8. LANDSLIDE RISK EVALUATION

A disaster is often a sequence of
apparently harmless, little mistakes.

Before I step into a puddle,
I'd like to know how deep it is.

Risk assessment is the final goal of many landslide investigations. It lays at the fuzzy boundary between science, technology, economy and politics, including planning and policy making. Assessing landslide risk is a complex and uncertain operation that requires the combination of different techniques, methods and tools, and the interplay of various expertises pertaining – among the others – to geology and geomorphology, engineering and environmental sciences, meteorology, climatology, mathematics, information technology, economics, social sciences and history. Despite the indisputable importance of landslide risk evaluation for decision making, comparatively little efforts have been made to establish and systematically test methods for landslide risk assessment, and to determine their advantages and limitations.

In this chapter, 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 quantitative (probabilistic) and qualitative (heuristic) approaches. I then make various examples of probabilistic, heuristic, and geomorphological landslide risk assessments. The examples include: (i) the determination of societal and individual levels of landslide risk in Italy, and a comparison with risk levels posed by other natural and man-made hazards, and by the principal medical causes of deaths in Italy, (ii) a preliminary attempt to establish the geographical distribution of landslide risk to the population in Italy, (iii) the determination of rock fall risk to vehicles and pedestrians along roads in the Nera River and the Corno River valleys, in eastern Umbria, (iv) the design and application of a geomorphological method for the determination of heuristic levels of landslide risk at selected sites in Umbria, based on information obtained from the interpretation of multiple sets of aerial photographs of different ages, combined with the analysis of historical information on past landslide events, and pre-existing knowledge on landslide type and abundance, (v) an attempt to determine 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.

8.1. Literature review

Literature on landslide risk is less ample than the literature on landslide mapping and landslide susceptibility and hazard assessment. This has several reasons, including: (i) the inherent difficulty to ascertain landslide risk – an operation that requires the preliminary assessment of landslide abundance, susceptibility and hazard, (ii) a generalized lack of relevant information to determine landslide risk, heuristically or using probabilistic methods, (iii) the interdisciplinary nature of landslide risk evaluation that requires the cooperative interplay of different expertises – a condition often difficult to obtain, and (iv) the fact that only recently have scientists, practitioners and decision makers demonstrated interest in landslide risk assessment studies.

Literature dealing with the general principles, theory, mathematics, economy, management, and philosophy of risk posed by natural hazards – including landslides – comprises: Starr (1969), IDNHR Advisory Committee, (1987), Slovic 1987), Ale (1991), Canadian Standards Association (1991), UNDRO (1991), The Royal Society (1992), Funtowicz and Ravetz (1995), Horlick-Jones *et al*. (1995), Olshansky (1990, 1996), Stern and Fineberg (1996), Keller *et al*. (1997); Quarantelli (1998), National Research Council (1999), Tobin (1999), Woo (1999), Alexander (2000, 2002), Papadopoulos *et al*. (2000), Batabyal and Beladi (2001), Skidmore (2001), Vecchia (2001) and Sandin (2004). In recent years, a few books and technical reports specifically aimed at reviewing and discussing the principles, concepts and definitions of landslide risk, at examining the theory of landslide risk assessment, and at proposing quantitative and qualitative methods for the evaluation of landslide risk have been published. These references include: Cruden and Fell, eds. (1997), Vecchia, ed. (2001), Wise *et al*., eds. (2004a), Lee (2004), Glade *et al*., eds. (2005) and Hungr *et al*., eds. (2005). Significantly, the majorities of the references is the cooperative result of multi-author efforts, or represent the outcome of conferences or specialized technical workshops.

A systematic and critical evaluation of the literature on landslide risk is beyond the scope of this work. An initial, but sufficiently complete review of the literature reveals that books, scientific papers and technical reports on landslide risk cover a large and diversified spectrum of topics, including:

(i) Nomenclature, concepts and definitions, an important and often overlooked aspect or landslide risk assessment. Recognized nomenclature and clearly stated definitions allow for establishing standards and for comparing the results of risk assessments (Varnes and IAEG Commission on Landslides and other Mass-Movements, 1984; Canadian Standards Association, 1991; ANCOLD, 1994; Fell, 1994, 2000; Canuti and Casagli, 1996; Chowdhury, 1996; Cruden and Fell, 1997; Evans, 1997; International Union of Geological Sciences Committee on Risk Assessment, 1997; Morgenstern, 1997; Geotechnical Engineering Office, 1998; Australian Geomechanics Society, 2000; Raetzo *et al*., 2002; Guzzetti *et al*., 2003a; Committee on the Review of the National Landslide Hazards Mitigation Strategy; 2004; Lee, 2004; Technical Committee on Risk Assessment and Management, 2004; Vandine *et al*., 2004a, 2004b; Wise *et al*., 2004a; Crozier, 2005; Crozier and Glade, 2005; Fell *et al*., 2005; Glade *et al*., 2005; Reichenbach *et al*., 2005; VanDine *et al*., 2005);

(ii) Principles, theory, probability methods and modelling approaches, which lay at the foundation of scientific landslide risk assessment (Varnes and IAEG Commission on Landslides and other Mass-Movements, 1984; Einstein, 1988, 1997; Canadian Standards Association, 1991; ANCOLD, 1994; Fell, 1994; Wu *et al*., 1996; Cruden and Fell, 1997; Fell and Hartford, 1997; Vecchia, 2001; Wise *et al*., 2004a; Xie and Xia, 2004; Guzzetti *et al*., 2005b,c; Plattner, 2005);

(iii) Assessment, application and discussion of case studies. In landslide risk assessment, demonstration, comparison and critical analysis of the results of risk evaluations are the best way of testing theories, methods and models (Stevenson, 1977, 1978; Fukuoka, 1978; Lessing *et al*., 193; Brand, 1988; Neeley and Rice, 1990; Olshansky, 1990; Carrara *et al*., 1991b; Morgan *et al*., 1992; Anderson *et al*., 1996; Eusebio *et al*., 1996; Leroi, 1996; Cruden, 1997; Cruden and Fell, eds. 1997; ERM-Hong Kong, 1998; Geotechnical Engineering Office, 1998; Michael-Leiba *et al*., 1999; Alexander, 2000; Budetta, 2002; Cardinali *et al*., 2002a; Dai *et al*., 2002; Guzzetti *et al*., 2003a, 2003b; Bonnard, *et al*., 2004; Chatterton, 2004; Guzzetti *et al*., 2004c; Lee, 2004; Wise *et al*., 2004a; Crosta *et al*., 2005; Fell *et al*., 2005; Glade *et al*., 2005; Leroi *et al*., 2005; Malone, 2005; Michael-Leiba *et al*., 2005; Reichenbach *et al*., 2005; Roberds, 2005; Sorriso-Valvo, 2005);

(iv) Management and mitigation methods and strategies. Risk assessment as such is of little interest to society. Risk assessment becomes useful when it provides insight on mitigation strategies and management methods (Fleming *et al*., 1979; Olshansky and Rogers, 1987; Flageollet, 1989; Anderson *et al*., 1996; Baum and Johnson, 1996; Einstein, 1997; Fell and Hartford, 1997; Roberds *et al*., 1997; Geotechnical Engineering Office, 1998; Malone, 1998; Swanston and Schuster, 1989; Australian Geomechanics Society, 2000; Fell, 2000; Dai *et al*., 2002; Chowdhury and Flentje, 2003; Davis *et al*., 2003; Bonnard, *et al*., 2004; Committee on the Review of the National Landslide Hazards Mitigation Strategy; 2004; Wise *et al*., 2004a; Butler and DeChano, 2005; Crozier, 2005; Fannin *et al*., 2005; Fell *et al*., 2005; Flentje *et al*., 2005; Hollenstein, 2005; Pflügner, 2005; Plattner, 2005; Leroi *et al*., 2005; Plattner, 2005; Michaels, 2005; Wieczorek *et al*., 2005);

(v) Vulnerability, assessment of the consequences, damage and socioeconomic significance, including cost-benefit analysis and insurance. Establishing the societal and economic consequences of slope failures is of primary interest. It is particularly significant when consequences to the population are ascertained (Hungr, 1981, 1997; Schuster and Fleming, 1986; Taylor and Brabb, 1986; Alexander, 1989, 2000; Brabb and Harrod, 1989; DRM Délégation aux Risques Majeurs, 1990; Olshansky, 1990; Brabb, 1991; Morgan, 1991; Morgan *et al*., 1992; Barton and Nishenko, 1994; Fell, 1994; Mejía-Navarro *et al*., 1994, 1996; Leone et al., 1996; Evans, 1997; Cruden and Fell, 1997; Morgenstern, 1997; Wong *et al*., 1997; ERM-Hong Kong, 1998; Luckman *et al*., 1999; Alexander, 2000, 2005; Australian Geomechanics Society, 2000; Guzzetti, 2000; Schuster and Highland, 2001; Dai *et al*., 2002; Kong, 2002; Raetzo *et al*., 2002; Chau *et al*., 2003; Davis *et al*., 2003; Guzzetti *et al*., 2003a, 2005b,c; Salvati *et al*., 2003; Glade, 2004; Wise *et al*., 2004a; Crozier and Glade, 2005; Düzgün and Lacasse, 2005; Glade and Crozier, 2005; Koler, 2005; Leventhal and Walker, 2005; Leroi *et al*., 2005; Paus, 2005; Petley *et al*., 2005; Pflügner, 2005; Reichenbach *et al*., 2005; Roberds, 2005; Wong, 2005; Yin and Wang, 2005);

(vi) Perception, acceptance and acceptable criteria. To some extent, risk is a matter of acceptance, which is related to perception. Establishing individual and collective levels for landslide risk, and comparing it to the risk posed by other natural, technological and societal hazards, is an important field of investigation (Starr, 1969; Whitman, 1984; Slovic, 1987; The Royal Society, 1992; ANCOLD, 1994; Fell, 1994; Sobkowicz, 1996; Finlay and Fell, 1997; Cruden and Fell, 1997; ERM-Hong Kong, 1998; Guzzetti, 2000; Dai *et al*., 2002; Nicol, 2004;

Butler and DeChano, 2005; Düzgün and Lacasse, 2005; Fell *et al*., 2005; Harmsworth and Raynor, 2005; Leroi *et al*., 2005; Plattner, 2005; Wong, 2005);

(vii) Awareness, preparedness, planning and decision making, and public education. The final scope of any risk assessment effort should be the reduction of the consequences. This often needs planning, dissemination of information, and education (Starr, 1969; Slovic, 1987; Ahlberg *et al*., 1988; Swanston and Schuster, 1989; Olshansky, 1990; Ale, 1991; Cruden and Fell, eds. 1997; Yim *et al*., 1999; Spiker and Gori, 2000, 2003; Brabb, 2002; Raetzo *et al*., 2002; U.S. Geological Survey, 2002; Solana and Kilburn, 2003; Bonnard *et al*., 2004; Committee on the Review of the National Landslide Hazards Mitigation Strategy, 2004; Hollenstein, 2005; Malone, 2005; McInnes, 2005);

(viii) Multiple hazards risk assessment. In many areas mass movements are not the sole natural hazard posing a threat. Investigating the relationships between multiple hazards, and deciding on the associated risk, is a poorly explored subject of increasing interest (IDNHR Advisory Committee, 1987; Barton and Nishenko, 1994; Horlick-Jones *et al*., 1995; ERM-Hong Kong, 1998; National Research Council, 1999; Vecchia, 2001; Glade and Evlerfeldt, 2005; Guzzetti *et al*., 2005b,c).

Some of the listed references (and many others not listed here) discuss methods, techniques and procedures to determine the risk associated with single, natural or artificial slopes (e.g., Yong *et al.*, 1977; Whitman, 1984; Brand, 1988; Chowdhury, 1988, 1996; Vedris, 1990; Popa and Fatea, 1996; Ragozin, 1996; Morgenstern, 1997; Malone, 1998; Ho *et al*., 2000; Kong, 2002; Chowdhury and Flentje, 2003; Sivakumar Babu and Mukesh, 2003; Bonnard, *et al*., 2004; Sassa *et al*., 2004; Xie and Xia, 2004; Bromhead, 2005; Jakob and Weatherly, 2005; Nadim *et al*., 2005; Roberds, 2005; Wong, 2005). To be consistent with the scopes of the work (declared in § 1.2), the risk posed by single slopes or individual landslides will not be considered in this chapter.

Many of the cited references cover two or more of the subjects listed here. This explains why several references are listed under more than one heading.

8.2. Concepts and definitions

The aim of risk evaluation is substantially different from that of landslide susceptibility or hazard assessment. When assessing landslide susceptibility (§ 6) or hazard (§ 7), the interest is on the single slope or the mapping unit where landslides can occur, posing a threat and eventually causing damage. When attempting to establish landslide risk, the focus is on the asset, i.e., the element at risk that may suffer damage from a harmful landslide. This apparently insignificant difference has large consequences. The first, to determine landslide risk information on slope failures and their expected evolution is necessary, but insufficient. Estimation of landslide risk requires information on the type, abundance, distribution, vulnerability and value of the assets in the study area. The second, if it is possible to zone an area for landslide susceptibility or hazards, it is generally unfeasible to zone an area for landslide risk. Risk is an attribute of an element and not of the area where the element is located. In the same area (e.g., in the same slope or mapping unit) many elements may be present, each with a different type or degree of vulnerability. Further, the distribution and abundance of the elements at risk in an area may change with time. As an example, traffic along roads varies during the day, and the number of residents in mountain resorts varies seasonally.

The difference between susceptibility or hazard assessment and risk evaluation is reflected in the definition of the scopes of landslide risk evaluation. In their well-known report, Varnes and the IAEG Commission on Landslides and other Mass-Movements (1984) established that:

landslide risk evaluation aims to determine the expected degree of loss due to a landslide (specific risk) and the expected number of live lost, people injured, damage to property and disruption of economic activity (total risk). (8.1)

The definition of Varnes and his IAEG collaborators, with some modifications, is largely accepted by investigators of landslide risk. Much of what will be shown in this chapter is based on this general definition of landslide risk. For the interested readers, a modern and comprehensive review of landslide risk assessment principles, including an assessment of the definition and discussion of appropriate probability methods, can be found in Vandine *et al.* (2004).

8.2.1. Vulnerability and consequence

To establish landslide risk, information on the damage caused by mass movements is compulsory. Mass movements cause damage to "elements" that, according to Varnes and his IAEG collaborators (1984), comprise the population, properties, economic activities, including public services, etc., subject to landslide risk in a given area. A more comprehensive listing of elements at risk – not including the population – is given by Alexander (2005). In the technical literature on economics and risk evaluation, elements at risk are often referred to as assets. Vulnerability is a measure of the possible or expected damage to an element at risk. According to Varnes and his IAEG collaborators (1984), vulnerability, W_L, is the degree of loss to a given element – or a set of elements – at risk resulting from the occurrence of a landslide of given magnitude. Hence, vulnerability is a measure of the robustness or the fragility of an element, or a measure of its exposure to or protection from the expected potentially damaging landslide (Vandine *et al*., 2004). In mathematical language this can be expressed as (Einstein, 1988)

$$W_L = P[D \geq 0 \mid L] \ (0 \leq D \leq 1) \tag{8.2}$$

where, D is the expected damage to an element, given the occurrence of a hazardous landslide. In equation 8.2, vulnerability is the probability of total loss or damage to a specific element, or the proportion of loss of damage to an element, given the occurrence of a landslide (Vandine *et al*., 2004). In both cases, vulnerability is expressed on a scale from 0 to 1, zero meaning no damage and one expressing complete loss. Vandine *et al*. (2004) considered the temporal effect on vulnerability and proposed the following definition:

$$W_L = P[L \mid T] \tag{8.3}$$

Equation 8.3 indicates that vulnerability of an element at risk is conditional on the element (e.g., a person, car, road or house) being at the site at the time of the landslide.

According to Alexander (2000a,b, 2005), vulnerability can be considered as the ability of an element to withstand mass movements of given types or sizes, or in terms of value. The element value can be expressed in any of three different ways: (i) monetary value, i.e., the price or current value of the asset, or the cost of replacing it with a similar or identical asset if it were totally lost or written off, (ii) intrinsic value, i.e., the extent to which an asset is considered important and irreplaceable, and (iii) utilitarian value, i.e., the usefulness of a given asset, or the monetary value of its usage averaged over a specified length of time. Human life constitutes a special case in that its intrinsic value when threatened by a hazard such as landslides is incalculable. Despite this, several measures are used in actuarial work to put a monetary value on death or injury. The first, the value of a statistical life, simply allots a standard figure, based on lost earnings, which was, for industrialized countries and in 1990s figures, about US$1.75 million for death, $10,000 for serious injury, and $1000 for minor injury (Alexander, 2000). The second, termed the private value of a statistical life, is based on lost earnings, medical expenses, and indirect costs. The third, known as the social value of a statistical life includes the private value, plus foregone taxes and general medical, emergency, legal, court and public assistance administration costs. Foregone taxes are estimated by developing an age, sex and income profile of potential victims and calculating their future tax liabilities. On this basis, the average monetary values of a human life have been variously estimated at between US$873,000 and $7 million (Alexander, 2000). The wide diversity reflects not only age, social status and earning capacity, but also the value of court awards when damages are sought.

Vulnerability can also be expressed heuristically, describing in qualitative (descriptive) terms the expected damage to the elements at risk. In this context, damage is a proxy for vulnerability, and vulnerability to structures and infrastructure can be described as, e.g., (i) aesthetical or minor, where the functionality of building and roads is not compromised and the damage can be repaired, rapidly and at low cost, (ii) functional or medium, where the functionality of structures or infrastructure is compromised, and the damage takes time and large resources to be fixed, and (iii) structural or total, where buildings and transportation routes are severely or completely damage, and they require extensive work to be fixed, and demolition and reconstruction may be required. Vulnerability to people can be described by the number of expected casualties (e.g., none, few, numerous, very numerous), or by the type of expected damage to the population, e.g., (i) no damage, where damage to the population is not expected, (ii) direct damage, where casualties (deaths, missing persons and injured people) are expected, (iii) indirect damage, where only socio-economic damage is expected, and (iv) temporary damage, where temporary or permanent loss of private houses is foreseen (i.e., evacuees and homeless people) (Cardinali *et al*., 2003; Guzzetti *et al*., 2004; Reichenbach *et al*., 2005).

An asset not necessarily is a permanent, fixed feature. As an example, the number of pedestrians and vehicles along a road changes during the day. When establishing the landslide risk to elements that may change with time, the temporal probability must be considered. To accomplish this, Vandine *et al.* (2004) proposed to ascertain the “consequence”. A consequence is the effect of a hazard to an element at risk, given some kind of temporal effect (on the hazard and on the vulnerability). Determination of the consequence includes considerations on the spatial and the temporal probability of the hazardous event, and on the vulnerability of the element. In mathematical language, this can be expressed as (Vandine *et al.*, 2004):

$$C = P(S \mid H) \times P(T \mid S) \times W(L \mid T) \tag{8.4}$$

where C is the consequence, $P(S \mid H)$ is the probability that there will be a spatial effect, given a specific harmful landslide (e.g., a debris flow will inundate a given area, or a rock fall will reach a road), $P(T \mid S)$ is the probability that there will be a temporal effect, given that there is a spatial effect (e.g., a person or a car may or may not be in the way when the debris flow inundates the area, or when the falling rock reaches the road), and $W(L \mid T)$ is vulnerability, i.e., the probability of loss or damage, given the temporal effect (e.g., vulnerability of the person or the car may depend on time) (Vandine *et al*., 2004). Equation 8.4 means that a consequence is the result (i.e., the joint conditional probability) of where the hazard will occur, of when it will occur, and on the vulnerability, which also may vary with time. When it is certain that there will be a specific spatial effect of the hazard (e.g., a debris flow will without doubt inundate a house, $P(S \mid H) = 1$), and if the location of the element at risk is permanent (e.g., a house is present in the area that will be inundated by the debris flow, $P(T \mid S) = 1$), consequence and vulnerability coincide.

Consequence can be expressed quantitatively and qualitatively. A quantitative measure of consequences is given in the range between 0 and 1, as the probability of total loss or damage to the element, or as a proportion of loss or damage to the element, depending on the unit of measure used for vulnerability. Consequence can be expressed qualitatively using descriptive consequence ratings, such as very low, low, moderate, high, or very high likelihood of total loss or damage to the element. When the probability of some loss or damage is known or assumed to be certain, consequence ratings can be expressed using terms such as no loss or damage, minor loss or damage, major loss or damage, or total loss or damage (complete destruction) (Vandine *et al*., 2004).

8.2.2. Risk analysis

Various definitions of risk have been proposed in the literature, including partial risk, specific risk, specific value risk, total risk, and multiple risk (Vandine *et al*., 2004). Varnes and the IAEG Commission on Landslides and other Mass-Movements (1984) proposed the definition of risk adopted by UNDRO (Office of the United Nations Disaster Relief Co-ordinator) for all natural hazards, be applied to the risk posed by mass movements, namely:

Specific landslide risk, R_S, is the expected degree of loss due to a landslide. (8.5)

Specific landslide risk, as defined in proposition 8.5, is most commonly expressed by the product of landslide hazard, H_L, and of landslide vulnerability, W_L, or

$$R_s = H_L \times W_L \tag{8.6}$$

In equation 8.6, both landslide hazard (H_L, eq. 7.3) and landslide vulnerability (W_L, eq. 8.2) are expressed as probabilities. Hence, specific landslide risk, W_L, is also expressed as a probability, namely, the joint probability of landslide hazard and vulnerability, given the occurrence of a landslide. This is assuming independence of hazard and vulnerability. However, recalling that hazards depends on a probability estimate of landslide magnitude (§ 7.3), a proxy for area, volume, velocity, kinetic energy or momentum, vulnerability may depend on hazard. If vulnerability is dependent from hazard, specific landslide risk becomes

$$R_s = (H_L) \times (W_L \mid H_L) \tag{8.7}$$

which means that specific landslide risk is the probability of the hazard, multiplied by the probability of the expected damage (vulnerability), conditioned on the hazard. Equation 8.7 is applicable when, for example, damage to a specific element at risk is a function of the magnitude (e.g., the size or velocity) of the harmful landslide.

Specific value risk is the worth of loss or damage to a specific element, excluding human life, resulting from a specific hazardous affecting landslide. Like vulnerability, specific value risk can be expressed using monetary, utilitarian and intrinsic value estimates. Multiple risk is the risk to more than one specific element from a single specific hazardous affecting landslide, or the risk to one specific element from more than one specific hazardous affecting landslide. Multiple partial risk, multiple specific risk, and multiple specific value risk can also be estimated by applying standard probability concepts (Vandine *et al*., 2004).

Finally, total landslide risk, R_T, was defined as

the expected number of lives lost, person injured, damage to property, or disruption of economic activity due to a landslide (8.8)

by Varnes and the IAEG Commission on Landslides and other Mass-Movements (1984), and as

the risk to all specific elements from all specific hazardous affecting landslides (8.9)

by Vandine *et al*. (2004). In the latter definition total landslide risk is expressed as a probability, and it can be estimated using standard probability concepts and methods.

8.2.3. Discussion

In the previous pages, concepts and definitions useful for landslide risk assessment were presented and discussed, together with their mathematical (probabilistic) formulation. From a practical point of view, the given definitions can be used in several of different ways, depending on: (i) the scope of the analysis, (ii) the availability, quality and reliability of the necessary information, (iii) the extent of the study area, (iv) the resources available to complete the analysis, (v) the experience and skill of the investigator, and (vi) the existence of established thresholds for acceptance of risk.

In general, when attempting to establish landslide risk, two main approaches are possible: (i) a quantitative (probabilistic) approach, and (ii) a qualitative (heuristic) approach. Quantitative landslide risk analysis (QLRA) uses numerical values and mathematical methods to estimates objective probabilities, e.g., the probability of loss of life, or the probability of damage to a structure or infrastructure due to mass movements. QLRA investigates the relationships between the frequency of the damaging events and the intensity of their consequences, and seeks to establish quantitative (numerical) acceptable or tolerable thresholds. When applied to establish risk to the population, QLRA can be used to establish probabilistic levels of individual and collective risk. The former is most commonly investigated by computing mortality rates, which are given by, e.g., the number of deaths per 100,000 of any given population over a pre-defined period. The latter is ascertained by constructing f-N or F-N plots, which describe the relationship between the frequency of the damaging events and their intensity, as measured by the number of fatalities (§ 8.3). Another method of QLRA consists in the event tree decomposition (e.g., Budetta, 2002; Nicol, 2004; Vandine *et al*., 2004). The method is based on: (i) the systematic decomposition of risk into all the individual (single) components, (ii) the quantitative estimation of the probability (or the monetary, intrinsic and utilitarian values) for each single component of the risk, and (iii) an estimate of the risk, for all the possible established outcomes. Event trees can be constructed for specific risk and for specific value risk. In the first case the method provides probability estimates, and in the second case it provides monetary estimates (e.g., actual costs).

QLRA often requires a catalogue of landslides and their consequences, the latter measured quantitatively. Compilation of lists or catalogues of landslides and their consequences is a difficult, time consuming, expensive and uncertain operation, mostly because of the lack of relevant information (Guzzetti *et al*., 1994; Ibsen and Brunsden, 1996; Glade, 1988; Glade *et al*., 2001). A few of such lists have been prepared for landslides with human consequences (Evans, 1997; Guzzetti, 2000; Kong, 2002; Salvati *et al*., 2003; Guzzetti *et al*., 2005b,c). When this information is available, levels of individual and societal risk can be determined.

However, the completeness, time span and reliability of the landslide catalogue greatly affect the reliability of such quantitative risk assessments.

When attempting to evaluate specific and total landslide risk for a single site or an entire region where slope failures are likely to take various forms or pose various threats, the quantitative approach can prove impracticable, uneconomical or even impossible (Guzzetti *et al*., 2003). It may not be easy to ascertain the magnitude, frequency and forms of evolution of landslides in an area, and detailed and reasonably complete catalogues of historical events and their consequences may not be readily available. As an alternative to quantitative risk assessment, a qualitative approach can be pursued in such a way as to establish qualitative levels of landslide risk. Qualitative landslide risk analysis (qLRA) uses relative qualitative (descriptive) ratings, and may result in designing landslide scenarios.

A landslide scenario is a description of one or several hypothetical, potentially damaging landslide events, including the consequences on the population, properties, economic activities, and the landscape. As in a theatre play, a scenario should include: (i) the "actors", i.e., the assets involved in or affected by the event, including the population; and (ii) the "context", i.e., the temporal arrangement and evolution and the geographical location of the event and the assets, including the social, economical, administrative and legal aspects directly or indirectly related to the event. For a scenario, a probability of occurrence should be established. The probability can be determined quantitatively, e.g., modelling an historical record of landslide events, or it can be established empirically, e.g., by using external information. The probability of a scenario associated with rare events may be difficult (or impossible) to determine quantitatively, and can be decided using geomorphological inference, the personal experience of the investigator, or other information. The design of a landslide scenario for a given area is a complex, largely empirical procedure that involves: (i) identification of the assets and their vulnerability, (ii) identification of the types of slope processes present in the study area, (iii) accurate mapping of the existing landslides, and (iv) assessment of the possible (or probable) evolution of the slope movements. The latter, can be ascertained qualitatively by experts, or it can be determined quantitatively using mathematical or physically-based models which simulate the expected evolution of a landslide. Multiple landslide scenarios can be prepared, one scenario for each landslide or landslide types present in the study area.

With regard to precision accuracy and reliability, quantitative landslide risk estimates are not necessarily better than qualitative estimates. In landslide risk analysis, the precision and reliability of an estimate does not depend on the use of numbers or probabilistic equations. It rather depends on whether all the components of the analysis have been appropriately considered and on the availability, quality, and reliability of the required data (Vandine *et al*., 2004).

8.3. Evaluation of landslide risk to individuals and the population

Quantitative landslide risk assessment (QLRA) can be used to determine the risk posed by landslides to identified individuals or the population (Cruden and Fell, 1997; Fell and Hartford, 1997; Evans, 1997; Guzzetti, 2000; Wise *et al*., 2004; Nicol, 2004; Guzzetti *et al*., 2005b,c). Most commonly, the method requires a catalogue of landslides and their human consequences, i.e., deaths, missing persons, injured people, evacuees and homeless. The completeness and time span of the catalogue affect the reliability of the risk assessments. Only a few lists of landslides with human consequences have been prepared. Such lists are mostly limited to specific areas or individual countries (Evans, 1997; Guzzetti, 2000; Kong, 2002; Salvati *et al.*, 2003; Nicol, 2004; Guzzetti *et al.*, 2005b,c).

When a sufficiently complete catalogue of landslide events with human consequences is available, levels of individual and societal risk can be determined (Cruden and Fell, 1997; ISSMGE TC32, 2004; Wise *et al.*, 2004). Individual risk is the risk posed by a hazard to any identified individual and it is commonly expressed using mortality (or death) rates, which are usually given by the number of deaths per 100,000 of any given population over a pre-defined period. Societal (or collective) risk is the risk imposed by a landslide on society as a whole, and it is established by investigating the relationship between the frequency of the damaging events and their intensity, as measured by the number of deaths, fatalities or casualties. The relationship between the frequency of the harmful events and their consequences is shown on cumulative (F-N) or non-cumulative (f-N) plots (Cruden and Fell, 1997; Evans, 1997; Guzzetti, 2000). When such plots are prepared in log-log scale, the relationship between the number of events and the number of the consequences in each event exhibits a linear trend. This is important because, in principle, it allows determining the frequency and magnitude of large events (i.e., events with numerous fatalities) by studying the frequency and magnitude of the small events, i.e., those resulting in few fatalities. A linear trend in a log-log plot suggests a power law scaling, and power laws are commonly used to model such probability distributions (Evans, 1997; Guzzetti, 2000; Guzzetti *et al.*, 2005b,c).

Quantitative landslide risk assessment allows determining acceptable risk levels. Acceptable levels of individual and collective landslide risk can be determined by comparison with other natural, technological and societal hazards for which acceptable risk levels have already been established (e.g., Whitman, 1984; Fell and Hartford 1997; Salvati *et al.*, 2003; Nicol, 2004; Guzzetti *et al.*, 2005b). In the following, examples will be given of the use of QLRA techniques to determine landslide risk to the population in Italy.

8.3.1. Landslide risk to the population in Italy

In Italy, information exists to determine quantitatively the risk posed by landslides to the population, and to compare it with the risk posed by other natural and man made hazards, and by the leading medical causes of death. Systematic information on landslides with human consequences in Italy was first compiled by Guzzetti (2000), for the period between 1279 and 1999. Guzzetti *et al*. (2005b) revised this information and compiled an updated catalogue for the 2096-year period from 91 BC to 2004. The new catalogue lists 2444 events with human consequences, of which 1305 events with casualties. In the examined period, landslide casualties were at least 13,250, comprising 10,892 deaths, 85 missing persons, and 2273 injured people. The catalogue also lists 1331 events with homeless or evacuated people, for a total population exceeding 180,000. The new catalogue of Guzzetti *et al*. (2005b,c) also lists systematic information on floods with human consequences in the period from 1195 to 2004, and systematic information on earthquakes with human consequences in the period from 51 AD to 2004. Figure 8.1 shows the historical distribution of landslide events with casualties in Italy, for the period from 1500 to 2004. In the graph, open squares indicate the number of fatalities in each event, and open triangles the number of the injured people. Grey squares indicate landslide events for which casualties are known to have occurred but for which the exact, or even an approximate number, is unknown. Between 1500 and 2004, the most catastrophic year for landslides was 1963 with 1950 casualties, 1921 of which occurred at Vajont. The second worst year was 1618, when 1200 people were killed by the Piuro rockslide-avalanche (Lombardy), followed by 1765 with about 600 deaths at Roccamontepiano (Abruzzo).

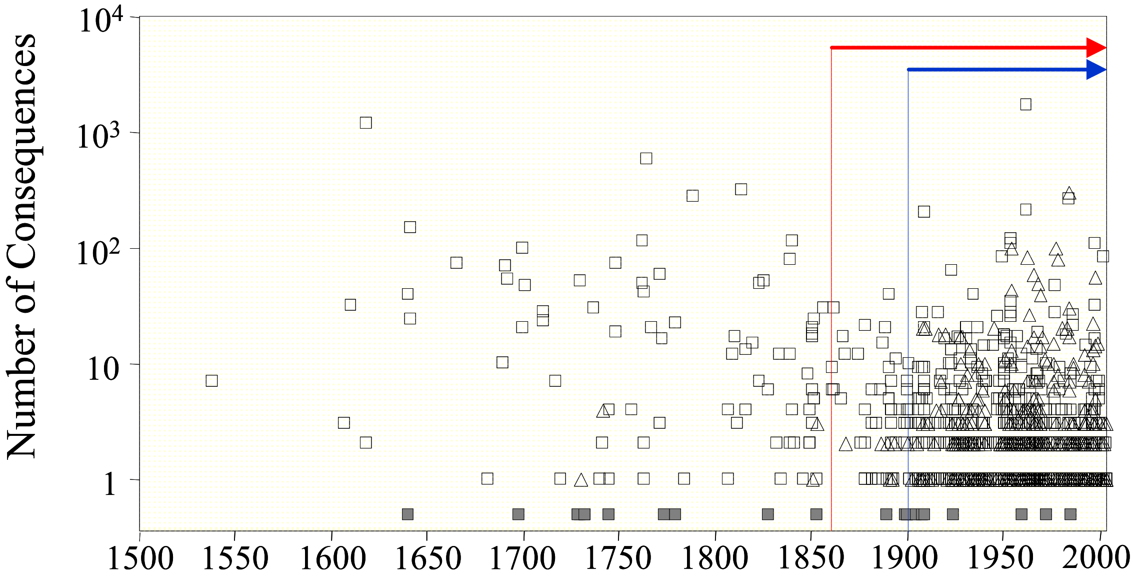

Figure 8.1 – Historical distribution of damaging landslide events in Italy, from 1500 to 2004. Open squares, fatalities; open triangles, injured people; grey squares, events for which casualties occurred in unknown number. Red and blue lines show period for which individual and societal landslide risk to the population was determined, respectively.

Inspection of Figure 8.1 reveals a different abundance of the damaging events with time. Only 17 events with fatalities are listed in the catalogue before 1700. In the graph, the absence of recorded events in any given period may be due either to incompleteness in the catalogue or to variation in the conditions that led to mass-movements. Determining the relative importance of the two causes is difficult, as it requires assessing the completeness of the historical catalogue, a non-trivial task.

To evaluate the completeness of a catalogue of natural events, Guzzetti (2000) proposed an empirical approach based on the comparison of the cumulative curves of damaging events of increasing intensity. Application of the method to the Italian catalogue of landslides with human consequences was discussed in § 4.3.1. Results of the analysis, shown in Figure 4.9, indicate that the completeness of the archive varies with the intensity of the events. For very large intensity events (≥ 100 fatalities) the catalogue is probably complete after 1600. For medium (≥ 10 fatalities) and low (≥ 3 fatalities) intensity events the catalogue is probably complete only after 1900. If all events are considered, the catalogue is substantially complete for statistical purposes starting in 1900 and complete after 1950. This information is mandatory to properly determine landslide risk to the population.

8.3.1.1. Individual landslide risk

In Italy, nationwide information on population is available from 1861 to 2004 from censuses carried out every ten years by the *Istituto Nazionale di Statistica* (*ISTAT*, the Italian Census Bureau, http://www.istat.it). By combining information on population with the annual number of fatalities caused by landslides, the average death rate for slope failures in the 145-year period between 1861 and 2004 can be calculated. Results are given in Table 8.1, together with the mortality rates for floods, earthquakes, volcanic eruptions and snow avalanches. Table 8.1 also lists mortality rates for technological and human-induced hazards, and for the leading medical causes of deaths in Italy, for different periods.

Table 8.1 – Mortality rates for natural, technological and human-induced hazards in Italy, for different periods. Sources of information: 1, Italian Alpine Club (1986-2001); 2, Aviation Safety Network (1990-2003); 3, ISTAT (1990-2000); 4, ISPSEL (1995-2002); 5, EuRES (1991-2002); 6, Istituto Superiore di Sanità (1990-2003).

PERIOD	HAZARD	MEAN	MIN	MAX	STDV
1861 - 2004	Landslides	0.09	0.0	3.80	0.33
	Floods	0.05	0.0	0.90	0.11
	Earthquakes	2.42	0.0	228.9	20.55
	Volcanoes	0.005	0.0	0.60	0.05
1900 - 2004	Landslides	0.11	0.0	3.80	0.38
	Floods	0.06	0.0	0.90	0.11
	Earthquakes	3.22	0.0	228.9	24.12
	Volcanoes	0.007	0.0	0.60	0.05
1950 - 2004	Landslides	0.14	0.002	3.80	0.52
	Floods	0.04	0.0	0.38	0.07
	Earthquakes	0.12	0.0	4.41	0.64
	Volcanoes	0.007	0.0	0.60	0.05
1990 - 2004	Landslides	0.05	0.002	0.34	0.08
	Floods	0.02	0.0	0.11	0.03
	Earthquakes	0.007	0.0	0.05	0.02
	Volcanoes	0.0003	0.0	0.002	0.0007
	Snow avalanches[1]	0.032	0.016	0.065	0.017
	Airplane accidents[2]	0.02	0.00	0.20	0.06
	Road accidents[3]	11.61	10.29	13.21	0.87
	Workplace accidents[4]	2.48	2.06	2.52	0.16
	Homicides[5]	1.83	1.10	3.19	0.61
	Drug overdose[6]	2.02	1.48	2.45	0.38
	All types of disease[6]	967.5	955.1	983.7	9.03
	Heart diseases[6]	129.4	127.8	134.2	2.88
	Cancer[6]	270.3	260.6	276.1	5.31
	Diabetes[6]	31.40	28.58	34.12	1.96
	AIDS[6]	5.54	2.18	8.31	2.18
	Influenza[6]	1.38	0.73	2.00	0.48

Inspection of Table 8.1 and Figure 8.2 allows for the comparison of individual risk posed by different hazards, and for studying the variation of mortality with time. If one considers the 144-year period from 1861 to 2004, average mortality due to natural hazards was largest for earthquakes (2.42), followed by landslides (0.09), floods (0.05) and volcanic events (0.005). Similarly, for the period between 1900 and 2004, the average death rates are 3.22 for earthquakes, 0.11 for landslides, 0.06 for floods, and 0.007 for volcanic events.

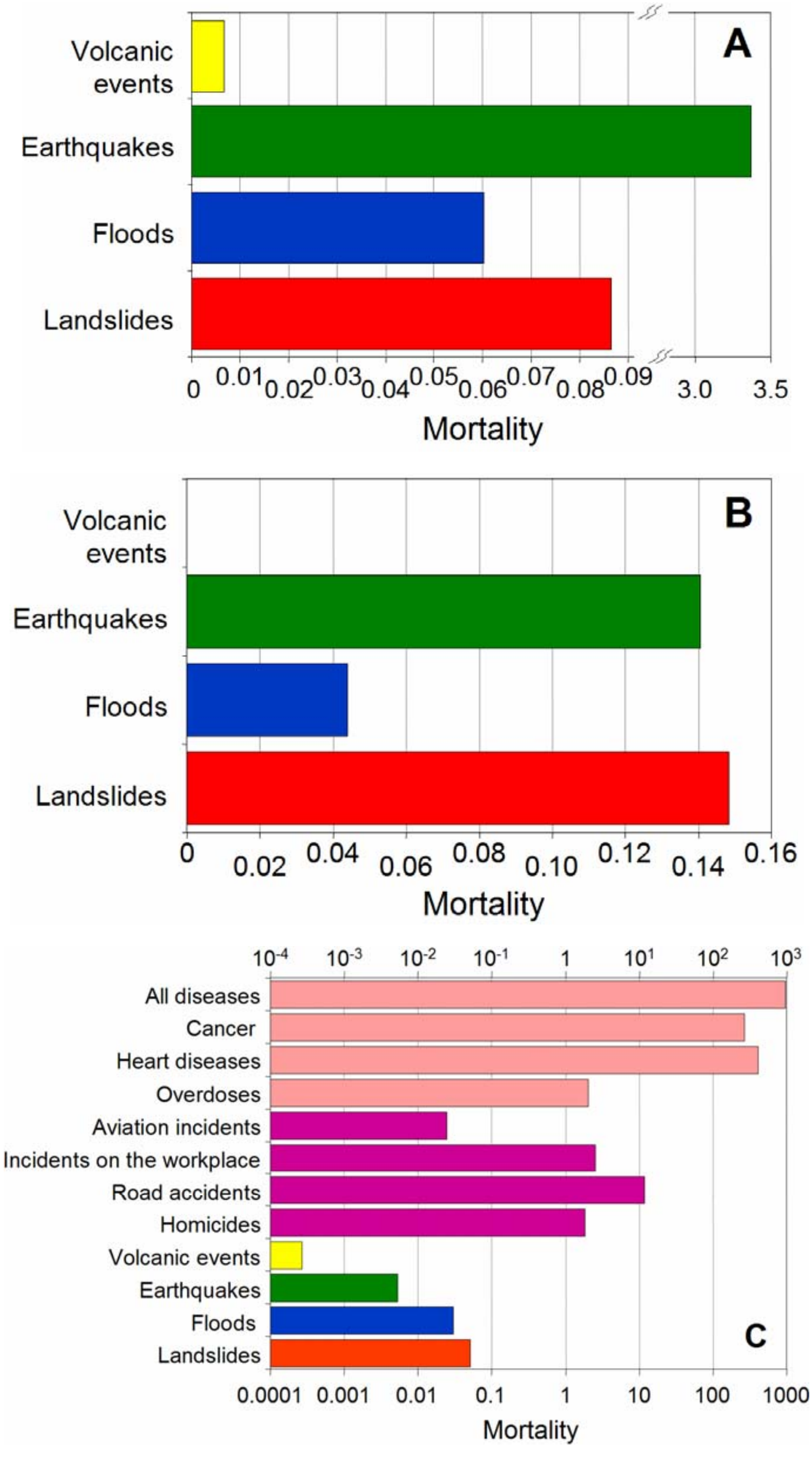

Figure 8.2 – Mortality rates for natural, technological and societal hazards and for the leading medical causes of deaths in Italy. (A) Mortality for natural hazards in the period 1900-2002. (B) Mortality for natural hazards in the period 1950-2002. (C) Mortality for natural, technological and societal hazards and the principal medical causes of deaths in Italy in the period 1980-2002.

The ranking of the most destructive natural hazards changes in the post World War II period, when the average landslide mortality was 0.14, a value similar to the mortality for earthquakes (0.12), and more that three times larger than the mortality for floods (0.04). In the period, the death rate for volcanic events was 0.007. The change in the ranking of the most destructive hazards is largely due to the Vajont landslide event that caused 1921 fatalities, and to the lack of earthquakes that resulted in several thousands of fatalities. However, it should be noted that in the period the single event that caused the largest number of fatalities was the Irpinia-Basilicata earthquake (2483 deaths) (Boschi *et al*., 1997). In the 25-year period from 1980 to 2004, landslides were the primary cause of fatalities due to natural hazards in Italy (0.048), followed by floods (0.025), earthquakes (0.007) and by volcanic events (0.0003). Since 1990, the landslide mortality has been about twice the flood mortality, confirming that in Italy slope movements are more dangerous than floods (Guzzetti *et al*., 2003c).Further inspection of Table 8.1 and Figure 8.2 reveals that for the period from 1980 to 2004 levels of individual risk posed by natural hazards, including landslides, are much lower that those posed by the leading medical causes of deaths, and lower than or equivalent to the risk posed by technological and societal hazards. In particular, it is worth noticing that in the considered period landslide mortality was higher that the mortality caused by aviation accidents, a technological hazards for which large investments are made to increase safety.

A known limitation of the mortality criteria lies in the fact that they depend on the size of the population with which they are associated, that may change with time. Figure 8.3 shows variation in the population in Italy from 1861 to 2000. In the period, the population in Italy increased from 22.16 million in 1861 to 57.88 million in 2003, an increase of 161.2%. In the same period the average number of landslide fatalities per year (i.e., the total number of fatalities divided by the length of the period) was 39.2 Thus, the average landslide mortality decreased from 0.18 to 0.07. The latter figure may lead to the conclusion that risk imposed by landslides to the population has more than halved over the last 145 years. If the average mortality has decreased (because the population has increased), the abundance and geographical distribution of the population have changed.

Figure 8.3 shows that the population of Italy increased differently in various physiographical regions. The increase was largest in the “plains” (300.8%), moderate in the “hills” (117.9%), and least in the “mountains” (44.6%). Starting in the 1920s, and more substantially in the second half of the 20th century, there has been a migration from mountainous areas into urban areas that are generally located in the plains or lowland hills. Consequently, the increase in the urban population has been larger than that in rural and mountain areas, some of which have suffered net losses in the number of inhabitants (Guzzetti, 2000; Guzzetti *et al*., 2005b,c).

Considering these changes, landslide mortality rate for the entire country decreased significantly in the period 1861 to 1920, decreased less distinctly in the period 1920-1970, and remained roughly constant in the period 1970-2004. In mountain areas, the death rate for landslides is considerably higher than the rates in other physiographic regions. In the mountains, the death rate decreased significantly in the period from 1861 to 1920, remained about constant in the period from 1920 to 1950, and increased noticeably after 1950. In mountain areas, where many tourist resorts were developed, seasonal residency may increase the size of the population exposed to landslide risk (Guzzetti, 2000; Guzzetti *et al*., 2005b,c).

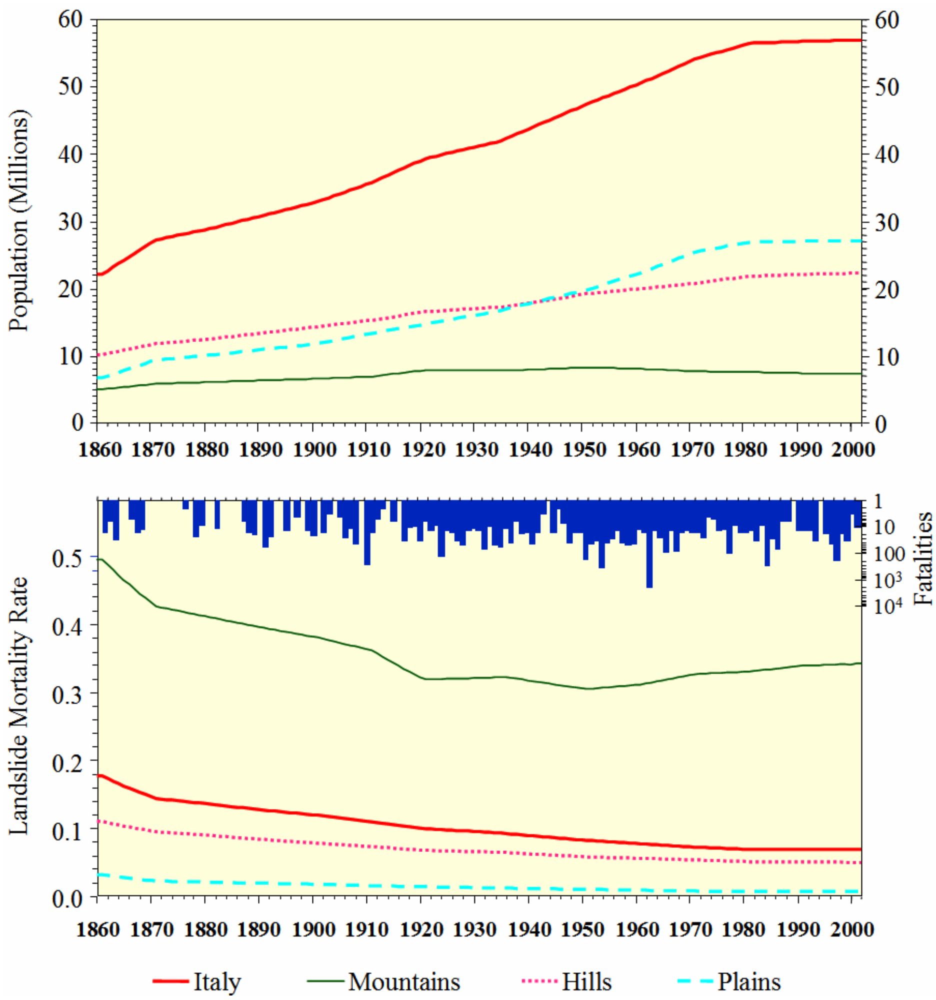

Figure 8.3 – Population and landslide mortality rates in Italy from 1860 to 2004. Upper graph: distribution of the population in different physiographical regions. Lower graph: lines show landslide mortality rates for different physiographical regions; histogram shows yearly number of landslide fatalities (log scale). Source of population data: *Istituto Nazionale di Statistica*.

8.3.1.2. Societal landslide risk

Estimates of societal risk are obtained by investigating the relationship between the frequency of the landslide events and their intensity, as measured by the number of fatalities. Figure 8.4.A shows the non-cumulative frequency-consequences plot (f-N plot) for landslides in Italy. The plot shows, for each intensity class as measured by the number of fatalities, the corresponding number of events. To minimize problems of database completeness, only the section of the historical catalogue considered substantially complete was used to construct the graphs, i.e., the subset from 1900 to 2002. In the log-log plot the relationship between the number of the events (N_E) and the number of fatalities (N_F) in each event exhibits a distinct linear trend, at least in the range between 1 and ~30 fatalities (more than 97% of the events). This suggests a self-similar scaling behaviour of the losses, which is important, because in principle it allows the use of frequent, small intensity events to estimate the rate of occurrence of rare, large events. However, the tail of the raw distributions (which contain less than 3% of the events, in the range from 30 to several hundreds fatalities) is erratic, and not adequate to fit a power law to the data.

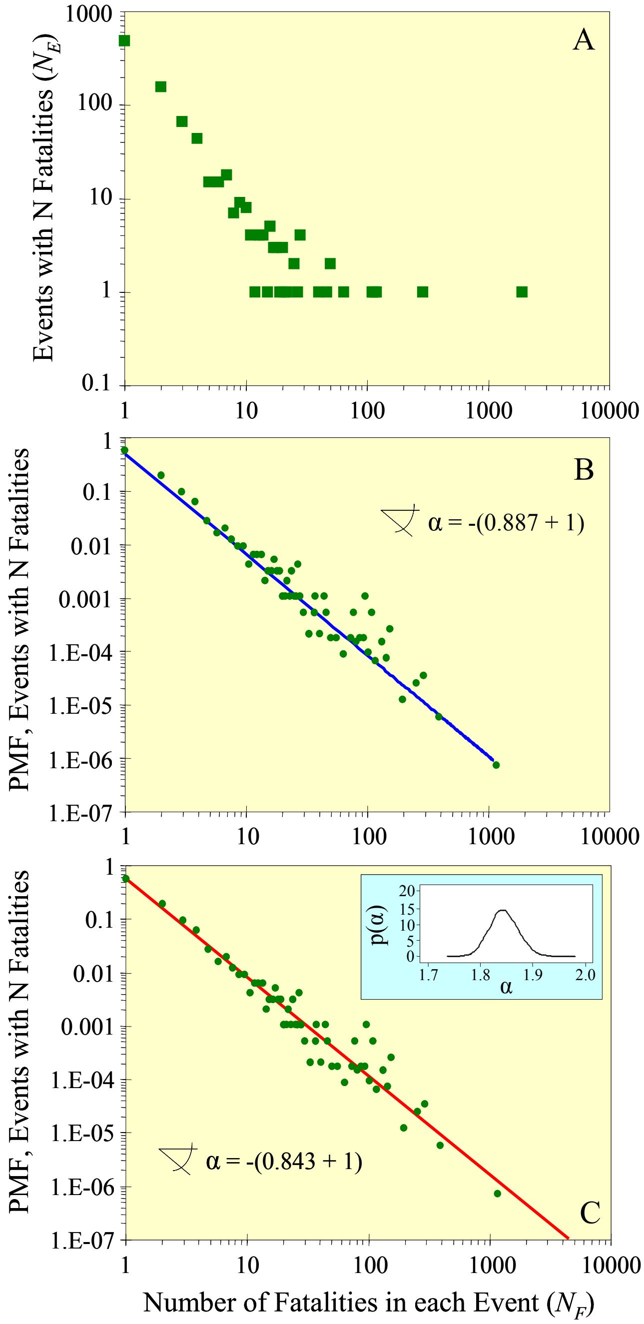

Figure 8.4 – Societal landslide risk in Italy. (A) Green squares show number of fatal landslide events in the period between 1900 and 2002 in Italy. (B) Probability mass function of fatal events. Green dots show binned data. Blue line is a linear fit (least square method) to the binned data in the range from N_F = 1 to $N_F = N_{FMAX}$. (C) Bayesian statistical treatment. Green dots show binned data. Red line shows model results, in the range from N_F = 1 to N_F = 3000. Inset shows distribution of α, the slope of the red line.

To get a better sense of the shape of the tail, the distribution must be estimated. To accomplish this various statistical techniques are available. Figure 8.4.B shows the result of the application of a variable-width binning technique. The method requires establishing equally spaced logarithmic bins, and counting the number of occurrences in each log bin. The number of occurrences in each bin is then normalized to the total number of occurrences to obtain an estimate of the probability mass function[1] (Guzzetti *et al.*, 2005b,c). In Figure 8.4.B, the number of fatalities (N_F) caused by harmful landslide events is shown versus the estimated probability mass function (*pmf*) of the events with N_F fatalities. In the figure, there is a clear (log-log) linear relationship between the event intensity, measured by the number of reported fatalities (N_F), and the probability of the event, which permits a straightforward linear regression ("fit"). The estimated distribution can be approximated by a power law. The log-log linear trend of the regression fit extends for three orders of magnitude, indicating a consistent power law scaling behaviour of the landslide fatalities.

The weakness of the described approach is the need to "bin" the data. Although the variable-width binning technique performs this task well, binning can be avoided altogether if the raw data are treated using a full probability model and model parameters are inferred directly from the data through, e.g., Bayesian techniques. When data samples appear to be power law distributed, there are two probability distributions that statisticians use to model them: (i) the Pareto distribution prescribes a power law probability for the size of a random event, given that the size can take any fractional value above a given minimum value; (ii) the zeta distribution also prescribes a power law probability for the size of a random event, which takes an integer value of at least one. Numbers of fatalities are integer values. So, if one wants to treat the frequency distributions of such data as a power law, a zeta distribution model must be assumed, in which the number of fatalities N_F has a *pmf*:

$$P(N_F) = \frac{N_F^{-(\alpha+1)}}{\zeta(\alpha+1)} \tag{8.10}$$

where $P(N_F)$ is the probability that N_F fatalities will occur in a single random event, α is the power law exponent, and ζ is the Riemann zeta function. In this model, there is no upper limit to the number of fatalities that can occur in a single event (Guzzetti *et al*., 2005b,c).

Each harmful event is treated as an independent and uncorrelated stochastic event, and the number of fatalities N_F is modelled as a ζ random variate. The inventory of harmful events is combined into *likelihood*, which is the relative probability that all the harmful events would cause the observed number of fatalities. It is obtained by multiplying together, for all N_e events, the probability that each harmful event should have caused the reported number of fatalities:

$$L(a \mid \{N_F\}) = P(N_F[1]) \times P(N_F[2]) \times \ldots \times P(N_F[N_\mathrm{e}]) \tag{8.11}$$

Since each N_F is a zeta variate,

$$L(a \mid \{N_F\}) = \frac{\{N_F[1] \times N_F[2] \times \ldots \times N_F[N_\mathrm{e}]\}^{-(a+1)}}{\{\zeta(\alpha+1)\}^{N_e}} \tag{8.12}$$

One needs to estimate the value of the power law scaling exponent α. Bayes' theorem allows to infer the probability distribution of α given the data $\{N_F\}$. This is called the posterior distribution of α:

$$\textit{posterior probability } (\alpha \mid \{N_F\}) \propto \textit{likelihood } (\alpha \mid \{N_F\}) \times \textit{prior probability } (\alpha) \tag{8.13}$$

[1] The probability distribution of a discrete random variable is represented by its probability mass function (*pmf*).

The difficulty of a Bayesian analysis lies in the concept implicit in this equation: that one has some *a priori* idea of the likely value of the scaling exponent α, and that this idea is revised when one looks at the data $\{N_F\}$. The way in which the idea is revised depends on the model understanding of how likely a certain value of α is, given the observations $\{N_F\}$: hence the term “likelihood”. The likelihood moulds the prior probabilistic description of the scaling exponent α into a posterior probability distribution for α.

Ideally, in a Bayesian analysis the prior distribution has only a very weak effect on the posterior inference, and most of the information comes from the likelihood. Many Bayesian treatments use what are called “non-informative” priors, which are designed to be as vague a statement as possible about the model parameters, so as not to bias the inference unduly. A uniform distribution is a “weakly informative” prior that provides little information about the model parameters. The steepness of the power law α-1 is assumed to be anywhere in the range between -1 and -3. Hence, a weakly informative prior for the zeta scaling exponent takes the form

$$\textit{prior probability}\ (\alpha) = U(0,2) \tag{8.14}$$

Hence, *a priori*, we consider any value of α between zero and two as equally likely.

The challenge in Bayesian modelling is to turn the proportionality in equation 8.13 into an equality, i.e. to normalize the right hand side of the equation so that it becomes a true probability. For most Bayesian models, normalization is only possible through numerical integration. A method of numerical integration is Markov chain Monte Carlo (MCMC) sampling, in which (pseudo)random samples are generated in such a way that their distribution obeys (asymptotically) the posterior distribution. Guzzetti *et al*. (2005b,c) have implemented an MCMC solution of the zeta power law distribution model for fatalities caused by natural hazard using software called WinBUGS (*http://www.mrc-bsu.cam.ac.uk/bugs*). The results of the Bayesian MCMC analysis are shown in Figure 8.4.C.

Figure 8.4 allows for a comparison of the results of the Bayesian treatment of the raw data (red line in Figure 8.4.C) with those of the linear regression fits to the binned data (blue line in Figure 8.4.B), and with the raw data, in the form of the observed frequency of events (Figure 8.4.A). In the examined period (from 1900 to 2004), the actual frequency of landslide events that resulted in one fatality was 4.69 (483 events in 103 years). This figure compares to the estimate of 4.27 obtained from the linear fit of the data, and to the estimate of 4.98 obtained by the Bayesian model. Hence, for landslide events that resulted in one fatality, the linear regression fit slightly underestimates the landslide frequency, and the Bayesian model slightly overestimates the landslide frequency.

8.3.2. Comparison of risk posed by different natural hazards in Italy

For Italy, information exists to compare the societal risk posed by different natural hazards. Figure 8.5 shows estimates of societal risk for landslides, floods, earthquakes and volcanic events. The estimates were obtained applying the Bayesian method described in § 8.3.1.2. Data used to obtain the estimates of societal risk span the period from 1900 to 2004 and were collected by Guzzetti *et al*. (2005b,c).

The steepness of the curves in the log-log plots of Figure 8.5 indicates the relative frequency of the small, less intense events versus the large, more destructive events. For a given number of fatalities, a steeper curve assesses a lower (predicted) frequency of events than a gently dipping curve, which predicts a higher frequency of harmful events. Assuming that the more intense events, i.e. the events that result in a large number of fatalities, represent a higher societal risk, a larger frequency of intense events represents a higher societal risk. Based on this assumption, earthquakes pose the highest societal risk, followed by volcanic eruptions, landslides and floods. Landslides and floods have similar exponents of the power law scaling. However, the statistical analysis for landslide fatalities exhibits a slightly lower exponent than the analysis for flood fatalities, indicating that the (predicted) frequency of intense events is larger for landslides than for floods. This suggests that in Italy societal risk posed by landslide events is larger than the corresponding risk posed by floods. The predicted probability for low intensity events (i.e., fewer than 5 fatalities) is larger for floods and landslides, followed by earthquakes and by volcanic events. For events having 5 or more fatalities, the probability is larger for earthquakes. The predicted yearly frequency of landslide and flood events with fatalities is considerably larger than that for the earthquakes and the volcanic events, at least up to event with 180-200 fatalities. Mass movements are second only to earthquakes in the frequency of very large intensity events (> 200 fatalities).

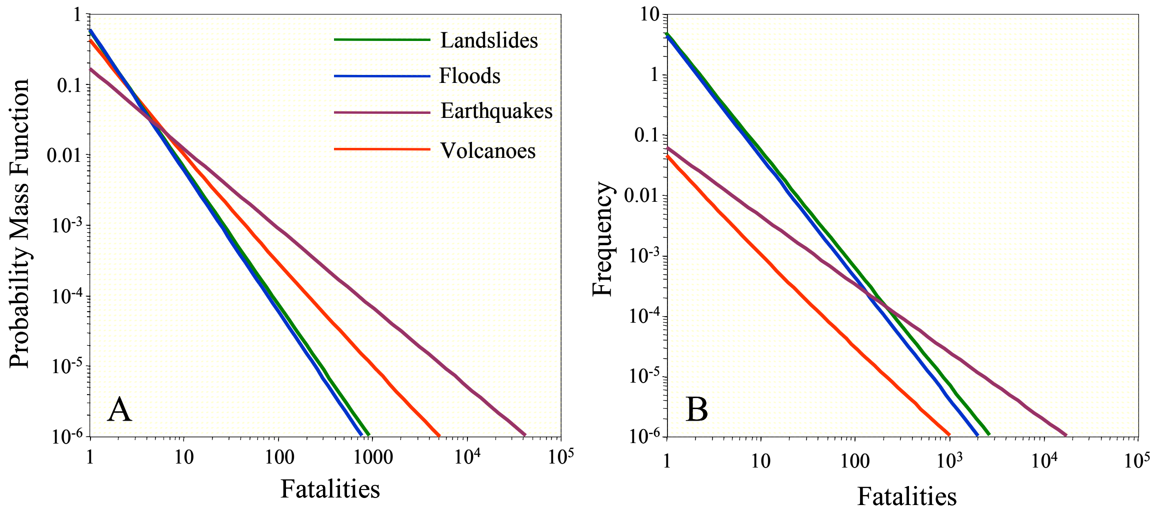

Figure 8.5 – Societal risk due to landslides (green line), floods (blue line), earthquakes (violet line) and volcanic events (red line) in Italy. (A) Probability mass function of fatalities. (B) Frequency of fatal events per year. Data to construct the curves span the period from 1900 to 2004.

Guzzetti *et al.* (2005c) compared the curves shown in Figure 8.5 with the historical distribution of the damaging events. The comparison revealed that the frequencies of the very high intensity events are underestimated. Landslide events with 1000 or more fatalities have an estimated yearly frequency smaller than 7×10^{-6}. Inspection of the catalogue reveals that from 1410 to 2004 at least twice (in 1618, at Piuro, and in 1963, at Vajont) individual landslides killed more than 1000 people. For earthquakes, events with 10,000 fatalities have an estimated frequency of $\sim2\times10^{-6}$. In the available record, 10 events caused more than 10,000 fatalities.

Even considering the uncertainty in the determination of the total number of fatalities and the confidence intervals for the probabilistic estimates, mismatch exists between the predicted and the observed frequencies for very large intensity events. This may indicate one or more of the following: (i) the relationship between fatal events and their consequences is not power-law distributed over the entire range of fatalities – violating a fundamental assumption of the adopted model, (ii) fatalities are power law distributed, but the rate of occurrence of small to medium intensity events differs from that of high and very high intensity events (a higher rate) – two power law models are required, one for small events and one for large events, (iii) human induced events that caused fatalities in very large numbers (e.g., Vajont) bias the statistics – this may not be applicable to earthquakes or volcanic eruptions, (iv) the uncertainty in the exact number of fatalities for some of the events affects the statistics, (v) the uncertainty in establishing the exact cause of fatalities when multiple hazards coexist for the same event – e.g., fatalities caused by an earthquake and associated tsunami, or by a flood induced by a landslide (e.g., Vajont); (vi) the increase in population density has affected the rate of the most catastrophic events significantly in the 20th century – hence, the record of fatal events for the most recent part of the catalogue (1900-2004) cannot be used to explain the frequency of events in the entire historical record. The comparison shown in Figure 8.5 puts in the proper collective perspective the harmful effects of natural hazards on the population in Italy.

8.3.3. Geographical distribution of landslide risk to the population in Italy

The assessments of landslide risk discussed in the previous sections (§ 8.3.1 and § 8.3.2) provide quantitative estimates for the societal and the individual risk levels in Italy, including a comparison of risk posed by landslides with those posed by other natural and man-made hazards. This is important information. However, the examined risk analysis does not provide insight on the geographical distribution of landslide risk to the population in Italy.

Salvati *et al*. (2003) published a synoptic map showing the location of sites affected by fatal landslide and flood events in Italy (Figure 8.6). Analysis of the map reveals that fatal landslide events occurred in 539 Municipalities (6.6%), and that the fatal events are not equally (or homogeneously) distributed in the country. Even excluding the areas where harmful events are not expected (e.g., the large Po and Veneto plains, in northern Italy), the distribution of the historical harmful landslide events remains inhomogeneous. The northern (Alpine) regions have suffered more deaths and missing persons (6365) than those in the centre of the country (1149) and the south (2399). This is largely due to the geological and morphological settings. In the Alps, abundant loose debris on steep slopes and in mountain catchments makes destructive debris flows common. The presence of high relative relief and the cropping out of hard rocks, such as granite, metamorphic rocks, massive limestone and dolomite, encourage rock falls, rock slides and rock avalanches. Landslides of these types are particularly dangerous because of their high or very high velocity and considerable momentum. The large number of casualties in the Campania region of southern Italy is mostly the result of debris flows in areas where a thin cover of volcanic ash overlies limestone on steep slopes, another particularly hazardous geological setting.

In Italy, sufficient information exists to attempt the modelling of the geographical distribution of past fatal landslide events. With some limitation, this can be considered an attempt to model the geographical distribution of landslide risk to the population. The goal can be achieved through multivariate modelling of environmental factors. The same factors used to determine landslide hazard at the national scale (§ 6.4), including morphological, lithological, pedological, and historical variables, and the same mapping unit (i.e., the municipality), can be used to determine the spatial occurrence of past fatal landslide events. For simplicity, municipalities in large plains or open flat areas are excluded from the analysis. Where terrain gradient is very low, harmful landslides cannot occur. Based on the average terrain gradient computed from the national 90 m × 90 m DEM, 1499 municipalities with an average slope less or equal to 0.8 degrees were identified, and excluded from the analysis. As the dependent variable for the statistical analysis, the presence or absence of fatal landslide events in each municipality in the 80-year period from 1900 to 1979 is used. In this period, 639 fatal landslide events caused 4298 deaths and 46 missing persons, in 420 municipalities. Results of the statistical modelling are shown in Figure 8.7 and in Tables 8.2 and 8.3.

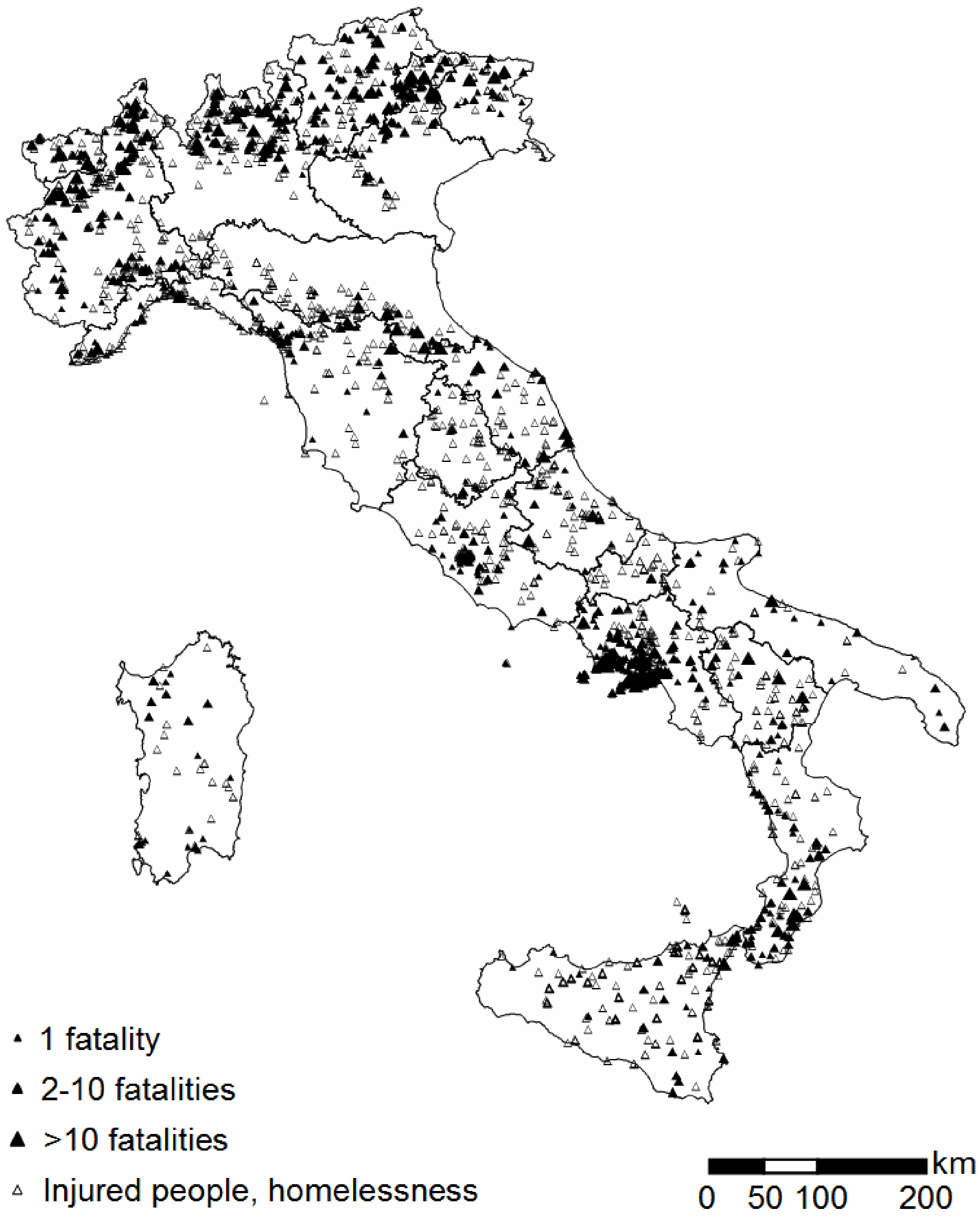

Figure 8.6 – Map showing the distribution of landslides with human consequences in Italy from AD 1300 to 2002. The size of the symbol indicates the magnitude of the event: Small symbol, 1 dead or missing person; medium symbol, 2-10 deaths or missing persons; large symbol, more than 10 deaths or missing persons. Open symbols indicate sites where injured people, homeless people or evaluated people were reported.

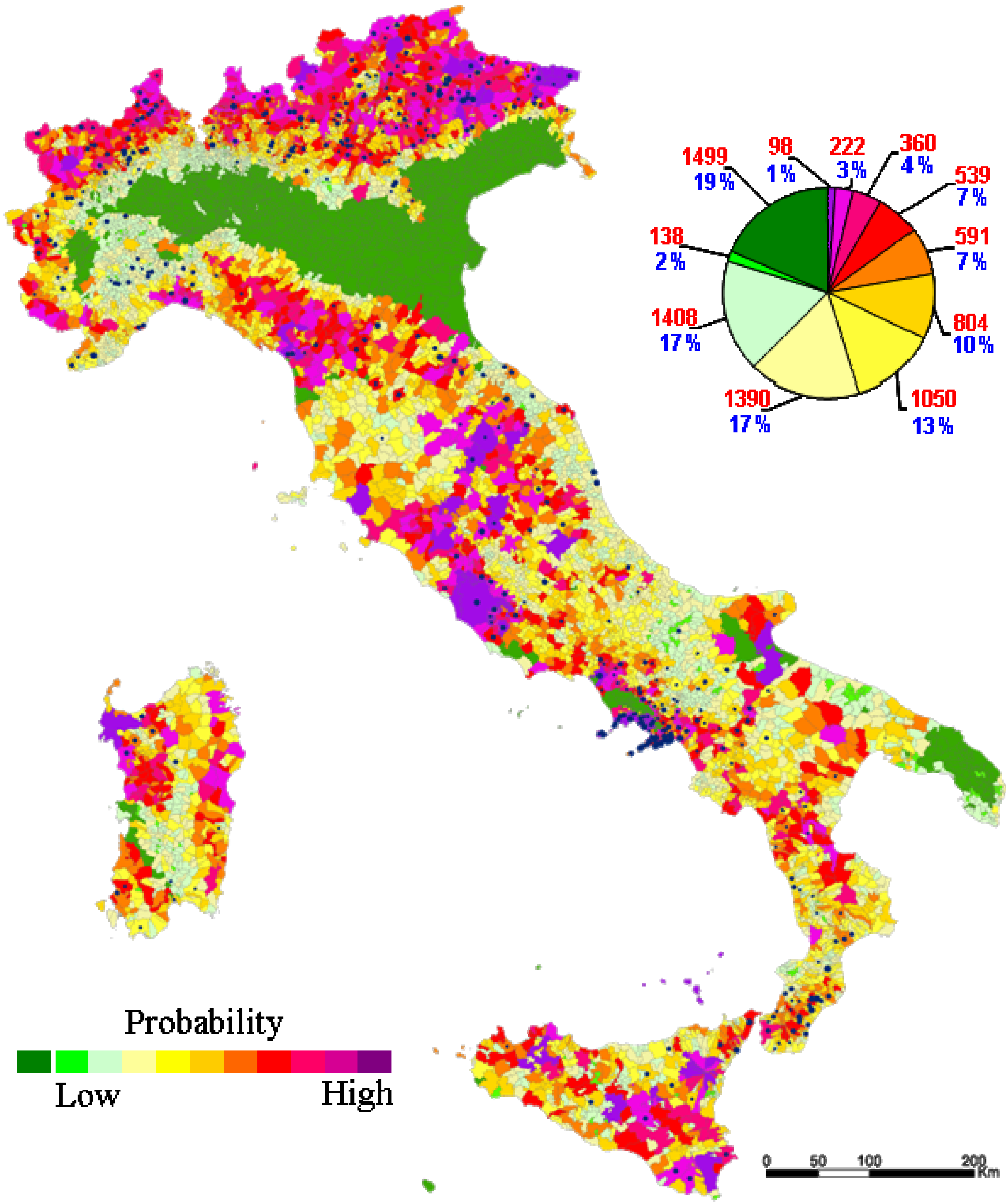

Figure 8.7 – Map showing the probability of spatial occurrence of fatal landslide events in Italy, on the basis of local terrain conditions. Probability of spatial occurrence is shown in 10 classes, from very high (dark violet) to very low (green) values. Dark green colour shows municipalities excluded from the analysis on the basis of average terrain gradient. Black dots show municipalities that suffered fatal landslides in the 80-year period from 1900 to 1979. The pie chart shows the number (red) and the percentage (blue) of municipalities in each probability class.

Figure 8.7 shows the probability of spatial occurrence of fatal landslide events, given a set of geo-environmental conditions. This is equivalent to susceptibility, i.e., the likelihood of a landslide event with fatalities occurring in a municipality on the basis of the local terrain setting (§ 7.) For display purposes, in Figure 8.7 the probability of spatial occurrence of fatal landslide events is shown in 10 classes, from very high (dark violet) to very low (green) values. In the map, municipalities excluded from the analysis on the basis of the very low mean terrain gradient are shown in dark green. The pie chart shows the number (in red) and the percentage (in blue) of municipalities in each probability class.

Table 8.2 lists the 13 variables selected by a stepwise discriminant function as the best predictors of the occurrence of fatal landslide events in the municipalities. The standardized discriminant function coefficients (SDFC) show the relative importance of each variable as a predictor of landslide risk to the population in Italy. Variables with large coefficients (in absolute value) are strongly associated with the presence or the absence of fatal landslide events in the municipalities. The sign of the coefficient tells if the variable is positively or negatively correlated to the occurrence of fatal events. Inspection of Table 8.2 reveals that the range in slope angle (0.792), the presence of regosols (0.629), lithosols (0.356) and of volcanic soils (0.308) are the conditions most correlated to the occurrence of fatal landslide events.

Table 8.2 – Variables entered into the discriminant model as the best predictors of the presence of fatal landslide events in the 6604 municipalities exhibiting average terrain gradient greater than 0.8 degrees. Most important standardized discriminant function coefficients (SDFC) are shown in bold. Negative or positive sign of the coefficients indicates variables contributing toward risk (green) or safety (red).

VARIABLES DESCRIPTION	*SDFC*
Mean terrain elevation	**-.275**
Podzolic soil	-.115
Sandstone	-.090
Low grade metamorphic rocks	.111
Plain area	.177
Podsols	.204
Maximum mean annual rainfall	.211
Historical events in neighbouring municipalities	.255
Drainage network area	**.285**
Volcanic soil	**.308**
Lithosols	**.356**
Regosols	**.629**
Range in terrain slope	**.792**

Table 8.3 shows a comparison between the municipalities classified as "safe" or "at risk" by the model (columns), and the municipalities that did not or did suffer fatal landslides in the period from 1900 to 1979 (rows). The table also shows the overall model correct classification, which is 74.4%. The latter figure indicates that about ¾ of the municipalities defined "at risk" or "safe" by the model, did or did not experience fatal landslides in the considered period, respectively. Inspection of Table 8.3 indicates that, among the municipalities that were correctly classified by the discriminant model, those that did not suffer fatalities were classified more efficiently (i.e., in larger number, 75.1%) that those that experienced fatal landslide events (only 64.8%). We attribute the difference in the model ability to classify municipalities "at risk" or "safe", to the much larger number of municipalities that did not suffered fatal landslide events (6184, 93%) in the catalogue, and the correspondingly much lower number of municipalities with landslide fatalities (420, 7%).

Statistical classification methods, such as discriminant analysis used here, suffer from large inequalities between the two groups.

Table 8.3 – Comparison between municipalities classified as safe or at risk by the model, and municipalities that experienced or did not experience fatal landslides in the period from 1900 to 1979.

			PREDICTED GROUPS (MODEL)	
			GROUP 0 SAFE MUNICIPALITIES	GROUP 1 MUNICIPALITIES AT RISK
ACTUAL GROUPS (CATALOGUE)	GROUP 0	MUNICIPALITIES THAT EXPERIENCED FATAL LANDSLIDE EVENTS	75.1 % (class 1)	24.9 % (class 3)
	GROUP 1	MUNICIPALITIES THAT DID NOT EXPERIENCE FATAL LANDSLIDE EVENTS	35.2 % (class 4)	64.8 % (class 2)

Overall percentage of municipalities correctly classified is 74.4%.

As previously discussed (e.g., § 6.5.1.2), Table 8.3 reveals model fit, but does not prove the ability of the model to predict the spatial occurrence of "future" fatal landslides. For this purpose, a form of temporal model validation is required (Chung and Fabbri, 2003). This can be obtained by comparing the forecasted spatial distribution of fatal landslide events as predicted by the model, with the distribution of fatal landslides occurred in a period not used to construct the model. The catalogue of historical fatal landslide events covers the period from 1900 to 2004. To prepare the statistical model, the portion of the model for the 80-year period between 1900 and 1979 was used. One can use the remaining 25-year period from 1980 and 2004 to validate the model (validation period). In the validation period, the historical catalogue lists 210 fatal landslide events that produced 829 deaths and 39 missing persons, in 170 municipalities.

Two tests can be performed to evaluate the model ability to predict "future" fatal events. The first test consists in computing the number of municipalities that suffered fatal landslide events in the validation period, in each probability class. The second test is similar, and requires computing the total number of fatalities recorded during the validation period, in each probability class. Results are shown in Figure 8.8. In this figure, the histograms show the number of municipalities (Figure 8.8.A) and the number of fatalities (Figure 8.8.B) in each probability class, and the curves show the cumulative number of municipalities that suffered fatalities (Figure 8.8.A) and the cumulative number of fatalities (Figure 8.8.B) in each probability class. Bars are shown using the same colours used to display the spatial probability in Figure 8.7. Inspection of Figure 8.8.A reveals that 59.2% of the fatal landslide events in the period between 1980 and 2004 occurred in municipalities classified at very high (22.9%, dark violet and violet) or high (36.3%, dark red and red) risk, and 20.6% of the 210 fatal landslide events occurred in municipalities predicted having a low (15.9%, light and dark yellow) or very low (4.7%, light green and green) risk. The remaining 20% of the fatal events occurred in municipalities of uncertain classification (dark and light orange colours). Analysis of Figure 8.8.B indicates that 53.4% of the landslide fatalities in the 25-year validation period occurred in municipalities classified at very high (15.4%, dark violet and violet) or high (38.0%, dark red and red) risk, and that 7.3% of the fatalities occurred in municipalities predicted having a low (4.9%) or very low (2.4%) risk. A large number of fatalities (340, 39.3%) occurred in municipalities of uncertain classification.

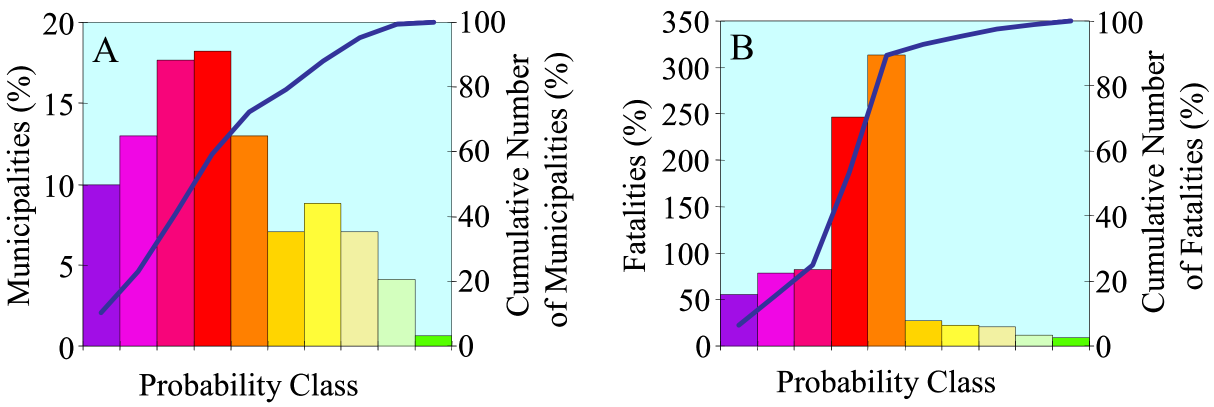

Figure 8.8 – Validation of the model predicting the probability of spatial occurrence of fatal landslide events in Italy. Validation period is the 25-year period from 1980 to 2004. (A) Percentage (histogram) and cumulative percentage (blue line) of municipalities classified by the model in 10 probability classes. (B) Percentage (histogram) and cumulative percentage (blue line) of fatalities in the municipalities classified by the model in 10 probability classes. Bar colours match colours used to display landslide probability in Figure 8.7.

8.3.3.1. Discussion

Strictly speaking, the model discussed before is a susceptibility model (§ 6). Indeed, the model aims at explaining the spatial (geographical) distribution of the areas (the municipalities) where past fatal landslide events have occurred. Assuming that all conditions have remained the same – and this may not be the case (e.g., population and population density have changed significantly in Italy, see Figure 8.3) – the model can help predict where fatal landslide events may occur in the future in Italy. In recent years, the Italian Government and the National Department of Civil Protection have repeatedly attempted to establish a compulsory national insurance against natural hazards. The attempts have failed. Among the reasons for the inability to establish the mandatory insurance was the lack of a credible rationale for establishing such insurance. The describe analysis, despite its uncertainties and limitations, provides the data, the rationale and a preliminary analysis of the risk posed by landslides to the population of Italy, and it may contribute to the establishment of compulsory insurance.

8.3.4. Landslide risk to vehicles and pedestrians along roads

A particular case of risk to individuals is the risk imposed by landslides to vehicles and pedestrians. In the literature, attempts have been made to evaluate quantitatively (probabilistically) the risk posed by rapid moving slope failures (e.g., rock falls) to vehicles or pedestrians travelling along roads subject to landslide hazards (Pierson *et al.*, 1990; Bunce *et al.*, 1997, Hungr and Beckie, 1998; Hungr *et al.*, 1999; Budetta, 2002; Budetta and Panico, 2002). In particular, the "Rockfall Hazard Rating System", introduced by the Oregon Highway Division (Pierson *et al.*, 1990), uses a simple approach to estimate rock fall risk to vehicles based on the calculation of the average vehicle risk index, *AVR*, given by:

$$AVR = \frac{L_H \times V_H \times ADT}{PSL} \tag{8.15}$$

where, L_H is the length of the hazard zone, in km, V_H is the percentage of a vehicle that at any time can be expected to be within the hazard zone, *ADT* is the average daily traffic, i.e., the number of cars per day along the examined road, and *PSL* is the posted speed limit, in km/h. *AVR* measures the percentage of time a vehicle is present in a rock fall hazard zone, or the average number of vehicles expected in a hazard zone at any time. Values of *AVR* smaller that 100% indicate that less than one vehicle is expected in the hazard zone at any time. Values of *AVR* greater than 100% indicate that, on average, more than one vehicle is expected within the hazard zone at any time.

8.3.4.1. Landslide risk to vehicles along the Nera River and the Corno River valleys

In § 7.5, the hazard posed by rock falls along the Nera River and the Corno River valleys was examined. Rock fall hazard was ascertained through the combined analysis of: (i) the recurrence of rock fall events, determined from historical information, (ii) the frequency-volume statistics of rock falls in the area, obtained from a recent event inventory, and (iii) the results of a process-based, spatially distributed rock fall simulation model. The available information on rock fall hazards was combined in a GIS with a map of the transportation network to identify the road sections potentially subject to rock falls. Information on the location and type of rock fall defensive measures, including revetment nets, elastic fences, concrete walls and artificial tunnels, was used to estimate the efficacy of the defensive structures and to determine the level of the residual rock fall risk along the roads. Despite the installation of new and extensive defensive measures, residual rock fall risk was found to be still important along the roads in the Nera River valley.

Given the available information on rock fall hazard in the Nera River and the Corno River valleys (§ 7.5.3), an attempt can be made to measure the risk to the vehicles travelling along two regional roads (SS 209 and SS 305) located at or close to the bottom of the valleys. The position and length of the roads is known from topographic base maps at 1:10,000 and 1:5000 scale. The length of the roads in each hazard class is obtained in a GIS by intersecting the road and the hazard maps. To calculate the *AVR* index the following assumptions are made: (i) an average value of 5 meter is selected for the vehicle length; (ii) and V_H, the percentage of the vehicle expected to be within the hazard zone, is set to 100%; (iii) *ADT* is set to 3000 vehicles per day, based on information from the Regional Transportation Office; (iv) the average speed limit is set to 70 km/h; (v) the traffic is considered uniform during the day; and (vi) the distance between vehicles is considered constant, for simplicity.

Three estimates of the risk imposed by rock falls to vehicles were performed, and results are summarized in Table 8.4 (see also § 7.5.3). The first risk estimate was obtained not considering the presence of the existing rock fall defensive structures (i.e., revetment nets, elastic fences, concrete walls and artificial tunnels) (Table 8.4.A). For the second estimate all the defensive measures were considered in the analysis, regardless of their efficacy in mitigating rock fall hazards (Table 8.4.B). Lastly, the third estimate considered solely the retaining structures that were judged to be (totally) effective in the mitigation of rock fall hazards (Table 8.4.C). For the three hazard estimates, the average time a vehicle travelling the average speed at 70 km/h will remain in each hazardous zone, and the average number of vehicles expected at any time in the hazard zones were calculated. Results are listed in Table 8.4.

Table 8.4 – Rock fall risk to vehicles travelling along two regional roads in the Nera River and the Corno River valleys. See § 7.5 for explanation of hazard classes and rock fall hazard modelling. (A) Risk to vehicles not considering the existing rock fall defensive structures. (B) Risk to vehicles considering all existing rock fall defensive structures. (C) Risk to vehicles considering only rock fall defensive structures that are effective in mitigating rock fall hazard. *AVR* shows the number of vehicles per day in each hazard class. Travel time, time and percent of time a vehicle travelling at 70 km/h will remain in each hazard class. Cars, is the expected number of vehicles at any time in each hazard class.

	ROCK FALL HAZARD CLASS	ROAD LENGTH	AVR	TRAVEL TIME		CARS
		km		%	minutes	#
A	Very low (VL)	2.36	10,114	26.05	2.02	4.21
	Low (L)	1.83	7843	20.20	1.57	3.27
	Intermediate (M)	1.84	7886	20.31	1.58	3.29
	High (H)	2.13	9129	23.51	1.83	3.80
	Very High (VH)	0.90	3857	9.93	0.77	1.61
	Total	9.06	38,829		7.77	16.18
B	Very low (VL)	1.08	4629	37.11	0.93	1.93
	Low (L)	0.82	3514	28.18	0.70	1.46
	Intermediate (M)	0.54	2314	18.56	0.46	0.96
	High (H)	0.44	1886	15.12	0.38	0.79
	Very High (VH)	0.03	129	1.03	0.03	0.05
	Total	2.91	12,471		2.49	5.20
C	Very low (VL)	1.26	5400	30.96	1.08	2.25
	Low (L)	0.89	3814	21.87	0.76	1.59
	Intermediate (M)	0.80	3429	19.66	0.69	1.43
	High (H)	0.94	4029	23.10	0.81	1.68
	Very High (VH)	0.18	771	4.42	0.15	0.32
	Total	4.07	17,443		3.49	7.27

Analysis of the results indicates that the existing rock fall defensive measures greatly reduce the AVR, but confirms that a level of residual risk still exists along the considered regional roads in the Nera River and the Corno River valleys. Reduction of the *AVR*, of the average time a vehicle will remain in a dangerous zone, and of the total number of vehicles in hazardous areas, is higher where rock fall risk is estimated to be very high (*VH*). This confirms that rock fall defensive structures were installed where the hazard was most severe. The analysis also suggests that even where the hazard is not particularly severe, rock fall risk to the vehicles is not negligible, particularly where the expected frequency of rock falls is high.

8.4. Geomorphological landslide risk evaluation

Cardinali *et al*. (2002b), Guzzetti *et al*. (2004) and Reichenbach *et al*. (2005) described an attempt to determine qualitative landslide risk levels in Umbria. The method is based on the geomorphological interpretation of multiple sets of aerial photographs of different ages (a process of multi-temporal landslide mapping), aided by the analysis of historical information on past landslide events. The method involves the definition of the study area and the careful scrutiny of the "state of nature", i.e., of all the existing and past landslides that can be identified in the study area. The possible short term evolution of the slopes, the probable type of failures and their expected frequency of occurrence, are inferred from the observed changes in the distribution and pattern of landslides. The information is used to estimate the landslide hazard, and to evaluate specific and total levels of landslide risk. More precisely, the method involves: (i) the preliminary definition of the extent of the study area, (ii) the compilation of a multi-temporal landslide inventory map, including landslide classification, (iii) the definition of landslide hazard zones, (iv) the assessment of landslide hazard, using a two-digit positional index, (v) the identification and mapping of the elements at risk, including an assessment of their vulnerability to different landslide types, (vi) the evaluation of specific landslide risk, using a three-digit positional index, and (vii) the determination of total landslide risk levels. The proposed method is a form of Structured Expert Judgment.

8.4.1. Definition of the study area

Preliminary to the landslide hazards and risk assessment is the definition of the area to be investigated. This apparently trivial problem is essential to the analysis and the application of the results. For the purpose of the investigation, a "site" was defined as an area bounded by drainage and divide lines around the place selected for the landslide risk assessment. Thus, a site is an ensemble of one or more adjacent "elementary slopes" or watersheds. In general, major divides and drainage lines are used to outline a site. Where this is not possible, minor divides or drainage lines are used. In Umbria, mapping of elementary slopes or watersheds was accomplished at 1:10,000 scale, using large-scale topographic base maps, locally aided by the analysis of recent, large and medium scale aerial photographs. At each site, the number and the extent of the elementary slopes depended on the local geological and morphological setting, and on the type, number and extent of landslides.

8.4.2. Multi-temporal landslide map

For each site, the spatial distribution of landslides is ascertained through the interpretation of multiple sets of vertical, stereoscopic aerial photographs, and detailed field surveys. In Umbria, for a period of about 60 years (from 1941 to 2001), seven sets of aerial photographs taken in different years are available. The oldest photographs were taken in 1941, and the youngest in 1997. Nominal scale of the aerial photographs ranged from 1:13,000 to 1:73,000. Only three sets of photographs cover the entire territory, whereas the other flights were limited to specific areas. Field surveys used to complete the inventory and to test the methodology were carried out mostly in the years 2000 and 2001 (Antonini *et al.*, 2002a).

To prepare the multi-temporal landslide inventory map, landslides were first identified on aerial photographs taken in 1954-55. This set was selected because it was the oldest flight covering the entire Region, because the aerial images were taken in a period when intense cultivation of the land by mechanical equipments had not started, and the forms of old and recent landslides were clearly visible on the photographs (Guzzetti and Cardinali, 1989, 1990). The other sets of aerial photographs were analysed separately and in conjunction with the 1954-55 photographs and with the other flights. In this way separate landslide inventory maps were prepared, one for each set of aerial photographs and for the field surveys. Landslide information collected through the interpretation of aerial photographs or mapped in the field was transferred to 1:10,000 scale topographic base maps. The different landslide maps were overlaid and merged to obtain a single, multi-temporal landslide inventory map (§ 3.3.4). The process required adjustments to eliminate positional and drafting errors. The multi-temporal landslide inventory map was then digitised and stored into a GIS database.

In the separate inventory maps and in the multi-temporal inventory, landslides were classified according to the type of movement, and the estimated age, activity, depth, and velocity. A degree of certainty in the recognition of the landslide was also attributed. Landslide type was defined according to Varnes (1978), and the International Geotechnical societies' UNESCO Working Party on World Landslide Inventory, WP/WLI (1990, 1993, 1995). Landslide age, activity, depth, and velocity were decided based on the type of movement, the morphological characteristics and appearance of the landslide on the aerial photographs and in the field, the local lithological and structural settings, the date of the aerial photographs, and the results of site specific investigations carried out to solve local instability problems (Antonini *et al*. 2002a). Landslide relative age was defined as recent, old or very old, despite ambiguity in the definition of the age of a mass movement based on its appearance (McCalpin, 1984). Landslides were classified active where they appeared fresh on the aerial photographs, or where movement was known from monitoring systems. Mass movements were classified as deep seated or shallow, depending on the type of movement and the landslide volume. The latter was based on the type of failure, and the morphology and geometry of the detachment area and the deposition zone. Landslide velocity was considered a proxy of landslide type, and classified accordingly. Rotational or translational slides, slide earth-flows, flows, and complex or compound slides were classified as slow moving failures. Debris flows were classified as rapid movements. Rock falls and topples were classified as fast moving landslides (WP/WLI, 1995). The adopted classification scheme, and in particular the evaluation of landslide age, activity, velocity and depth, included uncertainty and undoubtedly suffered from simplifications. The classification required geomorphological inference, but fitted the available information on landslide types and process in Umbria (e.g., Felicioni *et al*., 1994; Guzzetti *et al*., 1996, 2003a, 2004; Cardinali *et al*., 2002b); Reichenbach *et al*., 2005).

8.4.3. Landslide frequency

Information on landslide frequency is essential to assess landslide hazard. The frequency of slope failures can be obtained through the analysis of historical records of landslide occurrence (Guzzetti *et al*., 1999b). In general, a complete record of past landslides from which to derive the frequency of occurrence of landslide events is difficult to obtain for a single landslide or a slope (Tommasi *et al.*, 1986; Ibsen and Brunsden, 1996; Glade, 1998; Guzzetti *et al*., 1999b). In the investigated areas, landslide frequency was ascertained based on the analysis of the multi-temporal inventory map. Four classes of landslide frequency were defined based on the number of events recognized in the 47-year observation period from 1954 to 2001 (Table 8.5).

Table 8.5 – Geomorphological landslide risk assessment in Umbria. Frequency of landslide events, F_L.

Landslide Frequency			Events in the Observation Period
Category	Index	Ratio	
Low	1	1/47 (0.02)	1
Medium	2	2/47 (0.04)	2
High	3	3/47 (0.06)	3
Very high	4	> 3/47 (> 0.06)	> 3

The frequency of landslides, F_L, during the observation period was ascertained based on: (i) the number of events inferred from the analysis of the aerial photographs, (ii) the landslide events observed in the field, and (iii) the information on landslide events obtained from technical reports, historical accounts and chronicles. No distinction was made between events inferred through the interpretation of aerial photographs and events identified in the field or described in technical or historical reports.

8.4.4. Landslide intensity

Definition of landslide hazard requires information on landslide intensity (or magnitude, Guzzetti *et al*., 1999a). For the Umbria Region landslide intensity, I_L, was assumed to be a measure of the destructiveness of the landslide (Hungr, 1997; Raetzo *et al*., 2002), and was defined as a function of the landslide volume, v_L, and of the landslide expected velocity, s_L,

$$I_L = f(v_L, s_L) \tag{8.16}$$

Table 8.6 shows how the intensity level was assigned to each landslide based on the estimated volume and the expected velocity. Landslide volume (v_L) was estimated based on the landslide type defined in the inventory map. For slow moving landslides, volume depends on the estimated depth of movements; for rapid moving debris flows on the size of the contributing catchment and on the estimated volume of debris in the source areas and along the channels; for fast moving rock falls on the maximum size of a single block, obtained from field observations, or from the estimated volume of rock slide deposits. The expected landslide velocity depends on the type of failure, its volume and the estimated depth of movement. For any given landslide volume, rock falls were assigned the highest landslide intensity, debris flows an intermediate intensity, and slow moving landslides the lowest intensity.

Table 8.6 – Geomorphologic landslide risk assessment in Umbria. Landslide intensity, I_L, in four classes, based on the estimated landslide volume, v_L, and the expected landslide velocity, s_L.

ESTIMATED LANDSLIDE VOLUME	EXPECTED LANDSLIDE VELOCITY		
(m^3)	FAST-MOVING ROCK FALL	RAPID-MOVING DEBRIS FLOW	SLOW-MOVING SLIDE
< 0.001	Slight (1)		
0.001 – 0.5	Medium (2)		
0.5 – 500	High (3)	Slight (1)	
500 – 10,000	High (3)	Medium (2)	Slight (1)
10,000 – 500,000	Very High (4)	High (3)	Medium (2)
> 500,000		Very High (4)	High (3)
>> 500,000			Very High (4)

8.4.5. Landslide Hazard Zones

Landslide hazard was evaluated in the areas of evolution of existing (i.e., mapped) landslides. For the purpose, the concept of “landslide hazard zone” (LHZ) was introduced. A LHZ was defined as the area of possible (or probable) short-term evolution of an existing landslide, or a group of landslides, of similar characteristics (i.e., type, volume, depth, velocity), identified from the aerial photographs or observed in the field. In a LHZ an existing landslide can grow upslope, develop down slope, or expand laterally. A LHZ is therefore a form of landslide scenario designed using geomorphological inference.

The multi-temporal landslide inventory map was exploited to identify and map a LHZ. Within each elementary slope, the area of possible evolution of each landslide, or group of landslides, was mapped based on the observed location, distribution and pattern of landslides, their style of movement and activity, and the local lithological and morphological setting. To design a LHZ, the observed partial or total reactivation of the existing landslides, the lateral, head (retrogressive) or toe (progressive) expansion of the existing landslides, and the possible occurrence of new landslides of similar type and intensity were considered.

Separate landslide scenarios were identified for the different type of failures observed in the elementary slope, e.g., fast-moving rock falls and topples, rapid-moving debris flows, and slow-moving slump earth-flows, block slides or compound failures. LHZ included the crown area and the deposit of the existing landslides, and the area of possible direct or indirect influence of the landslide. LHZs were identified based on the local topographic, morphological and geological settings, and the type and extent of landslides. For slow-moving failures (e.g., slide, slump earth-flow, block slides, and compound failures) LHZ was limited to the surroundings of the existing landslide, or group of landslides. This limitation is justified in Umbria where the evolution of these landslides is predictable in space (Cardinali *et al*., 2000). For relict (i.e., very old) landslides the LHZ overlapped in places with the entire elementary slope. For debris flows the LHZ included the source areas, the river channels and the depositional areas on alluvial or debris fans. For rock falls, topples and minor rock slides, LHZ included the rock cliffs from where landslides detached, and the talus, debris cones, or debris slopes along which rock falls travelled, and the places where they deposited.

8.4.6. Landslide hazard assessment

Landslide hazard depends on the frequency of landslide movements (F_L) and on the landslide intensity (I_L), or

$$H_L = f(F_L, I_L) \tag{8.17}$$

The estimate of landslide hazard, H_L, was obtained by combining the value of landslide frequency, ascertained based on the number of landslide events of the same type observed within each LHZ (Table 8.5), and landslide intensity, in four classes, based on the estimated landslide volume and the expected landslide velocity (Table 8.6). Levels of landslide hazard were shown using a two-digit, positional index (Table 8.7). In this index, the right digit indicates the landslide intensity, I_L, and the left digit shows the estimated landslide frequency, F_L. The index expresses landslide hazard keeping distinct the two components of the hazard. This facilitates landslide hazard zoning, allowing the user of the zoning to understand if hazard is due to a high frequency of landslides (i.e., high recurrence), to a large intensity (i.e., large volume and high velocity), or to both.

Table 8.7 – Geomorphological landslide risk assessment in Umbria. Landslide hazard (H_L) classes based on estimated landslide frequency, F_L (Table 8.1) and landslide intensity, I_L (Table 8.2).

Estimated Landslide Frequency	Landslide Intensity			
	Slight (1)	Medium (2)	High (3)	Very high (4)
Low (1)	1 1	1 2	1 3	1 4
Medium (2)	2 1	2 2	2 3	2 4
High (3)	3 1	3 2	3 3	3 4
Very high (4)	4 1	4 2	4 3	4 4

It should be understood that values of the landslide hazard index in Table 8.7 do not provide an absolute rank of hazard levels. Although extreme values are easily defined, intermediate conditions of landslide hazard are more difficult to rank. A landslide that exhibits a low frequency and a slight intensity (H_L = 11) will certainly have a hazard much lower than a landslide exhibiting very high frequency and intensity (H_L = 44). Deciding if the hazard of a landslide with a very high frequency and a slight intensity (H_L = 41) is higher (or lower) than that of a landslide with a low frequency and a very high intensity (H_L = 14) is not straightforward, and may be a matter of local judgement.

8.4.7. Vulnerability of elements at risk

To ascertain risk, one needs to know the type and location of the vulnerable elements (§ 8.2.1). Information on the elements at risk was compiled through the preparation of specific maps at 1:10,000. These maps showed the location and type of the built up areas, the structures and the infrastructure, and were obtained by analysing large-scale topographic base maps, and the most recent aerial photographs available for each study area. Care was taken in precisely locating the elements at risk within or in the vicinity of the landslides and the LHZ. Maps showing vulnerable elements were digitised, registered to the multi-temporal landslide map, and stored into a GIS database.

To classify the elements at risk a legend with eleven classes was adopted (Table 8.8). Of the eleven classes, six referred to built-up areas and structures (houses, buildings, industry and farms, sports centres, and cemeteries), four to the transportation network (roads and railways), and one to mining activities (quarries). For the risk to the population, the assumption was made that houses, buildings and roads in the study area were a proxy for population density, and the population was considered to be vulnerable because of the presence of structures and infrastructure. As an example, in a densely populated zone vulnerability to the population was considered higher than for sparse, farming structures. Along a secondary road vulnerability to the population was considered lower than along a high transit road.

Table 8.8 – Geomorphological landslide risk assessment in Umbria. Types of element at risk (for structures and infrastructure).

CODE	ELEMENTS AT RISK
HD	Built up areas with a high population density
LD	Built up areas with a low population density and scattered houses
IN	Industries
FA	Animal farms
SP	Sports facilities
Q	Quarries
MR	Main roads, motorways, highways
SR	Secondary roads
FR	Farm and minor roads
RW	Railway lines
C	Cemeteries

In general, evaluating the vulnerability of the elements at risk to different landslide types is a difficult and uncertain operation. To estimate vulnerability in Umbria, a straightforward approach was adopted, based on the inferred relationship between the intensity and type of the expected landslide, and the likely damage the landslide could cause. Table 8.9 illustrates the expected damage to buildings and roads, and to the population, if affected by landslides of different type and intensity. The table was constructed based on the information of the damage caused by slope failures in Umbria (Felicioni *et al*., 1994; Alexander, 2000; Cardinali *et al*., 2000; Antonini *et al*., 2002b), field experience and judgement, and on the review of the scant literature on landslide vulnerability (Morgan *et al*., 1992; Michael-Leiba *et al*., 1999, 2003;

Alexander, 1989, 2000; Fell, 1994, 2000). A crude estimate (i.e., few, many, and very many) of the number of people potentially subject to landslide risk was also considered, based on the extent and type of the built-up areas.

In Table 8.9, damage to structures and infrastructure was classified as: (i) aesthetical (or minor) damage, where the functionality of buildings and roads was not compromised, and the damage could be repaired, rapidly and at low cost, (ii) functional (moderate or medium) damage, where the functionality of structures or infrastructure was compromised, and the damage required time and large resources to be fixed, and (iii) structural (severe or total) damage, where buildings or transportation routes were severely or completely damaged, and required extensive work to be fixed, and demolition and reconstruction might be required (Alexander, 2000). Damage to the population was classified as: (i) direct, where casualties (deaths, missing persons and injured people) were expected, (ii) indirect, where only socio-economic damage was expected, and (iii) temporary for permanent loss of private houses (i.e., evacuees and homeless people). Direct damage to the population was foreseen for rapid and fast moving landslides, or for high intensity, slow moving slides. Indirect damage to the population was assigned where landslides could cause functional or structural damage to infrastructure, with negative socio-economic effects to public interests. Homeless were expected where functional or structural damage to buildings was foreseen.

Table 8.9 – Geomorphological landslide risk assessment in Umbria. Vulnerability, W_L, the expected damage to the elements at risk (i.e., buildings, structures and infrastructure) and to the population. For elements at risk: A, aesthetical (or minor) damage; F, functional (or medium) damage; S, structural (or total) damage. For population: N, no damage; D, direct damage (fatalities); I, indirect damage; H, homeless people. For classes of elements at risk see Table 8.8. For landslide intensity see Table 8.6.

Landslide Intensity		Elements at Risk											
		Structures and Infrastructure											Population
		Buildings						Roads				Others	
		HD	LD	IN	FA	SP	C	MR	SR	FR	RW	Q	
Slight	Rock fall	A	A	A	A	A	A	A	A	A	A	A	N
	Debris flow	A	A	A	A	A	A	A	F	F	A	A	N
	Slide	A	A	A	A	A	A	A	F	S	A	A	N
Medium	Rock fall	F	F	F	F	F	F	F	F	F	F	F	D, I, H
	Debris flow	F	F	F	F	F	F	F	F	F	F	F	D, I, H
	Slide	F	F	F	F	F	F	F	S	S	F	F	I
High	Rock fall	S	S	S	S	S	S	S	S	S	S	S	D, I, H
	Debris flow	S	S	S	S	S	S	S	S	S	S	S	D, I, H
	Slide	S	S	S	S	S	S	S	S	S	S	S	I, H
Very high	Rock fall	S	S	S	S	S	S	S	S	S	S	S	D, I, H
	Debris flow	S	S	S	S	S	S	S	S	S	S	S	D, I, H
	Slide	S	S	S	S	S	S	S	S	S	S	S	I, H

8.4.8. Specific landslide risk

Landslide risk is the result of the complex interaction between the "state of nature" (i.e., landslide hazard, (H_L) and the expected vulnerability to the elements at risk (W_L), or

$$R_S = f(H_L, W_L) \tag{8.18}$$

This general relationship was adopted to ascertain the specific landslide risk, R_S, i.e., the risk at which single or multiple elements (e.g., building, roads, etc.) are subject when a landslide occurs (Einstein, 1988). Specific landslide risk was defined separately for each class of elements at risk and for each landslide type present in each LHZ. If more than a single type of elements at risk was present in a LHZ, a different value of specific risk was computed for each class.

To determine specific landslide risk Table 8.10 was used, which correlates the expected damage to the landslide hazard, loosely ranked from low (11) to high (44) values. Construction of Table 8.6 required extensive discussion, and it was largely based on the analysis of damage caused by two recent regional landslide events in Umbria (§ 3.3.3): the rapid snow melting that triggered thousands of failures in January 1997 (Cardinali *et al.*, 2000), and the Umbria-Marche earthquake sequence of September-October 1997 that caused mostly rock falls (Antonini *et al.*, 2002b). Information on past landslide damage in Umbria was also considered (Felicioni *et al.*, 1994; Alexander, 2000).

Table 8.10 – Geomorphological landslide risk assessment in Umbria. Levels of specific landslide risk, R_s, based on landslide hazard (H_L, Table 8.3) and landslide vulnerability (W_L, Table 8.5). Only damage to elements at risk (structures and infrastructure) is considered. Levels of landslide hazard are loosely ranked from low (11) to high (44) values.

High ↓ Landslide Hazard ↑ Low	Vulnerability (Expected Damage)		
	Aesthetic (minor) damage	Functional (major) damage	Structural (total) damage
1 1	A 1 1	F 1 1	S 1 1
1 2	A 1 2	F 1 2	S 1 2
1 3	A 1 3	F 1 3	S 1 3
2 1	A 2 1	F 2 1	S 2 1
1 4	A 1 4	F 1 4	S 1 4
2 2	A 2 2	F 2 2	S 2 2
2 3	A 2 3	F 2 3	S 2 3
3 1	A 3 1	F 3 1	S 3 1
3 2	A 3 2	F 3 2	S 3 2
2 4	A 2 4	F 2 4	S 2 4
3 3	A 3 3	F 3 3	S 3 3
4 1	A 4 1	F 4 1	S 4 1
4 2	A 4 2	F 4 2	S 4 2
3 4	A 3 4	F 3 4	S 3 4
4 3	A 4 3	F 4 3	S 4 3
4 4	A 4 4	F 4 4	S 4 4

To show the level of specific risk, a third digit was added to the left of the two-digit landslide hazard index. The third digit described the expected damage (i.e., aesthetical, functional or structural, see Table 8.9). Thus, the specific risk index shows, from right to left, the landslide intensity, the landslide frequency, and the expected damage caused by the specific type of landslide. As for the hazard index, the landslide specific risk index (R_S) does not provide an absolute ranking of risk levels. The extreme conditions are easily ranked: a house having an R_S = *A11* (i.e., aesthetical damage due to a low frequency and slight intensity landslide) poses a lower risk than a dwelling with R_S = *S44* (i.e., expected structural damage caused by a very high frequency and very high intensity landslide). Deciding for the intermediate conditions may not be straightforward. Decision should be made on a case-by-case basis, considering the type of elements at risk, their vulnerability, the possible defensive measures, and the economical and social implications of landslide risk.

8.4.9. Total landslide risk

Where an absolute ranking of landslide risk is required, total risk has to be determined (Varnes and the IAEG Commission on Landslides and other Mass–Movements, 1984; Einstein, 1988). Total landslide risk is the ensemble of all the specific landslide risk levels. Different strategies can be used to lump the detailed information given by the specific landslide risk index, into a limited number of classes of total landslide risk. Cardinali *et al*. (2002b) attributed a value of total landslide risk to the entire study area, based on the largest specific landslide risk attributed in the study area. Reichenbach *et al*. (2005) adopted a different strategy and attributed to each LHZ a value of total landslide risk, in five classes, based on the type and severity of the largest specific landslide risk attributed in the LHZ (Table 8.11).

Table 8.11 – Geomorphological landslide risk assessment in Umbria. Relationships between classes of total landslide risk, type of landslides, and expected damage to structures, infrastructure and the population in Umbria.

TOTAL RISK	LANDSLIDE TYPE	DAMAGE	
		STRUCTURES AND INFRASTRUCTURE	POPULATION
VERY HIGH	Rapid and fast-moving	Structural and functional	Casualties and homeless people expected, indirect damage expected
HIGH	Slow-moving	Structural and functional	Casualties not expected. Homeless people and indirect damage expected
MEDIUM	Slow-moving, fast and rapid-moving of slight intensity	Aesthetic	Homeless people and indirect damage expected
LOW	Relict, large, slow-moving of very low frequency	Structural and functional	Homeless people and indirect damage expected
VERY LOW	Landslides are present	Null (elements at risk not present)	Null (population not present)

Very high total landslide risk was assigned to LHZs where rapid and fast-moving landslides could cause direct damage to the population. These were the areas where debris flows and rock falls could result in casualties or homeless people. High total landslide risk was assigned to the areas where slow-moving landslides could cause structural and functional damage to structures and infrastructure. In these areas casualties were not expected. Moderate total landslide risk was attributed where aesthetic damage to vulnerable elements was expected, as a consequence of slow moving slope failures and fast or rapid moving landslides of slight intensity. Large or very large, relict deep-seated landslides could cause structural and functional damage to structures and infrastructure, homeless people and indirect damage to the population. Such areas were assigned low total landslide risk, because they were not expected to move entirely under the present climatic and seismic conditions. Lastly, a very low value of total landslide risk was assigned where landslides were identified and landslide hazard was ascertained, but elements at risk or the population were not present in the LHZ.

8.4.10. Geomorphological landslide risk evaluation in Umbria

The described methodology was utilized to ascertain landslide risk in 79 towns in Umbria Region (Figure 8.9) (Cardinali *et al*., 2002b, Guzzetti *et al*., 2004; Reichenbach *et al*., 2005). In the following sub-sections, I present two examples of specific and total landslide risk assessment for Collevalenza and the Terria villages. Other examples can be found in Cardinali *et al*. (2002b) and Reichenbach *et al*. (2005).

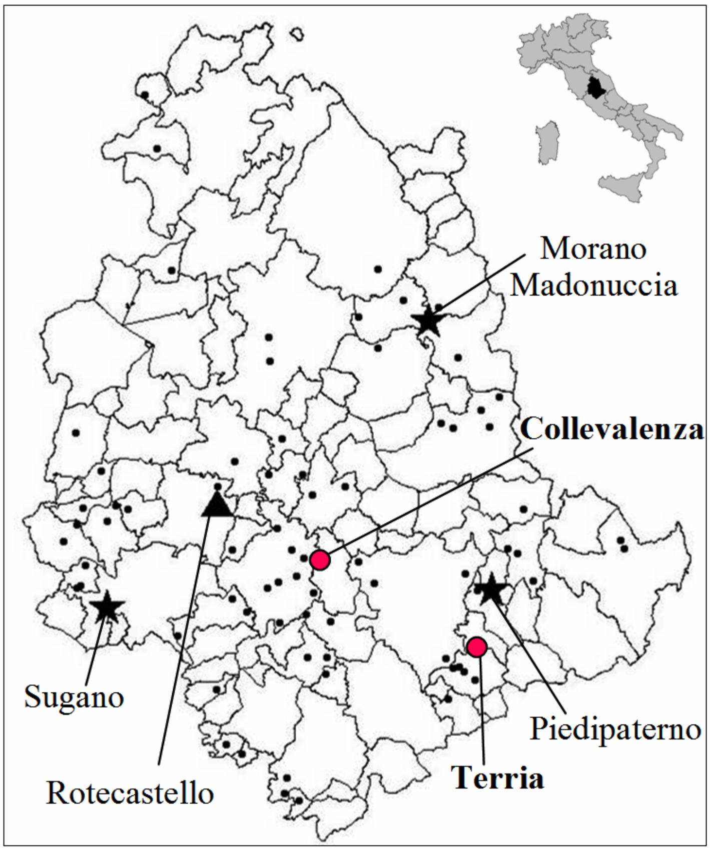

Figure 8.9 – Umbria Region. Location of sites where landslide risk was ascertained. Small dots show location of 79 sites where landslide risk was ascertained. Large dots show location of sites discussed in the next two sub-sections. Triangle shows the location of the village of Rotecastello where risk was determined by Cardinali *et al*. (2002b). Stars show location of sites described by Reichenbach *et al*. (2005).

8.4.10.1. Collevalenza village

The Collevalenza village, in the Todi Municipality, is located in central Umbria and is constituted by a small historic centre and sparse houses placed along the Provincial road 414. The village is located on a SE-NO trending divide, at an elevation of about 350 metres a.s.l. In the area, crop out clay and sand deposits, Plio-Pleistocene in age. Sand predominates at higher elevation, and clay is most abundant in the lower part of the slopes. In the Collevalenza study area we identify four elementary slopes, for a total area of about three square kilometres.

For the study area a multi-temporal landslide inventory map was compiled through the systematic interpretation of three sets of aerial photographs, and field surveys. Aerial photographs were flown in August 1954 at 1:33,000 scale, in June 1977 at 1:13,000 scale, and in April 1997 at 1:20,000 scale. Field surveys were carried out in March 1997, shortly after a major landslide triggering event (Cardinali *et al*., 2000), and in February 2001 (Antonini *et al*., 2002a). Shallow and deep-seated landslides were identified in the three sets of aerial photographs, and were classified based on the relative age, inferred from the date of the aerial photographs, and on the prevalent landslide type (Figure 8.10). A total of 149 landslides were identified and mapped in the study area, for a total landslide area of 0.96 km^2. The territory affected by slope movements extends for 0.83 km^2, equivalent to 26.4% of the study area. In the study area the transitional and rotational slides originate from the upper part of the slopes, and down slope from thick layers of sand present along the main divide. Soils, weathered deposits and pre-existing landslide deposits, allow small, shallow slides and flows to develop. Relict landslides are present only in the eastern part of the study area. Historical information and reports on landslide events indicate that slope movements in the area are triggered chiefly by prolonged rainfall and by rapid snow melting. Such events are relatively frequent in this part of Umbria.

In the Collevalenza study area 20 LHZs were identified, of which: 10 for slow-moving, shallow landslides of slight intensity (4-6, 8, 10-13, 15, 17 in Figure 8.10.A and B), 1 for slow-moving, deep-seated of medium intensity (20 in Figure 8.10.C and D), 7 for slow-moving, deep-seated landslides of medium and high intensity and shallow landslides of slight intensity (1-3, 7, 9, 14, 16 in Figure 8.10.C and D), and 2 for very old (relict) landslides (18-19 in Figure 8.10.E and F). For each LHZ landslide frequency was obtained through the interpretation of the available sets of aerial photographs, and from information obtained in the field in 1997 and 2001 (Table 8.12). In the 47-year observation period, landslide frequency ranges from low (1 event) to very high (6 events). The highest frequency was observed in a LHZ where shallow soil slips and earth flows occurred repeatedly (1 in Figure 8.10.A and B). Several landslides were mapped as active at the date of the photographs or the field surveys. Information on the location and type of the vulnerable elements in the study area was obtained from large-scale topographic base maps at 1:10,000 scale, prepared in 1999 from aerial photographs taken in 1997. By combining this information with the landslide hazard assessment, specific landslide risk was ascertained for each vulnerable element or group of vulnerable elements. Separate levels of specific landslide risk were attributed to the vulnerable elements that were subject to hazards posed by different landslide types. Table 8.12 lists the results of the risk assessment.

The landslide risk assessment indicated that deep-seated slides of medium to high intensity and medium frequency (1, 2, 14, 16 in Figure 8.10.C and D) pose the highest threat to the vulnerable elements in the study area (Table 8.12). In LHZs 1, 2, 14, 16 functional damage to built-up areas (LD) and structural damage to the transportation network (SR, FR) are expected. In these LHZs up to 100 homeless people are possible. Significant levels of specific landslide risk are also expected where shallow landslides with high (8, 9, in Figure 8.10.A and B) or very high (1, 3, 10, 11, 12, 14, 16 in Figure 8.10.A and B) frequency of occurrence are present. In these LHZs, damage ranges from structural to aesthetic, and affects mostly low-density built-up areas (LD), and roads of various categories (SR, FR). Based on the available information, in the Collevalenza study area shallow landslides are not expected to threaten the population. The two very old (relict), deep-seated slides identified in the area (18, 19 in Figure 8.10.E and F) exhibit very low frequency and high intensity, and eventually will produce structural damage to low density build-up areas (LD).

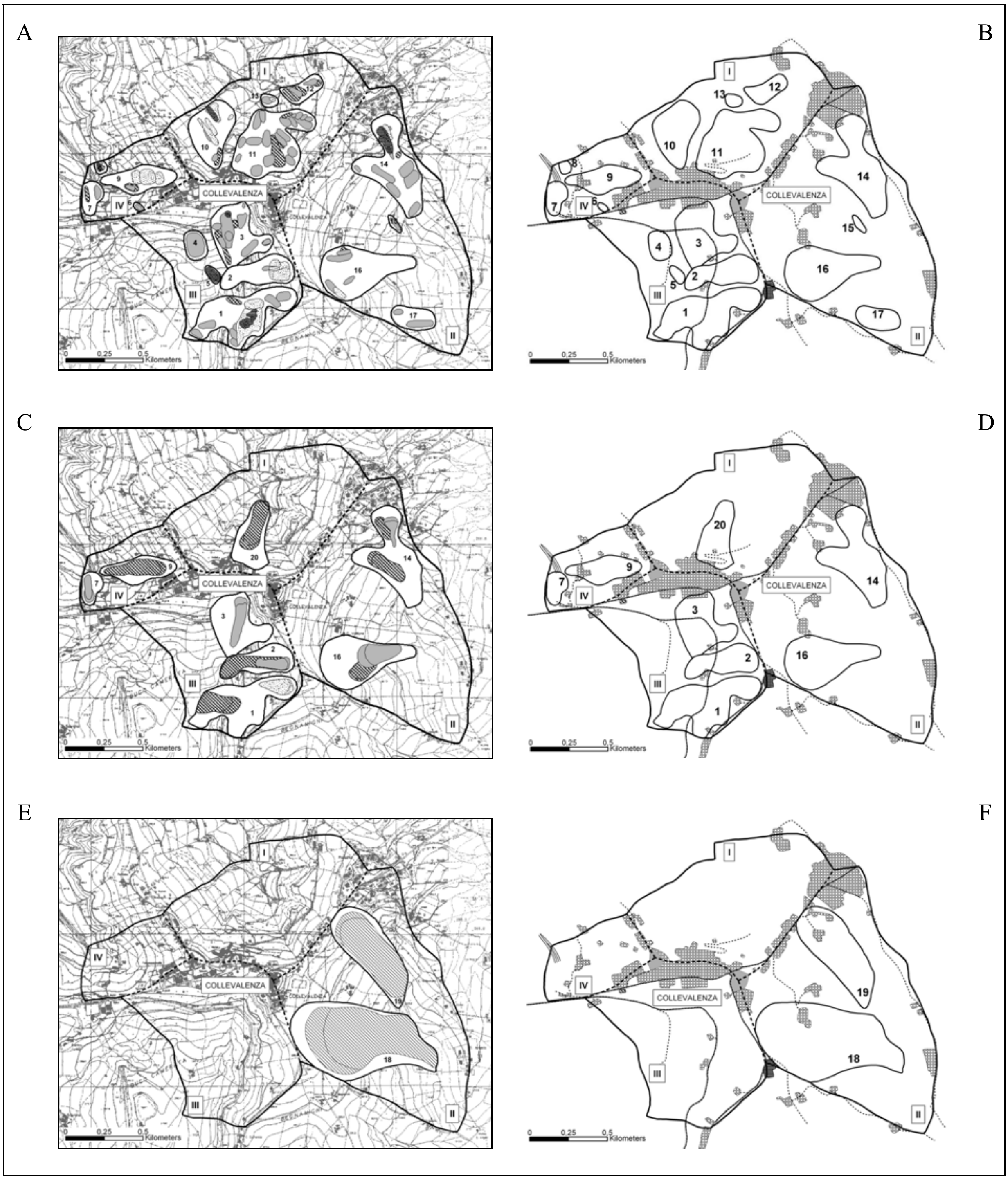

Figure 8.10 – Specific landslide risk assessment for the village of Collevalenza, central Umbria (see Figure 8.9 for location). Maps A, C, and E show the multi-temporal inventory for shallow slides, deep-seated landslides, and large and very old landslides, respectively. Patterns and shades of grey indicate landslides of different age ascertained from the dates of the aerial photographs. White areas are LHZs. Maps B, D, and F, show elements at risk and LHZs for shallow slides, deep-seated landslides, and large and very old landslides, respectively. Patterns and shades of grey indicate vulnerable elements of different type. Arabic numbers indicate the 20 LHZs identified in the study area and listed in Table 8. Roman numbers indicate the four elementary slopes. Original maps at 1:10,000 scale.

Table 8.12 – Collevalenza study area. Classification of specific, R_S, and total, R_T, landslide risk. Legend: *LHZ*, landslide hazard zone; F_L, landslide frequency (Table 8.5); I_L, landslide intensity (Table 8.6); H_L, landslide hazard (Table 8.7); *E*, type of element at risk (Table 8.8); W_L, vulnerability of elements at risk (Table 8.9); *P*, vulnerability of population (Table 8.9).

LHZ #	Landslide Type	F_L	I_L	H_L	E	W_L	P	R_S	R_T
1	Deep-seated slide	2	2	2 2	LD	F	H	F 2 2	High
					SR	S	N	S 2 2	
	Shallow slide	6	1	4 1	LD	A	N	A 4 1	
					SR	S	N	S 4 1	
2	Deep-seated slide	2	2	2 2	LD	F	H	F 2 2	High
					SR	S	N	S 2 2	
	Shallow slide	2	1	2 1	LD	A	N	A 2 1	
					SR	S	N	S 2 1	
3	Deep-seated slide	1	2	1 2	LD	F	H	F 1 2	High
					SR	S	N	S 1 2	
	Shallow slide	5	1	4 1	LD	A	N	A 4 1	
					SR	S	N	S 4 1	
4	Shallow slide	1	1	1 1	FR	S	N	S 1 1	Medium
5	Shallow slide	2	1	2 1	N	-	-	-	Very low
6	Shallow slide	1	1	1 1	N	-	-	-	Very low
7	Deep-seated slide	1	2	1 2	FR	S	N	S 1 2	Medium
	Shallow slide	2	1	2 1	FR	S	N	S 2 1	
8	Shallow slide	3	1	3 1	N	-	-	-	Very low
9	Deep-seated slide	1	2	1 2	LD	F	H	F 1 2	Medium
					FR	S	N	S 1 2	
	Shallow slide	3	1	3 1	LD	A	N	A 3 1	
					FR	S	N	S 3 1	
10	Shallow slide	4	1	4 1	N	-	-	-	Very low
11	Shallow slide	4	1	4 1	LD	A	N	A 4 1	Medium
					FR	S	N	S 4 1	
12	Shallow slide	4	1	4 1	N	-	-	-	Very low
13	Shallow slide	2	1	2 1	N	-	-	-	Very low
14	Deep-seated slide	2	2	2 2	LD	F	H	F 2 2	High
					FR	S	N	F 2 2	
	Shallow slide	5	1	4 1	LD	A	N	A 4 1	
					FR	S	N	S 4 1	
15	Shallow slide	1	1	1 1	N	-	-	-	Very low
16	Deep-seated slide	2	2	2 2	LD	F	H	F 2 2	High
	Shallow slide	4	1	4 1	LD	A	N	A 4 1	
17	Shallow slide	1	1	1 1	N	-	-	-	Very low
18	Very old, deep-seated slide	1	3	1 3	LD	S	H	S 1 3	Low
					FR	S	N	S 1 3	
19	Very old, deep-seated slide	1	3	1 3	LD	S	H	S 1 3	Low
					FR	S	N	S 1 3	
20	Deep-seated slide	1	2	1 2	LD	F	H	F 1 2	High
					FR	S	N	S 1 2	

Inspection of Table 8.12 reveals that in the Collevalenza study area, for eight LHZs (5, 6, 8, 10, 12, 13, 15, 17) levels of landslide hazard were ascertained, but vulnerable elements are not present (N in Table 8.12). Hence, landslide risk does not presently exist in these LHZs. If houses, roads, or other elements at risk are constructed in the LHZs, landslide risk will materialize. It will then be straightforward to determine levels of specific landslide risk, based on the type of vulnerable elements, and of values of landslide hazard.

Table 8.12 illustrates levels of total landslide risk (R_T) for the 20 LHZs identified in the Collevalenza study area. Total landslide risk is estimated to be high for low-density built-up areas (LD) where deep-seated landslides are present (1, 2, 3, 7, 9, 14, 16, 18, 19, 20). This is chiefly because indirect damage to the population and homeless people are expected. Where low-density settlements (LD) and roads (SR, FR) are affected by shallow slides total landslide risk is medium (4, 11 in Figures 8.10.A and B). We attribute very low levels of total landslide risk to LHZs where landslide hazard was determined but that are currently free of vulnerable elements (5, 6, 8, 10, 12, 13, 15, 17). In these LHZs the estimate of total landslide risk will change significantly if building, roads, and other structures are constructed.

8.4.10.2. Terria village

Terria is a small village in the Ferentillo Municipality, located near the confluence of the Terria Torrent with the Nera River on a south facing slope at an elevation of 400 meters (Figure 8.11). The Terria Torrent drains a small and steep catchment that extends for about 5 km^2 on the western slope of Mount Birbone. Elevation in the area ranges from 260 meters, at the confluence with the Nera River, to 1426 m at the top of the ridge. In the lower part of the catchment, where the village is located, slopes are very steep, sub-vertical where rock cliffs are present. A large and old alluvial fan is present at the confluence of the Terria Torrent with the Nera River. The central part of the fan is deeply incised. On the middle and upper parts of the Terria catchment, slopes are regular, with a gradient of about 25-30 degrees. In the area crop out layered limestone, Jurassic to Cretaceous in age. Bedding dips regularly towards West, with an angle of about 30°. Along the Nera River and down slope from the main rock escarpments, debris deposits, 1 to 5 meters thick, are locally present (Guzzetti *et al.*, 2004).

In the Terria study area single elementary slope was identified, comprising the entire catchment of the Terria Torrent, for a total area of about five square kilometers (Figure 8.11). For the study area, the multi-temporal landslide inventory map was obtained by studying four sets of aerial photographs, and through field surveys. Aerial photographs were taken in August 1954 at 1:33,000 scale, in June 1977 at 1:13,000 scale, in 1993 at 1:36,000 scale, and in 1998 at 1:28,000 scale. Field surveys were completed in June 2000 (Antonini *et al.*, 2002a). Figure 8.11.A shows the landslides identified in the study area. Landslides were classified based on the prevalent type of movement and estimated age, inferred from the date of the aerial photographs. On the upper part of the catchment, a single large deep-seated and complex slide and a few small debris flows are present. Inspection of the inventory map reveals that landslides, mostly debris flows and rock falls, concentrate in the lower and middle part of the Terria catchment. Debris flow sources and channels were identified as active in the 1954 and the 1977 aerial photographs. Debris flow deposits and rock fall source areas cover a total of 20 hectares, 4% of the study area. Comparison of the 1954 and 1977 aerial photographs revealed a different road track on the apex of the alluvial fan located at the mouth of the Terria catchment. During the 24-year period from 1954 and 1977 one or more flash flood events associated with minor debris flows must have occurred in the area, inundating the road and producing damage. Fast-moving rock falls occur from the rock cliffs located mostly in the lower part of the catchment, where the main road and the village are located. On the 27 January 1998, boulders damaged the road connecting the village to the Regional Road 209, along the Nera River valley. Retaining nets were installed to protect the village from rock falls.

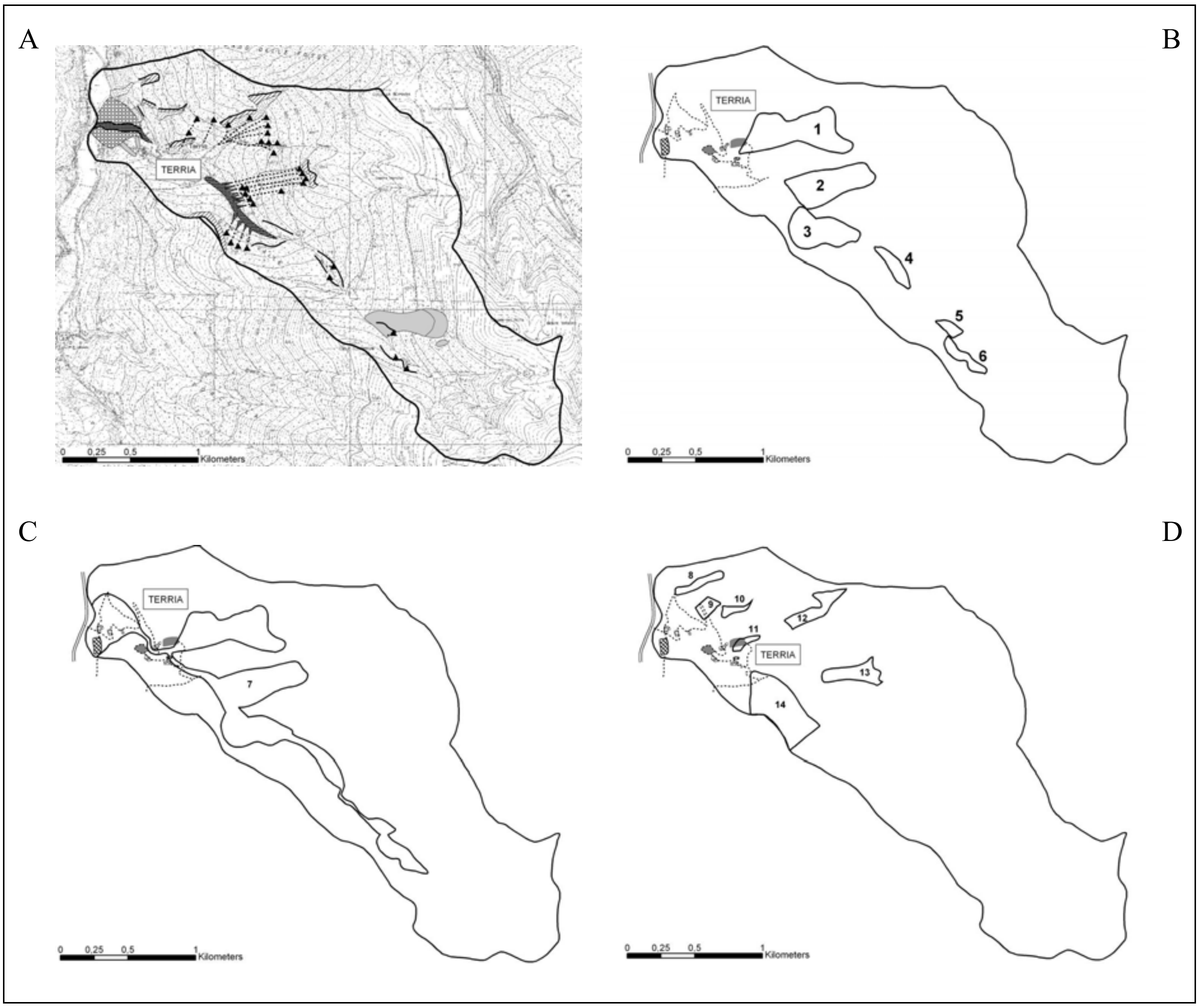

Figure 8.11 – Specific landslide risk assessment for the village of Terria, Umbria region (see Figure 8.9 for location). Map A shows the multi-temporal inventory map prepared by interpreting four sets of aerial photographs, taken in the period from 1954 to 1998, and field surveys in 2000. Patterns, symbols and shades of grey indicate landslides of different type and age. Maps B, C, and D, show landslide hazard zones (and elements at risk) for large debris flows, moderate debris flows, and rock falls, respectively. Arabic numbers refer to the 14 LHZs identified in the study area and listed in Table 8.13. Original maps at 1:10,000 scale.

Fourteen LHZs were identified in the Terria study area, of which: six for rapid moving debris flows with an expected volume of less than 10,000 cubic meters (1, 2, 3, 4, 5, 6 in Figure 8.11.B), one for rapid moving debris flows with an expected volume larger than 10,000 m^3 (7 in Figure 8.11.C), and seven for fast-moving rock falls (8, 9, 10, 11, 12, 13, 14 in Figure 8.11.D). For each LHZ landslide frequency was ascertained through the interpretation of the available aerial photographs, the historical information, and field reconnaissance in the area. For debris flows, landslide frequency was found ranging from low (1 event) to high (3 events). For rock falls landslide frequency was assigned as high, based on the available historical information and the field observations. Information on the location and type of the vulnerable elements in the study area was obtained from large-scale topographic maps at 1:10,000 scale prepared in 1992, and from aerial photographs taken in 1986 and in 1997. By combining this information with the landslide hazard assessment, levels of specific landslide risk were ascertained for each vulnerable element or group of vulnerable elements. Separate levels of specific landslide risk were attributed to the vulnerable elements that were subject to hazards posed by different landslide types. Table 8.13 lists the results of the risk assessment.

Based on the obtained risk assessment, in the Terria study area, fast-moving rock falls and rapid-moving debris flows pose the highest threat. Field evidence, information on past landslide events, and the location of the vulnerable elements with respect to the rock fall source, travel and deposition areas, together contribute to very high levels of specific landslide risk to vulnerable elements and the population. In the areas where rock falls occurred in the past, total or partial destruction of buildings (HD) and functional damage of roads (SR) is expected. The assessment does not consider the mitigating effect of the existing rock fall defensive structures (i.e., retaining nets) because the existing structures may not be adequate in stopping all rock falls (Guzzetti *et al*., 2003, 2004). Where rock falls are expected, fatalities and homeless people are possible. The lower part of the Terria catchment is subject to debris flows. In this area, debris flows can produce structural damage to buildings (HD, LD, FA) and roads (SR), and can cause direct damage to the population, including homeless people. In the medium part of the catchment, debris flow of slight intensity can produce aesthetic damage to buildings (HD) and functional damage to roads (SR).

Table 8.13 illustrates total landslide risk for the Terria study area. Total landslide risk was estimated to be very high where fast-moving rock falls and rapid-moving debris flows of high intensity are expected, casualties and structural damage to high density settlements and secondary roads are possible. Moderate total risk was considered possible where debris flows of slight intensity are expected.

Table 8.13 – Terria study area. Classification of specific, R_S, and total, R_T, landslide risk. Legend: *LHZ*, landslide hazard zone; F_L, landslide frequency (Table 8.5); I_L, landslide intensity (Table 8.6); H_L, landslide hazard (Table 8.7); *E*, type of element at risk (Table 8.8); W_L, vulnerability of elements at risk (Table 8.9); *P*, vulnerability of population (Table 8.9).

LHZ #	Landslide Type	F_L	I_L	H_L	E	W_L	P	R_S	R_T
1	Debris flow	3	1	3 1	HD SR	A F	N N	A 3 1 F 3 1	Moderate
2	Debris flow	2	2	2 1	-	-	-	-	Very low
3	Debris flow	1	2	1 2	-	-	-	-	Very low
4	Debris flow	1	1	1 1	-	-	-	-	Very low
5	Debris flow	1	1	1 1	-	-	-	-	Very low
6	Debris flow	2	1	2 1	-	-	-	-	Very low
7	Debris flow	1	3	1 3	HD LD SR FA	S S S S	D, H D, H D D	S 1 3 S 1 3 S 1 3 S 1 3	Very high
8	Rock falls	3	2	3 2	-	-	-	-	Very low
9	Rock falls	3	2	3 2	SR	F	D	F 3 2	Very high
10	Rock falls	3	2	3 2	-	-	-	-	Very low
11	Rock falls	3	2	3 2	HD	F	D, H	F 3 2	Very high
12	Rock falls	3	2	3 2	-	-	-	-	Very low
13	Rock falls	3	2	3 2	-	-	-	-	Very low
14	Rock falls	3	2	3 2	SR	F	D	F 3 2	Very high

8.4.11. Discussion

The described method to determine landslide hazards and to evaluate specific and total landslide risk complies with the existing definitions of landslide hazard (see § 6, § 7, Varnes and IAEG Commission on Landslides and other Mass-Movements, 1984; Guzzetti *et al*. 1999a, 1999b) and of landslide risk (see § 8.2, Varnes and IAEG Commission on Landslides and other Mass-Movements, 1984; Einstein, 1988; Cruden and Fell, 1997; Guzzetti, 2002). The method is empirical and subject to various levels of uncertainty, but has proved to be consistent, allowing for detailed and comparable assessments of landslide hazard and specific and total landslide risk levels in urban and rural areas in Umbria. The method allows the comparison of landslide hazard and risk in distinct and distant areas, and where different landslide types are present.

The method was applied in 210 landslide hazard zones located around or in the vicinity of 79 towns and villages in Umbria (Antonini *et al*., 2002a; Cardinali *et al*., 2002b; Guzzetti *et al*., 2004; Reichenbach *et al*., 2005). In these areas landslide hazard was determined, vulnerable elements were identified, and specific and total risk levels were evaluated. The time and human resources required for completing the risk assessment procedure at each site varied, depending on the extent of the study area, the number, type and scale of the aerial photographs, the available thematic and historical information, the extent and type of landslides present in the study area, and the local geological and morphological setting. On average, completion of the risk assessment procedure at each site required five days for a team of 3-4 geomorphologists, including bibliographical investigation, interpretation of the aerial photographs, field surveys, storage of landslide and other thematic information in the GIS database, and the production of the final hazard, vulnerability and risk maps.

The proposed method requires extensive geomorphological judgment. For this reason it should only be used by skilled geomorphologists. If the extent, type, distribution and pattern of past and present landslides are not correctly and fully identified, errors can occur, affecting the estimate of landslide hazards and risk. With this in mind, the definition of the temporal frequency of landslides from the analysis of the multi-temporal inventory map is particularly important. In the Umbria Region, the multi-temporal landslide maps cover a period of about 47 years, which is long enough to evaluate the short-term behaviour of slopes in the areas investigated. Should information on landslide frequency be available only for a shorter period of time (e.g., 10-15 years or less), the reliability of the hazard forecast will be reduced. If a landslide event fails to be recognized, the frequency of occurrence is underestimated, and hazard and risk estimates are negatively affected. It should be noted that the method estimates the expected landslide frequency based on what has happened (and was observed) in the recent past. If low frequency, high magnitude events did not occur or were not recognised in a LHZ, the hazard assessment in the area may be biased, and the actual landslide risk is underestimated. This is a limitation of the method.

The method allows for detailed and articulated hazard and risk assessments. Landslide hazard is determined separately for all the different landslide types that may be present in the study area. Specific landslide risk is determined independently for each type of vulnerable element in the study area. Thus, vulnerable elements may be subject to multiple levels of specific landslide risk, and landslide hazard may be ascertained where vulnerable elements are not present. The proposed method assesses landslide hazard in the areas of probable evolution of the existing landslides (i.e., in a landslide hazard zone). The method says nothing about the hazard outside a LHZ, even within the same elementary slope. In these areas minor landslides, mostly superficial failures can occur with a low frequency. For a regional, spatially distributed landslide hazard and risk assessment, other methods should be used (see § 6 and 7).

Uncertainty varies with the different steps of the method. The production of the separate landslide inventory maps and of the multi-temporal landslide map is less uncertain than the identification of the landslide hazard zones, or the possible spatial evolution of the existing landslides, which is obtained mostly through geomorphological inference. Landslides mapped through the interpretation of aerial photographs were carefully checked in the field, whereas the identification and mapping of LHZs was based on the observation of other landslides and on the inferred geomorphological behaviour of slopes. Evaluation of landslide frequency, which determines landslide hazards, is conditioned by the availability of aerial photographs and historical information, and by the investigator ability to recognize past and present landslide events. Estimates of landslide volume and velocity, which are essential for the evaluation of landslide intensity, also exhibit uncertainty.

Uncertainty arises also because a difference exists between geomorphological and historical information on landslides. Geomorphological information obtained through field mapping and the analysis of aerial photographs provides the basis for determining the prevalent landslide types and location, but provides poor constrain on the date (or the age) of the slope failures. Historical and archived information provides precisely the date and, more rarely, the time of occurrence of some of the landslide events, and the type and extent of damage caused by mass movements, but provide little information on the type of failures and the precise location and extent of the landslides. Combination of geomorphological and historical information on mass movements is not straightforward, and may be locally a matter of interpretation and local judgement.

The proposed method relies on a set of correlation tables, which are used to define landslide frequency (Table 8.1) and intensity (Table 8.2), to ascertain landslide hazard (Table 8.3), to evaluate the expected damage to the vulnerable elements (Table 8.5), and to attribute levels of specific (Table 8.6) and total (Table 8.7) landslide risk. The tables were based on empirical observations and on the investigators experience, but are also the result of a heuristic approach. Whenever possible, several possibilities should be evaluated and the differences compared after each attempt. The adopted tables fit the present understanding of landslide processes and match landslide damage in Umbria satisfactorily (Felicioni *et al*., 1994; Alexander, 2000; Cardinali *et al*., 2000; Antonini *et al*., 2002b; Guzzetti *et al*., 2003). However, the tables are not definitive, and should not be used unconditionally in all settings. If applied to other sites, or in other study areas, the tables should be carefully checked with the local information on landslide types and damage. If one, or more, of the tables is changed significantly, the hazard and risk assessment will vary, and may not be comparable to the one we have prepared. This is particularly important for Table 8.5 (vulnerability) and Table 8.6 (specific risk).

Landslide hazard and specific risk are expressed using a multiple-digit, "positional" index that shows, in a compact and convenient format, all the variables used to ascertain landslide hazard and risk (i.e., intensity, frequency, and vulnerability). The index allows for the ranking of risk conditions at the end of the risk assessment process, when all the necessary information is available, and not "a priori", based on pre-defined (often ill formalized) categories. This a major advantage of the method, giving risk managers and decision makers great flexibility in deciding which area exhibits the highest risk, and providing geologists and engineers with a clue about why any given vulnerable element is at risk. In addition, the use of a simple index to express levels of specific landslide risk makes it possible to adopt different schemes to determine levels of total landslide risk, depending on the priorities or the specific interests of the investigators or the end-users.

Lastly, the proposed method is not simple or straightforward. A dependable and consistent prediction requires multiple sets of aerial photographs and a team of experienced geomorphologists to interpret them. This cannot be considered a limitation: landslide hazard and risk assessments are difficult tasks, and require proper expertise and skills.

8.5. Assessing landslide damage and forecasting landslide impact

An alternative way of establishing semi-quantitative levels of landslide risk consists in investigating the damage caused by slope failures in the past, and in attempting to forecast the impact that landslides will have in the future, in a given area (Brabb, 1991). The former consists in studying archive or event inventories, the latter involves designing landslide scenarios (§ 8.2.3). Where a detailed historical catalogue of landslides and their consequences exists, and where inventory maps documenting individual landslide events have been prepared, the vulnerability of the elements at risk can be ascertained, and the sites repeatedly affected by catastrophic events can be determined. More precisely, historical and event information can be exploited to: (i) evaluate the most common type of landslide damage, (ii) determine the extent and spatial distribution of the damage, and (iii) obtain quantitative estimates of the cost of single or multiple landslides (e.g., Taylor and Brabb, 1972; Godt and Savage, 1999; Guzzetti *et al*., 2003b). Where a sufficiently detailed landslide inventory map and maps showing the population, structures, infrastructure, and land use types are available, simple geographical operations in a GIS allow determining where landslides may interfere with the elements at risk, providing estimates of the impact that landslides may have in the future in a given area (e.g., Garberi *et al*., 1999; Brabb *et al*., 2000; Antonini *et al*., 2002a; Guzzetti *et al*., 2003a).

In the following three sub-sections, I attempt to ascertain the type and extent of landslide damage caused past landslide events in Umbria, and to determine the expected impact that slope failures can have on the population, the structures and infrastructure, and the agriculture.

8.5.1. Landslide damage in Umbria

Due to the lithological, morphological and climatic setting, landslides are abundant in Umbria (Felicioni *et al*., 1994; Guzzetti *et al*., 1996; 2003a; Antonini *et al*., 2002a). In the region, landslides range from fast moving rock falls and debris flows, most abundant in mountain areas, to slow moving complex failures extending up to several hectares in the hilly part of the region. Mass movements occur almost every year in Umbria in response to prolonged or intense rainfall (Guzzetti *et al*., 2003a), rapid snow melting (Cardinali *et al*., 2000), and earthquake shaking (Bozzano *et al*., 1998; Esposito *et al*., 2000; Antonini *et al*., 2002b). Individual slope failures in Umbria can be very destructive and have caused damage at many sites, including the city of Perugia and the towns of Allerona, Assisi, Montone, Orvieto, Spoleto and Todi (for a review, see Felicioni *et al*., 1994).

Despite landslides occurring every year, the full extent of damage caused by slope failures in Umbria remains largely unknown. No systematic analysis of the archive (Felicioni *et al*., 1994; Guzzetti *et al*., 2003a; Guzzetti and Tonelli, 2004), geomorphological (Antonini *et al*., 2002b; Cardinali *et al*., 2002b; Reichenbach *et al*., 2005), and geotechnical (Felicioni *et al*.,

1994) information on damage caused by slope failures has been completed. Preliminary analysis of the information indicates that landslide damage is most severe to the transportation network and to built-up areas. Figure 8.12 shows examples of the damage caused by slope failures to houses and roads in Umbria. In general, damage to the transportation network is more widespread, whereas damage to the built-up area is more costly. In Umbria, landslide damage to the agriculture results in a temporal (seasonal) or permament loss (or reduction) of yield. Damage to the agiculture is larger in the rainy years. Fortunately, landslide damage to the population in Umbria is relatively low, when compared to the national estimates (§ 8.3 and Table 8.1).

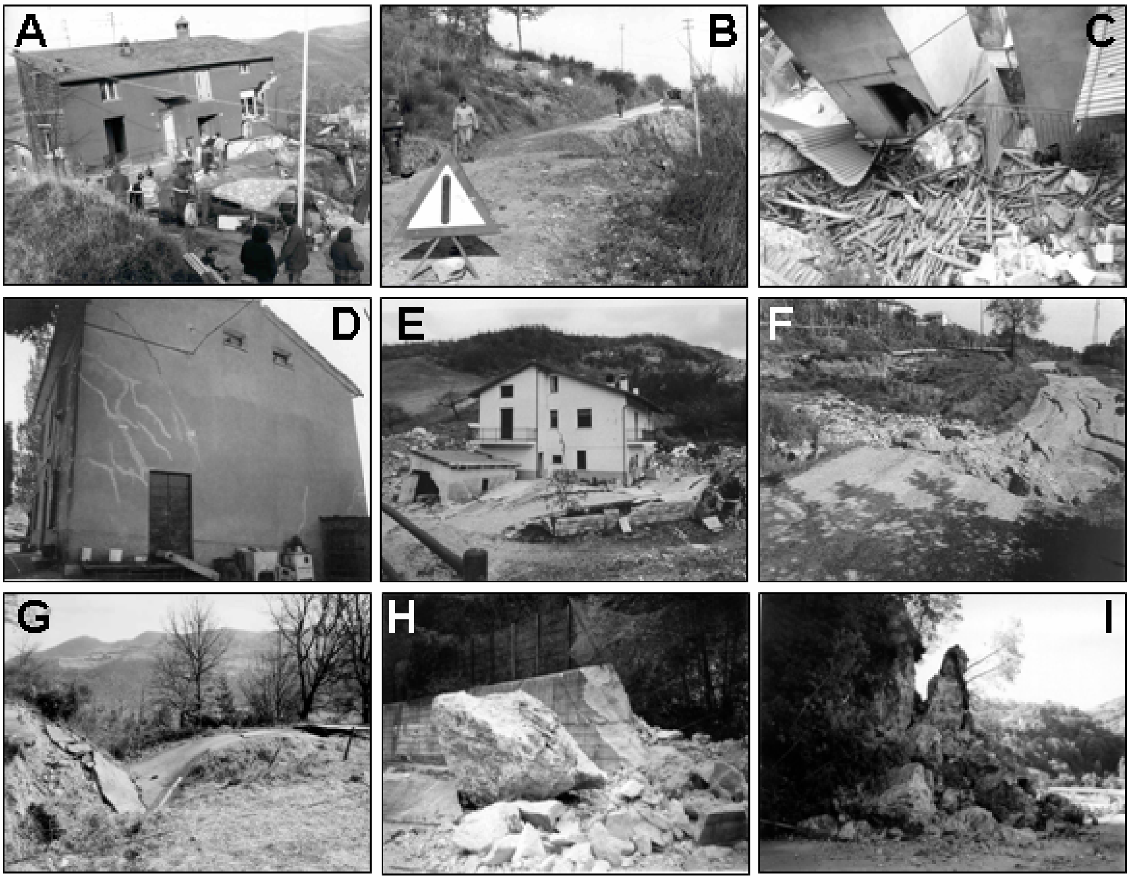

Figure 8.12 – Typical landslide damage in Umbria. (A) House destroyed by a deep-seated slide at Monteverde on December 1982. (B) Road damaged by the Monteverde landslide. (C) House damaged by a rock fall at Piedipaterno on 15 September 1992. (D) House damaged by a deep-seated landslide triggered by rapid snow melting in January 1997 at Bivio Saragano. (E) House destroyed by the Valderchia landslide of 6 January 1997. (F) Road damaged by a deep-seated slump at San Litardo in January 1997. (G) Road damaged by a deep-seated slump at Marcignano in January 1997. H) Damage due to rock falls triggered by the October 1997 earthquake along road SS 320. I) Rock fall and toppling failure caused by the September-October 1997 earthquakes along a provincial road near Stravignano.

8.5.1.1. Damage to the transportation network and the built-up areas

In Umbria, information on historical landslide events is the primary source of information on damage caused by slope failures. For the Region, the national archive inventory (§ 3.3.1.1) lists information on 281 sites where buildings and other structures were damaged by landslides, and 661 sites where roads and railways were damaged by slope failures. In the archive, damage is classified as: (i) light, where damage was aesthetic; (ii) severe, where the functionality of the building or the transportation line was compromised; and (iii) total, where a building was destroyed or a road or railway was interrupted. Along the transportation network about 34.2% of the damage was classified as light, 61.6% as severe and 4.2% as total damage. For the built-up areas, 26.5% of the damage was classified as light, 62.7% as severe, and 10.8% as total damage.

Additional information on the impact of slope failures on the built-up areas and the transportation network in Umbria can be obtained analysing three recent landslide event inventories. The prolonged earthquake sequence of September-October 1997 caused the largest impact to the transportation network (§ 3.3.3.3). Rock falls, topples and minor rock slides were mapped at 220 sites along approximately 600 kilometres of roads. These failures correspond to a density of 2.7 damaging landslides every kilometre. Along the Nera River and the Corno River valleys the density of rock falls was locally much higher. Two main regional roads (i.e., SS 320 and SS 209) running at the bottom of the valleys were interrupted at several sites and remained closed for weeks after the earthquakes, while remedial works were completed (Figure 8.12.H) (§ 7.5). The road interruptions caused severe transportation problems for the local population, and made it harder for the earthquake post-event relief efforts. At least € 15 millions (1998) were spent by the National Department of Civil Protection, the Regional Government, and the National Road Company for repairing the damage and for installing new defensive measures, including several hundreds of meters of rock fall elastic barriers and new artificial tunnels (Guzzetti *et al*., 2003a, 2004c).

Landslides triggered by the January 1997 snowmelt event (§ 3.3.3.2, Cardinali *et al*., 2000) caused damage mostly to the transportation network and to a few houses, some of which had to be abandoned (Figure 8.12.E). By intersecting in the GIS the map of the transportation network with the event landslide inventory map, 115 sites were identified where landslides triggered by rapid snowmelt intersected (i.e., interfered) with the road and railroad network. Sites damaged by landslides were found one every 56 kilometres of highways, every 32 kilometres of roads, and every 47 kilometres of railroads. An additional 112 sites where landslides were in the immediate vicinity of the transportation network were identified by drawing a buffer zone around each road or railway. Considering the buffer zone, the frequency of slope failures increased to one every 13 km of highways, 16 km of roads and 37 km of railways. In the area where the aerial photographs were available to complete the event inventory, 158 sites were identified where landslides intersected (73) or were close to (85) roads and railways. Damage to the transportation network was generally localized. The section of the roads affected by slope failures extended from a few tens to a few hundred meters. Estimates of the Regional Government suggest that the amount of money spent repairing the damage along the transportation network exceeded € 10 million (1997) (Guzzetti *et al*., 2003a).

Landslides triggered by rainfall events in the period from 1937 to 1941 (§ 3.3.3.1) probably caused damage to built-up areas, roads and railways (Guzzetti *et al*., 2003a). Unfortunately, very little information is available in the historical archive that in this period lists only 13 sites where landslide damage is reported. Intersection in a GIS of the map showing the transportation network with the event landslide inventory map (where available, i.e., in a 135 km^2 area) revealed that landslides have directly interfered with roads of various categories at 27 sites. This is an average of one damaging landslide every five kilometres of roads. At other 26 sites landslides were identified in the immediate vicinity of the transportation network. If the latter sites are considered, the frequency of landslides increases to one every two kilometres along the roads.

8.5.1.2. Damage to the population

The archive inventory (§ 3.3.1.1 and Figure 3.4) contains 65 records with information on landslide events with human consequences in Umbria. Analysis of the catalogue indicates that 22 persons died, 2 persons are missing, and 40 people were injured by slope failures, in a total of 29 landslide events with human consequences, in the period between 1917 and 2004. Seventeen casualties (8 deaths and 9 injured people) were related to human activities, i.e., accidents in the workplace, excavations and open pit mining. Limiting the analysis to the natural landslides, between 1917 and 2004 landslide disasters in Umbria resulted in 47 casualties, comprising 14 deaths, 2 missing persons, and 31 injured people. This is equivalent to an average of about 0.53 casualties per year. Natural landslide disasters with human consequences were 17, equivalent to an incident with casualties every 5.1 years, or an annual frequency of about 0.2. The largest landslide disaster in the region occurred on 10 May 1939 at Stifone, when six people were killed by a landslide along the railway connecting Terni to Orte. On 19 January 1963, 14 people were injured when a postal train derailed because of three landslides between the stations of Attigliano and Alviano (Guzzetti *et al*., 2003a).

The archive inventory also lists 34 landslide events for which a total of 897 homeless or evacuated people are reported. This figure is most probably underestimated, because for some of the events the catalogue reports information on houses that were destroyed or severely damaged without providing information on the number of homeless or the evacuated people. For other events the catalogue lists the number of families that were evacuated but not the number of people involved. This is a known bias in the archive inventory.

The national investigation on landslide risk to people described in § 8.3 indicated that, in the 105-year period from 1900 to 2004, at least 7494 casualties, comprising 5190 deaths, 88 missing persons and 2216 injured people were reported in Italy. This represents an average of 51.2 deaths or missing persons each year. Landslide events with casualties were 1102, equivalent to 10.7 incidents with casualties every year, or an annual frequency of 0.09 (Salvati *et al*., 2003; Guzzetti *et al*., 2005b,c). If compared to these figures, landslide risk to the population is low in Umbria. This is a consequence of the predominant type of failures causing damage in the region. Damaging slope failures are mostly slides, slide-earth flows and complex or compound movements that commonly travel short distances and move at slow to moderate velocity, allowing for the people to escape when a landslide occurs. As an example, in the early morning of 6 January 1997 a complex landslide involving ~ 1×10^6 m^3 of rock detached from a steep slope above Valderchia, NE of Gubbio (Figure 8.12.E). The landslide moved at an estimated velocity of some metres per hour (Cencetti *et al*., 1998). People in two houses in the path of the landslide heard the walls cracking but were able to escape from the windows. The two houses were rapidly destroyed but no one was killed or injured.

8.5.2. Landslide impact

For the Umbria region, information exists to attempt an assessment of the possible impact that mass movements can have on the built-up environment, on the transportation network, and on the agriculture. This can be obtained by analysing in a GIS the geographical relationships between the location of known landslides, as shown by a detailed landslide inventory map (e.g., § 3.3.2.2), and the location of the transportation network, the built-up areas, and the land use classes.

8.5.2.1. Expected impact to the transportation network and the built-up areas

Landslides in Umbria exhibit spatial persistence. In the region, slope failures tend to occur in the same place as existing landslides (§ 4.4, Cardinali *et al.*, 2000). This geomorphological characteristic of slope failures in Umbria can be exploited to determine the sites of possible future landslide impact. To achieve the result, the detailed geomorphological landslide inventory (§ 3.3.2.2) was intersect in the GIS with maps of the transportation network and of the built-up areas. To account for the possible mapping errors and the lack of geographical precision in the maps of the transportation network and of the built-up areas, a buffer zone was established around each road, railway, or built-up area. The size of the buffer was selected depending on the type of the vulnerable element (Table 8.14).

Table 8.14 – Buffers used in the GIS analysis of the relationships between landslides, built-up areas and the transportation network in Umbria. Buffer A defines the extent of the built-up area or the transportation network. Buffer B considers the area in the vicinity of the built-up area or the transportation network.

TYPE OF ELEMENT AT RISK		BUFFER A (m)	BUFFER B (m)
Highways, Freeways	4 lanes roads	50	150
All other roads	2 lane roads	25	80
Railways	all railways	20	50
Built-up areas	houses, buildings, structures	0	50

The GIS analysis identifies 4115 sites where landslides shown in the geomorphological inventory map intersect, i.e., may interfere, with the transportation network (Figure 8.13.A), and 6119 sites where landslides intersect with the built-up areas (Figure 8.13.B). The figures were obtained considering the largest buffer zones of Table 8.14. At these localities damage due to landslides can be expected, particularly during major landslide triggering events (e.g., prolonged rainfall, rapid snowmelt).

The GIS analysis further reveals that about 9.0% of all the landslides shown in the detailed geomorphological inventory map may cause a direct damage to roads or railways. More precisely, landslide damage can be expected on average every 2.3 km along the highways and freeways, every 1.2 km along the roads, and every 3.3 km along the railways. If roads and railways in the flat valleys and in the large intra-mountain basins (i.e., where landslides are not expected) are excluded from the analysis the figures decrease to 1.1, 0.9 and 2.5 km, respectively. Of all the sites where landslides interfere with the transportation network, 5.2% are characterised by slope failures that were classified as active in the geomorphological inventory map. At these sites damage caused by landslides should be expected with a higher probability than in other sites, where landslides were not recognized as active.

Intersection between the geomorphological inventory map and the map of the built-up areas (Figure 8.13.B) reveales that about 13.4% of the landslides shown in the inventory map intersect (i.e., interfere) with built-up areas. This percentage is an average of one site every 1.4 square kilometres. The figure decreases to one site every 1.1 square kilometres if large valley bottoms and intra-mountain basins are excluded from the analysis. Of all these sites, 4.5%

were affected by landslides that were classified as active in the geomorphological inventory map. These areas should be studied in greater detail in order to ascertain the actual landslide hazards and the associated risk, e.g. using the geomorphological method described in § 8.4.

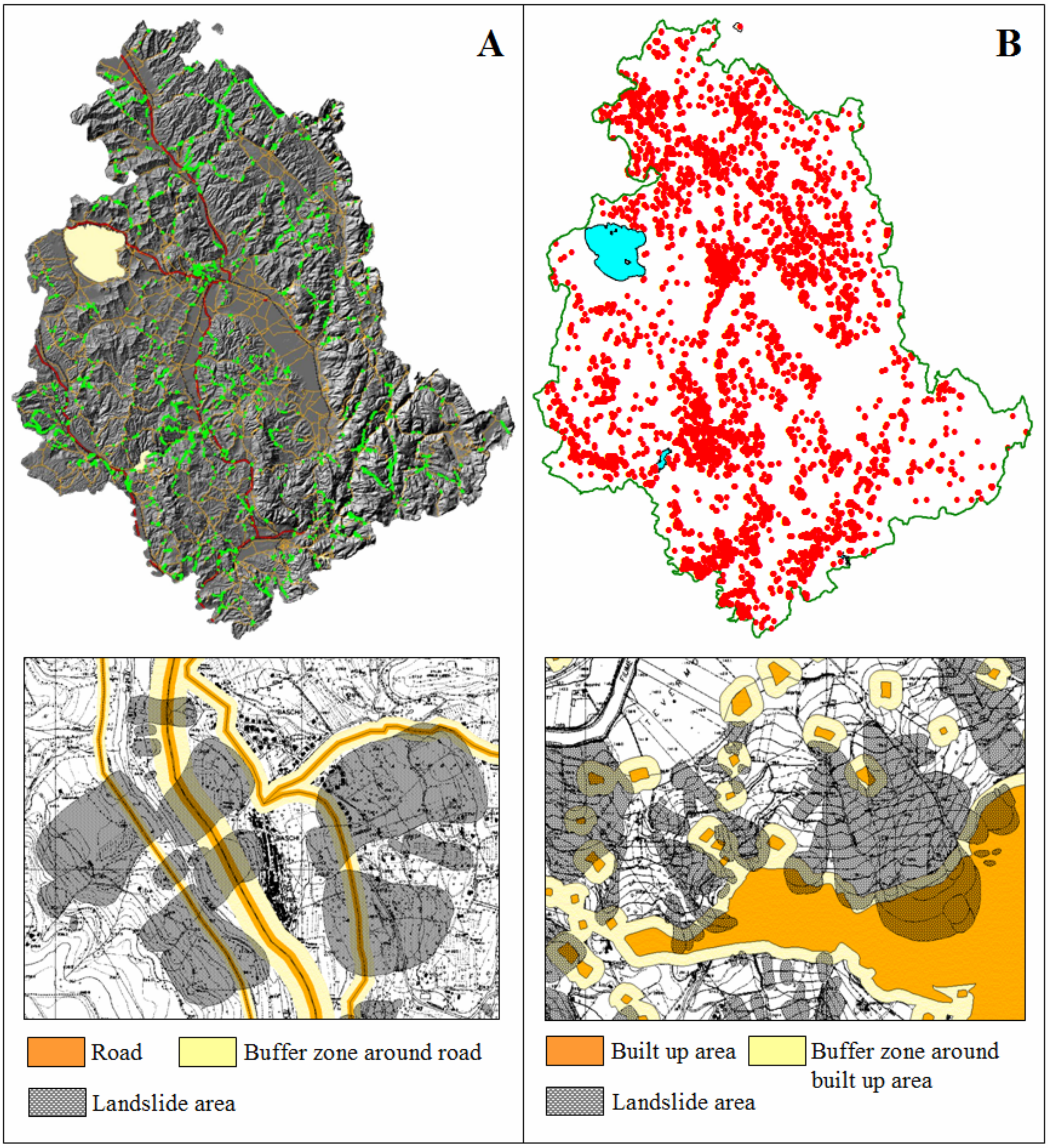

Figure 8.13 – Expected landslide impact in Umbria. (A) Green dots show the location of 4115 sites where known landslides intersect the transportation network. (B) Red dots show the location of 6119 sites where known landslides intersect built-up areas. Lower maps are enlargements showing cartographic detail and performed geographical analysis. Legend: grey pattern, landslide; orange, extent of infrastructure or structures; yellow, zone in the vicinity of structure or infrastructure (buffer B). For buffer size see Table 8.14.

8.5.2.2. *Expected impact to the population in the Perugia Municipality*

For the Perugia Municipality, the second largest in the Umbria region (449.92 km^2) and the one with the largest population (157,092 people, in 2001) and the largest population density (349 inhabitants/km^2), an attempt was made to determine the number and location of people potentially subject to landslide risk. This was accomplished by jointly analysing information on landslide abundance and on population density in the 710 census zones comprising the Municipality (Figure 8.14).

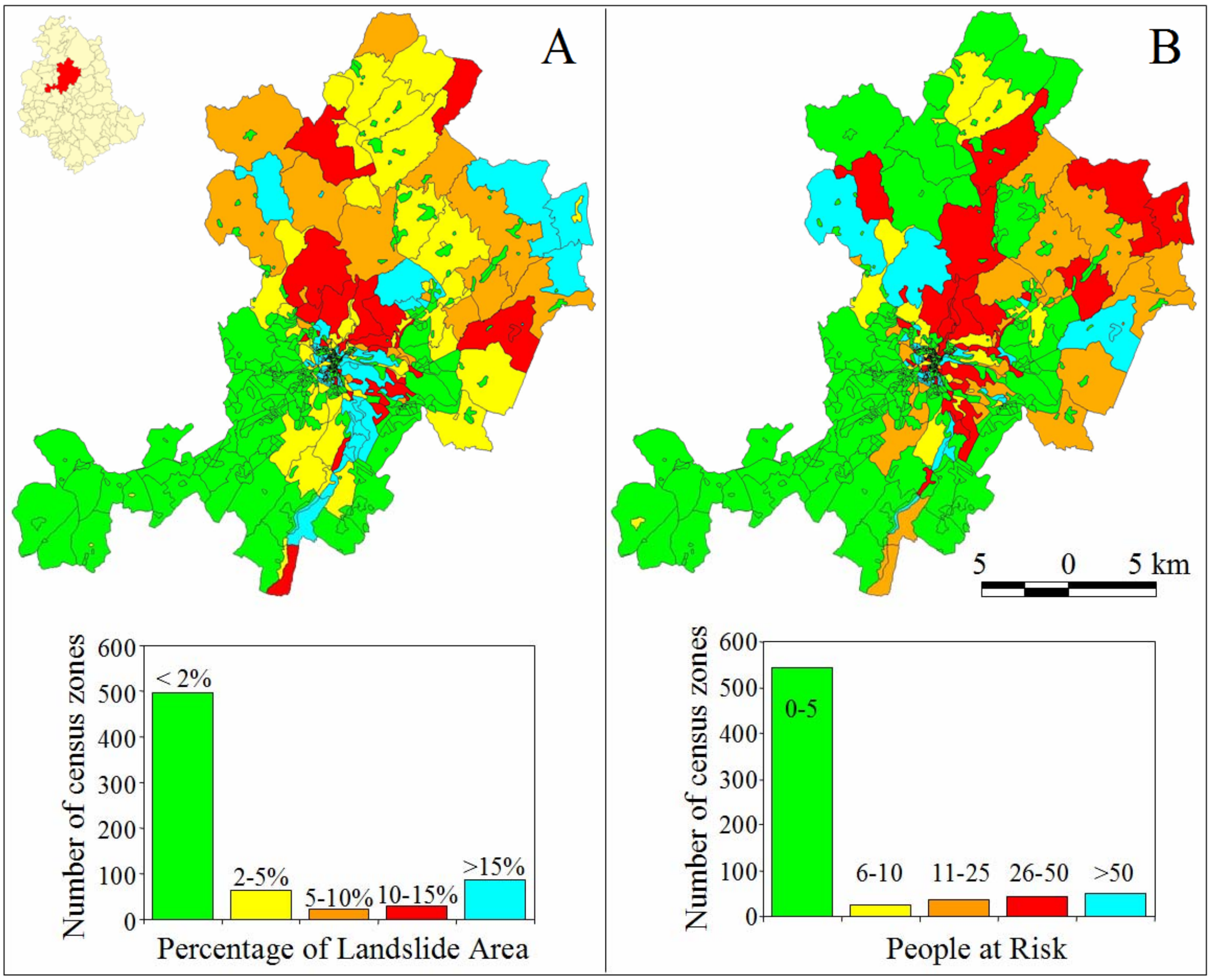

Figure 8.14 – Perugia Municipality, Umbria Region. (A) Map showing 701 census zones in the Municipality. Colours show percentage of landslide area in each census zone. Histogram shows abundance of census zones in five classes of the percentage of landslide area. (B) Map showing number of inhabitants potentially subject to landslide risk. Histogram shows abundance of census zones, in five classes of the number of people subject to landslide risk.

In the Perugia Municipality the detailed geomorphological inventory (§ 3.3.2.2) shows 2042 landslides, for a total landslide area of 29.80 km^2, corresponding to 6.6% of the territory. Active landslides are 187 and cover 0.56 km^2. The percentage of landslide area in the 701 census zones ranges from 0%, in landslide-free areas, to 100% where an entire census zone falls in a landslide area (Figure 8.14.A). Total landslide area is larger in the rural areas, and the percentage of landslide area in each census zone is larger in the urban area. The latter is the result of the small size of census zones in the urban area. Knowing the population of each census zone, the number of people potentially subject to landslide risk can be estimated (Figure 8.14.B). The analysis reveals that in the Perugia Municipality about 9100 people (5.8% of the population) live in a landslide area, or in the vicinity of a landslide. In at least nine census zones the number of inhabitants subject to landslide risk exceeds 200 people. These sites should be investigated in greater detail to determine the actual level of landslide risk, e.g. using the geomorphological method described in § 8.4.

8.5.2.3. Expected impact to the agriculture

Agriculture is an important economic resource for Umbria, olive trees and vineyards being the most important and profitable assets, followed by corn, sunflower and tobacco. For the Umbria Region, Antonini *et al.* (2002a) attempted an evaluation of the possible impact of mass movements on the agriculture. These authors intersected in a GIS the geomorphological landslide inventory map (§ 3.3.2.2) with a land use map prepared by the Umbria Regional Government in 1977. The land use map, in twelve classes, was originally obtained through the interpretation of large scale aerial photographs, and was considered by Antonini *et al.* (2002a) a proxy for the extent and spatial distribution of the agriculture in Umbria.

Results of the GIS analysis revealed that landslides are almost equally abundant in: (i) forest and woods (27%), (ii) in grass land, pasture and other land used for seasonal crops (e.g., corn, sunflower, etc.) (24%), and in areas with olive trees, vineyards and other specialized orchards (23%) (Figure 8.15). These figures confirm the potentially high impact of mass movements on the agriculture in Umbria.

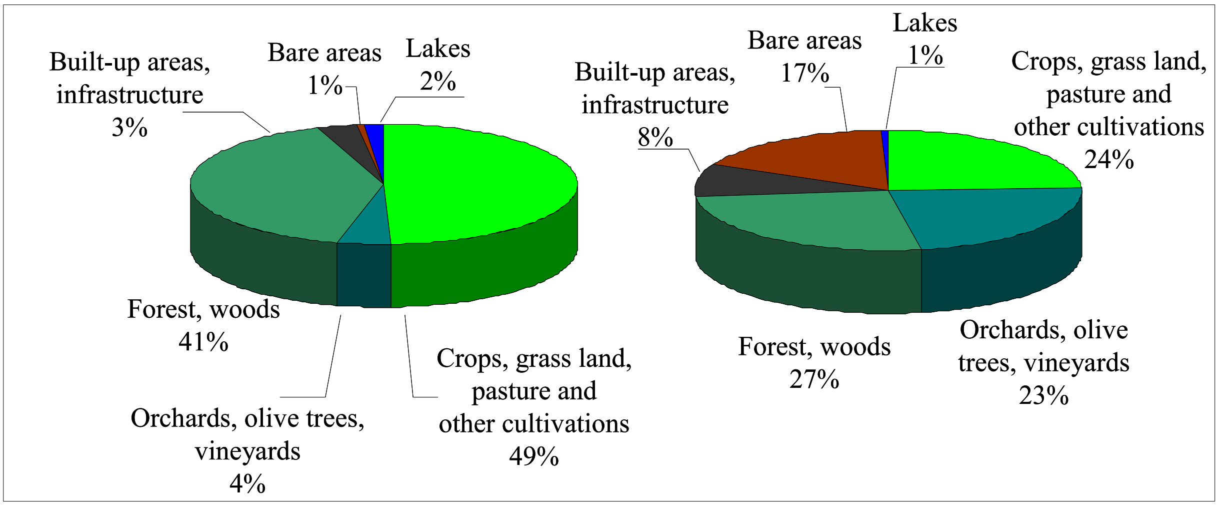

Figure 8.15 – Umbria Region. Left graph shows abundance of land use classes in the Region. Right graph shows abundance of landslides in each land use class.

8.5.3. Discussion

The methods presented in the previous sections, and the results obtained, illustrate the largest and best documented effort at determining landslide damage and at forecasting the possible impact of slope failures in the Umbria region. The analyses demonstrate how historical and event data can be used to determine the type and extent of past landslide damage, and how

GIS technology can be used to help determining the impact of slope failures on the population, the built-up areas, the transportation network and the agriculture.

The described approach is innovative and reliable. However, the described analyses should be considered preliminary, as they suffer from simplifications. For this reason, results may be locally inaccurate. Quality, completeness and resolution of the landslide inventory maps and of the maps showing the elements at risk largely affects the quality of the results. If existing landslides are not shown in the inventory, or if the extent or location of the built-up areas or the roads is not shown precisely in the maps, the GIS analysis is inevitably erroneous. Identification of the areas where known landslides may interfere with the transportation network and the built-up areas did not consider the possibility that a landslide can travel a long distance from the source area. This may affect significantly the impact analysis, particularly in mountain areas where debris flows and rock falls that can travel long distances are common. The GIS analysis may also be biased locally by the presence of tunnels below landslide shear planes, and of bridges or viaducts not affected by shallow landslides. In built-up areas remedial works may have been completed, reducing landslide hazards. However, the mitigating effect of the remedial measures was not considered.

Estimation of landslide risk to the population in Umbria is also affected by uncertainty. The impact of landslides on the population depends on many factors, including: (i) the location, type and frequency of landslides, (ii) the abundance and distribution of the population, and (iii) the number and location on the vulnerable elements related to the presence of the population (e.g., homes, schools, offices, utilities, roads, etc.). If buildings or homes are built in dangerous landslide areas, the risk to the population will increase. Where defensive measures have been installed (e.g., rock fall fences along railways), proper maintenance is required to maintain the existing safety levels. If the performance of the defensive measures is reduced, risk to the population will increase, as the risk to the structures and infrastructure.

The assessment of landslide risk to the population in the Perugia Municipality is a first-order estimate. The analysis does not take into consideration the exact location of the landslides and the population in the census zones. In a census zone, landslides may exist but they may not pose a threat to the population. For simplicity, the analysis was performed considering only the extent of the landslides shown in the geomorphological inventory map. Possible enlargements of a landslide due to its movement or to reactivations were not considered. Debris flows and rock falls were not shown in the considered inventory map. Hence, the risk associated with these types of landslide was also not considered. Changes in the distribution and abundance of population will also affect the risk assessment.

Despite these inherent limitations, the ensemble of the results obtained confirms that mass movements in Umbria represent a societal and economic problem that should not be overlooked.

8.6. Summary of achieved results

In this chapter, I have:

(a) Shown that reliable methods for determining and ranking landslide risk can be established.

(b) Demonstrated that landslide risk can be determined at various geographical scales using probabilistic or heuristic (geomorphological) approaches.

(c) Proposed a geomorphological method for the determination of landslide risk.

(d) Shown that where sufficient information is not available to attempt a probabilistic or heuristic (geomorphological) assessment of landslide risk, the expected impact of slope failures can be established exploiting landslide information and GIS technology.

This responds to Question # 6 and partly to Question # 7 posed in the Introduction (§ 1.2).