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### 3. LANDSLIDE MAPPING

*When you don't know what you are doing,  
do it with great precision.*

*If your data are imprecise,  
draw a thick line.*

Any serious attempt at ascertaining landslide hazard or at evaluating landslide risk must begin with the collection of information on where landslides are located. This is the goal of landslide mapping. The simplest form of landslide mapping is a landslide inventory, which records the location and, where known, the date of occurrence and types of landslides that have left discernable traces in an area (Hansen, 1984; McCalpin, 1984; Wieczorek, 1984). Inventory maps can be prepared by different techniques, depending on their scope, the extent of the study area, the scales of base maps and aerial photographs, the quality and detail of the accessible information, and the resources available to carry out the work (Guzzetti *et al.*, 2000).

In this chapter, I first critically discuss the various types of landslide inventories and the methods and techniques used to prepare them. Then, I present landslide inventories of different types and scales prepared for Italy, the Umbria Region, and for selected areas in the Umbria Region, including the Collazzone area.

#### 3.1. Theoretical framework

Before discussing the various types of landslide inventories, it is useful to attempt to establish the rationale for a landslide inventory. A landslide inventory depends on the following widely accepted assumptions (Radbruch-Hall and Varnes, 1976; Varnes *et al.*, 1984; Carrara *et al.*, 1991; Hutchinson and Chandler, 1991; Hutchinson, 1995; Dikau *et al.*, 1996; Turner and Schuster, 1996; Guzzetti *et al.*, 1999a):

- (a) Landslides leave discernible signs, most of which can be recognized, classified and mapped in the field or from stereoscopic aerial photographs (Rib and Liang, 1978; Varnes, 1978; Hansen, 1984; Hutchinson, 1988; Turner and Schuster, 1996). Most of the signs left by a landslide are morphological, i.e., they refer to changes in the form, position or appearance of the topographic surface. Other signs induced by a slope failure may reflect lithological, geological, land use, or other types of surface or sub-surface changes. If a landslide does not produce identifiable (i.e., observable, measurable) changes the mass movement cannot be recognized and mapped, in the field or by using remotely obtained images.

- (b) The morphological signature of a landslide (Pike, 1988) depends on the type (i.e., fall, flow, slide, complex, compound) and the rate of movement of the slope failure (Pašek, 1975; Varnes, 1978; Hansen, 1984; Hutchinson, 1988; Cruden and Varnes, 1996; Dikau *et al.*, 1996). In general, the same type of landslide will result in a similar signature. The morphological signature left by a landslide can be interpreted to determine the extent of the slope failure and to infer the type of movement. From the appearance of a landslide, an expert can also infer qualitative information on the degree of activity, age, and depth of the slope failure. Since morphological convergence is possible and the same morphological signs may result from different processes, care must be taken when inferring landslide information from, e.g., aerial photographs.
- (c) Landslides do not occur randomly or by chance. Slope failures are the result of the interplay of physical processes, and landsliding is controlled by mechanical laws that can be determined empirically, statistically or in deterministic fashion (Hutchinson, 1988; Crozier, 1986; Dietrich *et al.*, 1995). It follows that knowledge on landslides can be generalized (Aleotti and Chowdhury, 1999; Guzzetti *et al.*, 1999a).
- (d) For landslides we can adopt the well known principle, which follows from uniformitarianism (Lyell, 1833), that *the past and present are keys to the future* (Varnes *et al.*, 1984; Carrara *et al.*, 1991; Hutchinson, 1995; Aleotti and Chowdhury, 1999; Guzzetti *et al.*, 1999). The principle implies that slope failures in the future will be more likely to occur under the conditions which led to past and present instability. Mapping recent slope failures is important to understand the geographical distribution and arrangement of past landslides, and landslide inventory maps are fundamental information to help forecast the future occurrence of landslides.

Ideally, identification and mapping of landslides should derive from all of these assumptions. Failure to comply with them limits the applicability of inventory maps and their derivative products (i.e., susceptibility, hazard or risk assessments) regardless of the methodology used or the goal of the investigation. Unfortunately, satisfactory application of all of these principles proves difficult, both operationally and conceptually (Guzzetti *et al.*, 1999a).

## 3.2. Landslide recognition

Landslides can be identified and mapped using a variety of techniques and tools, including: (i) geomorphological field mapping (Brunsdon, 1985; 1993), (ii) interpretation of vertical or oblique stereoscopic aerial photographs (air photo interpretation, API) (Rib and Liang, 1978; Turner and Schuster, 1996), (iii) surface and sub-surface monitoring (Petley, 1984; Franklin, 1984), and (iv) innovative remote sensing technologies (Mantovani *et al.*, 1996; IGOS Geohazards, 2003; Singhroy, 2005), such as the interpretation of synthetic aperture radar (SAR) images (e.g., Czuchlewski *et al.*, 2003; Hilley *et al.*, 2004; Catani *et al.*, 2005; CENR/IWGEO, 2005; Singhroy, 2005), the interpretation of high resolution multispectral images (Zinck *et al.*, 2001; Cheng *et al.*, 2004), or the analysis of high quality DEMs obtained from space or airborne sensors (Kääb, 2002; McKean and Roering, 2003; Catani *et al.*, 2005). Historical analysis of archives, chronicles, and newspapers has also been used to identify landslide events, to compile landslide catalogues, and to prepare landslide maps (e.g., Reichenbach *et al.*, 1998; Salvati *et al.*, 2003).

Traditionally, visual interpretation of stereoscopic aerial photographs has been the most widely adopted method to identify and map landslides (Rib and Liang, 1978; Turner and

Schuster, 1996). Interpretation of aerial photographs proves particularly convenient to map landslides because:

- (a) A trained investigator can readily recognize and map a landslide on the aerial photographs, aided by the vertical exaggeration introduced by the stereoscopic vision. The vertical exaggeration amplifies the morphological appearance of the terrain, reveals subtle morphological (topographical) changes, and facilitates the recognition and the interpretation of the topographic signature typical of a landslide (Rib and Liang, 1978; Pike, 1988).
- (b) National and local governments, geological surveys, environmental and protection agencies, research organizations and private companies have long obtained stereoscopic aerial photographs for a variety of purposes. In most places these aerial photographs are available and can be used for geomorphological studies including the compilation of landslide inventory maps. The availability of multiple sets of aerial photographs for the same area (e.g., Figure 3.1) allows investigating the temporal and the geographical evolution of slope failures (Guzzetti *et al.*, 2005a,d).
- (c) For a trained geomorphologist, interpretation of the aerial photographs is an intuitive process that does not require sophisticated technological skills. The technology and tools needed to interpret aerial photographs are simple (e.g., a stereoscope) and inexpensive, if compared to other monitoring or landslide detection methods. Information obtained from the aerial photographs can be readily transferred to paper maps or stored in computer systems.
- (d) The size (on average 21 cm × 21 cm) and scale (from 1:5000 to 1:70,000) of the aerial photographs allows for the coverage of large territories with a reasonable number of photographs. Most important, the typical size of a landslide (i.e., from a few tens to several hundred meter in length or width) fits well inside a single pair of stereoscopic aerial photographs, allowing the interpreter to work conveniently. The side and lateral overlaps typical of stereoscopic aerial photographs allow the interpreter to find (most of the time) a suitable combination of photographs to best identify and map the landslides.
- (e) The resolution of the available optical aerial photographs remains unmatched by satellite imagery, including the very high resolution images (Emap International, 2002). The highest resolution panchromatic satellite images currently commercially available have a ground resolution of about 60-70 cm, which is similar or coarser than the resolution of medium to high altitude aerial photographs flown at 1:33,000 scale or smaller. In addition, the very high resolution satellite imagery most commonly lacks stereoscopy (particularly for the past), is more expensive, and requires specialized software to be treated. Also, for practical purposes the quality of the aerial photographs printed from large format negatives remains unmatched by images shown on computer screens.

Recognition of any geomorphological feature, including landslides, from stereoscopic aerial photographs is a complex, largely empirical technique that requires experience, training, a systematic methodology, and well-defined interpretation criteria (Speight, 1977; Rib and Liang, 1978; van Zuidan, 1985). The photo-interpreter classifies geological objects and morphological forms based on his or her experience, and on the analysis of a set of characteristics (a “signature”) which can be identified on photographic images. These include shape, size, photographic colour, tone, mottling, texture, pattern of objects, site topography and setting (Ray, 1960; Miller, 1961; Allum, 1966; Rib and Liang, 1978; van Zuidan, 1985).

Shape refers to the form of the topographic surface. Because of the vertical exaggeration of stereoscopic vision, shape is the single most useful characteristic for the classification of an object (e.g., a landslide) from aerial photographs. Size describes the area extent of an object. Knowing the physical dimensions of an object is seldom enough for classification, but it can be very useful to identify properties such as extent and depth. Colour, tone, mottling and texture depend on the light reflected by the surface, and can be used to infer rock, soil and vegetation types, the latter being a proxy for wetness. Mottling and texture are measures of terrain roughness and can be used to identify surface types and the size of debris. Pattern is the spatial arrangement of objects in a repeated or characteristic order or form, and is used to infer rock type and resistance to erosion, as well as the presence of fractures, joints, faults and other tectonic or structural lineaments. Topographic site is the position of a place with reference to its surroundings. It reflects morphometric characters such as height difference, slope steepness and aspect, and the presence of convexities or concavities in the terrain. Topographic site is particularly important to identify landslides, which are locally marked by topographic anomalies. Setting expresses regional and local characteristics (lithological, geological, morphological, climatic, vegetation, etc.) in relation to the surroundings. Site topography and setting are particularly suited to inferring rock type and structure, attitude of bedding planes, and presence of faults and other tectonic or structural features (Ray, 1960; Miller, 1961; Allum, 1966; Amadesi, 1977; van Zuidan, 1985).

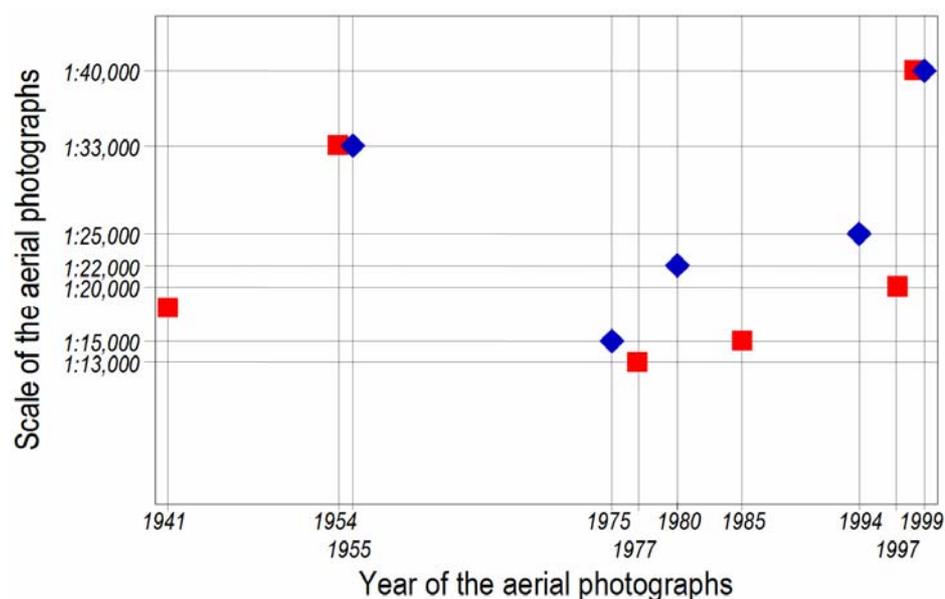


Figure 3.1 – Years of stereoscopic aerial photographs available for two landslide areas in the Italian Apennines. Red squares: Collazzone area (§ 2.4). Blue diamonds: Staffora River basin (§ 2.6). X-axis, year of the aerial photographs; y-axis, scale of the aerial photographs.

By employing the relationship between a form and a geological or geomorphological feature, morphological correlation is used to classify an object on the basis of photographic interpretation. For example, an upper concavity and lower convexity on a slope typically indicates the presence of a landslide. Furthermore, the combination of cone-shaped geometry (in plan) and upwardly convex slope profile is diagnostic of an alluvial fan, a debris cone, or a debris flow deposition zone. A closed depression in limestone terrain (i.e., a sinkhole) may harbour residual deposits, while a gentle slope at the foot of a steep rock cliff is usually a talus

deposit. Great care must be taken when inferring the characteristics and properties of geological and geomorphological objects from aerial photographs because morphological convergence is possible. For instance, in glacial terrain landslide and moraine deposits may appear similar; and in steep terrain a deep-seated gravitational deformation may look like a tectonic structure.

All the previously described interpretation criteria are commonly used by the photo-interpreter – albeit often unconsciously – in preparing a landslide inventory map. Due to the large variability of landslide phenomena (see § 1 and Figure 1.1), not all landslides are clearly and easily recognizable from the aerial photographs or in the field. Immediately after a landslide event, individual landslides are “fresh” and usually clearly recognizable. The boundaries between the failure areas (depletion, transport and depositional areas) and the unaffected terrain are usually distinct, making it relatively easy for the geomorphologist to identify and map the landslide. This is particularly true for small, shallow landslides, such as soil slides or debris flows. For large, complex slope movements, the boundary between the stable terrain and the failed mass is transitional, particularly at the toe. The limit may also be transitional along the sides, where tension cracks arranged in an *en échelon* pattern are common. For large deep-seated landslides, identifying the exact limit of the failed mass may not be easy even for fresh failures, particularly in urban or forest areas. Landslide boundaries become increasingly indistinct with the age of the landslide. This is caused by various factors, including local adjustments of the landslide to the new morphological setting, new landslides, and erosion (Malamud *et al.*, 2004a). Brandinoni *et al.* (2003) and Korup (2005c) outlined limitations of mapping landslides from aerial photographs in heavily forested mountain terrain. In particular, Brandinoni *et al.* (2003) noted significant error bars and frequency underestimates resulting from the interpretation of aerial photographs, when compared to detailed field studies.

To prepare a landslide inventory map through the interpretation of aerial photographs a legend is needed. The legend must meet the project goals, must be capable of portraying important (or even subtle) geomorphological characteristics, and must be compatible with the technique used to capture the information, i.e., with the scale, type and vintage of aerial photographs, the scale of the map, the type of stereoscope, the availability of morphological/geological data, the complexity of the terrain, and the time and resources available. Ideally the legend should be prepared (and agreed upon) by the users before interpretation of the aerial photographs begins (Brabb, 1996). In reality, the legend tends to be changed during a photo-interpretation project. Classes are added, deleted, split or merged to conform to local geomorphological settings, the type, abundance and pattern of landslides, the interpreter’s experience and preferences, and new findings.

The experience gained in compiling landslide inventory maps in Italy through the interpretation of aerial photographs at different scales and for territories ranging from few tens to several thousands square kilometres (e.g., Guzzetti and Cardinali, 1989; 1990; Antonini *et al.*, 1993; 2000; 2002a; 2002b; Cardinali *et al.*, 1994; 2001; 2003; 2005; Carrara *et al.*, 1991; Guzzetti *et al.*, 2004a; Barchi *et al.*, 1993; Galli *et al.*, 2005; see also § 2.2), has shown that landslides can be classified according to the type of movement, and the estimated age, activity, depth, and velocity. In general, landslide types are defined according to Varnes (1978), the WP/WLI (1990) and Cruden and Varnes (1996) or a simplified version of these well-know landslide classification schemes. Mass movements are classified as deep-seated or shallow, depending on the type of movement and the estimated landslide volume. The latter is based on the type of failure, and the morphology and geometry of the detachment area and the deposition zone. For deep-seated slope failures, the landslide crown (depletion area) is usually

mapped separately from the deposit (e.g., Figure 3.2). Landslide age, activity, depth, and velocity are inferred from the type of movement, the morphological characteristics and appearance of the landslide on the aerial photographs, the local lithological and structural setting, and the date of the aerial photographs (Antonini *et al.*, 2002b). Landslide age is commonly 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; Antonini *et al.*, 1993). Landslides are classified active (WP/WLI, 1993) where they appear fresh on the aerial photographs (of a given date). Landslide velocity (WP/WLI, 1995) can be considered a proxy of landslide type, and classified accordingly. Most importantly, a degree of certainty in the identification and mapping should be attributed to each landslide feature. The latter information reveals important when using the landslide inventory for susceptibility, hazard or risk assessments. It is worth remembering that any landslide classification scheme adopted for mapping landslides from aerial photographs or in the field suffers from simplifications, requires geomorphological deduction, and is somewhat subjective. To limit the drawbacks inherent in any classification, the categorization and the resulting inventory maps should be checked against external information on landslide types and process available for the investigated area (Guzzetti *et al.*, 2003; 2005).

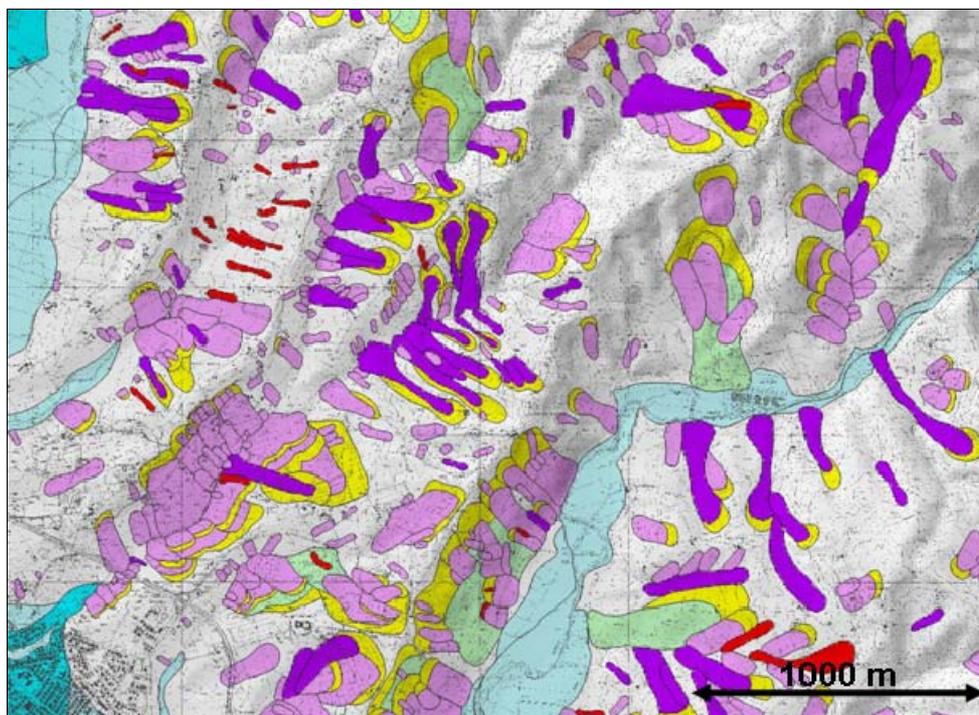


Figure 3.2 – Portion of a landslide inventory map for the Umbria region, central Italy. Original scale 1:10,000. Legend: red, recent landslide deposit identified in aerial photographs taken in 1977; dark violet, recent landslide deposit identified in aerial photographs flown in 1954; light violet, old landslide deposit identified in the 1954 aerial photographs; green, very old landslide deposit identified in the 1954 aerial photographs; yellow, depletion area of deep-seated landslide; light blue, recent alluvial sediment; dark blue, recent alluvial fan deposit..

In addition to portraying the distribution and types of landslides, an inventory map may show other geomorphological features related to, or indicative of, mass movements (e.g., Cardinali, 1990; Antonini *et al.*, 1993). These include: (i) escarpments from which rock falls or debris flows may originate; (ii) alluvial fans and debris cones, where debris flows, debris avalanches,

and rock falls may travel and deposit; (iii) badlands and other surface erosion features, where a variety of slope processes, including various types of mass movements originate but may not be singularly discernable; and (iv) recent alluvial deposits, chiefly along the valley bottoms, where landslides are not present or expected.

Figure 3.2 shows an example taken from a landslide inventory map prepared for the Umbria region of central Italy (Antonini *et al.*, 2002; Guzzetti *et al.*, 2003). The map was obtained by interpreting two sets of aerial photographs, flown in 1954 and in 1977. The adopted legend includes: (i) landslide deposits; (ii) landslide crown areas for deep-seated slides; (iii) alluvial fans and debris cones; and (iv) recent alluvial deposits. In Figure 3.2, landslides are shown on the map based on the estimated age, inferred from morphological appearance and the date of the aerial photographs. Recent landslides in 1977 are shown in red, and recent landslides in 1954 are shown in dark violet. Old landslides are shown in light violet, and very old landslides are shown in green. The crown area of all deep-seated landslides is shown in yellow, regardless of the inferred landslide age. For shallow landslides no distinction is made between the deposit and the crown area. The adopted legend is rather complex and required extensive efforts from the interpreters. However, its systematic application allowed obtaining a detailed, comprehensive and effective view of landslide phenomena in Umbria (Guzzetti *et al.*, 2003).

### 3.3. Landslide inventories

A landslide inventory is the simplest form of landslide map (Pašek, 1975; Hansen, 1984; Wieczorek, 1984). Landslide inventory maps can be prepared by different techniques, depending on their purpose, the extent of the study area, the scales of base maps and aerial photographs, and the resources available to carry out the work (Guzzetti *et al.*, 2000). For convenience, landslide inventory maps can be classified based on their scale or the type of mapping (i.e., archive, geomorphological, event, or multi-temporal inventories). Small-scale, synoptic inventories (<1:200,000) are compiled mostly from data captured from the literature, through inquiries to public organisations and private consultants, by searching chronicles, journals, technical and scientific reports, or by interviewing landslide experts. Small-scale landslide maps can also be obtained through the analysis of aerial photographs (Cardinali *et al.*, 1990). Medium-scale landslide inventories (1:25,000 to 1:200,000 e.g., Guzzetti and Cardinali, 1989; Antonini *et al.*, 1993; 2002a; Cardinali *et al.*, 2001; Duman *et al.*, 2004) are prepared through the systematic interpretation of aerial photographs at print scales which range from 1:60,000 to 1:10,000 and by integrating local field checks with historical information. Large-scale inventories (>1:25,000) are prepared, usually for limited areas, using both the interpretation of aerial photographs at scales usually greater than 1:20,000 and extensive field investigations, which make use of a variety of techniques and tools that pertain to geomorphology, engineering geology and geotechnical engineering (Wieczorek, 1984; Guzzetti *et al.*, 2000; Reichenbach *et al.*, 2005). Antonini *et al.* (2000, 2002a,b) prepared large-scale landslide inventory maps at 1:10,000, for areas ranging from a few hundred to a few thousand square kilometres, in central and northern Italy. The large-scale inventories were compiled through the interpretation of medium and large scale aerial photographs, supplemented by limited field checks.

#### 3.3.1. Archive inventories

Archive inventories are a form of landslide database (WP/WLI, 1990), and report the location of sites or areas where landslides are known to have occurred. Archive inventories are compiled

from data captured from the literature (Radbruch-Hall *et al.*, 1982), through inquiries to public organisations and private consultants (Nemčok and Rybár, 1968; Inganäs and Viberg, 1979), or by searching chronicles, journals, technical and scientific reports, and by interviewing landslide experts (Guzzetti *et al.*, 1994; Guzzetti and Tonelli, 2004). They can be compiled for a province (Govi and Turitto, 1994; Migale and Milone, 1998; Glade, 1998; Coe *et al.*, 2000; Godt and Savage, 1999), a river basin (Troisi, 1997; Monticelli, 1998), a physiographic region (Eisbacher and Clague, 1984), or an entire country (Catenacci, 1992; Reichenbach *et al.*, 1998b; Salvati *et al.*, 2003). Archive inventories may record all landslide events that are known to have occurred, or only those events that have caused damage, e.g., to the population (Salvati *et al.*, 2003); and may cover periods ranging from a few years to several centuries (Eisbacher and Clague, 1984; Salvati *et al.*, 2003). The UNESCO Working Party on World Landslide Inventory has proposed a method for systematically reporting landslide information, and for constructing a landslide database (WP/WLI, 1990). In Italy, considerable experience exists on the compilation of landslide archive inventories. In the following, I illustrate a nation-wide attempt at compiling and using historical information on landslide and flood events in Italy, which I had the opportunity to lead.

### 3.3.1.1. The AVI archive inventory and the SICI information system

In 1989, the Italian Minister of Civil Protection requested the Italian National Research Council (CNR), Group for Hydrological and Geological Disasters Prevention (GNDCI), to compile an archive inventory of sites historically affected by landslides and floods in Italy, for the period 1918-1990 (Guzzetti *et al.*, 1994). The idea of systematically collecting historical information on landslides was not new in Italy. In 1907-1910, the geographer Roberto Almagià published two volumes and a map at 1:500,000 scale, of which Figure 3.3 shows a portion, describing hundreds of landslides in the Apennines.

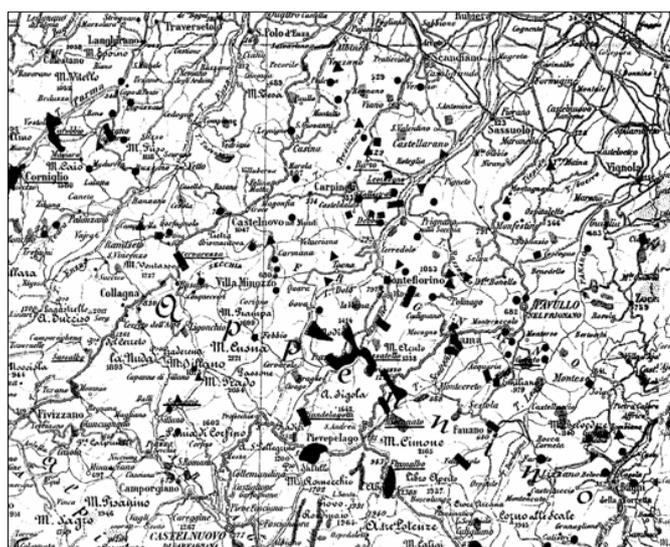


Figure 3.3 – Portion of the archive inventory map prepared by Roberto Almagià for the Italian Apennines in 1907-1910. Original map scale 1:500,000.

To respond to the Minister request, in the period from 1990 to 1992 CNR GNDCI designed and completed an inventory of historical information on landslides and floods in Italy. The project became known as the AVI project (AVI is an Italian acronym for “Areas Affected by Landslides and Floods in Italy”, *Aree Vulnerate Italiane*). Guzzetti *et al.* (1994) described the

original inventory, including the framework to collect, compile and summarize the information, the structure of the database used to store the data, a critical analysis of the type and amount of information collected, a description of the preliminary results obtained, and a discussion of possible applications of the historical information.

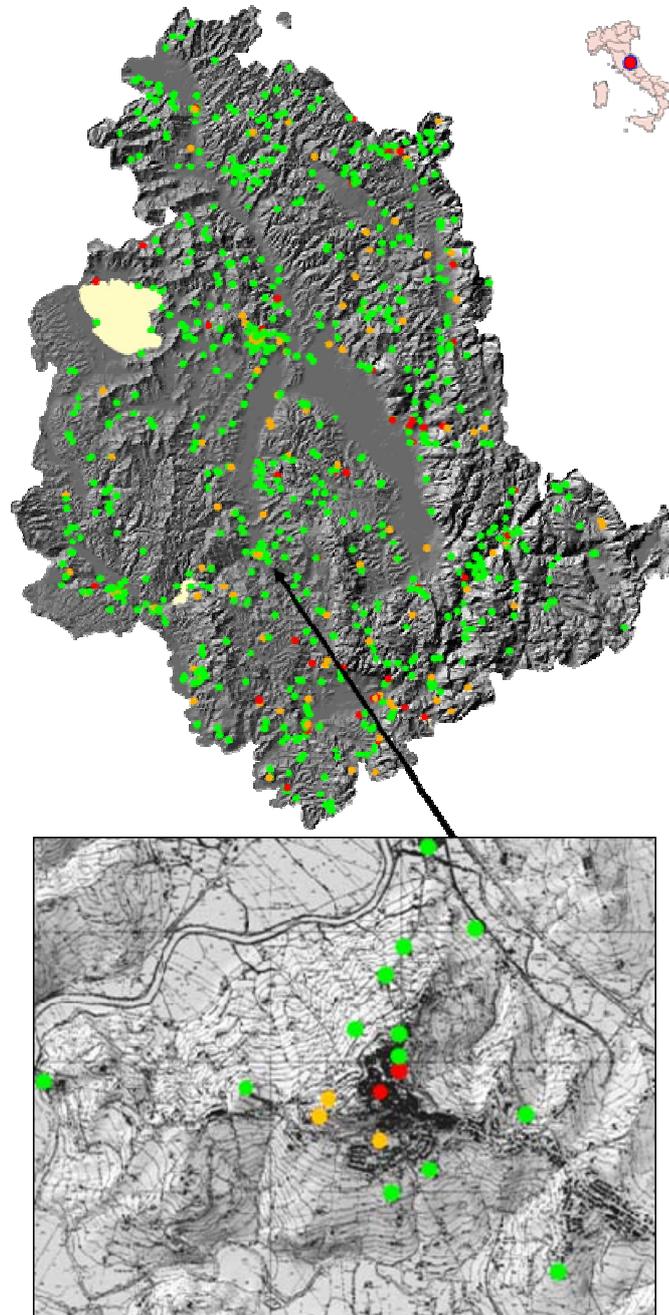


Figure 3.4 – Upper map shows density and pattern of historical landslide events. Lower map shows enlargement near Todi. Legend: green, 1 event; orange, 2-3 events; red, 4 or more events. Source of information: AVI national archive inventory of landslide events.

Since 1992, considerable efforts were made to keep the database updated and to search for new data on historical landslide (and flood) events (Guzzetti and Tonelli, 2004). The inventory was updated for the period 1991-2001 by systematically searching more than fifty local or

regional journals, and by reviewing technical and event reports, and scientific papers and books published by CNR GNDCI. From 1999 to 2003, the web pages of eleven regional and national newspapers were searched daily for information on landslide (and flood) events. In this period, an average of 700 newspaper articles was found every year, which represent about 75% of the information found through the systematic screening of local and regional newspapers carried out in the newspaper libraries (Guzzetti and Tonelli, 2004).

The exact or the approximate date of occurrence is known for many slope movements listed in the AVI archive inventory. Combined with the information on the location of the events, the date allowed preparing the first national catalogue of sites historically affected by landslides (and floods) in Italy (Cardinali *et al.*, 1998b). The catalogue lists the date and location (i.e., region, province and municipality) of 23,606 landslide events at 15,956 sites. Figure 3.4 shows the portion of the catalogue for the Umbria region, in Central Italy.

The complexity of the AVI database, the availability of new historical catalogues and databases, the large amount of available historical data, and increasing requests from the national, regional and local governments, from scientists, geologists, engineers and planners, from civil protection personnel and concerned citizens, has guided the transition of the AVI database from a simple storage of historical data into an information system on landslide and flood events capable of responding to the requests of different users. The result of this long lasting effort is SICI, an Italian acronym for information system on geo-hydrological catastrophes (*Sistema Informativo sulle Catastrofi Idrogeologiche*) (Guzzetti and Tonelli, 2004). SICI (<http://sici.irpi.cnr.it>) is a collection of databases containing historical, geographical, damage, hydrological, and bibliographical information on landslides and floods in Italy. The information system currently contains ten modules (AVI, GIANO, FATALITIES, ABPO, LOMBARDY, DPC, LAWS, REFERENCES, DISCHARGE, SEDIMENT), seven of which are completely or partially available to the public (Figure 3.5).

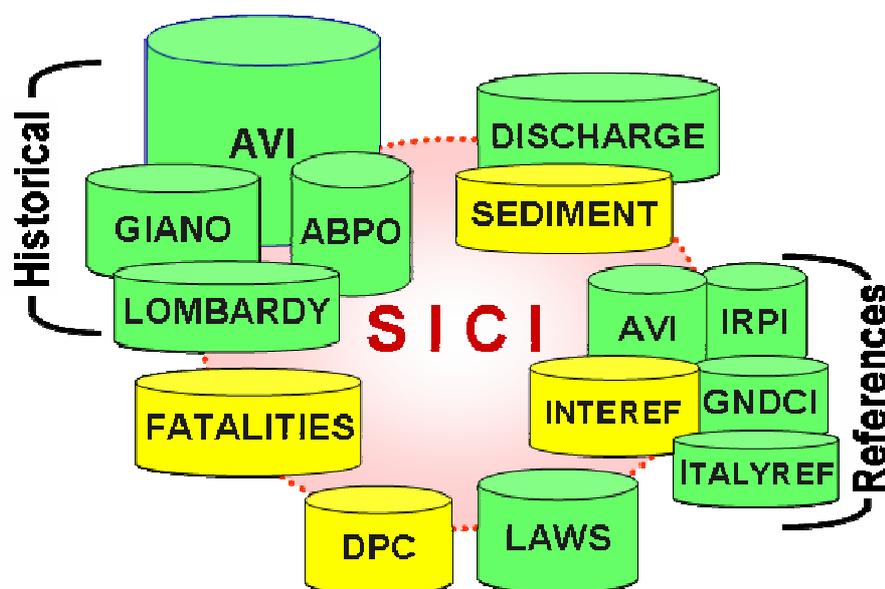


Figure 3.5 – Structure and modules of SICI, the information system on historical landslides and floods in Italy. Legend: green, modules publicly available through the SICI home page (<http://sici.irpi.cnr.it>); yellow, modules with restricted access. From Guzzetti and Tonelli (2004).

The AVI module contains the database of the AVI project (Guzzetti *et al.*, 1994). It represents the largest and most important module of SICI, at least for the 20th century. The latest release of the database contains 31,182 entries (records) on landslides, equivalent to a density of about one landslide site per 14 square kilometres. The AVI module also contains a bibliographical database listing 2027 references used to compile the historical archive. Figure 3.6 shows the geographical distribution of the sites historically affected by landslides and floods inventoried by the AVI project (Reichenbach *et al.*, 1998b). Figure 3.7 portrays the temporal distribution of the available historical information on landslide events in Italy, from 1900 to 2002. Stored in the database are also about 90,000 newspaper articles with information on hydrological or geological catastrophes; 24% of them are available as digital Adobe® Acrobat® PDF files (Guzzetti and Tonelli, 2004).



Figure 3.6 – AVI national archive inventory. Geographical distribution of the inventoried historical landslide and flood events in Italy (Reichenbach *et al.*, 1998b). Map available at [http://sicimaps.irpi.cnr.it/website/sici/sici\\_start.htm](http://sicimaps.irpi.cnr.it/website/sici/sici_start.htm).

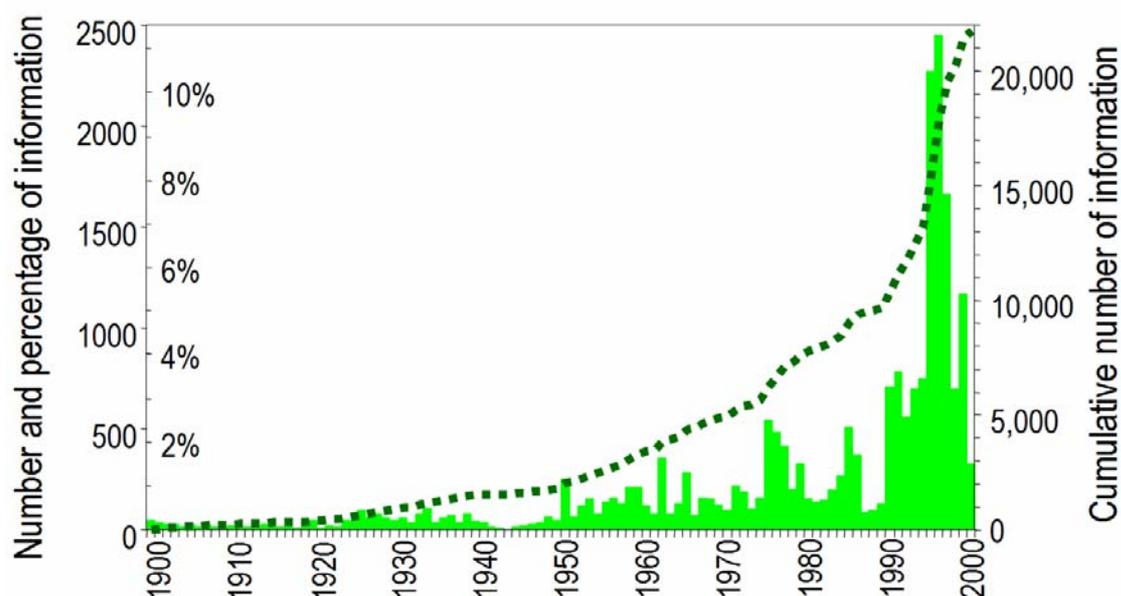


Figure 3.7 – AVI national archive inventory. Temporal distribution of the information on historical landslide events in the period between 1900 and 2002.

The GIANO module contains information on single or multiple landslides, inundations and snow avalanches in Italy in the 18th and 19th centuries. The module was obtained from a larger archive compiled in the eighties by *SGA Storia Geofisica e Ambiente* for *ENEA*, the Italian energy research institute, and aimed at collecting the effects of all natural disasters in Italy in the period from 1000 to 1900. Information in the GIANO module covers the period from 1700 to 1899 and refers to 793 flooding events and 356 landslide events. There are 2132 “testimonials” (i.e., single entries) on landslides, of which 884 are in the 18th century and 1248 in the 19th century. SGA collected the historical information from 177 bibliographical references, including catalogues, “repertoires”, scientific reports and other historical sources. Figure 3.8.A shows the geographical distribution of 356 landslides and 793 floods inventoried in the GIANO database. The GIANO module lacks the completeness and accuracy of the AVI database, mostly due to the difficulty in collecting information from historical sources and testimonies. Some duplication of information exists with the AVI database. As an example, historical landslides in the catalogues compiled by *Almagià* in 1907 and 1910 are listed in both databases. Despite these limitations, GIANO is a major contribution to the SICI information system. It extends the breath of the AVI database to the 18th and 19th centuries and it provides a multi-secular perspective on the extent of landslides and floods in Italy.

The FATALITIES module contains information on landslides and floods which have resulted in deaths, missing persons, injured people, evacuees and homeless people in Italy, in the 724-year period between 1279 and 2002 (Guzzetti, 2000; Guzzetti *et al.*, 2005a,b). Non systematic information on snow avalanches with human consequences is also listed in the database. The module lists 4534 records, of which 2379 are on landslides and snow avalanches with human consequences and 2155 on floods that resulted in fatalities or injured people. Figure 3.8.B shows the geographical distribution of landslide and flood sites with casualties in Italy in the period from 1900 to 2002. FATALITIES is important because it provides quantitative data for assessing landslide and flood risk to the population (Guzzetti *et al.*, 2005b,c) (see § 8.3.1).

The ABPO module contains information on landslides, snow avalanches and floods in the Po River basin, the largest watershed in Italy. The Po River Basin Authority collected the historical information as an aid for the preparation of the watershed master plan. The information was collected from a variety of sources, including historical and archive documents that span the period from 1300 to 1995. The ABPO module contains 4171 records, listing 5990 sites affected by 1647 floods, 1995 landslides and 536 snow avalanches (Figure 3.7.C). Information on the type and extent of damage caused by inundations, slope failures and snow avalanches is available for a few sites. Inspection of Figure 3.8.C reveals that only the events that have occurred in the mountains and in the hilly part of the river basin are considered. Flooding events which have occurred in the Po plain, along the Po River and its major tributaries, are not listed in the database.

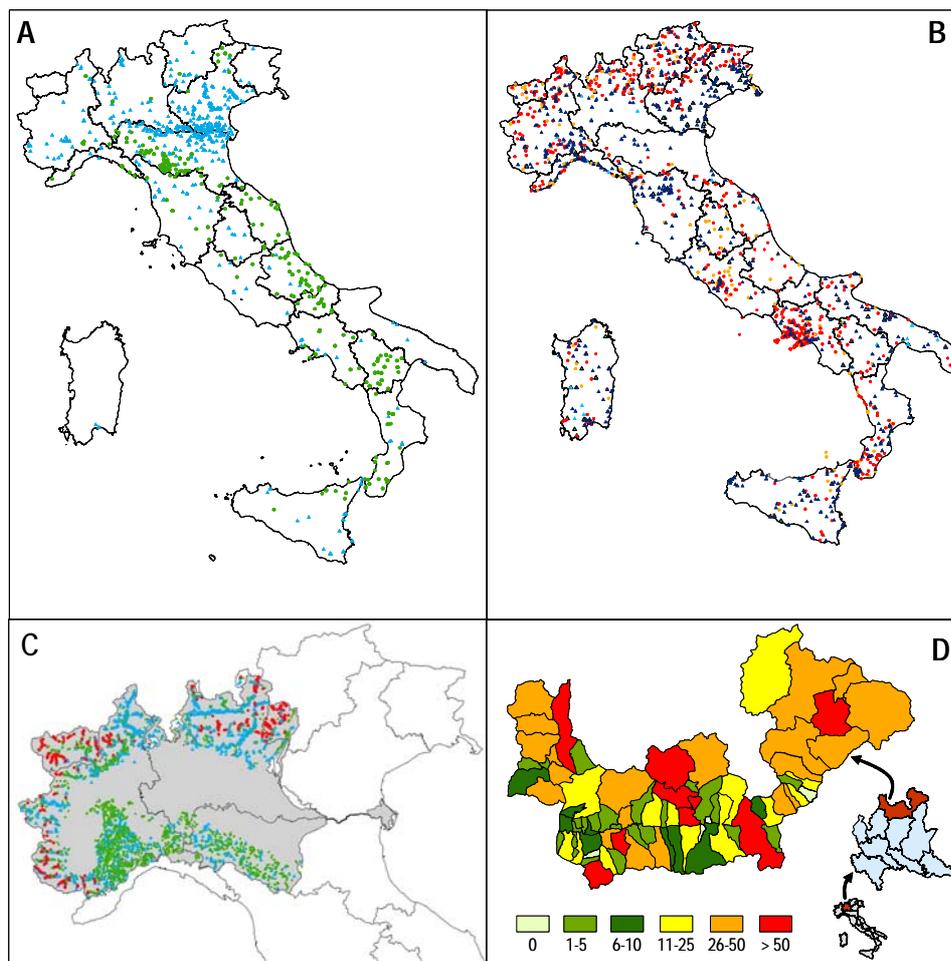


Figure 3.8 – Historical information for four of the ten modules of SICI (Guzzetti and Tonelli, 2004). (A) Distribution of 356 landslides (green dots) and 793 inundations (blue triangles) inventoried in the GIANO database from 1700 to 1899. (B) Distribution of landslides and floods with casualties from 1900 to 2002. Legend: red, landslide site with fatalities; yellow, landslide site with injured people; blue, flood site with fatalities; light blue, flood site with injured people (Salvati *et al.*, 2003). (C) Distribution of landslides (green), floods (blue), and snow avalanches (red) that have interfered with structures and the infrastructure in the Po River basin from 1300 to 1995. (D) Map showing municipalities in the Sondrio province, Lombardy region. Municipalities are coloured based on the number of landslide and flood events in the period from 500 to 1993.

The LOMBARDY module contains information on 3765 landslides, debris flows and flooding events in Valtellina and Val Chiavenna, two Alpine valleys in the Sondrio province (Lombardy, northern Italy), in the period from 500 to 1993 (Figure 3.8.D). The historical database contains 2948 records, listing information obtained by systematically searching 590 bibliographical references and historical documents, which were found in local archives by Govi and Turitto (1994). LOMBARDY is a particularly valuable addition to the SICI information system because it provides a measure of the quantity and quality of information that can be expected from a systematic search of historical information in the Italian Alps.

The DPC module contains information on 1389 local surveys and technical activities performed by CNR GNDCI experts and scientists in the period between 1990 and 2000. The investigations were requested by the Mayor of a municipality or the Prefect of a province, and were conducted on behalf of the National Department of Civil Protection (DPC) to investigate landslides and floods that posed an imminent threat to the population. The LAWS module contains information and documents on Italian laws, decrees, and ministry orders on hydrological and geological hazards (Fastelli, 2003a). The database covers the period from 1970 to 2002, and lists 1255 legislative acts. The REFERENCES module is a collection of bibliographical and reference catalogues, for a total of more than 8000 national and international references. Lastly, the DISCHARGE and SEDIMENT modules contain data on daily water discharge and on daily sediment yield. Measurements of mean daily water discharge are available for 111 gauging stations in central Italy, in the period from 1929 to 1996. Data on sediment yield are available for 117 stations and cover (non systematically) the 68-year period from 1929 to 1996.

### 3.3.2. Geomorphological inventories

A geomorphological inventory map shows the sum of many landslide events over a period of some, tens, hundreds or even many thousands of years. Geomorphological inventories are typically prepared through the systematic interpretation of one or two sets of aerial photographs, at print scales ranging from 1:10,000 to 1:70,000, aided by field checks. Geomorphological inventory maps cover areas ranging from few tens to few thousands square kilometres, at mapping scales ranging from 1:10,000 to 1:100,000 (which usually corresponds to publication scales ranging from 1:50,000 to 1:500,000) depending on the extent of the study area, the availability, scale and number of the aerial photographs, the complexity of the study area, and the time and resources available to complete the project.

Typically, a single map is used to portray all different types of landslides. Alternatively, a set of maps can be prepared, each map showing a different type of failure, i.e. deep-seated slides, shallow failures, debris flows, rock falls, etc. (Cardinali *et al.*, 1990). In recent years, availability of GIS technology has facilitated the production of geomorphological landslide databases, which store different information on landslides, and allow for the display and the publication of multiple, complex inventory maps. Besides showing landslides, geomorphological inventory maps may also portray other features related to mass movements, including escarpments, alluvial fans and debris cones, badlands and other surface erosion features, and recent alluvial deposits. In the production of geomorphological inventories, attempts at classifying landslide age and degree of activity based on the morphological appearance of the slope failure are hampered by the inherent difficulty of discriminating landslide age (i.e., the time elapsed since the first failure) from landslide activity (i.e., the state of motion of a landslide (WP/WLI, 1993)) based solely on the visual interpretation of the morphology of a landslide (McCalpin, 1984; Antonini *et al.*, 1993).

In Italy, geomorphological inventory maps are available for several areas. However, the scale, resolution and completeness of these inventories vary largely. Inventories prepared in the late seventies and in the eighties of the 20th century were typically compiled at 1:25,000 scale, chiefly through the interpretation of medium-scale aerial photographs, with limited field checks. Publication of these inventories was usually at 1:100,000 scale (e.g., IRPI and Regione Piemonte for Piedmont, Guzzetti and Cardinali (1989, 1990) for Umbria, and Antonini *et al.* (1993) for Marche). More recent inventories were compiled at 1:10,000 scale through the systematic interpretation of one or two sets of medium to large-scale aerial photograph, and field checks (e.g., Fossati *et al.*, (2002) for Lombardy, Antonini *et al.* (2002a) for Umbria). As part of a large geological mapping project, the Geological Survey of the Emilia-Romagna Region produced a geomorphological landslide inventory map at 1:10,000 scale. The inventory was obtained through systematic field mapping aided by the interpretation of medium-scale aerial photographs. A synoptic map showing the inventory was published at 1:250,000 scale (Bertolini *et al.*, 2002). In 1999, the Italian Geological Survey launched a project to compile a geomorphological landslide inventory map, with associated database, for the entire country. In this project the inventory map is produced at 1:25,000 scale, by assimilating information obtained through the interpretation of aerial photographs with information on landslides obtained from various historical and contemporary sources (Amanti, 2000; Amanti *et al.*, 2001).

In the next three sub-sections, I illustrate two examples of geomorphological landslide inventories prepared for the Umbria region, and I compare the two inventories, including a discussion of the resources required to prepare the landslide maps.

### **3.3.2.1. Reconnaissance geomorphological landslide inventory map for the Umbria Region**

Two landslide inventory maps have been made for the Umbria region. The first map is a reconnaissance inventory prepared by Guzzetti and Cardinali (1989, 1990) as a reconnaissance mapping effort aimed at obtaining general information on the distribution, abundance and type of mass movements in Umbria (Figure 3.9). The reconnaissance inventory of Guzzetti and Cardinali (1989, 1990) was partially revised by Antonini *et al.* (1993) for the Apennines mountain chain. In 1999, the Regional Government of Umbria adopted the map as part of the Regional Environmental and Urban Plan (*Piano Urbanistico e Territoriale della Regione dell'Umbria*) (Guzzetti *et al.*, 1999b).

The reconnaissance inventory was prepared by interpreting landslides observed on 1085 black and white, vertical aerial photographs flown in the period from 1954 to 1956, at 1:33,000 scale. Interpretation of the aerial photographs was locally aided by field checks, and was carried out by a team of two geomorphologists who worked simultaneously on adjacent strips. Inasmuch as side-lap between the photographs was 20-30%, a considerable part of the territory was analysed by both photo-interpreters. The landslide information, originally plotted on transparent plastic sheets placed over the aerial photographs, was transferred to 35 topographic maps, at 1:25,000 scale. Transfer of the landslide information to the base maps was accomplished by using a combined optical and manual technique, aided by a large-format photographic projector. The 35 quadrangles were then photographically reduced, assembled, and redrawn for final publication at 1:100,000 scale. Due to the scale of the published map, individual landslides with an area less than about one hectare were shown as points in the final inventory map (Guzzetti and Cardinali, 1990).

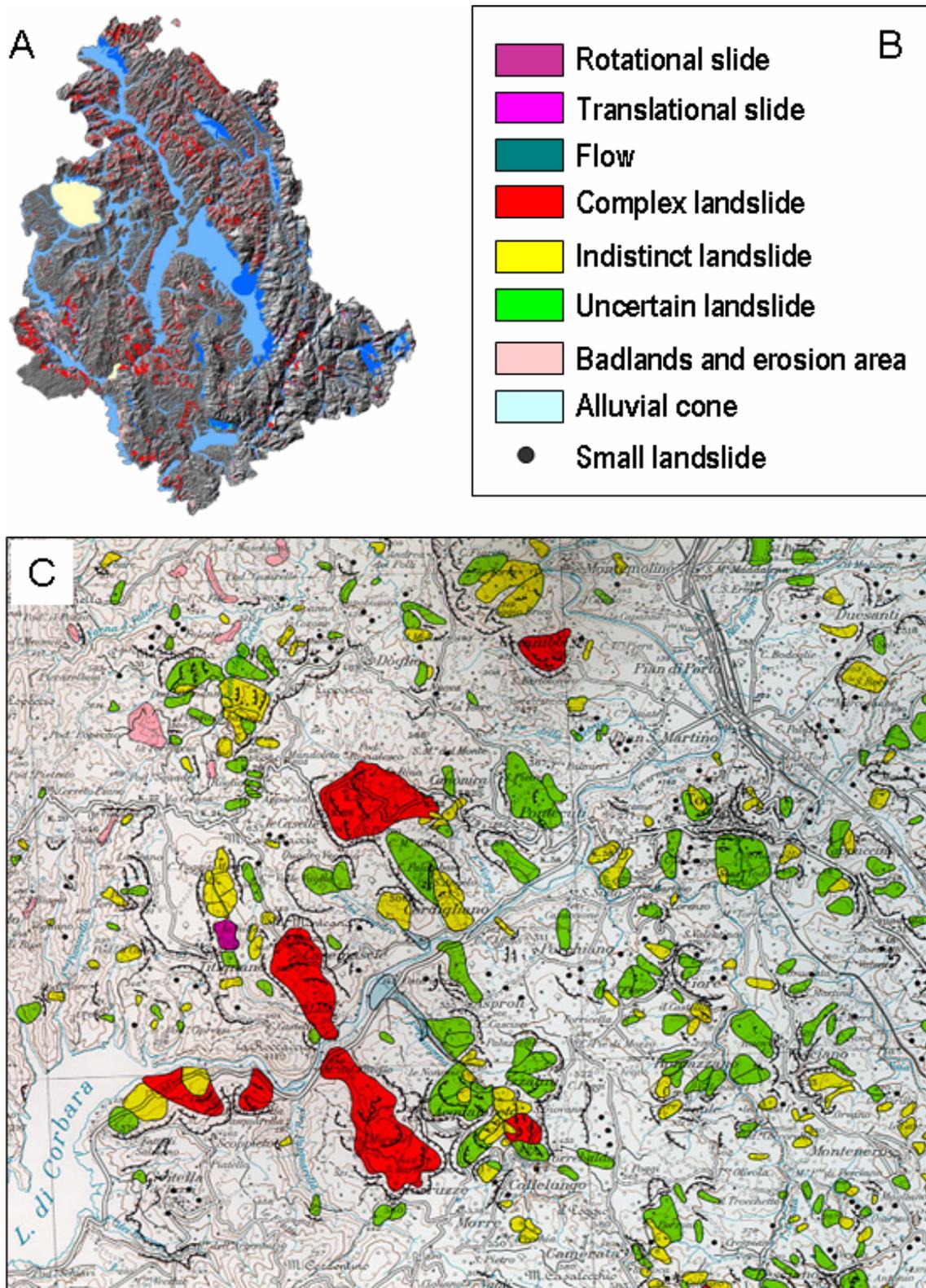


Figure 3.9 – Reconnaissance geomorphological landslide inventory map for Umbria. (A) Map showing the spatial distribution of landslides, shown in red. (B) Legend of the reconnaissance inventory. (C) Enlargement showing cartographic detail. Original scale 1:100,000. From Guzzetti and Cardinali (1989).

Mapping of the landslides took 9 months, for an average of about 470 square kilometres per man-month (Table 3.1). To obtain a digital version of the reconnaissance inventory map, the line work used to publish the map was scanned with a large format cartographic scanner. The raster representation of the geomorphological images was then changed into vector format using a semi-automatic procedure, which allowed assigning attributes to each line segment and to each point. Polygons were then constructed and labelled with appropriate codes. Preparation of the landslide digital cartographic database took about 2 months of a GIS specialist (Table 3.1).

In the reconnaissance inventory map, landslides are classified by their prevalent type of movement. For the purpose, a simplified version of the Varnes (1978) classification of mass movements is used. Landslides are classified as: (i) rock fall, (ii) rotational slide, (iii) translational slide, (iv) debris flow, debris slide or debris avalanche, and (v) complex slide, including earth flow. A separate class is used to show landslides for which the type of movement is undetermined. An additional class is adopted to identify hummocky topography and areas where no landslides were clearly recognized by the interpreters, but where morphological, geological and vegetation elements suggest the possible or probable presence of one or several slope failures. The reconnaissance landslide map also shows major escarpments, badlands and alluvial fans (Guzzetti and Cardinali, 1989, 1990).

In Umbria, the reconnaissance inventory shows 5277 landslide deposits, corresponding to an average density of 0.6 landslides per square kilometre. The mapped landslides cover a total area of 454.40 km<sup>2</sup>, 5.41% of the Umbria region. Landslides range in size from 3071 m<sup>2</sup> to 3.08 km<sup>2</sup>, and the most frequent (abundant) landslide has an area of about 25,400 m<sup>2</sup> (Table 3.1).

### **3.3.2.2. Detailed geomorphological inventory map for the Umbria Region**

The second landslide inventory map to cover the Umbria region was compiled by Antonini *et al.* (2002a) in the period from June 1999 to September 2001 (Figure 3.10) as part of a larger effort aimed at a better assessment of landslide hazard and risk in Umbria (Guzzetti *et al.*, 1996, 2003; Cardinali *et al.*, 2000, 2001, 2002; Antonini *et al.*, 2002a,b; Reichenbach *et al.*, 2005). A digital version of the map is available at [http://maps.irpi.cnr.it/website/inventario\\_umbria/umbria\\_start.htm](http://maps.irpi.cnr.it/website/inventario_umbria/umbria_start.htm). In 2002, the Regional Government of Umbria and the Tiber River Basin Authority adopted the map as part of the Tiber River watershed Master Plan (*Piano di Bacino*).

The new geomorphological inventory map was prepared at 1:10,000 scale by systematically re-interpreting the 1:33,000 scale aerial photographs flown in the period between 1954 and 1956. In addition, two new sets of vertical aerial photographs, flown in 1977 at 1:13,000 scale and in 1994 at 1:73,000 scale, were used. The first additional set was interpreted where flysch deposits and lake and continental deposits crop out. The second additional set was used to estimate the state of activity of the mapped landslides, at the date of the photographs.

Interpretation of the aerial photographs was aided by field surveys aimed at solving specific interpretation problems. Production of the new map benefited from the experience gained in the compilation of the reconnaissance map (Figure 3.9), from information on landslide types and distribution compiled for selected areas in Umbria in the period from 1990 to 2000 (Carrara *et al.*, 1991; Barchi *et al.*, 1993; Toppi, 1993; Lattuada, 1996; Cardinali *et al.*, 1994, 2000; Anonini *et al.*, 2002b), and from the production of the *Photo-geological and landslide inventory map for the Upper Tiber River basin* (Cardinali *et al.*, 2001).

A team of three geomorphologists completed the interpretation of the aerial photographs over a period of 28 months, for an average of 101 square kilometres per man-month. Two team members looked at each pair of aerial photographs using a mirror stereoscope (with a magnification of 4×) that allowed both interpreters to map contemporaneously on the same stereo pair. The third photo-interpreter, using a continuous-zoom stereoscope with a magnification of up to 20×, independently reviewed, and where necessary updated and corrected, the interpretations of the other two, and ascertained the activity of the mapped landslides using the small scale aerial photographs flown in 1994.

The landslide information was first plotted on transparent plastic sheets placed over the aerial photographs, and then transferred to 1:10,000 scale topographic maps. Transfer of the landslide information to the base maps was accomplished visually. The landslide information was then redrawn on stable, transparent sheets, which were individually scanned to obtain black and white, raster images of each map sheet. A scanning resolution of 300 dpi was used, which corresponds to a ground resolution of 0.1 m or less. The raster representation of the geomorphological line images was then changed into vector format using a semi-automatic procedure that allowed assigning attributes to each line segment. Polygons were then constructed and labelled with the appropriate codes, depending on their geomorphological properties. Lastly, map sheets were collected together in a geographical database, and colour plots were prepared to test the digitisation procedure. Production of the GIS database took 24 months and was accomplished by four GIS specialists (Table 3.1).

In the new inventory, landslides are classified according to the type of movement (WP/WLI, 1990; Cruden and Varnes, 1996), the estimated depth, degree of activity, and mapping certainty. Landslides are classified as: (i) rock fall, (ii) rotational slide, (iii) translational slide, (iv) debris flow, (v) complex or compound movement, and (vi) deep-seated gravitational deformation. For the deep-seated landslides, the crown area is mapped separately from the deposit. Landslide characteristics, including type of movement, depth and estimated degree of activity, were determined based on the local morphological characteristics, the appearance of the landslide on the aerial photographs, and the lithological and structural setting, including the attitude of the bedding planes with respect to the local slope. This is a significant innovation over the reconnaissance inventory (§ 3.3.2.1), where landslides were identified based solely on morphological criteria.

The new inventory shows 47,414 landslides, including 1563 debris flows and 131 rock falls shown as points, for a total landslide area of 712.64 km<sup>2</sup>, 8.43% of Umbria. The new map also shows: (i) 760 rock slopes identified as possible sources of rock falls, for a total area of 14.6 km<sup>2</sup>; (ii) 553 talus zones where rock fall deposits are abundant, for a total area of 12.1 km<sup>2</sup>; and (iii) debris deposits, alluvial cones and alluvial fans, for a total area of 365.9 km<sup>2</sup>. Based on the new inventory, landslide density in Umbria is 5.6 slope failures per square kilometre. Mapped landslides extend in size from 5 m<sup>2</sup> to 4.16 km<sup>2</sup>, with the most abundant (numerous) landslides having an area of ~ 1515 m<sup>2</sup> (Table 3.1). Landslides shown in the new geomorphological inventory are mostly slides, slide-earth flows and complex or compound slope movements. These types of movement represent the vast majority of the landslides recognized in Umbria. Debris flows (5.3%) were recognized in the Apennines mountain chain, where limestone predominates (Guzzetti and Cardinali, 1991, 1992). Rock falls and topples are present in all lithological complexes, and are most common where hard rocks, mostly limestone, sandstone, and volcanic rocks, crop out along steep slopes (Guzzetti *et al.*, 1996, 2003). The age of most of the landslides in the map remains unknown, but the oldest and largest failures are believed to be Holocene in age (Guzzetti *et al.*, 1996).

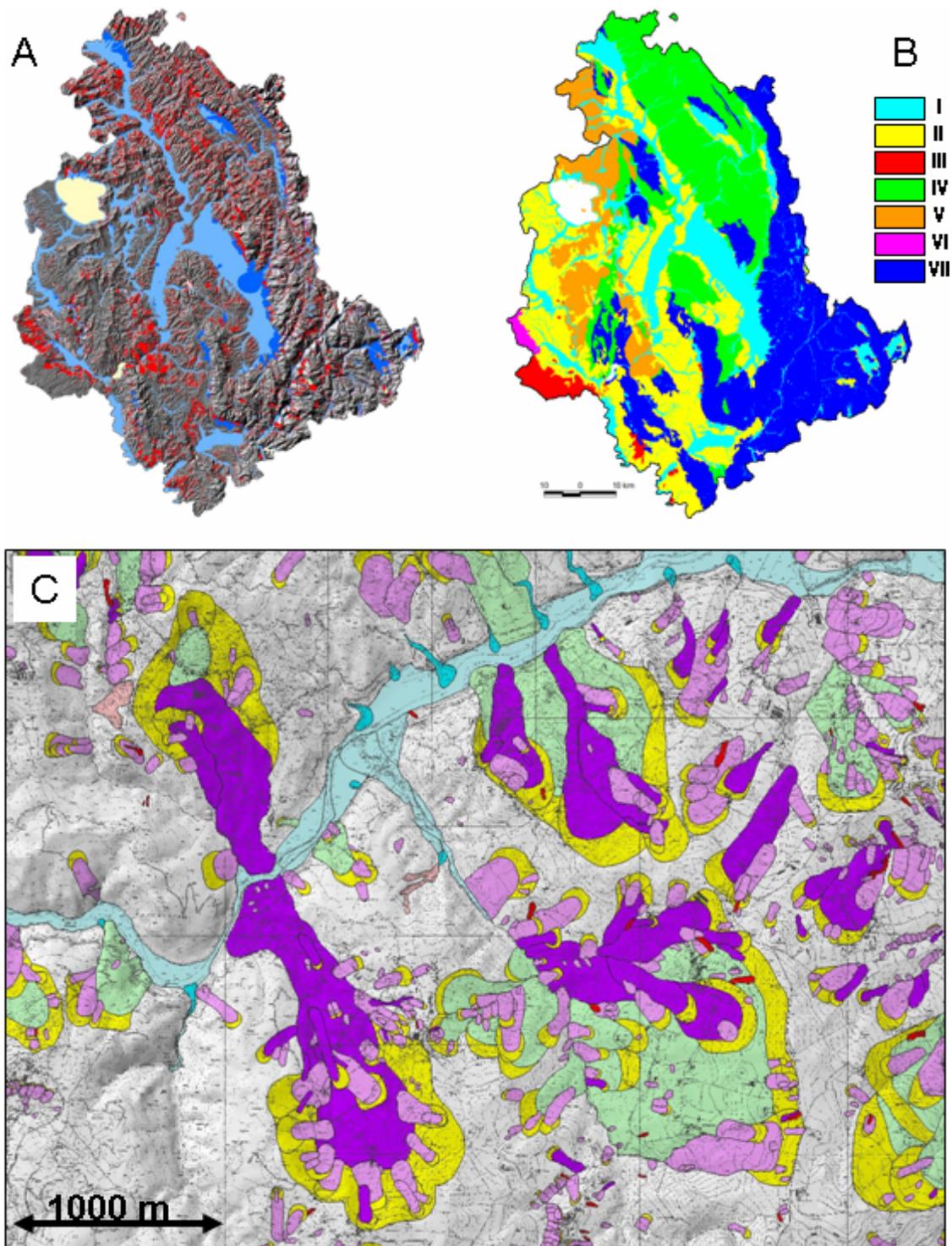


Figure 3.10 – Detailed geomorphological landslide inventory map for Umbria. (A) Map showing the spatial distribution of landslides, shown in red. (B) Main lithological domains in Umbria. (I) Recent alluvial deposits, (II) post-orogenic, marine, lake and continental sediments, (III) volcanic rocks, (IV) marly flysch (Marnosa Arenacea Fm.), (V) sandy flysch (Cervarola Fm.), (VI) Ligurian sequence, (VII) carbonate complex (Umbria-Marche stratigraphic sequence). (C) Enlargement showing cartographic detail for the same area shown in Figure 3.9. For map legend see text and caption of Figure 3.2. Original scale 1:10,000. Map available at [http://maps.irpi.cnr.it/website/inventario\\_umbria/umbria\\_start.htm](http://maps.irpi.cnr.it/website/inventario_umbria/umbria_start.htm).

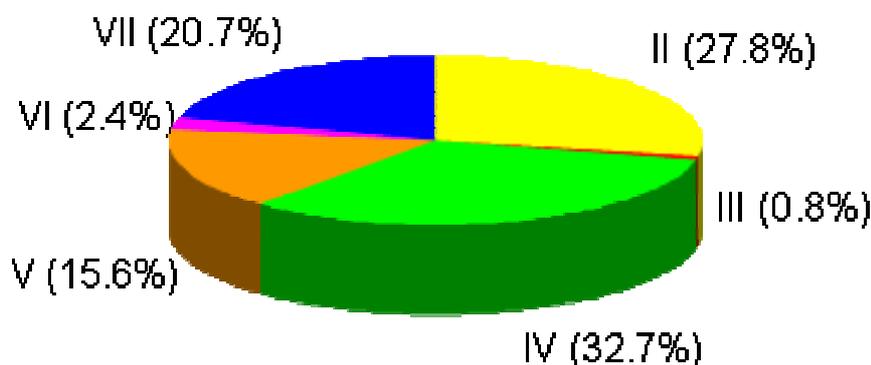


Figure 3.11 – Landslide abundance in the main lithological types in Umbria. (II) post-orogenic, marine, lake and continental sediments, (III) volcanic rocks, (IV) marly flysch (Marnosa Arenacea Fm.), (V) sandy flysch (Cervarola Fm.), (VI) Ligurian sequence, (VII) carbonate complex (Umbria-Marche stratigraphic sequence). Recent alluvial deposits (I, Figure 3.10.B) don't have landslides.

Inspection of Figure 3.10 reveals that landslides are not distributed evenly in the Umbria region (Figure 3.11). Failures are most abundant in the flysch complex, where 50.7% of all landslides were identified. Within this rock complex, the area where marly flysch crops out exhibits the largest number of landslides (32.7%). In the post-orogenic sediments complex and the carbonate complex landslide abundance is similar, 27.8% and 20.7%, respectively. Landslides are less abundant in the volcanic complex (0.8%). In this lithological domain, slope failures initiate mostly in the underlying marine clays and affect only the edge of the volcanic hard cap (Guzzetti *et al.*, 1996)

### 3.3.2.3. Comparison of the two geomorphological inventory maps in Umbria

A general comparison of the two regional geomorphological inventories is possible. As it is a detailed update of a previous reconnaissance mapping (Figure 3.9), the new geomorphological inventory (Figure 3.10) has improved the quality and spatial resolution of the landslide information. In the new – and more detailed – inventory, landslides are mapped more accurately, landslide boundaries follow more precisely the actual landslide geometry, better fitting morphological and lithological constrains (i.e., drainage lines, lithological boundaries, faults, bedding attitude, etc.).

The new geomorphological mapping resulted in an increase of 570% in the number of mapped landslides, and of 151% in the total extent of landslide area, with respect to the previous reconnaissance mapping. These figures quantify the improvement obtained with the new geomorphological inventory map. Visual comparison of the reconnaissance (Figure 3.9) and the detailed (Figure 3.10) geomorphological inventories confirms the better quality of the new mapping. Limited to the outcrop of lake and continental deposits, where large-scale (1:13,000 scale) aerial photographs were used in addition to the medium-scale photographs, the marked increase in the number and of the total area of mapped landslides is due to the larger scale of the photographs, that allowed for the recognition of smaller slope failures. Where flysch deposits crop out, interpretation of large-scale (1:13,000 scale) aerial photographs added limited new information, but allowed for an improved mapping of the landslide boundaries, and a better definition of the internal subdivisions of large landslide deposits.

I will attempt a more comprehensive comparison of the two regional geomorphological landslide inventories in § 3.4.1, where I will compare the two geomorphological landslide maps to a detailed multi-temporal landslide map prepared for the Collazzone area (§ 2.4).

Table 3.1 – Main characteristics of the two geomorphological inventory maps available for the Umbria Region. (I) Reconnaissance landslide inventory prepared by Guzzetti and Cardinali (1989, 1990) (Figure 3.9, § 3.3.2.1). (II) Detailed geomorphological landslide inventory prepared by Antonini *et al.* (2002a) (Figure 3.10, § 3.3.2.2).

		<i>Map I</i>	<i>Map II</i>
Type of inventory		Reconnaissance	Geomorphological
Date of inventory	year	1987-88	1999-2001
Area extent	km <sup>2</sup>	8456	8456
Sets of aerial photographs		1	2 (+1)
Scale of aerial photographs		1:33,000	1:33,000, 1:13,000 (1:73,000)
Scale of topographic base map		1:25,000	1:10,000
Scale of final (published) map		1:100,000	1:10,000
Time for photo-interpretation	month	9	28
Team for photo-interpretation	people	2	3
Rate of photo-interpretation	km <sup>2</sup> / man-month	470	101
Time for database construction	month	2	20
Team for database construction	people	1	4
Total number of mapped slides	#	5277	47,414
Total area affected by landslides	km <sup>2</sup>	454.40	712.64
Percent of area affected by slides	%	5.41	8.43
Landslide density	#/ km <sup>2</sup>	0.6	5.6
Smallest mapped landslide	m <sup>2</sup>	3071	5
Largest mapped landslide	km <sup>2</sup>	3.08	4.16
Average size of landslides	m <sup>2</sup>	84,169	12,058
Size of most abundant landslide	m <sup>2</sup>	~ 25,400	~ 1380

### 3.3.3. Event inventories

An event landslide inventory map shows all the slope failures triggered by a single event, such as an earthquake (e.g., Govi and Sorzana, 1977; Harp *et al.*, 1981; Agnesi *et al.*, 1983; Harp and Jibson, 1995; Antonini *et al.*, 2002b), rainstorm or prolonged rainfall period (e.g., Govi, 1976; Baumm *et al.*, 1999; Bucknam *et al.*, 2001; Guzzetti *et al.*, 2004; Sorriso-Valvo *et al.*, 2004; Cardinali *et al.*, 2005), or rapid snowmelt event (Cardinali *et al.*, 2000). Event inventories are commonly prepared by interpreting large to medium scale aerial photographs taken shortly after the triggering event, supplemented by field surveys, often very extensive. Good quality event inventories should be reasonably complete, at least in the areas for which aerial photographs were available and where it was possible to perform fieldwork. As a drawback, for practical reasons event inventories often cover only a part of the total geographic area associated with a landslide triggering event.

In the next sub-sections (§ 3.3.3.1 to § 3.3.3.2), I illustrate three examples of event landslide inventory maps prepared for selected areas in Umbria following landslide triggering events. The three inventory maps were prepared for: (i) the 1937-41 rainfall period (Figure 3.12.A), (ii) the January 1997 snowmelt event (Figure 3.12.B), and (iii) the September-October 1997 earthquake sequence (Figure 3.12.C). To prepare the three inventories, landslides were mapped on the same topographic maps used to compile the detailed geomorphological inventory map (Figure 3.10), i.e., CTR base maps at 1:10,000 scale. This facilitates the comparison of the three event inventories (§ 3.3.3.4 and Table 3.2), and of them with the detail geomorphological inventory map (§ 3.3.2.2).

### **3.3.3.1. Landslides triggered by prolonged rainfall in the period from 1937 to 1941**

The period between the summer of 1937 and the spring of 1941 was particularly wet in Umbria. In the period, the regional mean annual precipitation (MAP) was 1186 mm, 29.5% higher than the average MAP for the period between 1921 and 2000. Particularly severe rainfall events occurred on 6-7 October 1937, on 16-18 December 1937, on 14-15 May 1939, on 25 October 1940, and on 20 February 1941. During these events rainfall intensity locally exceeded 200 mm in one day. Some of the events affected limited areas, and other events involved the entire region. Precise information on the dates of slope failures occurred during this long wet period is not available. Archive information for the period is also scant, due the reduced number of elements at risk, but probably also as a result of the undemocratic administration. Interpretation of the aerial photographs revealed extensive and widespread landslides in most of the areas where the aerial photographs are available. Aerial photographs were taken in central Umbria in June 1941. The black-and-white photographs were taken both vertically (at an approximate scale of 1:18,000) and obliquely. Through the interpretation of 60 aerial photographs, covering an area of about 135 km<sup>2</sup> between Deruta and Todi in central Umbria, a detailed landslide inventory map was prepared at 1:10,000 scale for landslides triggered between September 1937 and May 1941 (Figure 3.12.A). The inventory contains 1072 landslides, for a total landslide area of 4.38 km<sup>2</sup>, 3.26% of the study area (Table 3.2). The average landslide density was 8 landslides per square kilometre, but locally landslide density was much higher, exceeding 50 landslides per square kilometre. Landslides were mostly shallow soil slides (65.0%), flows (23.7%), and earth flows (9.8%). Deep seated failures (1.5%) were translational and rotational slides, and complex slump-earth flows. Quite certainly, the numerous landslides caused damage at several localities. However, information on landslide damage is scarce, and for many areas inexistent.

### **3.3.3.2. Landslides triggered by rapid snow melt in January 1997**

In January 1997, the rapid melting of a thick snow cover caused abundant landslides in the Umbria region. Cardinali *et al.* (2000) conducted field investigations immediately after the event to identify and map the landslides, and to identify the areas where slope failures were most abundant. In these areas aerial photographs at approximately 1:20,000 scale were taken three months after the event, covering an area of 1896 square kilometers. Interpretation of the aerial photographs taken after the event allowed preparing a detailed event inventory map, compiled at 1:10,000 scale (Figure 3.12.B). The entire inventory lists 4235 landslides, for a total landslide area of 12.7 km<sup>2</sup> (Table 3.2). This corresponds to 0.15% of the Umbria region and to 0.22% of the investigated area (5664 km<sup>2</sup>). In the area where aerial photographs were available mapped landslides were 3837, covering 11.20 km<sup>2</sup>, 0.59% of the study area. Damage caused by slope failures to buildings and to the infrastructure was reported at 39 sites. Damage

to the agriculture was also severe. At several places wheat fields were severely affected by landslides. At many of these sites wheat was killed by the landslide and therefore not harvested.

#### **3.3.3.3. Landslide triggered by earthquakes in September-October 1997**

On 26 September 1997 the Umbria-Marche area of central Italy was shaken by two earthquakes of 5.6 and 5.8 local magnitude ( $M_L$ ). On 14 October 1997 the same area experienced another earthquake of similar magnitude ( $M_L = 5.5$ ). Following the main shocks field surveys were performed to map landslides triggered by the earthquakes, and to determine the main landslide types. Besides mapping landslides and co-seismic ground fractures, a detailed photo-geological and landslide inventory map was prepared for the area most affected by the earthquakes (Antonini *et al.*, 2002).

Information collected at 220 sites (Figure 3.12.C) and interpretation of aerial photographs taken after the earthquakes revealed that landslides were mostly rock falls, minor rockslides and topples that accounted for 93% of all the reported mass movements. The other landslides were equally distributed between debris falls or debris slides, and complex slides. New fractures were mapped in pre-existing landslide deposits, but no major landslide was reactivated to the point of catastrophic failure. Spatial analysis of the triggered slope failures showed that the distribution of rock falls fitted the observed macro-seismic intensity pattern. About 50% of all reported failures occurred within 8 km from the epicentral area, and the maximum observed distance of a landslide from one of the epicentres was 25 km. Slope failures caused damage mostly to the transportation network. Two state roads (SS 320 and SS 209) connecting Terni, to the south, with Visso, Norcia and Cascia, to the north and north-east, were damaged at several places by numerous rock falls ranging from small cobbles to rock slides 200 m<sup>3</sup> in volume. Casualties due to landslides were not reported, but at least one car was damaged by a rock fall.

#### **3.3.3.4. Comparison of the three event inventories in Umbria**

The three event inventories, prepared for events (or group of the events in the case of the 1937-1941 period) that occurred in Umbria between 1937 and 1997, provide useful information on the type, extent, persistence and abundance of slope failures caused by landslide triggering events. Comparison in a GIS of the spatial distribution of landslides triggered by the 1937-1941 rainfall period and the January 1997 snowmelt event, with the geographical distribution of the pre-existing landslides shown in the geomorphological inventory map (Figure 3.10, § 3.3.2.2) allows for estimating the spatial persistence of landslides. Approximately 89% of all the rainfall induced landslides triggered in the period 1937-1941 were located inside or within 150 meters from a pre-existing landslide. Similarly, about 75% of the snowmelt induced landslides fell inside pre-existing landslide deposits, i.e., they were reactivations, or they were located within 150 meters of an existing landslide.

This is an important information for the assessment of landslide hazard in Umbria (Guzzetti *et al.*, 1999b, 2003; Cardinali *et al.*, 2002a) because it provides the rationale for attempting to evaluate where landslides may cause damage in the future based on where landslides have occurred in the past using accurate landslide inventory maps.

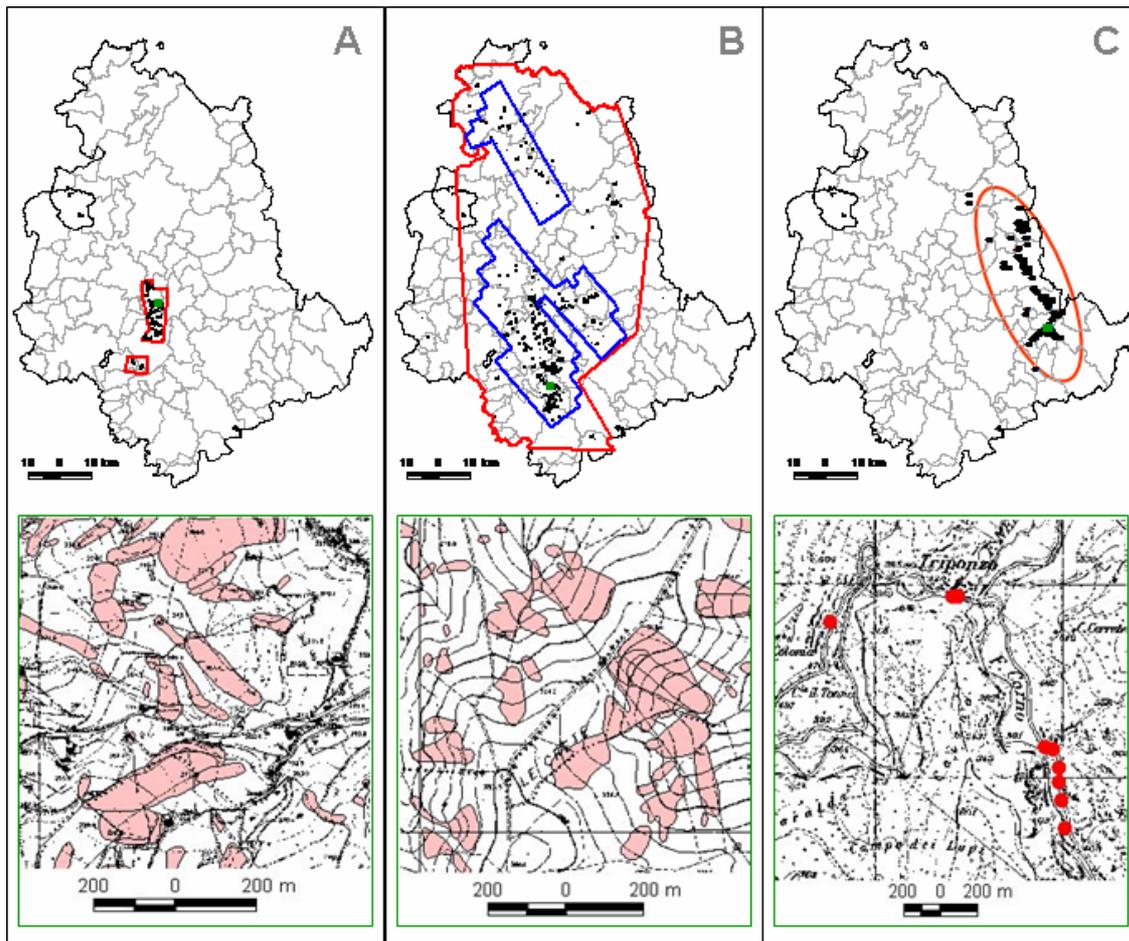


Figure 3.12 – Landslide event inventories in Umbria. Red lines show extent of study areas. (A) Landslides triggered by rainfall in 1937-1941. (B) Landslides triggered by rapid snowmelt in January 1997 (Cardinali *et al.*, 2000). Blue line shows extent of the area for which aerial photographs are available. (C) Landslides triggered by the September-October 1997 earthquakes (Antonini *et al.*, 2002). Lower maps are enlargements of portions of the upper maps. Original maps at 1:10,000 scale.

Table 3.2 – Comparison of landslide event inventories in Umbria. (I) Rainfall induced landslides in the period 1937-41 (1), and snowmelt induced landslides in January 1997 (2a) entire study area; (2b) area where aerial photographs were available. (II) September-October 1997 earthquake induced landslides.

$N_{LT}$ , total number of landslides;  $A_{LT}$ , total landslide area;  $A_{Lmin}$ ,  $A_{Lmax}$ ,  $\bar{A}_L$ , minimum, maximum, average landslide area;  $V_{LT}$ ,  $V_{Lmin}$ ,  $V_{Lmax}$ ,  $V_L$ , similar values for landslide volume;  $d_L$ , landslide density.

I	Event	Trigger	Mapped area km <sup>2</sup>	Inventory statistics						
				$N_{LT}$ #	$A_{LT}$ km <sup>2</sup>	$A_{LT}$ %	$A_{Lmin}$ km <sup>2</sup>	$A_{Lmax}$ km <sup>2</sup>	$\bar{A}_L$ km <sup>2</sup>	$D_L$ #/km <sup>2</sup>
(1)	1937-1941	Rainfall events	~ 135	1072	4.4	3.26	$7.3 \times 10^{-5}$	$1.1 \times 10^{-1}$	$4.0 \times 10^{-3}$	8.0
(2a)	January 1997	Snowmelt	~ 5660	4235	12.7	0.22	$3.9 \times 10^{-5}$	$1.5 \times 10^{-1}$	$3.0 \times 10^{-3}$	0.7
(2b)	January 1997	Snowmelt	~ 1900	3837	11.2	0.59	$3.9 \times 10^{-5}$	$1.5 \times 10^{-1}$	$2.9 \times 10^{-3}$	2.0
II	Event	Trigger	Mapped area km <sup>2</sup>	Inventory statistics						
				$N_{LT}$ #	$V_{LT}$ m <sup>3</sup>	$V_{Lmin}$ m <sup>3</sup>	$V_{Lmax}$ m <sup>3</sup>	$V_L$ m <sup>3</sup>	$D_L$ #/km <sup>2</sup>	
(3)	Sep.-Oct. 1997	Earthquakes	~ 1100	220	878.2	$9.9 \times 10^{-5}$	$2.0 \times 10^{+2}$	$5.7 \times 10^0$	0.2	

Guzzetti *et al.* (2003) attempted a comparison of the effects of the three landslide events on the transportation network. The analysis revealed that the largest number of sites with damage was reported as a result of earthquake induced landslides, mostly because of their proximity to the transportation network in the area affected by the earthquakes. Rock falls can be abundant even in areas of limited extent, and they can be very dangerous to people and destructive to structures even for small volumes (less than one cubic meter). In the mountain area where seismic shaking was most severe in 1997, roads most affected by the rock falls were located at or near the valley bottom. Landslides triggered by the rapid snowmelt in 1997 and by rainfall events in the period 1937-1941 were similar, and comprised shallow soil slides, slumps and slump-earth flows, and deep-seated slides, slide earth-flows and complex movements. These landslide types move slowly and with generally limited displacements. These types of movement explains why roads were damaged at several places, but were totally interrupted at only a few sites. It may also explain why landslides did not cause casualties. Despite the fact that the abundance of landslides and the average landslide density for the two events were different, the percentage of landslides that interfered with the transportation network was similar, 2.7% for the 1937-1941 rainfall events and 2.5% for the January 1997 snowmelt event. This may be important information for landslide risk assessment in Umbria.

### **3.3.4. Multi-temporal inventories**

A multi-temporal landslide map is the most advanced form of landslide inventory. It shows the location and types of failures in an area, and portrays their recent evolution in space and time. Preparing a multi-temporal inventory is a difficult and time consuming operation that involves the assimilation of multiple information, including: (i) information obtained by systematically interpreting all the aerial photographs available for a study area, irrespective of age, scale and type of the photographs; (ii) data gathered through field surveys, conducted primarily after landslide triggering events; (iii) information on the occurrence of historical landslide events, obtained by searching multiple archive and bibliographical sources; and where available, (iv) information on ground movements obtained through field instrumentations, topographic surveys, and remote sensing technologies (e.g., SAR, Lidar, etc.). Because of the difficulty and complexity in preparing a multi-temporal inventory, these maps are rare, and where they are available they cover areas of limited extent, ranging from few tens to few hundreds of square kilometres (e.g., Hovius *et al.*, 1996; Larsen and Torres-Sánchez, 1996, 1998; Cardinali *et al.*, 2004; Galli *et al.*, 2005; Guzzetti *et al.*, 2005).

Difficulties in preparing a multi-temporal inventory map include: (i) the availability of multiple sets of aerial photographs for the same area, that locally limits the possibility of producing the multi-temporal inventory; (ii) the ability to recognize, interpret, and map subtle morphological changes as slope movements; (iii) the difficulty of inferring consistently the age of the landslides based on their morphological appearance, particularly when the time between two successive flights is long (e.g., a decade or even larger); (iv) the possibility of mapping landslides of different age (obtained from different flights) on the same topographic maps, which may not portray the topography present on the aerial photographs (every time a landslide occurs it changes topography, locally significantly, but this is not shown in the base map); and (v) the difficulty of being precise and consistent when transferring the information on landslides from the aerial photographs to the base maps and in a GIS without losing information or introducing errors (where morphological changes are subtle it may be difficult to map and digitize the changes). To overcome these limitations, multi-temporal inventory

maps must be prepared by teams of well-trained, experienced and motivated geomorphologists.

#### **3.3.4.1. Multi-temporal landslide inventory for the Collazzone area**

For the Collazzone area, in central Umbria (§ 2.4), a multi-temporal landslide inventory map was prepared at 1:10,000 scale (Figure 3.13). The map was prepared through the interpretation of multiple sets of aerial photographs and detailed geological and geomorphological field mapping conducted in the period from January to March 1997, in the summer and autumn 2002, and in the period from September 2003 to April 2004. The six sets of aerial photographs used to prepare the multi-temporal map were taken: (i) in the summer of 1941 at 1:18,000 scale, (ii) on 30 August 1954 at 1:33,000 scale, (iii) on 13 June 1977 at 1:13,000 scale, (iv) on 1 July 1985 at 1:15,000 scale, (v) on April 1997 at 1:20,000 scale, and (vi) in the summer 1999 at 1:40,000 scale.

A team of two geomorphologists carried out the interpretation of the aerial photographs in the 5-month period from July to November 2002, for an average of 8 square kilometres per man-month. The two interpreters looked at each pair of aerial photographs using a mirror stereoscope (4× magnification) and a continue-zoom stereoscope (3× to 20× magnification). Both stereoscopes allowed the interpreters to map contemporaneously on the same stereo pair. The interpreters used all morphological, geological and landside information available from published maps, previous work carried out in the same area (including the two described regional inventories, shown in Figures 3.9 and 3.10), and discussion with other geologists and geomorphologists. Care was taken in identifying areas where morphology had changed in response to mass movements, and to avoid interpretation errors due to land use modifications or to the different views provided by aerial photographs taken at different dates.

The landslide information was drawn on transparent plastic sheets placed over the aerial photographs. Depending on the local abundance and complexity of the landslides, a single sheet or multiple sheets were used to map landslides of different ages (i.e., identified on aerial photographs of different dates). To transfer the landslide information from the aerial photographs to the base maps, at 1:10,000 scale, and to construct the GIS database, the procedure used to prepare the detailed geomorphological inventory (§ 3.3.2.2, Figure 3.10) was adapted to cope with larger and more complex landslide information. In the GIS database, landslides attributed to a single date (e.g., a rainfall event) or period were stored separately. Following this procedure, new and active landslides recognized, e.g., in the 1977 aerial photographs were stored in a separate layer than the landslides mapped as inactive in the same photographs. The procedure required intensive and time-consuming GIS work to correct topological and geographical errors. The obtained GIS database stores information on landslides attributed to twelve different dates or periods. The combination of the different layers represents the multi-temporal landslide inventory map.

In the multi-temporal inventory map, landslides are classified according to the type of movement, and the estimated age, activity, depth, and velocity. Landslide type is defined according to Cruden and Varnes (1996). Adopting the same procedure used to compile the detailed geomorphological inventory for Umbria (§ 3.3.2.2, Figure 3.10), for deep-seated slope failures, the landslide crown is mapped separately from the deposit. The distinction is not made for shallow landslides. Landslide age, activity, depth, and velocity were determined based on the type of movement, the morphological characteristics and appearance of the landslides on the aerial photographs, the local lithological and structural setting, and the date

of the aerial photographs. Landslide age is 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). The multi-temporal inventory map for the Collazzone area shows 2564 landslides, for a total mapped landslide area of 22.14 km<sup>2</sup> (Table 3.3), which corresponds to a landslide density of 32.2 slope failures per square kilometre. Due to geographical overlap of landslides of different periods, the total area affected by landslides in the study area is 16.47 km<sup>2</sup>, 20.69% of the investigated territory. Mapped landslides extend in size from 78 m<sup>2</sup> to 1.45 km<sup>2</sup>, and the most frequent slope failures shown in the map have an area of about 815 m<sup>2</sup> (Table 3.3).

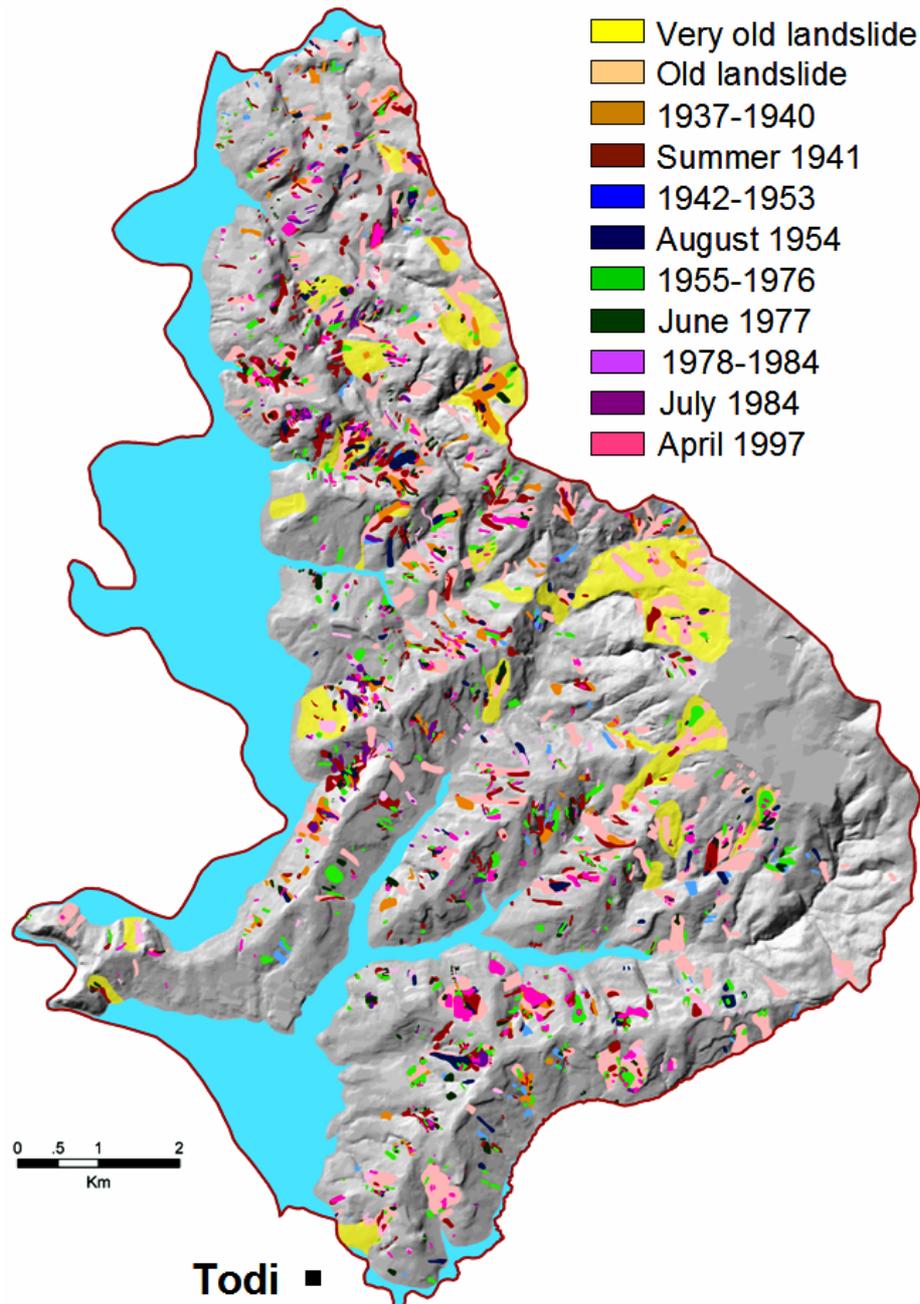


Figure 3.13 – Multi-temporal landslide inventory map for the Collazzone area. Landslides are portrayed with different colours, showing relative age, decided based on the date of the aerial photographs and the morphological appearance of the landslides. Original scale 1:10,000.

Table 3.3 – Main characteristics of the multi-temporal landslide inventory map prepared for the Collazzone area (Figure 3.13). See Table 3.1 for a comparison with the two regional geomorphological inventory maps (Figures 3.9 and 3.10).

Type of inventory	-	Multi-temporal
Date of inventory	year	2002 (2003-4)
Area extent	km <sup>2</sup>	78.8
Sets of aerial photographs	1/m	5
Scale of aerial photographs	1/m	1:13,000 to 1:33,000
Scale of topographic base map	1/m	1:10,000
Scale of final (published) map	1/m	1:10,000
Time for photo-interpretation	month	5
Team for photo-interpretation	people	2
Rate of photo-interpretation	km <sup>2</sup> / man-month	8
Time for GIS database construction	month	1
Team for GIS database construction	people	1
Total number of mapped landslides	#	2564
Total area affected by landslides	km <sup>2</sup>	16.47
Percent of area affected by landslides	%	20.90
Landslide density	#/ km <sup>2</sup>	32.5
Smallest mapped landslide	m <sup>2</sup>	78
Largest mapped landslide	km <sup>2</sup>	1.45
Average size of mapped landslide	m <sup>2</sup>	6421
Size of most abundant landslide	m <sup>2</sup>	~ 815

The average density of mass movements in the Collazzone area is 28 landslides per square kilometre but, in places, the density of slope failures is higher, exceeding 50 landslides per square kilometre. The majority of the mapped landslides are slides (76%). The remaining failures are equally distributed between flows (12%) and slide-earth flows (12%).

Cardinali *et al.* (2004) used the multi-temporal inventory map to investigate the spatial and temporal evolution of landslides in the Collazzone area. These authors extracted from the multi-temporal map all the landslides that were classified as active in each set of aerial photographs or during the field surveys. This allowed preparing a set of landslide maps, showing only active landslides of different ages. These maps are a proxy or event landslide inventories. The obtained maps were analysed separately and in combination, and the analysis revealed that the 1941 event was particularly severe and triggered many new and large landslides. The subsequent events triggered fewer, and generally smaller, landslides. The GIS analysis also revealed that landslide persistence is high when considering the ensemble of all pre-existing slope failures, but low or very low when comparing two consecutive inventories.

In § 6.5.1, I will exploit landslide information shown in the multi-temporal inventory map prepared for the Collazzone area to show how to validate a landslide susceptibility assessment, and to propose a general framework for the evaluation of the reliability and prediction skill of a landslide susceptibility forecast.

### 3.4. Factors affecting the quality of landslide inventories

A recognized limitation of landslide inventory maps refers to their intrinsic subjectivity, and to the difficulty of measuring their reliability and completeness (Guzzetti *et al.*, 2000; Malamud *et al.*, 2004a). Reliability, completeness and resolution are issues to consider when preparing and using an inventory map. An incomplete or unreliable inventory may result in erroneous susceptibility, hazard, and risk assessments.

The reliability of archive inventories depends largely on the quality and abundance of the information sources (Guzzetti *et al.*, 1994; Ibsen and Brunsten, 1996; Glade, 1998; Cruden, 1997; Glade, 2001). For inventory maps compiled through the interpretation of aerial photographs, the experience gained from surveys carried out in different parts of the world has shown that trained investigators can reliably detect landslides by standard photo-interpretation techniques coupled with systematic checks in the field (Soeters and van Westen, 1996; Rib and Liang, 1978). However, the reliability of these inventories (geomorphological, event or multi-temporal) depends on many factors, including: (i) landslide freshness and age, (ii) the persistence of landslide morphology within the landscape, (iii) the type, quality and scale of aerial photographs and base maps, including the scale of the final map, (iv) the morphological and geological complexity of the study area, (v) land use types and alterations, (vi) the quality of the stereoscopes used to analyse the aerial photographs, and (vii) the degree of experience of the interpreter who completes the inventory (Hansen, 1984; Fookes *et al.*, 1991; Carrara *et al.*, 1992; Ardizzone *et al.*, 2002).

Once a landslide is recognized in the field or from the aerial photographs it must be mapped, i.e. information about the landslide's location and characteristics is obtained and transferred onto paper. This operation is not trivial and is prone to errors. Since absolute coordinates of the boundaries of a landslide are seldom available, the geomorphologist uses available base maps and the topographical and morphological features shown on the maps to locate the landslide. Where the topographic map is accurate and shows the actual morphology, and where landslides have a distinct morphological signature, locating and mapping the landslide is straightforward and subject to little uncertainty. Where the topographic map does not represent faithfully the morphology or the landslide is not very distinct, significant location and mapping errors are possible. In placing the landslide on the topographic map, the geomorphologist uses all of the information on the map, including the position and shape of divides and drainage lines, the pattern of vegetation and land use, and the presence of vulnerable elements (e.g. roads, buildings, etc.). If these are not shown correctly or are incomplete, the mapping can be affected by errors and uncertainties. Consequently, the reliability of a landslide inventory map varies spatially, depending on morphology, hydrography, land-use pattern, presence of forest, and abundance and location of vulnerable elements. In addition, for large-scale landslide inventory maps (>1:20,000) the landslide and the topographic information are strictly coupled. Thus, landslides should be shown only with the topographic maps used to prepare the inventory.

Once the landslide has been mapped on paper, the information is digitized for further analysis and display. This last step in the production of a landslide inventory is also error-prone, and can introduce a variety of cartographic errors, some severe. An error in the location of a landslide boundary of only 1-2 mm on the topographic map (i.e. 10-20 m on the ground at 1:10 000 scale) may result in >5 per cent difference in landslide area for small (<1 ha) slope failures. After landslides are transferred to a GIS, computations of landslide areas are possible.

Any vector-based GIS system can calculate the area and perimeter of polygons used to represent the landslide. Thus, for a single landslide, computation of its area is straightforward. If the landslide deposit is mapped separately from the crown or depletion zone, the two will have to be combined before the total landslide area is computed. This operation can be performed automatically in a GIS, provided the polygons representing the landslides are properly coded. The coding operation is usually simple, but time-consuming, particularly for large datasets.

Landslide areas and perimeters obtained from the GIS are planar (i.e. projected) measurements that differ from the real ones. Ideally, one would prefer to know the actual area and perimeter of a landslide. Where a digital elevation model is available, local slope can be computed in a GIS and measurements of landslide perimeter and area corrected for topographic gradient. However, this operation is seldom done.

No standard procedure or absolute criteria has been established to measure the quality of a landslide inventory map. Most commonly, the quality of a landslide inventory map is ascertained by comparison with other landslide maps, available for the same or similar area, or prepared by the same geomorphologist or team of geomorphologists (e.g., Carrara *et al.*, 1992; Galli *et al.*, 2005). Ideally, comparison of two or more inventories should be aimed at determining how well the maps perform in: (i) describing the location, type, and abundance of landslides, (ii) determining the statistics of landslide areas, and (iii) providing reliable information to construct landslide susceptibility or hazard models. Significantly, these are the most important uses of landslide inventory maps. For the purpose, different tests can be performed to: (i) evaluate the degree of cartographic matching between the maps, (ii) compare the geographical abundance of landslides in the inventories, (iii) compare the frequency-area statistics of the landslides obtained from the inventories, and (iv) evaluate landslide susceptibility assessments obtained using the available inventories.

For the Collazzone area, three different landslide inventory maps are available, i.e. the two regional landslide maps discussed in § 3.3.2.1 and § 3.3.2.2, and the multi-temporal landslide map discussed in § 3.3.4.1. This opportunity can be exploited to test methods to compare landslide inventory maps to ascertain their quality. In the following sub-section, I will perform a preliminary analysis of the three inventories, discussing the main cartographic differences of geomorphological significance between the three landslide maps obtained through a simple GIS analysis. In § 4.2.2.1, I will further compare the three inventories in an attempt to determine the degree of cartographic matching between the three different landslide maps, and their ability to describe the distribution and density of slope failures in the Collazzone area. Lastly, in § 5.3 I will exploit the probability density distributions obtained for the three inventories to determine the degree of completeness of the individual landslide maps.

### **3.4.1. Quality of landslide inventory maps in the Collazzone area**

Figure 3.14 shows the three landslide inventory maps available for the Collazzone area, and Table 3.4 summarizes the main descriptive statistics for the three landslide maps. Inspection of Table 3.4 reveals a distinct increase in the number of landslides with enhanced accuracy of the mapping. The detailed geomorphological inventory (B in Figure 3.14) shows 44.6% of the total number of landslides shown in the multi-temporal inventory (C in Figure 3.14). The percentage reduces to 5.6% for the reconnaissance inventory (A in Figure 3.14). Results are different if the area of the mapped landslides is considered. The detailed geomorphological inventory shows 48.6% (8.00 km<sup>2</sup>) and the reconnaissance inventory shows 47.1% (7.75 km<sup>2</sup>)

of the total area covered by landslides (16.47 km<sup>2</sup>) in the multi-temporal inventory. The disparity in the number and in the area of the mapped landslides indicates that differences exist in the average size of the slope failures shown in the three landslide maps (Table 3.4). Indeed, the average landslide area in Map A (78,287 m<sup>2</sup>) is approximately 10 times larger than the average landslide area shown in Map B (7526 m<sup>2</sup>) and in Map C (8634 m<sup>2</sup>). This is a significant difference for landslide hazard assessment. When compared to Map B, the slightly larger extent of the average landslide area shown in Map C is due to the presence of a few very large landslides (area > 1 km<sup>2</sup>), erroneously not shown in the geomorphological inventory (Map B). Table 3.4 also shows that the area the most frequent landslide decreases with the increase in the completeness of the inventories. This area is ~ 32,000 m<sup>2</sup> for the reconnaissance inventory (Map A), ~ 1170 m<sup>2</sup> for the geomorphological inventory (Map B), and ~ 815 m<sup>2</sup> for the more accurate multi-temporal inventory (Map C). This is also a significant difference for landslide hazard assessment.

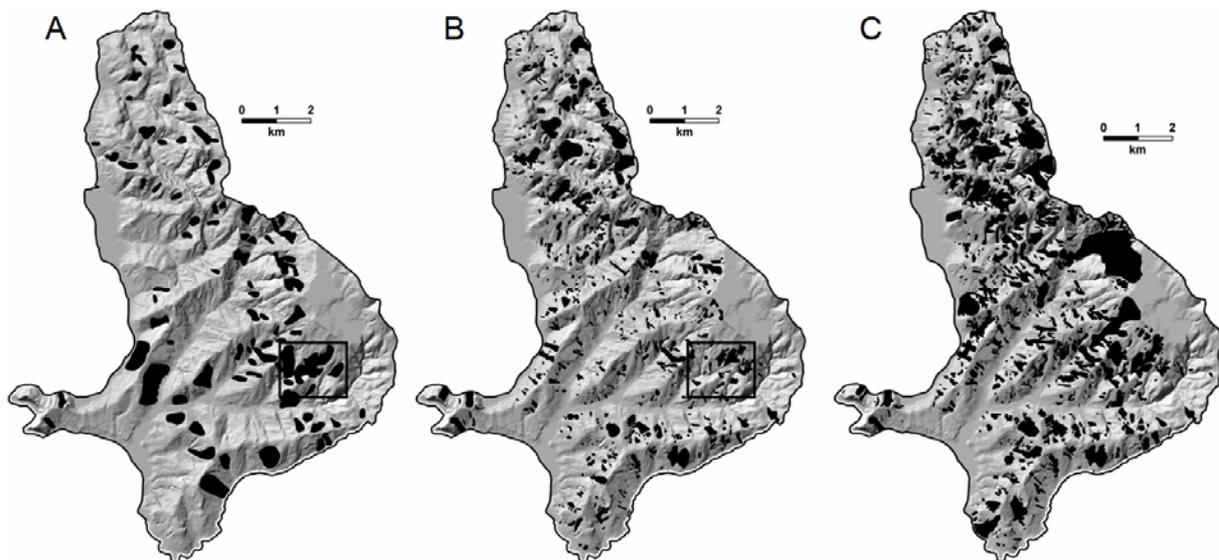


Figure 3.14 – Comparison of three landslide inventory maps available for the Collazzone area. (A) Reconnaissance geomorphological inventory (from Figure 3.9, § 3.3.2.1). (B) Detailed geomorphological inventory (from Figure 3.10, § 3.3.2.2). (C) Multi-temporal inventory (Figure 3.14, § 3.3.4.1).

Differences between the three landslide maps have many reasons. The different scales of the base maps used to draw the landslides (1:25,000 for Map A, 1:10,000 for Map B and Map C) and of the maps used to construct the GIS database (1:100,000 for Map A, 1:10,000 for Map B and Map C) contributed to the cartographic error, which was largest for the small-scale map (Map A). The type of study (i.e., reconnaissance, geomorphological, multi-temporal), which was a function of the time and the resources available to complete the investigation, also affected the accuracy of the mapping. Comparison of the figures shown in Tables 3.1, 3.3 and 3.4 suggests that the longer the time available for the investigation, the better the resulting inventory map.

The scale, type, date and number of the aerial photographs used to complete the investigation, and the amount of field work associated with the mapping, have certainly influenced the quality of the obtained inventory maps. Only one set of medium scale aerial photographs was

used to compile Map A, two sets of photographs were used to recognize the landslides shown in Map B, and six sets of photographs of different dates were used to obtain Map C (Figure 3.1).

Table 3.4 – Main characteristics of the three landslide inventory maps available for the Collazzone area. Map A, portion of the reconnaissance landslide inventory (§ 3.3.2.1, Figure 3.15.A) covering the Collazzone area. Map B, portion of the geomorphological landslide inventory (§ 3.3.2.2, Figure 3.15.B) covering the Collazzone area. Map C, multi-temporal inventory map for the Collazzone area (§ 3.3.4.1, Figure 3.15.C).

		<i>Map A</i>	<i>Map B</i>	<i>Map C</i>
Total number of mapped landslides	#	143	1143	2564
Total mapped landslide area	km <sup>2</sup>	7.75	8.60	22.14
Total area covered by landslides	km <sup>2</sup>	7.75	8.00	16.47
Percent of landslide area	%	9.73	10.05	20.69
Landslide density	#/ km <sup>2</sup>	1.79	14.36	32.19
Smallest mapped landslide	m <sup>2</sup>	12,174	99	78
Largest mapped landslide	km <sup>2</sup>	0.62	0.29	1.45
Average size of mapped landslide	m <sup>2</sup>	78,287	7526	8634
Area of most abundant mapped landslide	m <sup>2</sup>	~ 32,000	~ 1170	~ 815

The amount of field work was very limited for the reconnaissance inventory (Map A), limited for the geomorphological inventory (Map B), and extensive for the multi-temporal inventory (Map C). Where field work was performed errors and imprecision were corrected, and the geomorphologists were able to test and refine the photo-interpretation criteria used to recognize and map the landslides from the aerial photographs. The availability of additional geological, morphological and landslide information contributed to the quality of the inventory maps. The information was extremely limited for Map A, abundant for Map B, and very abundant for Map C. The photo-interpretation technique and the experience of the geomorphologists who completed the three inventories improved with time, resulting in a more accurate mapping. For the production of the reconnaissance inventory (Map A) the interpreters based landslide identification solely on the morphological appearance of the landslides. When preparing the detailed geomorphological map (Map B), in addition to the morphological appearance of the landslides, the interpreters considered the local lithological and structural settings, including the bedding attitude. For the compilation of the multi-temporal inventory (Map C), in addition to the morphological appearance and the local lithological and structural setting, the investigators considered the spatial evolution of the individual landslides. The improved interpretation technique resulted in less interpretation errors and in a better accuracy and completeness of the resulting landslide map.

Based on these considerations, one can safely rank the multi-temporal inventory (Map C) the best of the three available landslide maps in the Collazzone area. However, as I said before, other tests can be made to confirm this result. These tests will be conducted in the next chapters (e.g., § 4.2.2.1, § 5.3.1).

The rate of photo-interpretation, which is the average number of square kilometres of an inventory that a single investigator can complete in a unit of time (e.g., a month, Tables 3.1 and 3.3), provides a measure of the resources needed to prepare an inventory – an interesting parameter to compare landslide maps. The rate for the multi-temporal mapping (Map C) was 13-time higher than the rate for the geomorphological mapping (Map B), and 60-time higher

than the rate for the reconnaissance mapping (Map A). This implies that the team of two geomorphologists that completed the multi-temporal inventory map for the Collazzone area in 5 months would need 45 years to cover the entire Umbria Region (8456 km<sup>2</sup>), assuming the team uses the same technique and the same sets of aerial photographs. The figure compares with the 28 months needed by a team of three geomorphologists to complete the geomorphological map, and with the 9 months required by a team of two interpreters to compile the reconnaissance inventory (Table 3.1).

Based on these figures, I conclude that it is probably not feasible to prepare an accurate multi-temporal inventory map for the entire Umbria Region – or an area of similar extent and morphological complexity – with the proposed methodology. More generally, I conclude that at the regional scale, i.e., for areas extending for thousands of square kilometres, only geomorphological or event inventories can be obtained by teams of experienced geomorphologists. This somewhat limits the possibility of preparing reliable landslide hazard maps for large territories (§ 7).

### **3.5. Summary of achieved results**

In this chapter, I have:

- (a) Demonstrated the feasibility of landslide inventory maps that reliably cover areas extending for thousands of square kilometres. However, such maps need to be prepared by experienced geomorphologists.
- (b) Demonstrated the feasibility and importance of landslide event inventory maps. From such inventories, unique information is obtained which is of primary importance to determine landslide hazard and to evaluate the associated risk.
- (c) Shown that multi-temporal inventory maps prepared through the assimilation of multiple information are a superior type of landslide map. However due to their complexity, such maps can be prepared only for areas of limited extent.
- (d) Established the basis for measuring the quality of landslide inventory maps, which allows for a comparison of different maps prepared for the same area.

This largely responds to Questions # 1 and # 2 posed in the Introduction (§ 1.2).