2. STUDY AREAS

Ground truth is important.
It shows that your model is wrong.

Select data that
fit your model well.

In this chapter, I describe the study areas where the research illustrated and discussed in the following chapters was conducted. For each area, I provide general information on the type and abundance of landslides and on the local setting, including morphology, lithology, structure, climate, and other physiographic characteristics. For some of the areas, I give information on the type and extent of damage caused by the slope failures. Where appropriate, I provide a brief description of the topographic, environmental and thematic data used to perform landslide susceptibility zonings, landslide hazard assessments, and landslide risk evaluations.

Figure 2.1 shows the location of the six selected study areas, and Appendix 4 summarizes the main characteristics of the selected areas, and the type of research conducted in each area. The first of the select areas consists of the entire country of Italy. The second study area is the Umbria Region. Of the remaining areas, three are located in Umbria and one in the northern Apennines.

I have selected the study areas because of: (i) their significance for the scope of this work, (ii) the quality, completeness or abundance of the available landslide and thematic data, and (iii) exclusive data are available in some of the selected areas. Some of the selected areas are placed inside other study areas. As an example, the Collazzone area, south of Perugia, is located in Umbria, which is in central Italy. Selection of nested study areas allows for performing experiments and comparing results at different scales for the same geographic or physiographic region.

The geographical extent of the selected areas ranges from a few tens of square kilometres (e.g., Collazzone, § 2.4) to more than 300,000 square kilometres for Italy (§ 2.1). As a result of the large spectrum in the geographical extent of the selected areas, the scale of the investigations completed in the different study areas varies significantly, from the local scale (e.g., 1:5000 to 1:10,000 scale) to the national, synoptic scale (≥ 1:1,000,000 scale). The accuracy and precision of the available information and of the results obtained vary accordingly. I hope this will help to show how the same landslide problem (e.g., landslide mapping, landslide hazard assessment, or landslide risk evaluation) can be approached and – hopefully – solved at different scales.

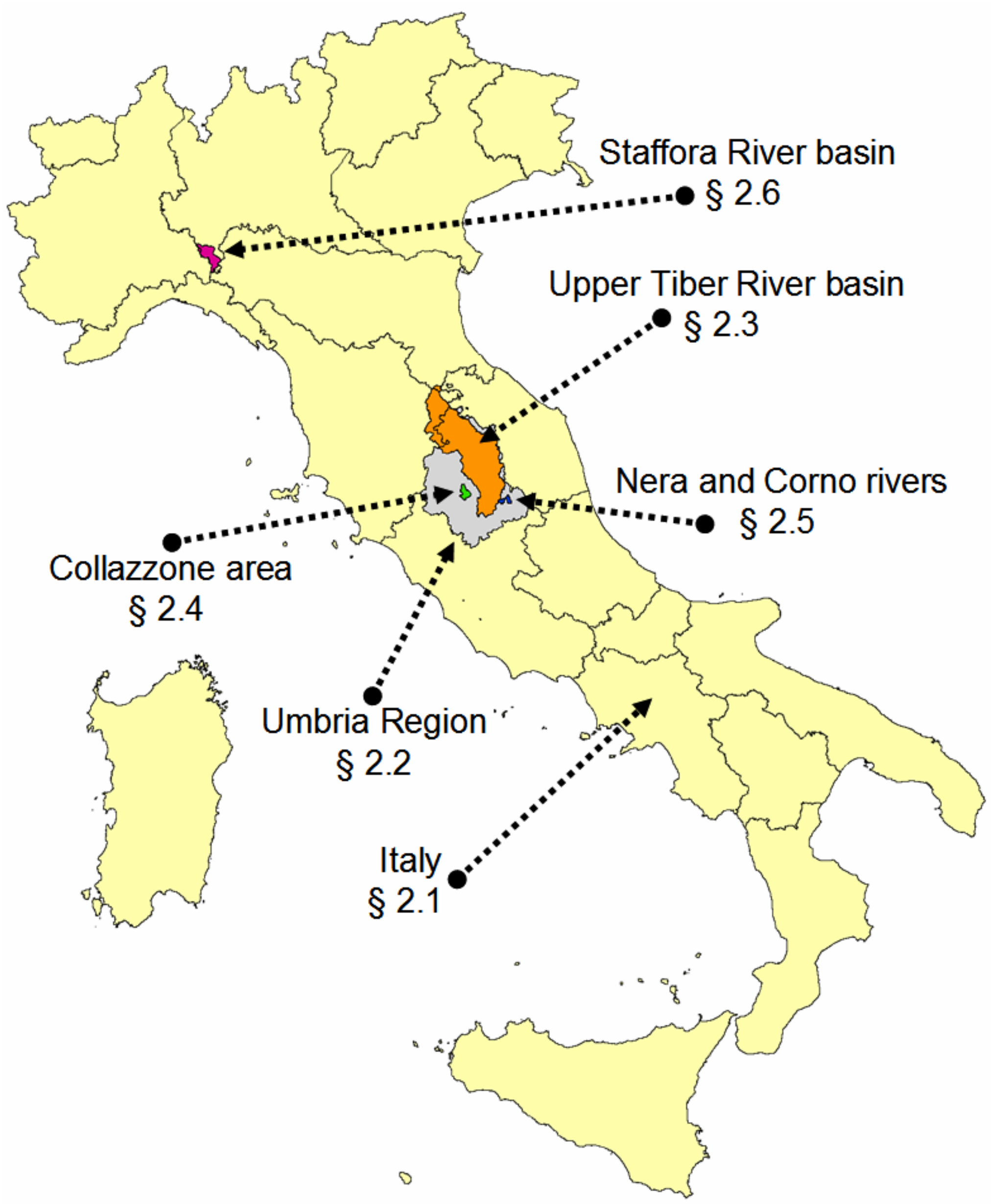

Figure 2.1 – Location of the study areas in Italy.

2.1. Italy

Landslides are abundant and frequent in Italy. Historical information describing landslides in Italy dates back to the Roman Age. Pliny the Elder reported landslides triggered by a large earthquake occurred during the Battle of Trasimeno, in the second Punic War in 264 BC. The societal and economic impact of landslides is high in Italy (Figure 2.2, § 8.3). In the 20th century, a period for which the information is available, the toll amounts to at least 7494 casualties, including 5190 deaths, 88 missing persons and 2216 injured people, and more than 160,000 homeless and evacuated people (Guzzetti *et al*., 2005c).

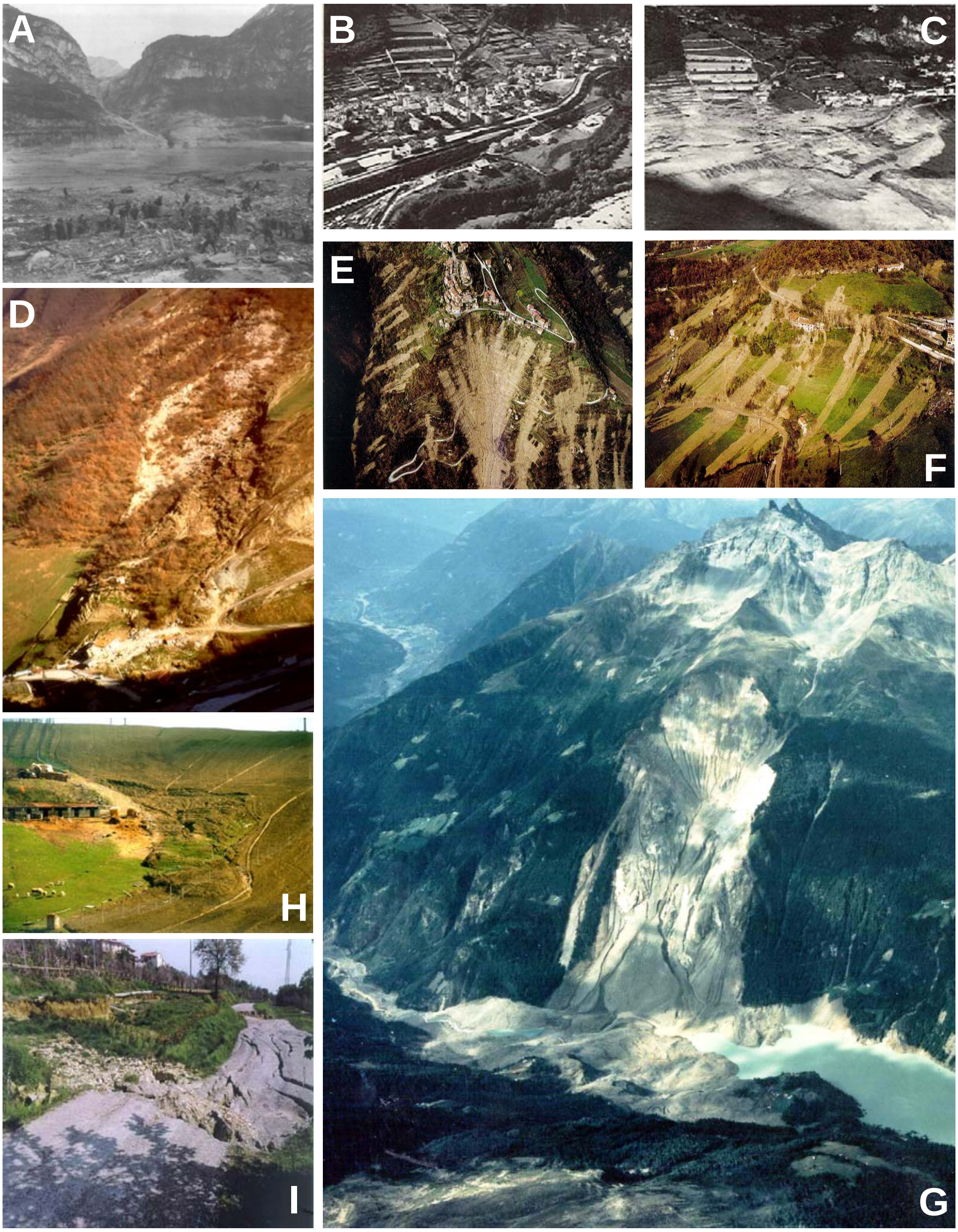

Figure 2.2 – Examples of landslides and landslide damage in Italy. (A) The inundation produced by the Vajont rock slide of 9 Ocotber 1963 on the village of Longarone (source: ANSA, Italy). (B) The village of Longarone before the inundation. (C) The village of Longarone after the catastrophic inundation. (D) Landslide at Valderchia, Umbria, triggered by heavy rainfall on 6 January 1997. The landslide destroyed 2 houses. (E) and (F) Soil slides and debris flows triggered by intense rainfall in November 1994 in Piedoment, Northern Italy (source: Casale and Margottini, 1996). (G) The Val Pola rock avalanche, in the Sondrio Province, triggered by heavy rainfall on 28 July 1985 (source: Crosta *et al*., 2004). (H) and (I) Rainfall induced landslides and typical landslide damage in Umbria.

In Italy, regional landslide events can be extremely destructive. The July 1987 catastrophic rainfall in the Southern Alps caused 61 fatalities and produced damage estimated at € 1.2 billion (Guzzetti *et al*., 1992; 2005c). Single landslides were also extremely costly. The Vajont slide of 9 October 1963 claimed 1917 lives and cost more than € 85 million; the Ancona landslide of 13 December 1982 caused damage estimated at € 1.3 billion; and the damage caused by the Val Pola rock avalanche of 28 July 1987 (§ 2.2.G) was estimated at € 800 million (Catenacci 1992, Alexander 1989). Figure 2.3 summarises the economic damage produced by individual and multiple landslides and flooding events in Italy in the period from 1910 to 2000 (Guzzetti and Tonelli, 2004). Guzzetti *et al*. (2005c) list 50 major landslide disasters that occurred in Italy from AD 1419 to 2002, and which resulted in 50 or more deaths or missing persons.

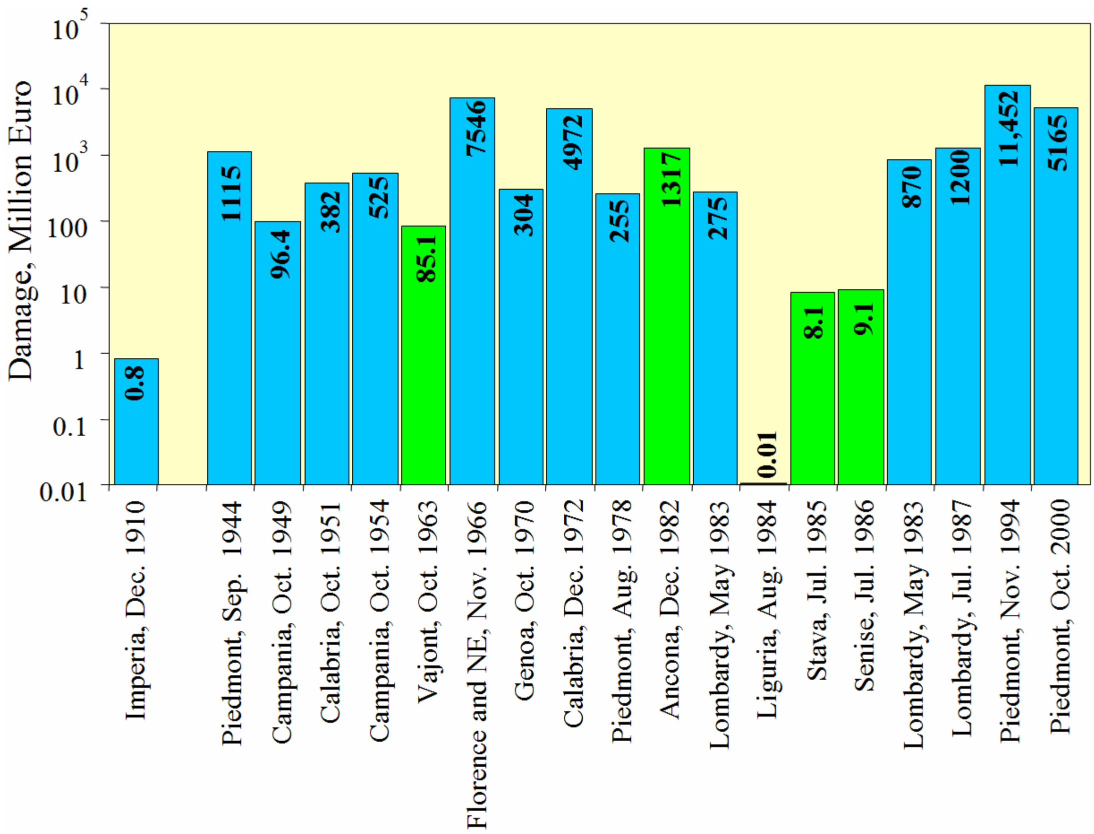

Figure 2.3 – Economic damage produced by individual landslides and flooding events in Italy in the period from 1910 to 2000. Green bars are single landslide events. Blue bars are multiple landslides and flooding events. Modified after Guzzetti and Tonelli (2004).

A few small scale, national datasets were available for this work. These datasets include: (i) a 90 m × 90 m DEM acquired by the Shuttle Radar Topography Mission (SRTM) in February of 2000 (Figure 2.4.A); (ii) a synoptic soil map obtained through the digitization of the Soil Map of Italy published at 1:1,000,000 scale by Mancini in 1966 (Figure 2.4.B); and (iii) a synoptic lithological map obtained through the digitization of the Geological Map of Italy published by Compagnoni and others in five sheets at 1:500,000 scale in the period from 1976 to 1983 (Figure 2.4.C). For statistical analyses (e.g., § 7.4), the large number of rock (145) and soil (34) units shown in the lithological and the soil maps, were grouped into 20 lithological types, 8 classes of soil thickness, and 11 classes of soil parent material.

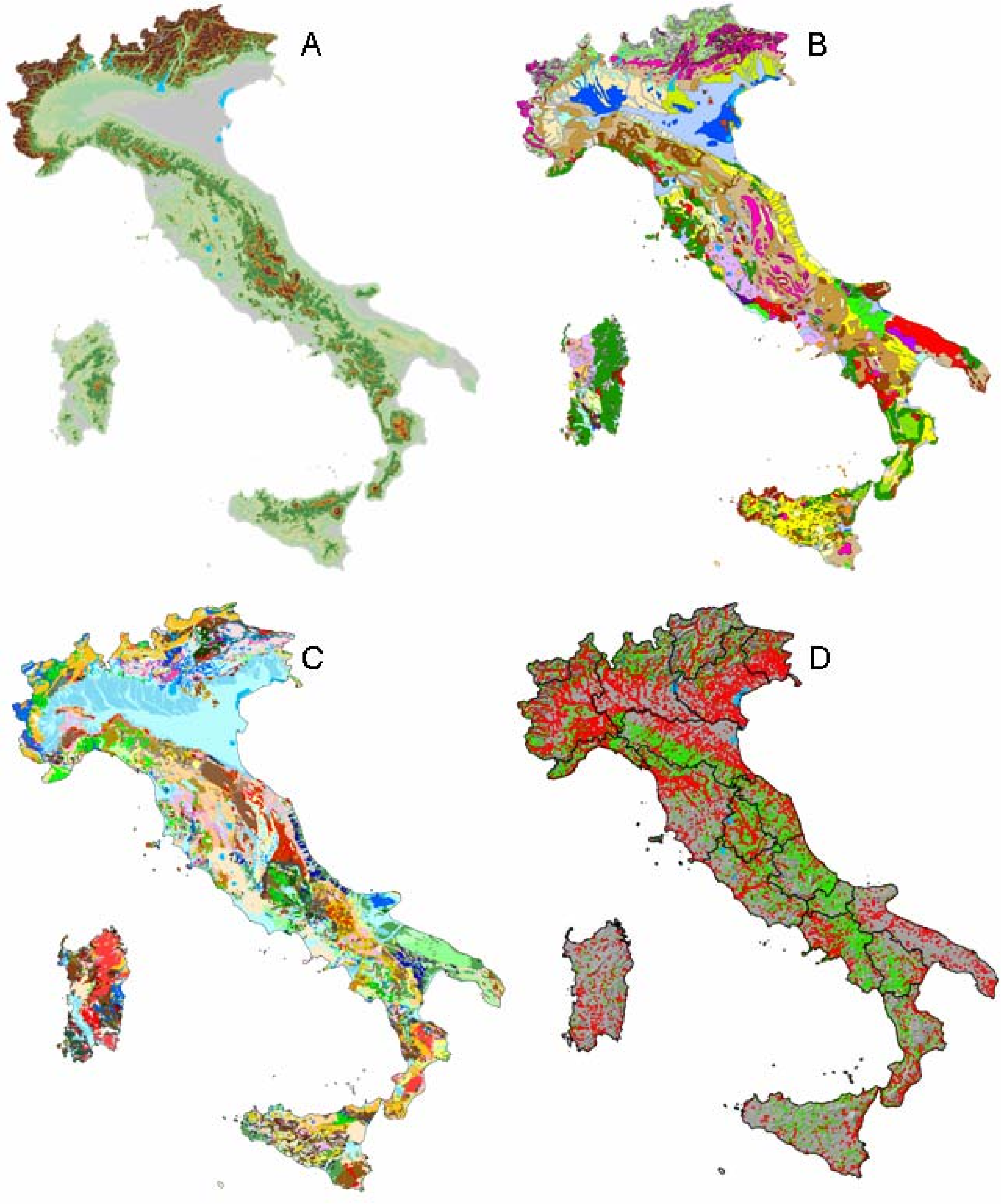

Figure 2.4 – Thematic data available for Italy and used in this work. (A) 90 m × 90 m Digital Elevation Model (DEM) acquired by the Shuttle Radar Topography Mission (SRTM) in February of 2000. (B) Soil map of Italy edited by Mancini *et al*. (1966). The original map, at 1:1,000,000 scale, shows 34 soil types. (C) Geological map of Italy published by Compagnoni *et al*. in the period from 1976 to 1983. The original map, at 1:500,000 scale, shows 145 geological units. (D) Map showing historical landslides (green dots) and inundations (red dots) in Italy (modified after Reichenbach *et al*., 1998b), available at http://sicimaps.irpi.cnr.it/website/sici/sici_start.htm.

For Italy, an inventory of historical information on landslides (and floods) was compiled by the National Group of Geo-Hydrological Protection (GNDCI), of the Italian National Research Council (CNR). Guzzetti *et al*. (1994) described the inventory and showed preliminary applications of the historical information. Guzzetti *et al*. (1996a) and Reichenbach *et al*. (1998b) published synoptic maps, at 1:1,200,000 scale, showing the location and abundance of the inventoried historical landslide and flood events in Italy (Figure 2.4.D). Reichenbach *et al*. (1998a) used the historical information and discharge records at several gauging stations along the Tiber River, to determine regional hydrological thresholds for the occurrence of landslides and inundation events in the Tiber River basin, in central Italy. More recently, Guzzetti and Tonelli (2004) presented a collection of databases containing historical, geographical, damage, hydrological, legislation and bibliographical information on landslides and floods in Italy.

In this work, the archive of historical landslide events in Italy is taken as the prototype of an archive landslide inventory (§ 3.3.1). The archive of historical landslides, in combination with morphological, hydrological, lithological and soil data available at the national scale (Figure 2.4) will be used to determine landslide hazard in Italy (§ 7.4).

For Italy, information exists on the human consequences of various natural hazards, including landslides. Guzzetti (2000) compiled the first catalogue of landslides with human consequences in Italy. Salvati *et al*. (2003) revised the landslide catalogue and compiled a new catalogue of floods with human consequences in Italy. Guzzetti *et al*. (2005b) updated the two catalogues prepared by Salvati *et al*. (2003) to cover the period from 91 BC to 2004, and the period from 1195 to 2004, respectively, and compiled a new catalogue of earthquakes with human consequences in Italy, and a list of volcanic events that resulted in casualties in Italy. Details on the sources of information and on the problems encountered in compiling the catalogues are given in Guzzetti (2000) and Guzzetti *et al*. (2005b,c).

In this work, the catalogue of landslides with human consequences in Italy will be used to test methods to evaluate the completeness of archive inventories (§ 4.3.1), and to determine levels of societal and individual landslide risk in Italy (§ 8.3.1).

2.2. Umbria Region, central Italy

The Umbria Region lays along the Apennines Mountain chain in central Italy, and covers an area of 8456 square kilometres (Figure 2.5.A). In the Region, the territory is hilly and mountainous, with large open valleys striking mostly NW-SE, and deep canyons striking NE-SW. Elevation of the hills and the mountains in the area ranges from 50 m (along the Tiber River valley) to 2436 m (at Monte Vettore, in the Monti Sibillini range). The area is drained by the Tiber River, which flows into the Tyrrhenian Sea. The climate is Mediterranean, with distinct wet and dry seasons. Rainfall occurs mainly from October to December and from March to May, with cumulative annual values ranging from 700 to more than 1300 mm (Figure 2.5.B). Snowfall occurs every year in the mountains and about every five years at lower elevations.

Sedimentary and subordinately volcanic rocks crop out in Umbria. The different rocks and sediments cropping out in the area can be grouped into four major groups, or lithological complexes (Guzzetti *et al*., 1996b) (Figure 2.5.C) namely: (i) carbonate rocks, comprising layered and massive limestone, cherty limestone and marl, (ii) flysch deposits, comprising layered sandstone, marl, shale and clay, (iii) volcanic rocks, encompassing lava flows, ignimbrites and pyroclasitc deposits, and (iv) marine and continetal sediments made up of clay, silty clay, fine and coarse sand, gravel and cobbles (Servizio Geologico Nazionale, 1980; Guzzetti *et al*., 1996b; Cardinali *et al*., 2001). Soils in the area reflect the lithological types, exhibit mostly a xenic moisture regime typical of the Mediterranean climate, and range in thickness from less than 20 cm where limestone, sandstone or volcanic rocks crop out along steep slopes, to more than 1.5 m in karst areas and in large open valleys.

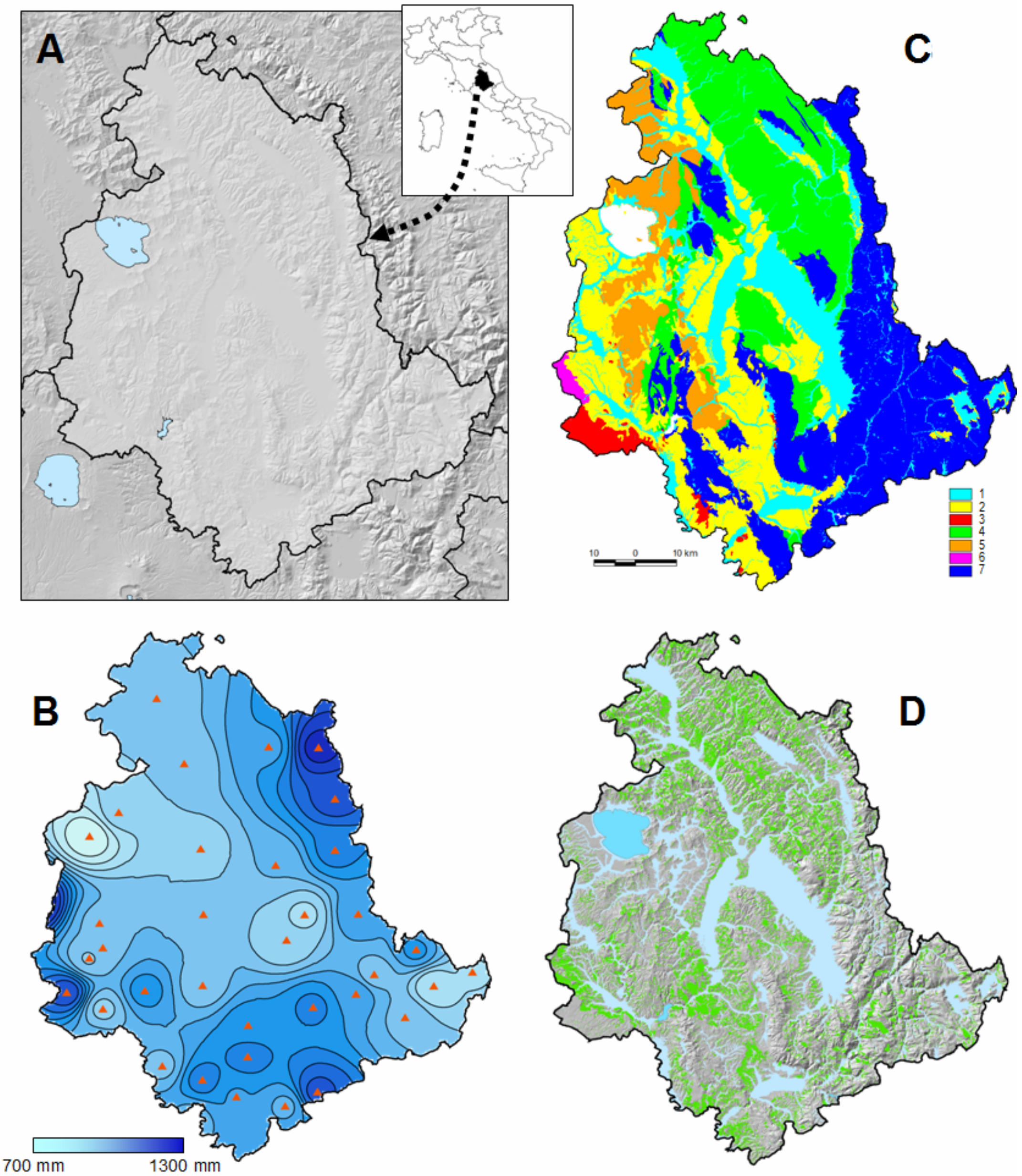

Figure 2.5 – Umbria Region, Central Italy. (A) Shaded relief image shows morphology in the region. (B) Map showing mean annual precipitation (MAP) obtained by interpolating the records of 34 rain gauges (red triangles) in the period from 1921 to 1950 (source: Servizio Idrografico Nazionale, 1955). (C) Simplified lithological map, modified after Servizio Geologico d'Italia (1980) and Cardinali *et al*. (2001); (1) Recent alluvial deposits, (2) Post-orogenic, marine, lake and continental sediments, (3) Volcanic rocks, (4) Marly flysch (Marnosa Arenacea Fm.), (5) Sandy flysch (Cervarola Fm.), (6) Ligurian allocthonous sequence, (7) Carbonate complex (Umbria-Marche stratigraphic sequence). (D) Geomorphological landslide inventory map prepared by Antonini *et al*. (2002a) (see § 3.3.2.2), map available at http://maps.irpi.cnr.it/website/inventario_umbria/umbria_start.htm.

Each lithological complex cropping out in Umbria comprises different rock types varying in strength from hard to weak and soft rocks (ISRM, 1978; Deer and Miller, 1966; Cancelli and Casagli, 1995). Hard rocks are layered and massive limestone, cherty limestone, sandstone, pyroclastic deposits, travertine and conglomerate. Weak rocks are marl, rock-shale (Morgenstern and Eigenbrod, 1974), sand, silty clay and stiff over-consolidated clay. Soft rocks are marine and continental clay, silty clay and shale. Rocks are mostly layered and subordinately structurally complex (Esu, 1977). The latter are made up by a regular superposition or a chaotic mixture of two or more lithological components (Morgenstern and Cruden, 1977; D'Elia, 1977; Esu, 1977).

The Umbria region has a complex structural setting resulting from the superposition of two tectonic phases associated to the formation of the Apennines mountain chain. A compressive phase of Miocene to early Pliocene age produced large, east-verging thrusts with associated anticlines, synclines and transcurrent faults, and was followed by an extensional tectonic phase of Pliocene to Holocene age, which produced chiefly sets of normal faults. The region is seismically active and has a long history of earthquakes (Boschi *et al*., 1998). Based on the available historical record (Boschi *et al*., 1997), the maximum earthquake intensity in Umbria ranges from 6 to 11 MCS, and the maximum earthquake local magnitude ranges between 4.7 and 6.7. Some of the historical earthquakes are known to have triggered landslides. The oldest reported seismically induced landslide in the area is probably a rockslide at Serravalle del Chienti (in the Marche Region, but close to the Umbria border), triggered by the 30 April 1279 earthquake (Boschi *et al*., 1998; Antonini *et al*., 2002b). The most recent seismically induced landslides occurred in the period from September 1997 to April 1998 as a result of the Umbria-Marche earthquake sequence (Antonini *et al*., 2002b; Bozzano *et al*., 1998; Esposito *et al*., 2000).

Due to the lithological, morphological, seismic and climatic setting, landslides are abundant in Umbria (Felicioni *et al*., 1994; Guzzetti *et al*., 1996b, 2003a). Landslide abundance and pattern vary largely within each lithological complex that is characterised by a prevalent geomorphological setting and by typical geotechnical and hydrogeological properties (Guzzetti *et al*., 1996b). Mass movements occur almost every year in the region in response to prolonged or intense rainfall (Guzzetti *et al*., 2003; Cardinali *et al*., 2005), rapid snow melting (Cardinali *et al*., 2005), and earthquake shaking (Antonini *et al*., 2002b; Bozzano *et al*., 1998; Esposito *et al*., 2000). Landslides in Umbria can be very destructive, and have caused damage at several sites (Figure 2.6). In the 20th century a total of 29 people died or were missing and 31 people were injured by slope movements in Umbria in a total of 13 harmful events (Guzzetti *et al*., 2003; Reichenbach *et al*., 2005).

Research on slope movements is abundant in Umbria. Landslide inventory maps were compiled by Guzzetti and Cardinali (1989, 1990) (§ 3.3.2.1), Antonini *et al*. (1993), Cardinali *et al*. (2001) (§ 2.3), and Antonini *et al*. (2002a) (§ 3.3.2.2). Such studies revealed that landslides cover about 8% of the territory. Locally, landslide density is much higher, exceeding 20% (Antonini *et al*., 2002b; Barchi *et al*., 1993; Carrara *et al*., 1991, 1995; Cardinali *et al*., 1994; Galli *et al*., 2005). Geomorphological relationships between landslide types and pattern, and the morphological, lithological and structural settings were investigated among others by Guzzetti and Cardinali (1992), Barchi *et al*. (1993), and Cardinali *et al*. (1994), and were summarized by Guzzetti *et al*. (1996b). Site-specific, geotechnical investigations on single landslides or landslide sites were conducted at several localities, mostly in urbanised areas (e.g., Crescenti, 1973; Tonnetti, 1978; Diamanti and Soccodato, 1981; Calabresi and Scarpelli, 1984; Lembo-Fazio *et al*., 1984; Canuti *et al*., 1986; Cecere and

Lembo-Fazio, 1986; Righi *et al*., 1986; Tommasi *et al*., 1986; Ribacchi *et al*., 1988; Capocecere *et al*., 1993; Felicioni *et al*., 1994). Landslide susceptibility assessments have been completed in test areas and for different landslide types by Carrara *et al*. (1991, 1995) and by Guzzetti *et al*. (1999b, 2003b, 2005d). Historical information on the frequency and recurrence of failures in Umbria was compiled by the nation-wide project that archived data on landslides and floods in Italy (Guzzetti *et al*., 1994; Guzzetti and Tonelli, 2004) (§ 3.3.1.1). This information was recently summarized by Guzzetti *et al*. (2003a). A reconnaissance estimate of the impact of landslides on the population, the transportation network, and the built-up areas in Umbria was attempted by Guzzetti *et al*. (2003a). Landslide risk assessments were performed at selected sites by Cardinali *et al*. (2002b) and by Reichenbach *et al*. (2005) (§ 8.4).

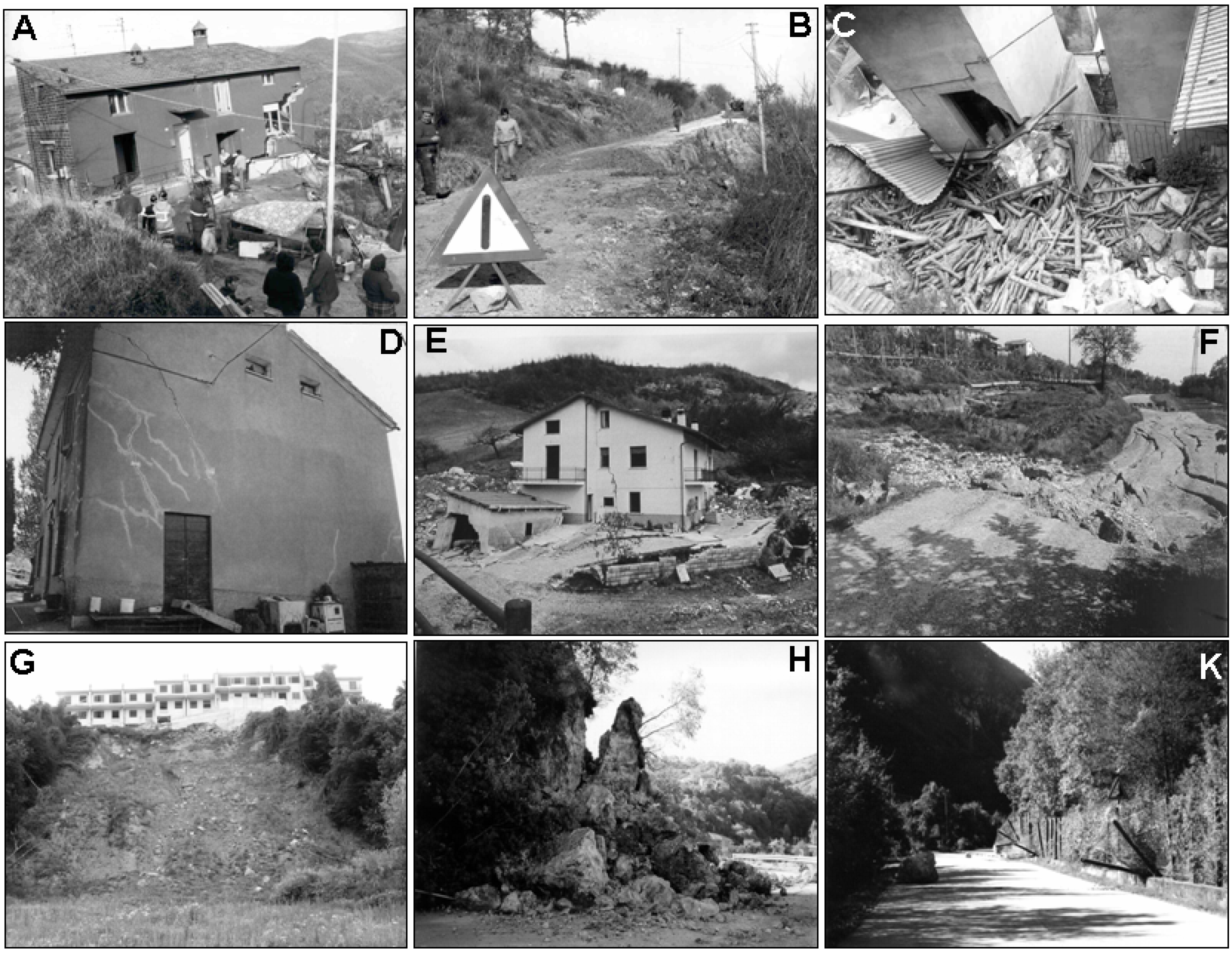

Figure 2.6 – Examples of typical landslide damage in Umbria. (A) House destroyed by a deep-seated slide at Monteverde on December 1982. (B) Road damaged by the Monteverde landslide. (C) Building damaged by a rock fall at Piedipaterno, on 15 September 1992. (D) House damaged by a deep-seated landslide triggered by rapid snow melting in January 1997 at Bivio Saragano. (E) House destroyed by the Valderchia landslide of 6 January 1997. (F) Road damaged by a deep-seated slide at San Litardo in January 1997. (G) Debris slides triggered by the December 2004 rainfall period at Porano. (H) Rock fall and toppling failure caused by the September-October 1997 earthquakes along a provincial road near Stravignano. (K) Rock falls caused by the September-October 1997 earthquakes along SS 320, along the Corno River valley.

Several of the examples presented in the next chapters will discuss or will use landslide, lithological, morphological, and thematic data available for Umbria. In § 3.3.2 I will present the geomorphological landslide inventory maps prepared by Guzzetti and Cardinali (1989, 1990) and by Antonini *et al*. (2002a). In § 3.4.1, the two geomorphological inventories will be compared with a detailed multi-temporal inventory map prepared for the Collazzone area. In § 3.3.3 I will present three recent landslide event inventory maps showing respectively: (i) slope failures triggered by rainfall in the period from the 1937 to 1941 in central Umbria, (ii) landslides triggered by rapid snow melting in January 1997 in Umbria, and (iii) rock falls triggered by the September-October 1997 earthquake sequence in the Umbria-Marche Apennines. In § 8.4 I will illustrate a geomorphological methodology to ascertain landslide risk devised and tested at selected sites in Umbria. Lastly, in § 8.5 I will discuss landslide damage in Umbria, including an attempt to identify areas of potential landslide impact to the built-up areas, the transportation network, and the agriculture.

2.3. Upper Tiber River basin, central Italy

The Upper Tiber River basin extends for 4098 km^2 in Central Italy, in the Umbria, Toscana and Emilia-Romagna Regions (Figure 2.7). Elevation in the area ranges from 163 m, at the basin outlet near Ponte Nuovo di Torgiano, to 1407 m, at Monte Fumaiolo, along the divide between the Adriatic Sea and the Tyrrhenian Sea.

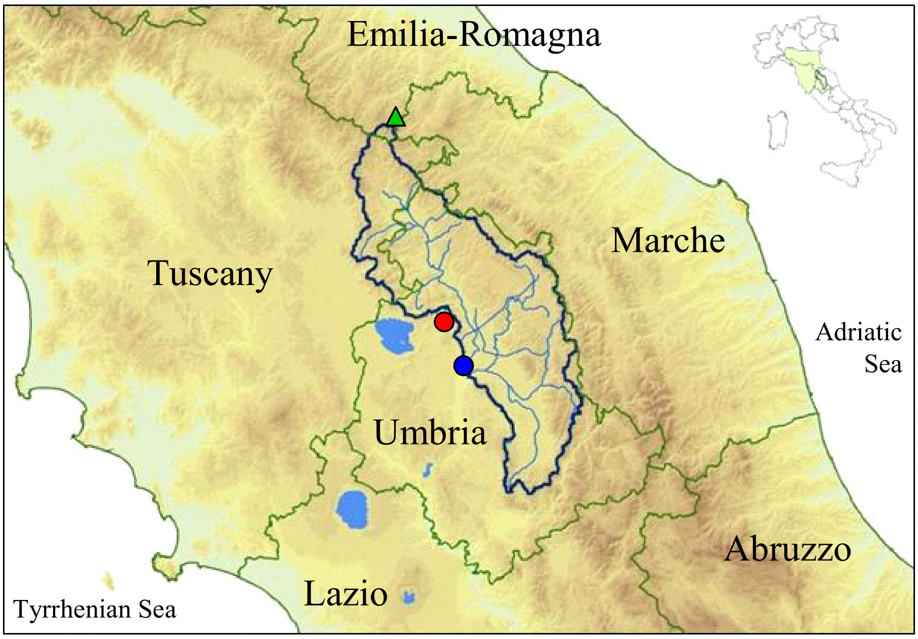

Figure 2.7 – Location of the Upper Tiber River basin, in Central Italy. Dark blue line shows main divide of the Upper Tiber River basin. Light blue lines show main drainage network in the catchment. Green lines show regional boundaries. Blue dot show location of the basin outlet, at Ponte Nuovo di Torgiano. Green triangle shows Monte Fumaiolo, where the springs of the Tiber River are located. Red dot shows the location of the city of Perugia.

For the Upper Tiber River basin, Cardinali *et al.* (2001) prepared a *Photo-Geological and Landslide Inventory Map of the Upper Tiber River Basin, Italy* (Figure 2.8, available at http://maps.irpi.cnr.it/website/tevere/tevere_start.htm). The map shows landslides, rock types, tectonics features, and attitude of bedding planes in the basin. The information shown in the map was obtained through the systematic analysis of stereoscopic aerial photographs flown at

1:33,000 scale and, limited to the outcrop of lake sediments and recent alluvial deposits, at 1:13,000 scale. Interpretation of the aerial photographs was aided by field surveys at the 1:10,000 scale, and by review of bibliographical data. In the photo-geological map, the rocks that crop out in the catchment are subdivided into 37 lithological units based upon the percentage of hard vs. soft rocks, as ascertained from photo-geological interpretation, field surveys, existing geological maps and other bibliographical data. Bedding plane domains were defined on the basis of photo-geological criteria as areas where the bedding plane attitude appeared to be constant. Within each bedding domain, the attitude of bedding planes was ascertained by comparing the bedding setting with the attitude of the local slope. Bedding dip, in eight classes, was estimated by comparing the local slope of terrain with bedding attitude in areas where bedding planes dipped towards the free face of the slope (Cardinali *et al.*, 2001).

The landslide inventory map for the Upper Tiber River basin shows more than 17,000 landslides, mostly deep seated and shallow slides and debris flows (Cardinali *et al.*, 2001). Deep seated landslides are chiefly translational and more rarely rotational slide, flow, slide earth-flow, complex and compound movements. The area of the deep seated landslides ranges from less than one hectare to more than one square kilometre. Landslides in this class mainly develop along sedimentary or tectonic discontinuities and are mostly dormant, but reactivations are present. Shallow landslides are slumps, earth flows and rotational or translational slides, locally exhibiting a flow component at the toe. Shallow failures mainly involve the colluvial cover and are mostly dormant, but recent, active and seasonal movements are locally present. Shallow landslides are particularly abundant on deep seated landslide deposits, where they occur as minor reactivations. Large debris flow deposits, consisting chiefly of granular materials, are deposited mostly along mountain streams and are most abundant where carbonate rocks crop out. Figure 2.9 shows the abundance of landslides in the 37 lithological units cropping out in the Upper Tiber River basin.

Next, Cardinali *et al*. (2002b) prepared a *Landslide Hazard Map of the Upper Tiber River Basin, Italy* (also available at http://maps.irpi.cnr.it/website/tevere/tevere_start.htm), showing landslide susceptibility in the catchment. I will discuss the statistical model constructed to obtain the susceptibility map in § 6.4, as an example of a landslide susceptibility zoning for a large area. The statistical model prepared to ascertain landslide susceptibility in the Upper Tiber River basin will be based upon a considerably large set of geo-environmental factors, including morphology, hydrology, lithology, structure, bedding attitude, and land use. Information on landslides, lithology, structure and attitude of bedding plane was obtained from the photo-geological and landslide inventory map of Cardinali *et al.* (2001). Morphometric and hydrological information was obtained from a DEM with a ground resolution of 25 m × 25 m. The digital terrain model was obtained from elevation information shown on topographic base maps published by the Italian Military Geographic Institute at 1:25,000 scale. Land use information was obtained through compilation in a GIS of land use maps published at 1:10,000 and 1:25,000 scale for the Umbria, Toscana and Emilia-Romagna Regions. Since the original land use maps had different legends, listing from 12 to more than 30 classes, merging of the land use classes was necessary. When merging the classes, care was taken in retaining information known or considered to be useful for explaining the presence or absence of landslides, their spatial distribution and abundance. Hence, forested areas were kept separated from re-forested terrain, and cultivated land was kept distinct from abandoned terrains. However, land use parcels showing woods with different tree species were merged, as were land parcels showing different types of specialized cultivations (e.g., vineyards, olive grows, fruit grows, etc.).

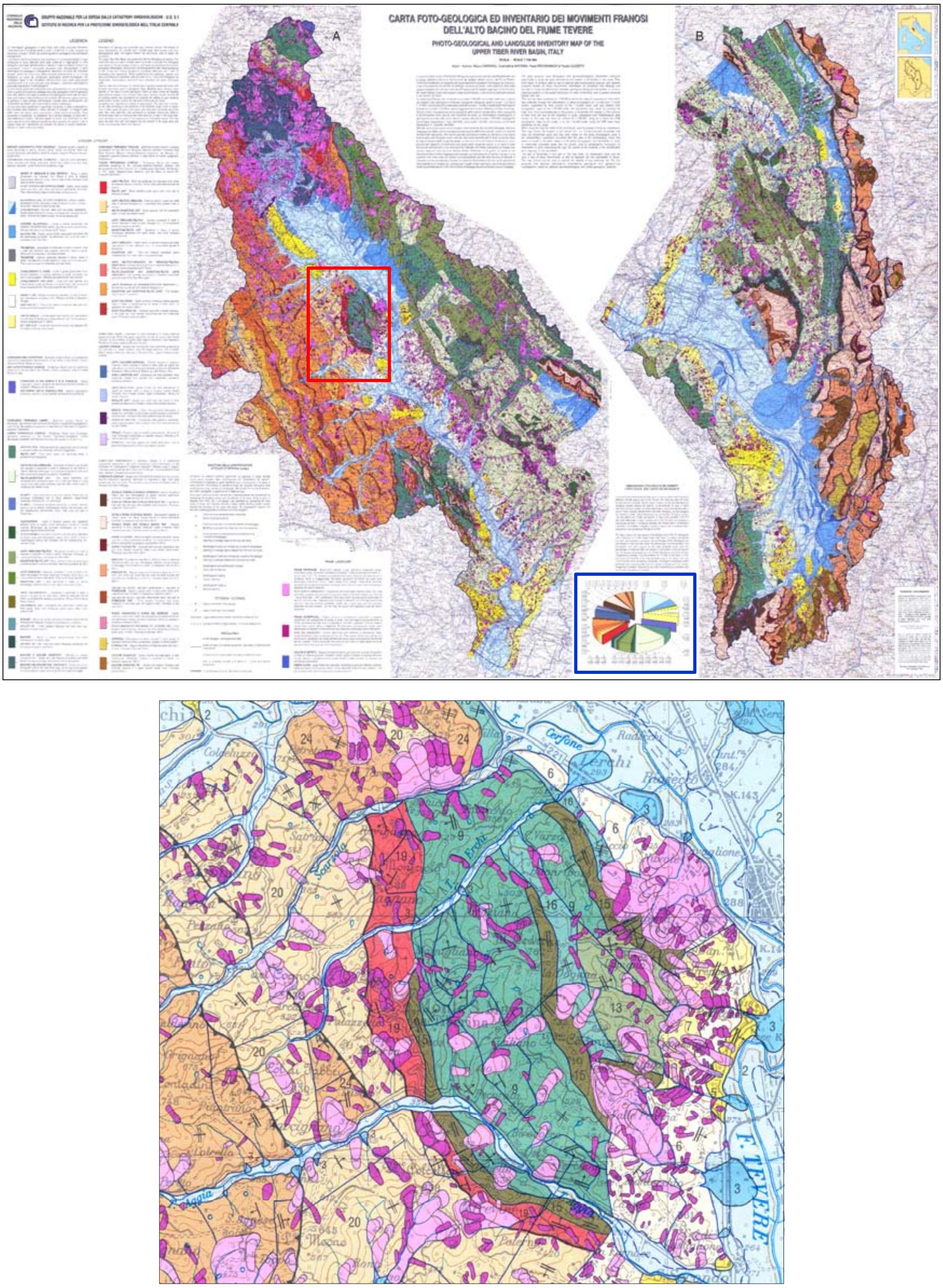

Figure 2.8 – Upper Tiber River basin. Upper map shows the *Photo-Geological and Landslide Inventory Map of the Upper Tiber River Basin, Italy* of Cardinali *et al.* (2001), available at http://maps.irpi.cnr.it/website/tevere/tevere_start.htm. Red line shows location of lower map. Blue line shows Figure 2.9. Lower map is an enlargement of a portion of the upper map showing cartographic detail. Colours show different rock types. Deep seated landslides are shown in pink. Shallow landslides are shown in violet.

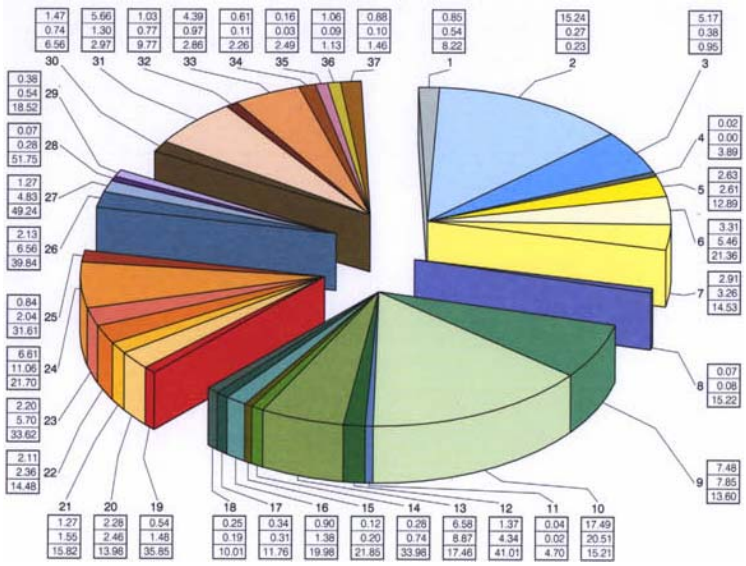

Figure 2.9 – Upper Tiber River basin. Abundance of lithological types and of landslides. Integer numbers indicate individual lithological units shown in the *Photo-Geological and Landslide Inventory Map of the Upper Tiber River Basin, Italy* (Cardinali *et al*., 2001). For each lithological unit, tables lists from top to bottom: (i) the percentage of the lithological unit with respect to the total basin area, (ii) the percentage of landslide area in the lithological unit with respect to the total landslide area, and (iii) the percentage of landslide area with respect to the extent of the lithological unit.

2.4. Collazzone area, Umbria Region

The Collazzone area extends for about 90 km^2 in central Umbria, south of Perugia (Figure 2.10.A). In the area, elevation ranges from 145 m, along the Tiber River valley, to 634 m, at Monte di Grutti. Minor tributaries of the Tiber River drain the area, where landscape is hilly, valleys are asymmetrical, and lithology and the attitude of bedding planes control the aspect and morphology of the slopes (Figure 2.10.B). Inspection of the available historical rainfall record reveals that precipitation is most abundant in the period between October and November, with a mean annual rainfall in the period from 1921 to 2001 of 884 mm.

In the area crop out old and recent sedimentary rocks, encompassing (Figure 2.10.C): (i) fluvial deposits, Holocene in age, along the main valley bottoms, (ii) continental gravel, sand and clay, Plio-Pleistocene in age, (iii) travertine deposits, Pleistocene in age, (iv) layered sandstone and marl, Miocene in age, and (v) thinly layered limestone, Lias to Oligocene in age (Conti *et al*., 1977; Servizio Geologico Nazionale, 1980; Cencetti, 1990; Barchi *et al*., 1991). Soils in the area range in thickness between 25 cm and 1.5 m, have chiefly a fine or medium texture, and exhibit a typical xenic moisture regime. The regional geomorphological landslide inventory maps of Guzzetti and Cardinali (1988, 1989) and of Antonini *et al*. (2002a) indicate that mass movements are abundant in the area, ranging in type and volume from large translational slides to deep and shallow flows.

For the Collazzone area, Galli *et al*. (2005) prepared a detailed landslide inventory map through the systematic interpretation of five sets of aerial photographs covering unsystematically the period form 1941 to 1997, extensive geological and geomorphological field surveys, and the review of bibliographical and archive data. In § 3.3.4.1 I will discuss this landslide inventory as an example of a multi-temporal landslide map.

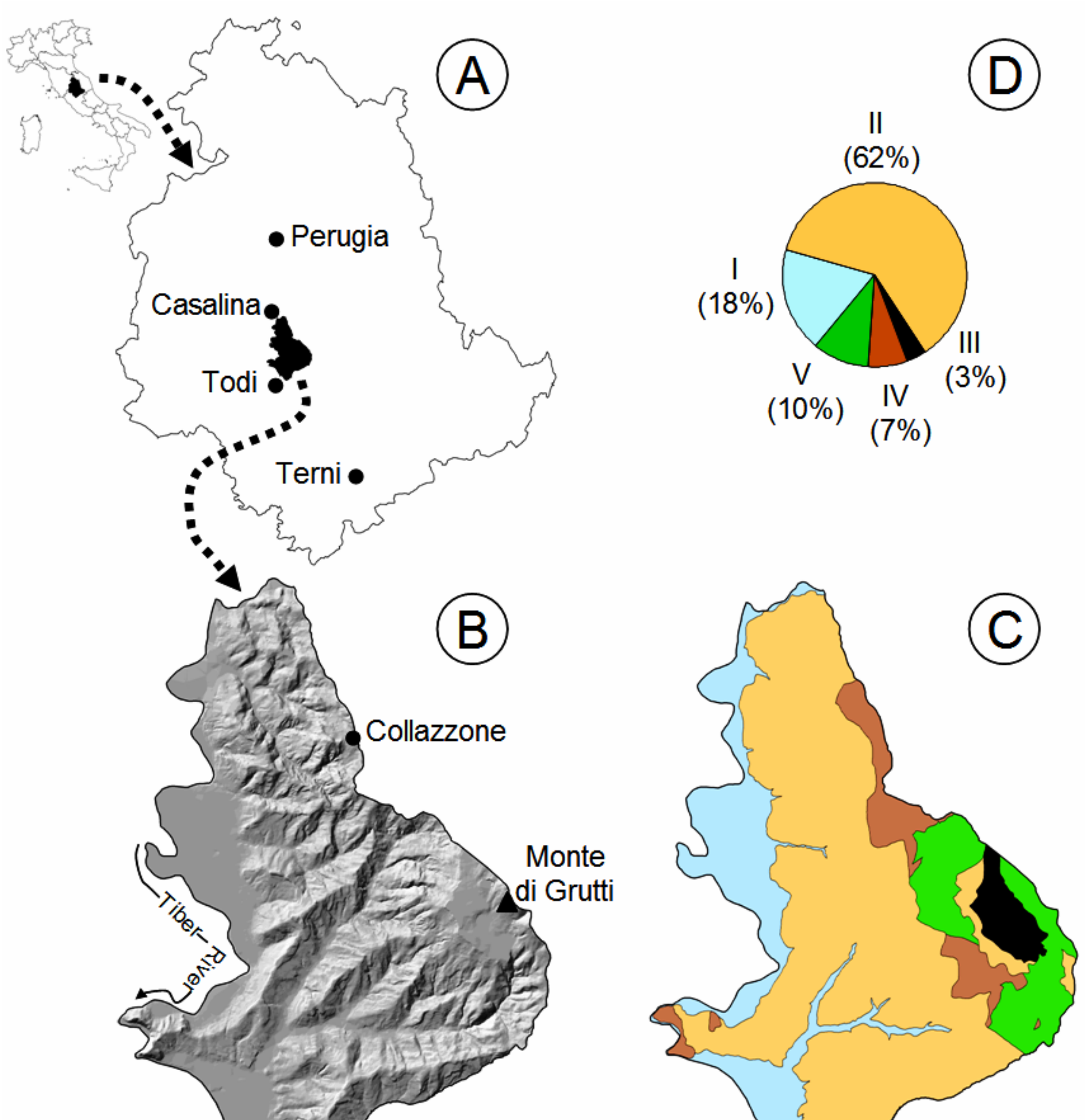

Figure 2.10 – (A) Location of the Collazzone study area in the Umbria region. (B) Shaded relief image of the Collazzone area, showing morphology of the area. (C) Lithological map for the Collazzone area. (D) Abundance of lithological types: (i) Alluvial deposits, (ii) Continental deposits, (iii) Travertine, (iv) Layered sandstone and marl, (v) Thinly layered limestone. Modified after Galli *et al*. (2005).

Guzzetti *et al*. (2005d) used the multi-temporal inventory map in combination with additional thematic information to prepare a landslide susceptibility model for the Collazzone area, and to test a validation scheme to verify the quality and performance of the obtained susceptibility estimate. I will discuss the susceptibility model and the proposed validation scheme in § 6.5.1.

The thematic information used to ascertain landslide susceptibility in the Collazzone area includes morphological, hydrological, lithological, structural, bedding attitude, and land use data. Morphological and hydrological information was obtained from a 10 m × 10 m DEM, prepared by interpolating 10 and 5 meter interval contour lines obtained from 1:10,000 scale topographic maps. Lithological and structural maps, at 1:10,000 scale, were prepared by Galli *et al*. (2005) through detailed field surveys aided by the interpretation of aerial photographs at various scales. Bedding plane domains were defined on the basis of the same photo-geological criteria adopted to prepare the *Photo-Geological and Landslide Inventory Map of the Upper Tiber River Basin, Italy* (Cardinali *et al*., 2001). Information on land use was obtained from a land use map compiled in 1977 by the Umbria Regional Government, and was locally revised by Guzzetti *et al*. (2005d) who interpreted recent aerial photographs, flown in April 1997 at 1:20,000 scale.

2.5. Nera River and Corno River valleys, Umbria Region

This study area extends for 48 km^2 south and south-weast of the village of Triponzo, in Valnerina, a geographical region comprising the northern part of the Nera River basin, in the south-eastern Umbria region (Figure 2.11). The Nera River and its major tributaries, including the Corno, Sordo, Vigi, and Tissino rivers, drain the western sector of the central Apennines, and locally flow into narrow valleys. Deep canyons where rock falls are common phenomena are present along the Nera River south of Visso, at Triponzo, Borgo Cerreto and Ferentillo, along the Corno River at Biselli and Balza Tagliata, and along the Vigi River near Sellano. In Valnerina, several roads, including three major regional roads (Strade Statali SS 209, SS 320 and SS 396), and a few towns (e.g., Triponzo, Borgo Cerreto, Piedipaterno and Ferentillo) are repeatedly affected by rock falls (e.g., Figures 2.6C and 2.6.K). Figure 2.12 shows examples of rock falls and rock fall damage in Valnerina.

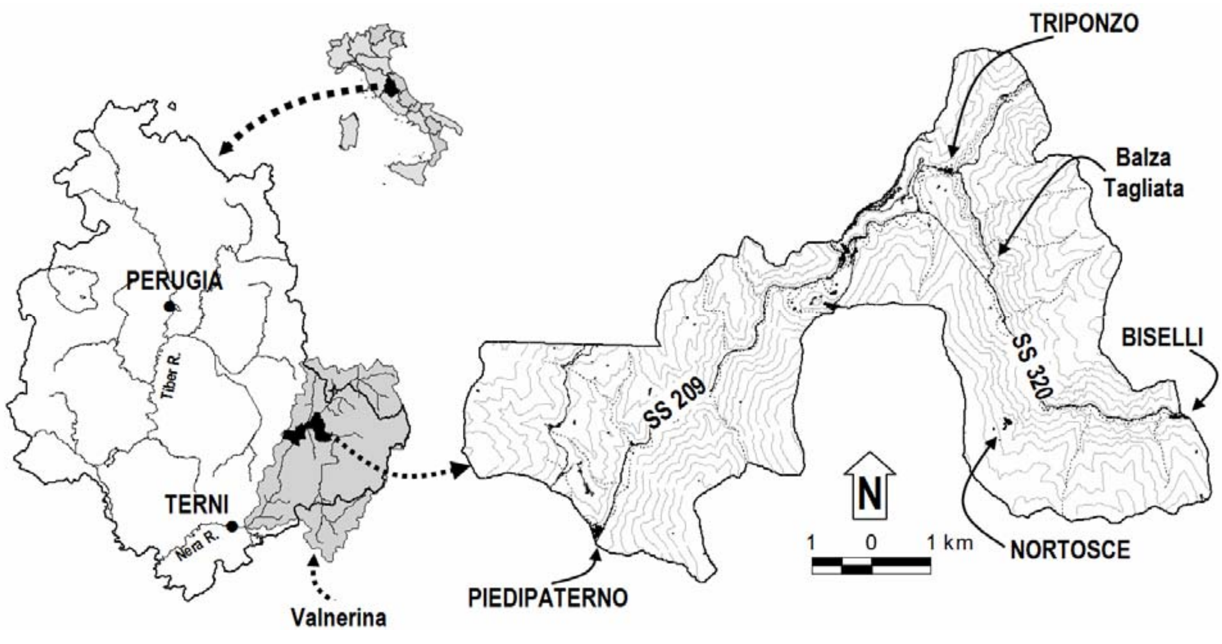

Figure 2.11 – Location of the Triponzo study area, in Valnerina, eastern Umbria. After Guzzetti *et al.* (2004b). Maps available at http://maps.irpi.cnr.it/website/valnerina/valnerina_start.htm.

In the area crop out sedimentary rocks pertaining to the Umbria-Marche stratigraphic sequence, Lias to Eocene in age. Rocks are mostly massive and layered limestone, cherty limestone, marly limestone and marl, with subordinate clay levels. Soils in the area are mostly thin and poorly developed. The geomorphological landslide inventory map completed for the Umbria Region by Antonini *et al*. (2002a) (§ 3.3.2.2) shows that in the entire Valnerina (i.e., the Nera River catchment, Figure 2.11) landslides cover more than 65 km^2, which corresponds to a proportion of about 6.3% of the territory. Landslides are deep-seated, complex or compound movements, and shallow failures, chiefly channelled debris flows and fast-moving rock slides, topples and rock falls. The last of these are triggered by various causes, including rainfall and freeze-thaw cycles, but are most abundant during earthquakes.

Figure 2.12 – Photographs showing rock falls triggered along roads in the Nera River valley and the Corno River valley by the September-October 1997 earthquake sequence in the Umbria-Marche Apennines. After Guzzetti *et al.* (2004b).

The earthquake sequence that affected the Umbria-Marche Apennines in the period from September to October 1997 produced abundant rock falls along the Nera River and the Corno River valleys (§ 3.3.3.3). Rock falls were particularly numerous along the Balza Tagliata gorge, SE of Triponzo (Figure 2.11). Through the interpretation of black and white aerial photographs flown at 1:20,000 scale a few weeks after the earthquakes, Antonini *et al*. (2002b) prepared a photo-geological map, at 1:10,000 scale, showing: (i) deep-seated landslides, (ii) shallow landslides, (iii) surface deposits, including talus deposits and debris cones, and (iv) the location of possible rock fall source areas. Oblique aerial photographs taken with a handheld camera from a helicopter immediately after the earthquakes were used to refine the mapping of rock fall source areas locally. Guzzetti *et al*. (2003) mapped the location of the earthquake induced slope failures, and analysed the frequency-volume statistics of the rock falls.

Guzzetti *et al*. (2004b) exploited the photo-geological map, and the map of the earthquake induced rock falls to determine rock fall hazard along the Nera and Corno rivers valleys. In addition to the described lithological and landslide information, to ascertain rock fall hazard a detailed digital terrain model and land use information were used. The DEM, with a ground resolution of 5 m × 5 m, was obtained by interpolating 10 and 5 meter interval contour lines obtained from 1:10,000 scale topographic base maps. Land use information was obtained from a regional land use map prepared at 1:10,000 scale through the interpretation of large-scale aerial photographs taken in 1977.

In § 7.5 I will discuss the obtained rock fall hazard model, including the mitigating effects of recently installed rock fall defensive measures, and the residual risk to vehicles travelling along the main roads in the Nera River and the Corno River valleys. Results of the models and thematic maps are available at http://maps.irpi.cnr.it/website/valnerina/valnerina_start.htm.

2.6. Staffora River basin, Lombardy Region, northern Italy

The Staffora River basin extends for 275 km^2 in the southern Lombardy region, in the northern Apennines of Italy (Figure 2.13). Elevation in the area ranges from about 150 m at Rivanazzano, to 1699 m at Monte. Chiappa. The Staffora River, a tributary of the Po River, drains the area. In the 42-year period from 1951 to 1991, annual rainfall in the area ranged from 410 to 1357 mm, with an average value of 802 mm. Inspection of the historical rainfall record indicates that precipitation is most abundant in the autumn and in the spring (Guzzetti *et al*., 2005a).

In the Staffora River basin crop out marine, transitional and continental sedimentary rocks, Cretaceous to Holocene in age (Servizio Geologico Nazionale, 1971). Marine sediments include: (i) sequences of layered limestone, marly-limestone, marl and clay, with ophiolites, (ii) disorganized, and highly fractured marl and clay, overlaid by massive sandstones, and (iii) shallow marine sediments pertaining to the Gessoso-Solfifera Formation. Transitional deposits feature conglomerates, with lenses of marl and sand, Oligocene in age. Fluvial and terraced deposits, Holocene in age, represent the continental deposits and outcrop along the main valley bottoms. Soils have a fine to coarse texture, largely depending on the parent material, exhibit a xenic moisture regime, and range in thickness from less than 50 cm to more than 1.5 meter.

The area has a complex structural setting resulting from the superposition of two main tectonic phases associated to the formation of the Apennines mountain chain. A compressive phase of Cretaceous to Eocene age produced large, east-verging thrusts with associated anticlines, synclines and transcurrent faults. Next, an extensional tectonic phase of Oligocene to Holocene age, produced chiefly normal faults. The lithological and the structural settings control the morphology of the area, which features steep and asymmetric slopes, dissected by a dense, locally actively eroding stream network. Landslides are abundant in the area, and range in type and size from large rotational and translational slides to deep and shallow flows. Some of the landslides are presumably very old in age. Very old landslides are mostly relict or dormant, and are partially concealed by forest and the intensive farming activity.

Guzzetti *et al*. (2005a) compiled a detailed multi-temporal inventory map for the Staffora River basin (Figure 2.14). The multi-temporal inventory was prepared at 1:10,000 scale through the interpretation of five sets of aerial photographs of different dates. Each set of aerial photographs was interpreted separately to obtain individual (separate) landslide inventory maps. Next, the individual landslide maps were merged in a GIS to obtain the multi-temporal inventory. In the separate inventory maps (Figure 2.14 A to E), landslides were classified according to the type of movement and the estimated age, activity, depth, and velocity. Landslide type was defined according to Varnes (1978) and the WP/WLI (1990). For deep-seated slope failures, the landslide crown was mapped separately from the deposit. Landslide age, activity, depth, and velocity were determined based on 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.

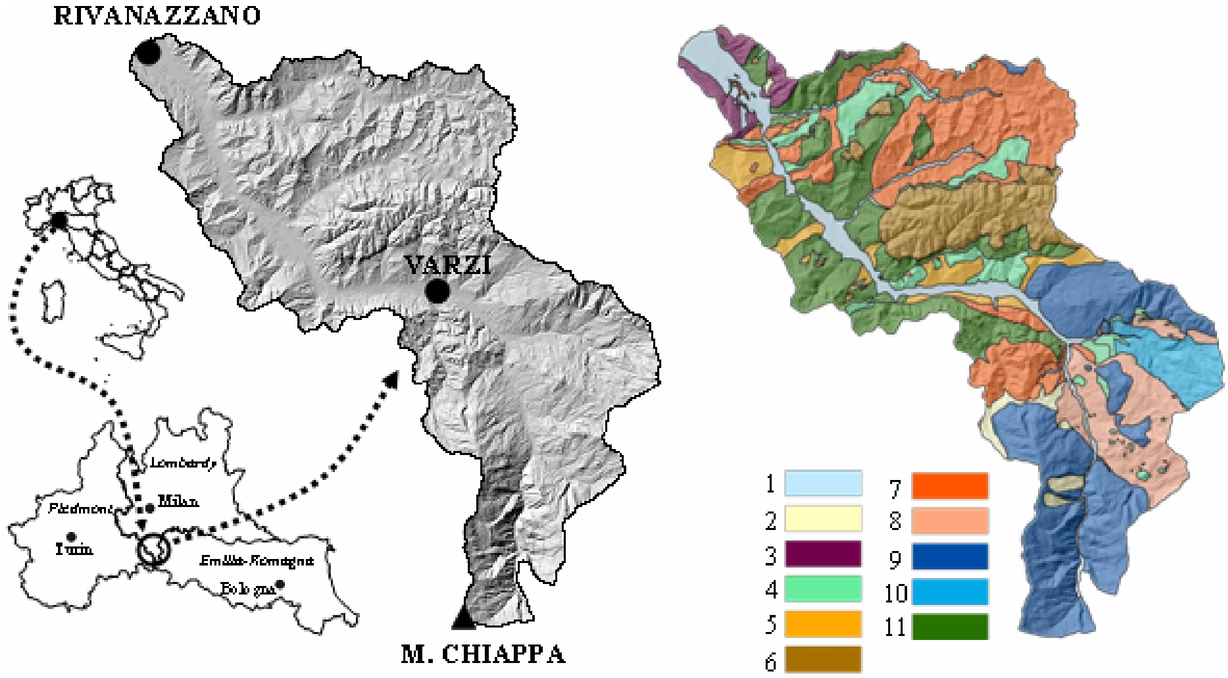

Figure 2.13 – Location, morphology and lithology of the Staffora River basin, in the northern Apennines of Italy. Left, location and general morphology of the area. Right, lithological map; (1) alluvial deposit, (2) detritus, (3) sand and gravel, (4) chaotic complex, (5) silty marl and clay, (6) massive sandstone, (7) layered sandstone, (8) layered sandstone with marl, (9) layered limestone with marl, (10) layered limestone, (11) layered marl with sandstone.

Landslides were classified active where they appeared fresh on the aerial photographs of a given date. A landslide was mapped active in an earlier flight and dormant in the subsequent photographs, if clear signs of movement were not identified in the more recent photographs; or the landslide was mapped continuously active if it appeared fresh in two or more flights, indicating repeated or continuous movements. Mass movements were classified as deep-seated or shallow, depending on the type of movement and the estimated landslide volume. The latter was based on the type of failure, and the morphology and geometry of the detachment area and the deposition zone. Landslide velocity (WP/WLI, 1995) was considered a proxy of landslide type, and classified accordingly (Cardinali *et al*., 2002a; Reichenbach *et al*., 2005).

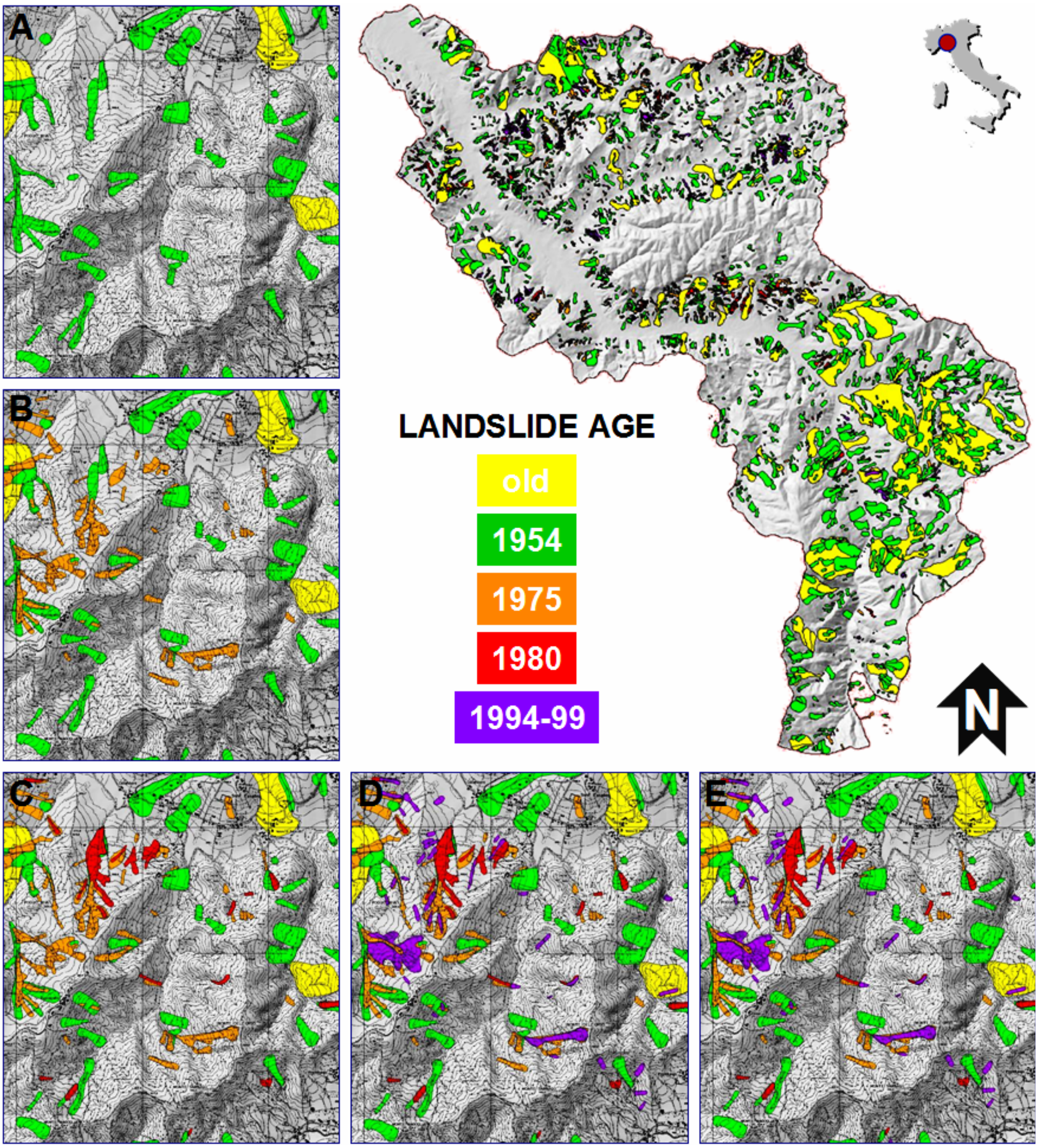

Figure 2.14 – Multi-temporal landslide inventory map for the Staffora River basin, southern Lombardy Region. Maps from (A) to (E) show, with different colours, landslides of different age, identified on aerial photographs of different age. Map available at http://maps.irpi.cnr.it/website/staffora/staffora_start.htm.

Table 2.1 shows the number, total extent and area statistics of the landslides identified in the different sets of aerial photographs. The largest number of failures and the largest landslide area were identified in the 1954 photographs, which also show landslides of much older age. In the other flights, only new and recent landslides were identified. The entire landslide inventory shows 3922 landslides, including 89 very old, relict mass movements. The multi-temporal map covering an undefined period from pre-1955 to 1999 (A_1–E_2 in Table 2.1) shows 3833 landslides, and does not include the relict landslides. The multi-temporal inventory map covering the 45-year period from 1955 to 1999 (A_2–E_2) shows 2390 landslides.

Guzzetti *et al*. (2005a) exploited the multi-temporal inventory map to ascertain landslide hazard in the Staffora River basin. In § 7.3 I will discuss in detail this experiment as a prototype example of a complete (comprehensive) landslide hazard assessment at the basin scale. To determine landslide hazard, in addition to the multi-temporal inventory, Guzzetti *et al*. (2005a) used morphometric, hydrological, lithological and land use information. Morphometric and hydrological information was obtained automatically from a digital terrain model with a ground resolution of 20 m × 20 m. The DEM was prepared by interpolating 10 meter interval contour lines obtained from 1:10,000 scale topographic base maps. Lithological information was obtained from existing geological maps, at 1:10,000 and 1:100,000 scale. Land use information was obtained through the interpretation of aerial photographs flown in the summer 1994 at 1:25,000 scale.

Table 2.1 – Staffora River basin. Landslide descriptive statistics obtained from the available multi-temporal inventory map (Figure 2.14). Characteristics of aerial photographs are: A; 18 July 1955, black and white, 1:33,000 scale. B; winter 1975, black and white, 1:15,000. C; summer 1980, colour, 1:22 000. D; summer 1994, black and white, 1:25,000. E; 22 June 1999, colour, 1:40,000. Percentage of landslide area (*) computed with respect to the total area covered by landslides (A_0–E_2).

INVENTORY	ESTIMATED LANDSLIDE AGE	LANDSLIDE		LANDSLIDE AREA				
		Number	Density	Total	Percentage*	Min	Mean	Max
		#	#/km^2	km^2	%	ha	ha	ha
A_0	very old (relict)	89	0.32	34.72	49.30	5.73	39.01	238.49
A_1	older than 1955	1443	5.27	38.24	54.30	0.09	2.79	82.67
A_2	1955 active	306	1.12	2.46	3.49	0.07	0.80	16.34
B_1	1955-1975	318	1.16	2.38	3.39	0.02	0.75	5.10
B_2	1975 active	685	2.50	4.41	6.26	0.01	0.65	11.47
C_1	1975-1980	89	0.32	1.32	1.87	0.04	1.48	11.91
C_2	1980 active	305	1.11	2.40	3.41	0.05	0.79	11.91
D_1	1980-1994	455	1.66	2.06	2.92	0.05	0.45	17.78
D_2	1994 active	175	0.63	1.36	1.94	0.05	0.78	7.79
E_1	1994-1999	19	0.07	0.65	0.93	0.36	3.43	11.91
E_2	1999 active	38	0.14	0.85	1.21	0.19	2.24	11.91
A_0–A_1	very old and older than 1955	1532	5.57	63.22	90	0.09	4.13	238.49
A_0–E_2	very old to 1999 active	3922	14.26	70.42	100	0.01	1.79	238.49
A_1–E_2	older than 1955 to 1999 active	3833	13.93	46.43	66	0.01	1.21	17.78
A_2–E_2	1955 active to 1999 active	2390	8.69	12.08	17	0.01	0.36	17.78