1. INTRODUCTION

No matter where you are going,
the road is uphill and against the wind.

A "*landslide*" is the movement of a mass of rock, debris, or earth down a slope, under the influence of gravity (Nemčok *et al.*, 1972; Varnes, 1978; Hutchinson, 1988; WP/WLI, 1990; Cruden, 1991; Cruden and Varnes, 1996). Different phenomena cause landslides, including intense or prolonged rainfall, earthquakes, rapid snow melting, and a variety of human activities. Landslides can involve flowing, sliding, toppling or falling movements, and many landslides exhibit a combination of two or more types of movements (Varnes, 1978; Crozier, 1986; Hutchinson, 1988; Cruden and Varnes, 1996; Dikau *et al.,* 1996).

The range of landslide phenomena is extremely large, making mass movements one of the most diversified and complex natural hazard (Figure 1.1). Landslides have been recognized in all continents, in the seas and in the oceans. On Earth, the area of a landslide spans nine orders of magnitude, from a small soil slide involving a few square meters to large submarine landslides covering several hundreds of square kilometres of land and sea floor. The volume of mass movements spans sixteen orders of magnitude, from a single cobble falling from a rock cliff to gigantic submarine slides. Landslide velocity extends at least over fourteen orders of magnitude, from creeping failures moving at millimetres per year (or even less) to rock avalanches travelling at hundreds of kilometres per hour. Mass movements can occur singularly or in groups of up to several thousands. Multiple landslides occur almost simultaneously when slopes are shaken by an earthquake or over a period of hours or days when failures are triggered by intense or prolonged rainfall. Rapid snow melting can trigger slope failures several days after the onset of the triggering meteorological event. An individual landslide-triggering event (e.g., intense or prolonged rainfall, earthquake, snow melting) can involve a single slope or a group of slopes extending for a few hectares, or can affect thousands of square kilometres spanning major physiographic and climatic regions. Total landslide area produced by an individual triggering event ranges from a few tens of square meters to hundreds of square kilometres. The lifetime of a single mass movement ranges from a few seconds in the case of individual rock falls, to several hundreds and possibly thousands of years in the case of large dormant landslides.

The extraordinary breadth of the spectrum of landslide phenomena makes it difficult – if not impossible – to define a single methodology to identify and map landslides, to ascertain landslide hazards, and to evaluate the associated risk. The experience gained in experiments and surveys carried out by geomorphologists and engineering geologists in many areas of the world has shown that different strategies and a combination of different methods and techniques have to be applied, depending on the type and number of the landslides, the extent and complexity of the study area, and the available resources. This makes landslide mapping, landslide susceptibility and hazard assessment, and landslide risk evaluation a unique challenge for scientists, planners and decision makers.

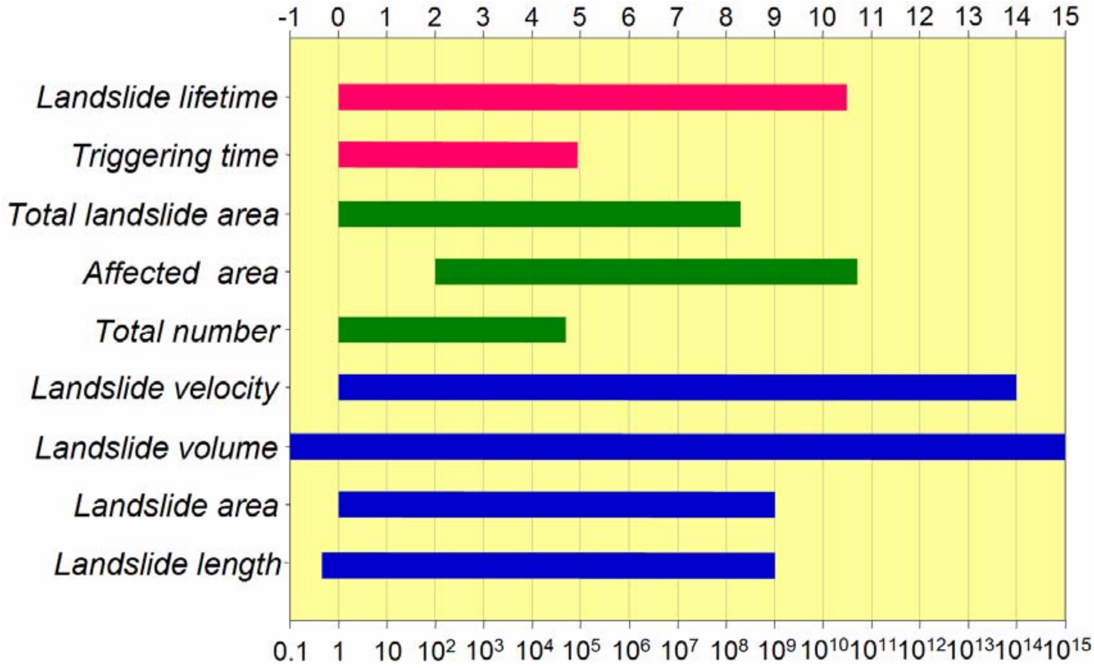

Figure 1.1 – The large spectrum of landslide phenomena. x-axes show order of magnitude (logarithmic scale). Landslide length, in metre, landslide area, in square metre, and landslide volume, in cubic metre, refer to a single slope failure. Landslide velocity is in metre per second. Total number is the number of landslides triggered by an event. Affected area is the territory affected by the trigging event, in square metre. Total landslide area is the cumulative landslide area produced by a triggering event, in square metre. Triggering time is the period of a landslide triggering event, in second. Lifetime is the lifetime of a landslide, in seconds. Figures in the graph are approximate and for descriptive purposes.

1.1. Significance of the problem

The population of Europe has grown from about 120 millions in 1700 to more than 750 millions in 2000. In the same period, the population of Italy has grown from 13 millions (in 1700), to 57 millions (in 2004) (Figure 1.2). The increase in the population is almost invariably associated with an intensive – and locally excessive – exploitation of the land, including development of new settlements, and construction of roads, railways, and other infrastructures. As an example, from 1950 to 1990 more than 100,000 kilometres of roads were built in Italy, the same as the total length of roads available in 1865. In the same period, the number and the extent of the built-up areas have grown substantially. In many areas of Italy, due to the local physiographical setting, expansion of new settlements and infrastructure occurred in dangerous or potentially hazardous areas. The growing population and the expansion of settlements and life-lines over hazardous areas have increased the impact of landslides in Italy, as in many other industrialized and developing countries.

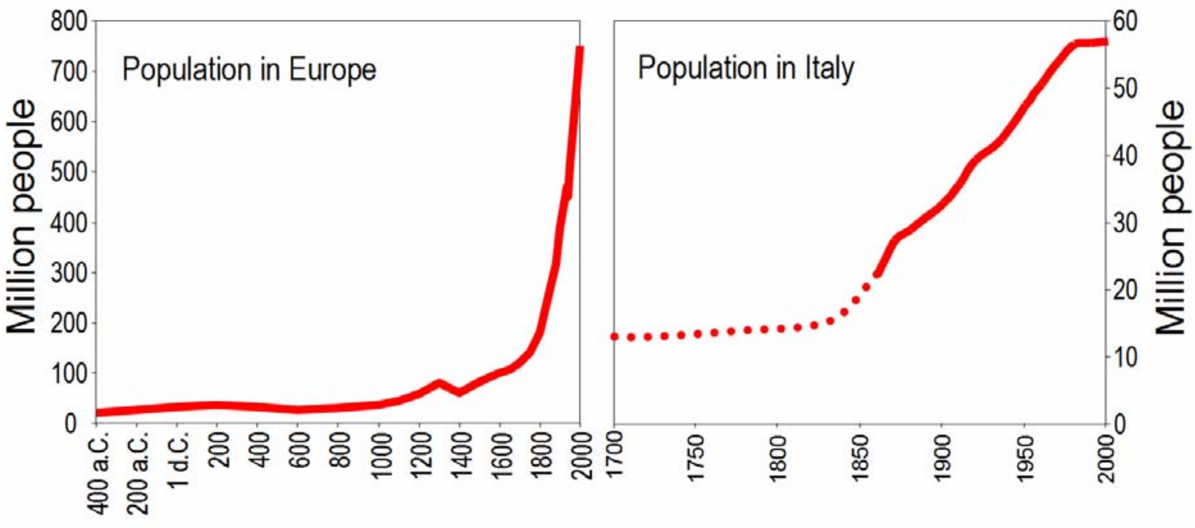

Figure 1.2 – Historical variation of the population in Europe (left) and in Italy (right).

Despite the physical (natural) phenomena being the same, the approaches to cope with landslides and their associated hazards and risk vary substantially in industrialized and developing countries. In industrialized countries, the extent and complexity of the problem and a generalized shortage of economic resources hampers systematic, long term investments in structural measures to substantially reduce the risk posed by natural hazards (Plattner, 2005). For landslides the problem is especially difficult (Brabb and Harrod, 1989; Brabb, 1991). Individual remedial measures can be very expensive, and most commonly mitigate the risk only in limited areas, often a single slope or a portion of a slope, making it economically impossible to lessen the hazards over large areas (i.e., an entire region) using structural (engineering) approaches. In developing countries societal and economic problems are often so large and serious that little attention is posed to the negative effects of natural hazards in general, and of landslides in particular. In these countries, the limited available resources are – ate best – invested primarily to improve health and education or to promote the economy, and little remains available to mitigate the catastrophic effects of natural hazards, including slope failures.

In many places the new issue seems to be the implementation of warning systems, and the adoption of new regulations for land utilisation aimed at minimising the loss of lives and property without investing in long-term, costly projects of ground stabilisation. In this framework, landslide hazard assessment and risk evaluation are particularly relevant, and pose a difficult challenge for scientists, civil defence managers, planners, land developers, policy and decision makers, and concerned citizens. Design and implementation of efficient and sustainable planning and land-use policies pose increasingly complex problems. These problems are different from the traditional problems of both pure and applied science. As regards to landslide hazard assessment and risk evaluation, on one side geomorphology is unable to provide a well-founded theory, and on the other side environmental issues and policy decisions challenge geomorphologists with very difficult questions.

Due to the large spectrum of landslide phenomena (Figure 1.1), to uncertainties in data acquisition and handling and in model selection and calibration, and to the complexity and vulnerability of modern societies, landslide mapping, landslide susceptibility zoning, landslide hazard assessment, and landslide risk evaluation appear out of the reach of the traditional puzzle-solving scientific approach, based on controlled experiments and on a generalised consensus among experts. Solutions to these challenging problems may come from a new scientific practice capable to cope with large uncertainties, varying expert judgements, and societal issues raised by hazard assessments and risk evaluations (Guzzetti *et al.*, 1999a).

In this context, increasing efforts are needed to make methods for landslide mapping, for landslide susceptibility zoning and hazard assessment and for risk determination, better documented and more reproducible. In one word: to make it more "scientific". Additional efforts are needed to transfer the scientific information on landslides and the associated hazards and risk into planning regulations, building codes and civil defence plans.

1.2. Ambition of the work

In a paper published in 1991 entitled "The World Landslide Problem", Earl E. Brabb, a pioneer in landslide mapping and in the application of landslide maps to planning and policy making, wrote:

> *(…) Landsliding is a worldwide problem that probably results in thousands of deaths and tens of billions of dollars of damage each year. Much of this loss would be avoidable if the problems were recognized early, but less than one percent of the world has landslide-inventory maps that show where landslides have been a problem in the past, and even smaller areas have landslide-susceptibility maps that show the severity of landslide problems in terms decision makers understand. Landslides are generally more manageable and predictable than earthquakes, volcanic eruptions, and some storms, but only a few countries have taken advantage of this knowledge to reduce landslide hazards.*
>
> *Landsliding is likely to become more important to decision makers in the future as more people move into urban areas in mountain environments and as the interaction between deforestation, soil erosion, stream-habitat destruction, and landsliding becomes more apparent. (…)*

Fifteen years later the situation has not changed significantly. Review of the literature (§ 13) indicates that despite the many published examples and the efforts of experts in different fields, particularly in the realms of geomorphology and engineering geology, consensus amongst scientists and professionals remains poor (or is even inexistent) on several aspects of landslide hazard assessment and risk evaluation.

Consensus lacks in particular on: (i) how to evaluate the quality and completeness of landslide inventory maps, (ii) how to obtain reliable estimates of landslide susceptibility, and how to test the quality and reliability of the obtained susceptibility estimates, (iii) how to define landslide hazard in a way that is useful to the end users, and (iv) what methods and data to use to successfully determine landslide risk. Further, experts quite often do not agree on: (i) the reliability and even the feasibility of landslide inventory maps over large regions, extending for thousands of square kilometres across physiographical boundaries, (ii) the possibility of producing reliable zonings of landslide susceptibility for large areas based on verifiable methods, (iii) the possibility of obtaining probabilistic landslide hazard assessments of practical use, and (iv) the opportunity to determine quantitative, empirical, and heuristic levels of landslide risk at different temporal and spatial scales. Consensus and standards are also lacking on how to display, use, and disseminate the results of landslide investigations, including the several types of landslide maps and models. Confusion is added by the unclear, vague or – often – incorrect use of the technical language. As an example, as noted by Guzzetti *et al*. (1999a), the same term "landslide" is often used to describe the process, the movement, and the deposit. Similarly, many authors confuse the terms "susceptibility" and "hazard", making it difficult to understand and compare the results of their work.

It is the ambition of this work to contribute to reduce some of these shortcomings by providing the scientific rationale, a common language, and a set of validated tools, for the preparation and the optimal use of landslide maps, of landside models, and of landslide forecasts.

More specifically, in this work I intend to address the following questions:

(1) Can landslide maps be consistently prepared for large areas, extending for thousands of square kilometres across major physiographical boundaries?

(2) Can we determine the quality, reliability and completeness of landslide maps?

(3) Can temporal information on landslides and their spatial evolution be obtained reliably for small and large areas? Can the temporal information be shown on maps, and exploited to determine landslide hazard and risk?

(4) How can we reliably estimate the statistics of landslide size? Can we use the obtained statistics do determine landslide hazard and risk?

(5) Can we zone a large territory according to its propensity to generate new or reactivated landslides, using verifiable methods? Can we measure the error associated with spatial landslide forecasts?

(6) Can we determine and rank the hazards posed by landslides using probabilistic forecasts? Can we measure the reliability of these forecasts?

(7) Can we contribute to mitigate landslide risk by establishing reliable methods to determine the risk?

(8) How can we best exploit available and innovative landslide maps, models and predictions, to mitigate landslide risk?

(9) Can we define a unified framework to determine landslide hazards and to evaluate the associated risk at different temporal and spatial scales?

The listed questions match ideas to prove and problems to solve. To look for satisfactory and feasible solutions to the proposed problems, I intend to: (i) establish the rationale on which to base landslide hazard assessment and risk evaluation, (ii) provide a set of mathematical models and tested techniques and methods capable of producing the desired landslide products and predictions, (iii) define appropriate standards of quality and verification procedures for different types of landslide maps and models, and (iv) offer relevant examples of various landslide cartographic products, obtained adopting the proposed models and methods.

I also intend to critically analyze traditional and innovative methods to map landslides, to zone a territory based on its susceptibility to mass movements, to determine and predict landslide hazards, and to evaluate landslide risk, at different geographical and temporal scales and in different physiographical environments.

As it will become clear later, the conception and the production of maps is a fundamental part of this work. This is not surprising, as maps are the tools that earth scientists prefer in order to portray geological information and convey it to other scientists, decision-makers, and the public. In the realm of natural hazards, maps are prepared to show where catastrophes have happened or where they are expected to occur, and can be used to divide up land areas into zones of different hazard and to show risk levels. Cartography is a crucial aspect of landslide hazard assessment and risk evaluation, and landslides are no exception.

In this context, landslide cartography must not be intended only as a set of drafting methods and computer tools available to portray landslide-related information on a map or on the screen of a computer. *Landslide Cartography* is an ensemble of theories, paradigms, models, methods, and techniques to obtain, analyze and generate relevant information on landslides, and to convey it to the end user, i.e., another scientist, a decision or policy maker, or the interested citizens. An ambition of this work is to contribute to base landslide cartography on a well established rationale. This will not prevent using empirical or heuristic approaches. To the opposite, I will show that the combination of various sources of information analyzed with a variety of methods and techniques provides the most advanced and – hopefully – the most useful response to many landslide hazard and risk problems. I also intend to show how to best exploit geomorphological reasoning, including geomorphological information, theories, methods and techniques, to better map landslides, to determine their hazards, and to evaluate the associated risk.

Ideally, a single ("unified") method for investigating landslides and for the production of relevant landslide cartographic products is desirable. A single method would guarantee consistency and would help comparing products and results obtained in different areas, by different investigators, and at different times. Unfortunately, due to the extraordinary breadth of the spectrum of landslide phenomena (Figure 1.1), such a unified method is difficult to obtain. Instead, I propose that a common set of tools, which I call a "*toolbox for landslide cartography*", can be used to map landslides, to determine the spatial persistence and the temporal recurrence of landslides in an area, to zone a territory on the expected susceptibility to mass movements, to determine and predict landslide hazards, and to evaluate the risk posed by slope failures at different spatial and temporal scales. Like in other scientific disciplines where science coexists with its day-to-day application (e.g., in the medical science and practice), a single tool (model, technique or method) cannot solve all problems, always and everywhere. Instead, a large and efficient set of tools proves more effective. In the framework of this work, the toolbox consists of an ensemble of scientific knowledge, case studies, reliable statistics, tested models, proven techniques, and verified procedures.

In the following chapters, I will show examples of landslide maps and models at scales ranging from the local (i.e., large scale) to the regional (i.e., small scale). In general, the models and methods that I will propose and discuss, and the resulting landslide products, are more suited to solve landslide problems at the basin scale, i.e., for areas ranging from a few tens to a several hundreds of square kilometres. However, I will make examples of landslide inventory maps, of hazard assessments, and of risk evaluations completed at the national (synoptic) scale, and at the local (large) scale. In this work, I will not enter the vast realm of the investigations at the site scale, i.e., for individual slopes; a problem more suited to engineering geologists and geotechnical engineers interested in monitoring single slope failures, and in devising the appropriate site specific remedial measurements. Still, I will show that some of the proposed methods (e.g., multi-temporal landslide mapping, § 3.3.4, or geomorphological landslide risk assessment, § 8.4) can be successfully applied at the site scale. In combination with other site-specific approaches and investigations, these methods can help understanding the local instability conditions and the evolution of an individual slope, or of a group of slopes.

At the end of the work, I will propose recommendations for the production and optimal use of landslide cartographic products. Much of what I present and discuss, including many of the examples and the final recommendations, are based on the results of landslide studies carried out in the central and the northern Apennines of Italy, and mostly in the Umbria Region. However, I believe that the selected examples are general, and that the lessons learned in the chosen test areas are applicable to other areas, in Italy and elsewhere.

1.3. Outline of the work

Different strategies and various layouts can be adopted for writing a thesis. I have decided not to adopt a traditional layout where the explanation of the methods follows the description of the available data, and it is followed by the analysis of the data, and the latter by the discussion of the results obtained. Given the complexity of the problem, and the lack of a unified framework to address landslide hazard and risk problems, I have decided for a different, hopefully equally interesting, structure based on the sequential discussion of landslide cartographic problems of increasing complexity, from landslide inventory making to landslide risk evaluation. This is justified by the following considerations. Although it is common understanding that risk evaluation is the ultimate goal a landslide investigation – at least in the context of this work – not all landside investigations are aimed at determining landslide risk. Landslide inventory maps can be used to determine susceptibility, hazard, and risk, but exist as independent (standalone) products, with several useful applications. Also, inspection of the literature (§ 13) reveals that researchers involved in the preparation of landslide maps and catalogues may not be equally interested in landslide hazard assessments or risk evaluations. Conversely, investigators of landslide risk problems are not inevitably interested in the methods and techniques used to prepare, compile, or verify a landslide inventory or susceptibility map. Thus, although a clear and logical chain links landslide inventories to landslide susceptibility maps and hazard models, and to landslide risk evaluations, the different landslide products pose different problems and – to some extent – are aimed at difference audiences.

Based on these considerations, I have found convenient to organize the discussion based on four broad categories of landslide products, namely: (i) inventory maps and their analysis, (ii) susceptibility zonings and their verifications, (iii) hazard assessments, and (iv) risk evaluations. Whithin this framework, the thesis is organized in thirteen chapters and six appendixes. Each chapter addresses a specific topic, or a group of related arguments. In each of the main chapters, I first set the scene by introducing the problem and by reviewing the relevant literature. Next, I define the appropriate concepts and the associated language, and I discuss the geomorphological framework and – where applicable – I introduce an appropriate mathematical formulation. To substantiate the discussion, I then present several examples of the different types of discussed landslide products. The latter is done to show that such products can really be prepared and are not only intellectual constructs. Where applicable, at the end of a chapter I list the main results obtained that contribute to answering the question listed in § 1.2.

Following this Introduction (§ 1), in Chapter 2, I describe the study areas where the research discussed in the next chapters was conducted. For each study area, I provide general information on the type and abundance of landslides and on the local setting, including geography, morphology, lithology, structure, climate, and other physiographic characteristics. For some of the areas, I provide information on the type and extent of the damage caused by the landslides, and a description of the topographic, environmental and thematic data used to perform landslide susceptibility zonings, landslide hazard assessments, and landslide risk evaluations.

In Chapter 3, I address Question # 1, by examining various types of landslide inventories, including archive, geomorphological, event and multi-temporal landslide maps. In this chapter, I present the rationale for the production of a landslide inventory map, I briefly outline the criteria used to recognize and map landslides from stereoscopic aerial photographs, and I discuss some of the key limitations of the different types of landslide inventories, including the complex issue of determining the quality of a landslide inventory map (Question # 2). I substantiate the discussion with examples of different types of landslide inventories at various scales, from the local to the national.

In Chapter 4, I discuss some of the most direct applications and preliminary analyses of landslide inventories, including the comparison of inventory maps prepared with different techniques, the assessment of the abundance and the (spatial) persistence of slope failures, and the estimate of the (temporal) frequency of occurrence of landslide events (Question # 3).

In Chapter 5, I show how to obtain frequency-area and frequency-volume statistics of landslides from empirical data obtained from landslide inventories (Question # 4). I then discuss possible applications of the obtained statistics of landslide size, with examples from the Umbria region.

In Chapter 6, I discuss landslide susceptibility zoning (Question # 5). I start by reviewing the principal methods proposed in the literature, including an analysis of the types of mapping units most commonly adopted, and of the relationships between the selected mapping units and the adopted susceptibility methods. I then introduce a probabilistic model for the assessment of landslide susceptibility. To discuss problems in the application of the proposed model and limitations of the obtained results, I present a landslide susceptibility assessment prepared for the Upper Tiber River basin, which extends for more than 4000 square kilometres in central Italy. Next, I examine the problem of the verification of the performance and prediction skills of a landslide susceptibility zoning. To substantiate the discussion, I illustrate the results of a comprehensive verification of a landslide susceptibility model prepared for a test area in Umbria.

In Chapter 7, I discuss the assessment of landslide hazard (Question # 6). I first examine a widely accepted definition of landslide hazard which I contributed to propose. I then introduce a probabilistic model for landslide hazard assessment that fulfils the examined definition, and I discuss problems with its application. Next, I show three examples of application of the proposed probability model for different types of landslides and at different scales, from the basin to the national scale. In the first example, I illustrate an attempt to determine landslide hazard in the Staffora River basin, a catchment in the northern Italian Apennines. For the purpose, I exploit a multi-temporal landslide inventory and thematic data on geo-environmental factors associated with landslides. In the second example, I describe an attempt to determine landslide hazard in Italy, based on synoptic information on geology, soil types and morphology, and an archive inventory of historical landslide events. In the last example, I examine the application of a physically-based computer model to simulate rock falls to determine rock fall hazard in a mountain area in Umbria.

In Chapter 8, I discuss landslide risk (Question # 7). After a brief review of the relevant literature, I present concepts and definitions useful for landslide risk assessment, including a discussion of the differences between probabilistic (quantitative) and heuristic (qualitative) approaches. I then make examples of risk evaluations, including: (i) the determination of societal and individual levels of landslide risk in Italy; (ii) the assessment of the geographical distribution of landslide risk to the population in Italy; (iii) the determination of rock fall risk to vehicles and pedestrians along mountain roads in Umbria; (iv) the geomorphological determination of landslide risk levels at selected sites in Umbria; (v) the assessment of the type and extent of landslide damage in Umbria based on the analysis of a catalogue of landslides and their consequences; and (vi) an effort to establish the location and extent of sites of possible landslide impact on the population, the agriculture, the built-up environment, and the transportation network in Umbria.

In Chapter 9, based on the assumption that 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, I compare the information content of different landslide maps, including various types of inventory maps, density maps, susceptibility maps, hazard maps, and landslide risk evaluations. Next, considering that the goal of landslide maps and models is helping planners and decision makers to better manage landslide problems and to mitigate landslide risk, 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 (Question # 8).

In Chapter 10, 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 the conclusions on what I have presented and discussed in the other chapters, and I propose the recommendations based mostly on the experience gained in landslide studies carried out in the central and the northern Apennines of Italy.

Chapter 11 is dedicated to the acknowledgments. Chapter 12 includes a glossary of the principal terms used in this work. Chapter 13 contains an extensive list of references on landslide cartography and the related topics. Lastly, four appendixes list: (i) the variables, mathematical symbols, and equations used in the text, (ii) the figure and table captions, (iii) the acronyms used in the text, (iv) the main characteristics of the six study areas selected to perform the experiments, (v) a short *curriculum vitae et studiorium*, and (vi) a list of the accompanying publications.

1.4. Specific personal contributions

This thesis is – at least partially – a synthesis of the results of 20 years of work in landslide cartography (i.e., landslide mapping, landslide map analysis, landslide susceptibility zoning, landslide hazard assessment, and landslide risk evaluation). Most of the work discussed in the thesis was conducted at the Research Institute for Geo-Hydrological Protection (*Instituto di Ricerca per la Protezione Idrogeologica*, IRPI) of the Italian National Research Council (*Consiglio Nazionale delle Ricerche*, CNR), in the framework of National, European and U.S. funded projects.

In the period, I have been involved in a number of projects aimed at mapping landslides and at determining landslide hazards and risk, at different scales, from the local to the national, and in different physiographical environments. Inevitably, the work conducted during such a long period and on several different topics and areas, is to some extent the result of team work. However, specific contributions can be singled out. In the following, I list what I consider my main contributions to the fields of research of interest to the thesis. For each heading, I provide the most relevant references.

(a) I prepared a small scale (1:100,000) landslide inventory map for New Mexico, which extends for more than 310,000 square kilometres in the south-western United States (Guzzetti and Brabb, 19887; Cardinali *et al.*, 1990). Based on this unique product, published by the U.S. Geological Survey at 1:500,000 scale, Brabb (1993) proposed a small-scale world-wide landslide inventory, as a contribution to the International Decade for Natural Disasters Reduction (IDNDR).

(b) I prepared regional landslide maps, published at 1:100,000 scale, for the Umbria and Marche Regions of Central Italy, for a total area of 18,000 square kilometres (Guzzetti and Cardinali, 1989; 1990; Antonini *et al.*, 1993). Based on the collected information and on targeted field work, I demonstrated the influence of structural setting and lithology on landslide type and patterns in the Umbria-Marche Apennines (Guzzetti *et al.*, 1996). I have further produced detailed landslide inventory maps for selected areas in the Umbria and Marche Regions of Central Italy (Carrara *et al.*, 1991, 1995; Barchi *et al.*, 1993; Cardinali *et al.*, 1994; 2005) and in the Lombardy Region of Northern Italy (Guzzetti *et al.*, 1992; Antonini *et al.*, 2000; Guzzetti *et al.*, 2005a). I was first to recognize and map debris flow deposits in the Umbria-Marche Apennines (Guzzetti and Cardinali, 1991, 1992), and to map "sakungen" (i.e., large deep-seated gravitational slope deformations) in Umbria (Barchi *et al.*, 1993). I used the obtained map to investigate the spatial distribution of landslides in different morphological and geological environments. I investigated methods to compare different landslide inventory maps and to establish the factors that affect the quality of the landslide maps (Carrara *et al.*, 1992; Ardizzone *et al.*, 2002; Galli *et al.*, 2005).

(c) I produced event inventory maps showing the location, abundance and type of landslides triggered by various events, including: intense rainfall in the Imperia Province (Guzzetti *et al.*, 2004a), intense rainfall in the Orvieto area (Cardinali *et al.*, 2005), rapid snow-melting in central Umbria (Cardinali *et al.*, 2000), and earthquake shaking in the Umbria-Marche Apennines (Antonini *et al.*, 2002b).

(d) I have conducted experiment on the application of methods, techniques and tools (including GIS, DBMS and statistical packages) for the assessment of landslide susceptibility. I was first to show that modern GIS technology coupled with multivariate statistical analysis could be successfully applied to zone a territory on landslide susceptibility, given a set of thematic environmental data and an accurate landslide inventory map (Carrara *et al.*, 1991). I further expanded the research to test the methodology using different landslide mapping methods, different terrain subdivisions, and different combinations of thematic explanatory variables (Carrara *et al.*, 1991, 1995; Guzzetti *et al.*, 1999, 2005a,d). In this framework, I have lead a long term research project aimed at collecting landslide information and thematic environmental data in the Upper Tiber River Basin, a catchment that extends for more than 4000 square kilometres in Central Italy (Cardinali *et al.*, 2001). The project resulted in a landslide susceptibility model and map for the entire basin, a unique result given the size and complexity of the area, and the amount of information treated (Cardinali *et al*., 2002b). I proposed methods, a ranking scheme, and acceptance thresholds for determining and ranking the quality of landslide susceptibility models and maps (Guzzetti *et al*., 2005d).

(e) I was first to propose a probabilistic model for the determination of landslide hazard at the basin scale that fulfils a widely accepted definition of landslide hazard, which I contributed to establish (Guzzetti *et al*., 1999a). I tested the proposed model (Guzzetti *et al*., 2005a,d), showing that all the information needed to complete a probabilistic landslide hazard assessment can be obtained from the systematic analysis of multiple sets of aerial photographs of different dates.

(f) I have studied the frequency-size statistics of landslides in different parts of the world. I was first to prove that for data sets obtained from high quality landslide event inventories, the "rollover" shown in the density distribution for small landslide areas is real and not an artefact due to insufficient mapping (Guzzetti *et al*., 2002). This observation is relevant for hazard assessments and erosion studies. I proposed a landslide magnitude scale for landslide-triggering events (Malamud *et al*., 2004a), and I have studied the relationships between landslides, earthquakes, and erosion (Malamud *et al*., 2004b)

(g) I have developed a physically-based, three-dimensional rock fall simulation computer program capable of producing outputs for small and large areas (up to thousands of square kilometres) relevant to the determination of rock fall hazard and risk (Guzzetti *et al*., 2002a). I have used the computer code to ascertain landslide risk in Umbria (Guzzetti *et al*., 2004c) and to define landslide hazard in the Yosemite Valley, California (Guzzetti *et al*., 2003b).

(h) I have been involved in various research efforts aimed at determining landslide risk. I devised a system to assign heuristic levels of landslide risk to elements at risk based on information obtained from topographical maps and the interpretation of multiple sets of aerial photographs. The system was successfully tested in 79 towns in Umbria (Cardinali *et al*., 2002; Guzzetti, 2004; Reichenbach *et al*., 2005). I investigated the type and extent of damage produced by mass movements in Umbria, and I identified the locations of possible future landslide impact on the population, the built-up areas, and the infrastructure (Guzzetti *et al*., 2003). I have used catalogues of landslide and flood events with human consequences in Italy – which I compiled – to determine the levels of individual and societal landslide and flood risk to the population of Italy (Guzzetti, 2000; Guzzetti *et al*., 2005b,c).

(i) I lead a nation-wide project aimed at collecting, organizing, and analysing historical information on landslide and flood events in Italy. The project resulted in the largest digital database of information on landslides in Italy (Guzzetti *et al*., 1994, Guzzetti and Tonelli, 2004). I have used the information stored in this database to ascertain landslide hazards and risk at the national scale and, in combination with historical river discharge records, to establish hydrological thresholds for the occurrence of mass movements in Central Italy (Reichenbach *et al*., 1998a).

(j) I have critically analysed and compared the information content of different landslide cartographic products, including inventory, density and susceptibility maps. Based on the different type of information shown on the maps, I have proposed the concept of a "landslide protocol" to link terrain domains to land use regulations (Guzzetti *et al*., 2000).