, where necessary. Adoption and implementation of a landslide protocol, including possible modifications to the existing legislation, is the task of decision makers and legislators. Geomorphologists can provide technical expertise to encourage the adoption of the landslide protocol, and can help designing the new legislation, where needed. Monitoring of the landslide protocol is essential. This complex operation should be performed by teams of experts, including geomorphologists, covering various expertises. Verifying the performance of a landslide protocol, or of specific rules within the protocol, requires establishing criteria and thresholds. The latter, is a very difficult task that requires various expertises and multiple iterations. When problems or deficiencies are outlined in an adopted protocol, these should be carefully considered and proper solutions should be searched, including specific (local) modifications to the existing rules, the introduction of local rules, and the introduction of new, general rules.

9.7. Summary of achieved results

In this chapter, I have:

(a) Critically evaluated the information content – including advantages and limitations – of different landslide maps and models, in view of their potential use by various end users.

(b) Shown that, despite limitations, all the discussed cartographic products have potential useful applications, but also that landslide cartographic products are specific (i.e., not interchangeable).

(c) Proposed the idea of a "*landslide protocol*", i.e. of a coherent and organized ensemble of rules linking terrain domains to land use regulations.

This responds to Question # 8 and contributes to respond to Question # 9 posed in the Introduction (§ 1.2).