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Landslide Risk to the Population of Italy and Its Geographical and Temporal Variations

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ABSTRACT

Landslides cause damage to the population in Italy every year. Using an updated version of a historical catalog of landslide events with human consequences, we employed a new approach to investigate landslide risk to the population in Italy over time. We studied the temporal and geographical variation of risk on the basis of two classifications of the Italian territory. We used (1) the five zones based on the average terrain elevation and the distance to the seacoast of the Italian municipalities and (2) the topographical areas based on a semi-quantitative, stepwise approach of derivatives of altitude. We estimated individual landslide risk levels in the five zones for the north, center, and south of Italy and for three different periods between 1861 and 2010. To determine new societal landslide risk levels, we established the probability of experiencing severe landslide events in the eight topographical areas by modeling the empirical distributions of events with a Zipf distribution. The catalog used covers the period 91 BC to 2011; the number of events in the catalog increased with time. The reduced number of events in the early part of the catalog is attributed to incompleteness, a known bias in non-instrumental records of natural events. To overcome problems of incompleteness in carrying out the risk analysis, we used the recent portion of the catalog between 1861 and 2010. We believe that the quantification of the risk posed by landslides to the population is an important step for increasing awareness of the problem among Italian administrators and citizens.

14.1. INTRODUCTION

During the 20th century and the first decade of the 21st century, landslides in Italy have killed or injured 8077 people in at least 1398 events at 1239 different sites. In the same period, the number of homeless and evacuees caused by landslides exceeded 211,000. These figures indicate that landslide risk to the population in Italy is severe and widespread and that establishing landslide risk levels to the population is therefore a problem of both scientific and societal interest.

Even though landslides are common in Italy and they cause damage to the population every year, little interest has been shown in this problem at both the scientific and political levels. A great deal of work has been done to evaluate and map the landslide risk for specific areas in Italy, but fewer studies have been carried out to assess landslide risk levels to the population.

Latter [1969] suggested that the number of deaths caused by landslides can be used as a measure of the magnitude of a landslide disaster, and *Morgan* [1991, 1997], *Cruden and Fell* [1997], *Fell and Hartford* [1997], and *Evans* [1997] attempted to establish landslide risk

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levels, and related definition criteria, on the basis of the number of people killed by slope failures. According to these authors, when we refer to the population, quantitative landslide risk analyses are aimed at defining individual and societal (collective) risk levels. Generally, the risk analyses require a catalog of landslides and their human consequences, that is, deaths, missing persons, injured people, evacuees, and homeless. Using the historical information on damage to the population of Italy, estimates of individual and societal risk levels at national scale were first determined by *Salvati et al.* [2003], and were revised by *Guzzetti et al.* [2005a, 2005b]. *Cascini et al.*, in 2008, established individual and societal risk owing to landslides in the Campania region (southern Italy) and *Salvati et al.* [2010] estimated societal landslide risk levels in the 20 Italian regions. Most of these previous findings are based on administrative classifications of the Italian territory that do not properly correspond with the morphological assets. Furthermore, for some Italian regions, there were not enough data to calculate correct regional estimates [*Salvati et al.*, 2010].

As in our previous works, we start with a very detailed description of the temporal and geographical distribution of harmful landslide events and landslide casualties for which there is information in the historical catalog. We then describe the new risk analyses: we established individual risk levels in the five elevation zones; we analyzed the variation of these risk levels in the north, center, and south of Italy; and for each elevation zone, we investigated their variation throughout the period 1861–2010. To establish societal landslide risk we calculated new frequency/density curves of harmful landslide events for each of the eight topographical areas into which the Italian territory was divided by *Guzzetti and Reichenbach* [1994]. The new results were compared with those of our previous regional study, and the density curves we have calculated for other natural hazards, such as floods, earthquakes, and volcanic activity were compared with the new ones for landslides, calculated at a national scale. We also analyzed possible connections between landslide events with casualties and other natural harmful events.

14.2. GLOSSARY

We use the term “fatalities” to indicate the sum of the deaths and the missing persons due to a harmful landslide event. Casualties indicate the sum of fatalities and injured people. Evacuees were people forced to abandon their homes temporarily, while the homeless were people that lost their homes. Human consequences encompass casualties, homeless people, and the evacuees. A fatal landslide event is an event that resulted in fatalities. Individual risk is the risk posed by a hazard (e.g., a landslide) to any unidentified individual. Societal (or collective) risk is the risk posed by a hazard (e.g., a landslide) on society as a whole. Intensity and severity are used as synonyms to measure the number of fatalities or casualties. For clarity, intensity is used to analyze and discuss individual risk, and severity for societal risk.

14.3. RECORD OF HARMFUL LANDSLIDE EVENTS IN ITALY

Using different sources of information, including archives, chronicles, newspapers, scientific journals, technical reports, and other bibliographical sources, *Salvati et al.* [2003]; *Guzzetti et al.* [2005b]; and *Salvati et al.* [2010] compiled a comprehensive historical catalog of landslide events with direct human consequences to the population of Italy. Details on the sources of information used, and on the problems encountered in compiling the historical record are given in *Guzzetti et al.* [2005b] and in *Salvati et al.* [2010]. For this work, we have updated the record of harmful landslide events in Italy to cover the 2102 year period 91 BC to 2011 (Table 14.1). We performed the update by: (1) searching systematically national newspapers available online and, where available, their digital databases, (2) obtaining daily information from Google Alert (http://www.google.com/alerts) using pre defined keywords, (3) searching blogs and other Internet resources for specific events, (4) searching digital newspaper libraries and digital catalogs of archive documents, and (5) reading chronicles and recently published local history books.

Table 14.1 Statistics of Landslides Events with Deaths, Missing Persons, Injured People, Evacuees, and Homeless in Italy for Different Periods

Parameter	91 BC to 2011	1861–1909	1910–1959	1960–2011
Length of period (yr)	2,102	49	50	52
Deaths (d)	14,779	595	1,792	3,416
Missing persons (m)	40	1	24	15
Injured people (i)	2,752	83	720	1,940
Fatalities (d + m)	14,819	596	1,816	3,431
Casualties (d + m + i)	17,571	679	2,536	5,371
Evacuees and homeless people	217,400	5,750	51,470	156,220
Largest number of casualties in an event	1,917	79	220	1,917

The updated record lists 3545 landslide events that have resulted in deaths, missing persons, injured people, evacuees, and homeless in Italy, from 91 BC to 2011 (2102 years). In the record, quantitative information on the number of the human consequences caused by harmful landslides is available for 3089 historical events, 87.1% of the total number of the events. These events resulted in at least 17,571 casualties and in at least 218,000 homeless and evacuated people. For 456 events in the catalog (12.9%) information exists that landslide events have caused direct damage to the population, but the exact or approximate extent of the damage remains unknown [*Salvati et al.*, 2010]. Qualitative information on the number of casualties is abundant in the oldest portion of the catalog, and quantitative information on the homeless and the evacuees is most abundant after 1900.

14.3.1. Temporal Distribution of Landslide Events

The historical record lists 3545 harmful landslides, 53 of which (1.5%) are undated. The oldest landslide in the record that probably resulted in deaths was caused by an earthquake that occurred in the Modena province, Northern Italy, in 91 BC. During this event, landslides destroyed rural settlements [*Boschi et al.*, 1995], but the number and type of the human consequences remain uncertain. Since then, for 60 landslides in the historical record only qualitative information on the consequences is available (open squares in Figure 14.1). The first event in the catalog with a known number of fatalities (24 deaths) occurred in 843 AD at Ceppo Morelli, in the Piedmont region, Northern Italy.

Inspection of the Figure 14.1 shows that the number of reported events has increased significantly after 1700, and considerably after 1900. The severity of the recorded events, measured by the number of casualties, has also changed with time. The few landslide events recorded in the oldest portion of the catalog caused a large number of casualties, although the largest disaster due to a single landslide occurred on 9 October 1963, when 1917 people were killed by the Vajont rockslide.

During the 1018 year period 843–1860, 131 landslide events have caused at least 8979 casualties, with an average of 68.5 casualties per event. The figure decreased to 4.7 casualties per event in the 100 year period 1861–1960, the result of 698 events with 3286 total casualties. In the most recent period 1961–2011, the average number of casualties per event has increased to 7.0. Differences in the average number of casualties per event indicate that the oldest events reported in the historical record were mainly catastrophic, but also that the first part of the record is incomplete for the medium- and the low-severity events [*Guzzetti*, 2000]. In the record, lack of occurrences in any given period may be due either to incompleteness or to variations in the conditions that led to slope failures, including climate anomalies, rainfall events, land-use changes, and human actions [*Glade et al.*, 2001; *Guzzetti et al.*, 2005b].

Figure 14.2a shows the monthly distribution of landslide events with casualties, and the number of landslide casualties in Italy, in the 151 year period 1861–2011. In this period, damaging landslides were common in all seasons, with a peak in the autumn when 436 harmful events (30.2%) have resulted in 4429 landslide casualties (51.8%). The majority of the landslide events (192) occurred in November, and the largest number of casualties were recorded in October (3441). To investigate possible variations in time of the monthly distribution of landslide

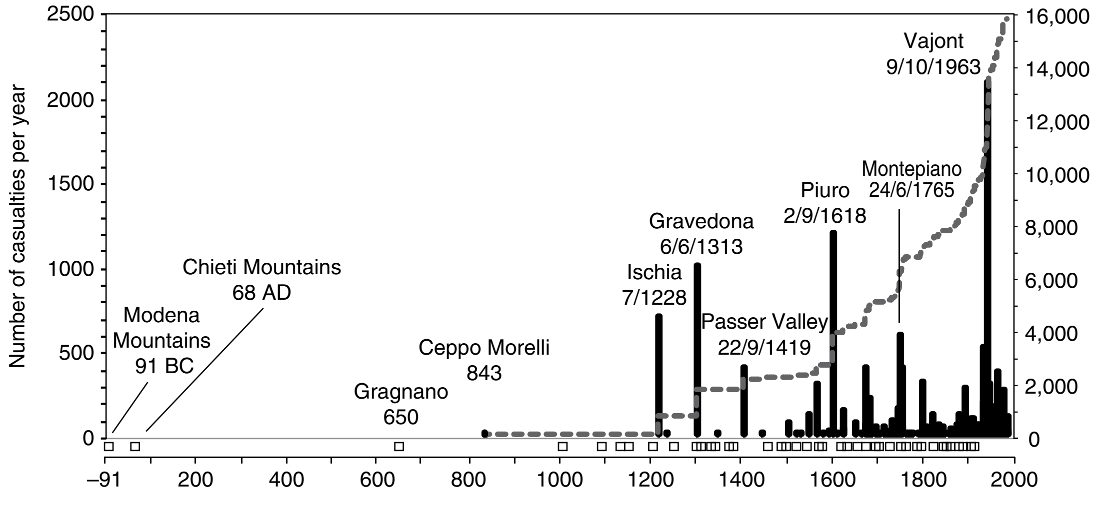

Figure 14.1 Historical record of landslide events with casualties in Italy in the 2102 year period 91 BC to 2011. Open squares show landslide events for which casualties occurred in unknown numbers. Dashed line shows the cumulative number of landslide casualties.

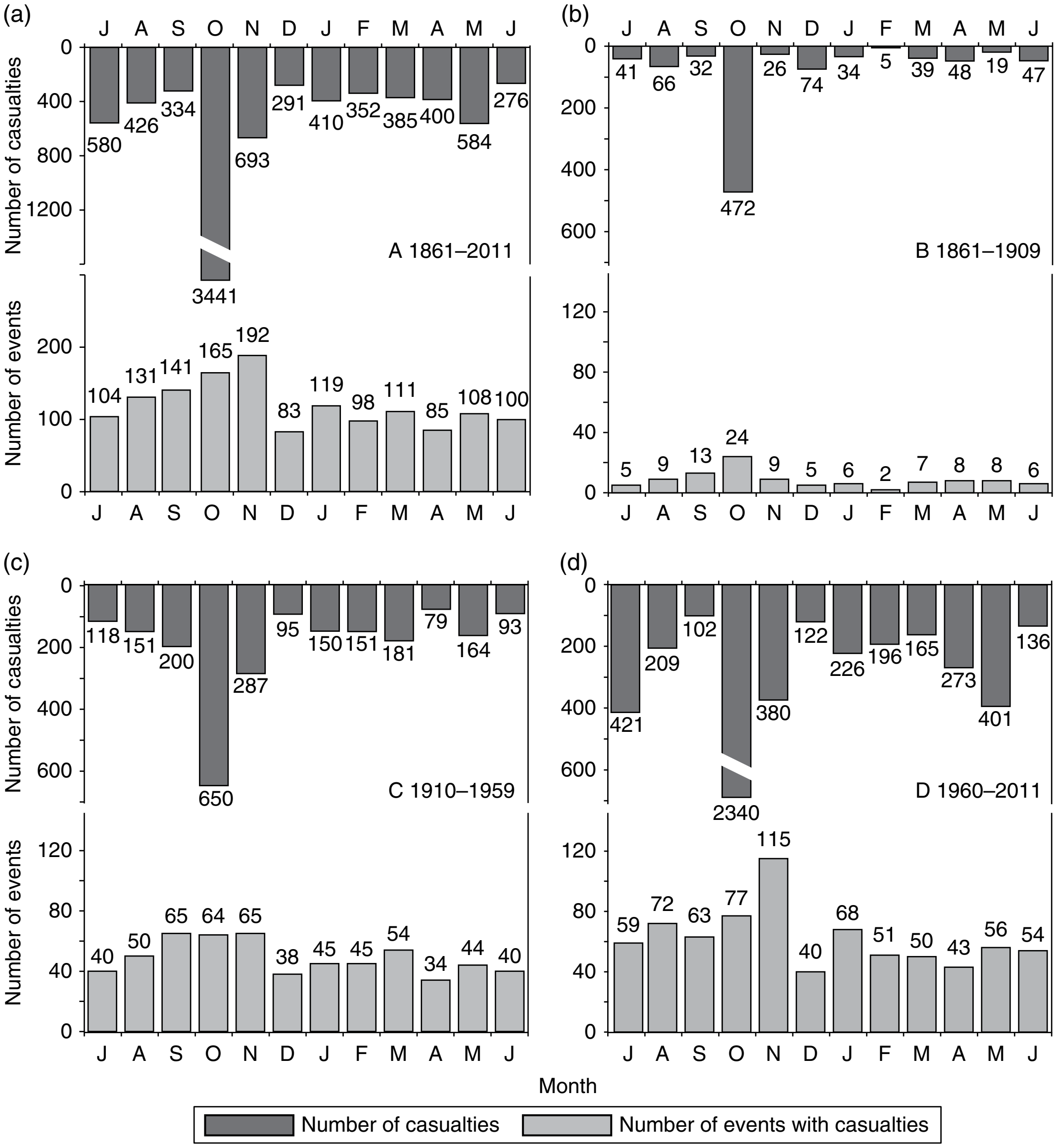

Figure 14.2 Monthly distribution of landslide events with casualties in Italy in the 151 year period 1861–2011 (a) and for three periods 1861–1909 (b), 1910–1959 (c), and 1960–2011 (d).

events with casualties, we segmented the historical catalog in three 50 year periods, that is, 1861–1909, 1910–1959, and 1960–2011 (Figure 14.2b–d).

Inspection of the bar charts reveals the strong increase in the number of casualties in October due to the Vajont catastrophe (broken columns in Figure 14.2a and d). It is also possible to see a slight variation in the monthly distribution of the landslide events with the peak value shifting from October to November. We explain the differences with possible variations in the distribution of the precipitation in the considered periods, possibly driven by climate changes.

14.3.2. Geographical Analysis

Information on the precise or approximate location of landslides with human consequences in Italy is available for most of the events listed in the historical record (97.6%). Figure 14.3 portrays the location of 3021 sites that have experienced one or more landslide events with human consequences. Harmful landslide events occurred in all of the 20 Italian regions, and in 1761 of the 8102 Italian municipalities (21.7%). As we described in previous investigations, the sites affected by harmful landslides are not distributed equally in Italy. Harmful landslides in the

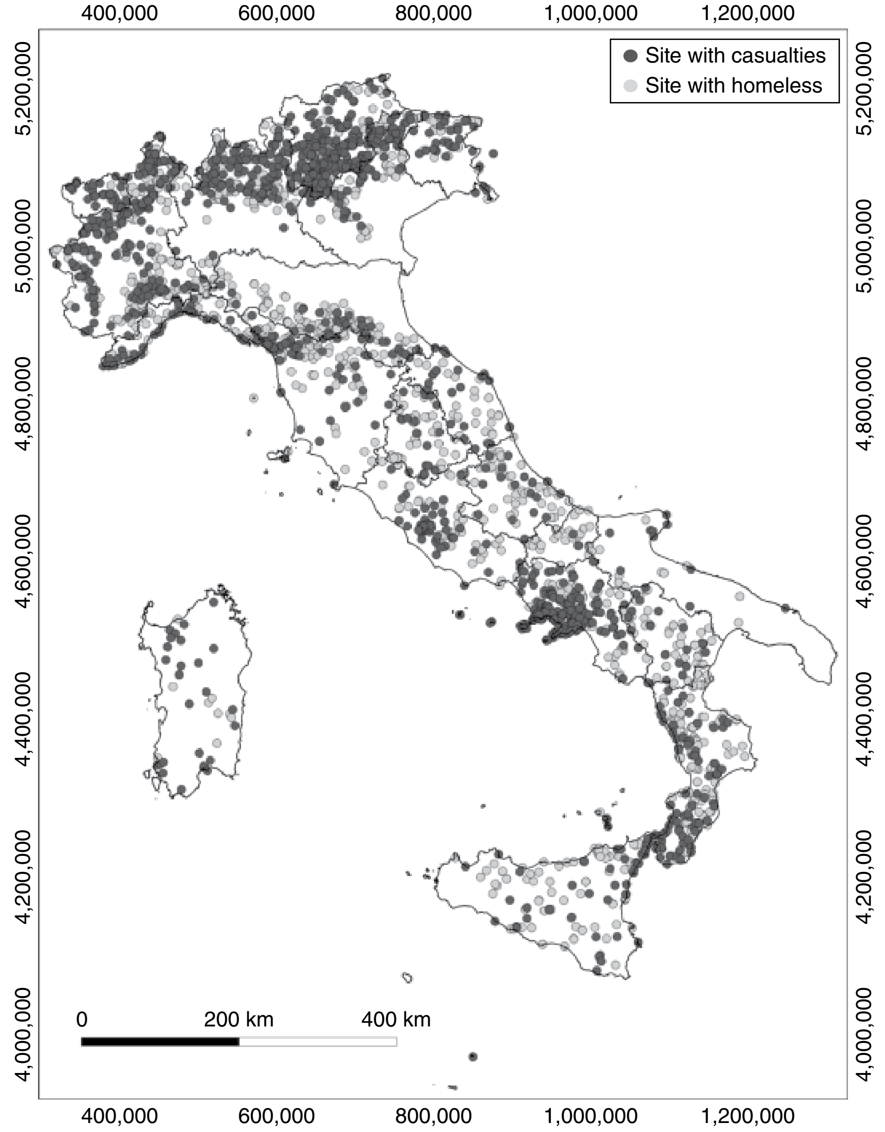

Figure 14.3 Map showing the location of 3021 sites affected by landslide events with direct consequences to the population in Italy in the 2102 year period 91 BC to 2011. Coordinate Reference System EPGS: 23032. Black dots show location of sites with landslide casualties (deaths, missing persons, injured people). Gray dots show location of sites with homeless and evacuated people.

historical record were more common in the Alps, in the Piedmont, and Liguria regions in Northern Italy, and in the Campania and Calabria regions in Southern Italy. Harmful landslide events occurred at many sites, but only at few sites human consequences were frequent [*Salvati et al.*, 2003; *Guzzetti et al.*, 2005b]. Using order statistics [*David and Nagaraja*, 2003], we find that of the 3021 landslide sites in the historical record, 2710 were affected once, 310 sites were affected 2 or more times, 8 sites were affected 5 or more times, and only 2 sites were affected 10 or more times. This indicates not only that landslide risk to the population is widespread in Italy but also that there are few sites where harmful events are frequent. The geographical persistence of landslides is highest in Campania, the region that experienced the largest number of landslide casualties (4105) in Southern Italy.

In our previous study, we analyzed the distribution of the number of landslide casualties in the 20 Italian regions for different periods (Figure 14.4). We used this temporal analysis to describe the most catastrophic and relevant landslide events that occurred in Italy. In the period 843–1860, a period for which we consider the historical catalog to be incomplete, the region that experienced the largest number of landslide casualties was Lombardy (2498; Figure 14.4c). In this region, the first catastrophic event occurred in June 1313 when a debris

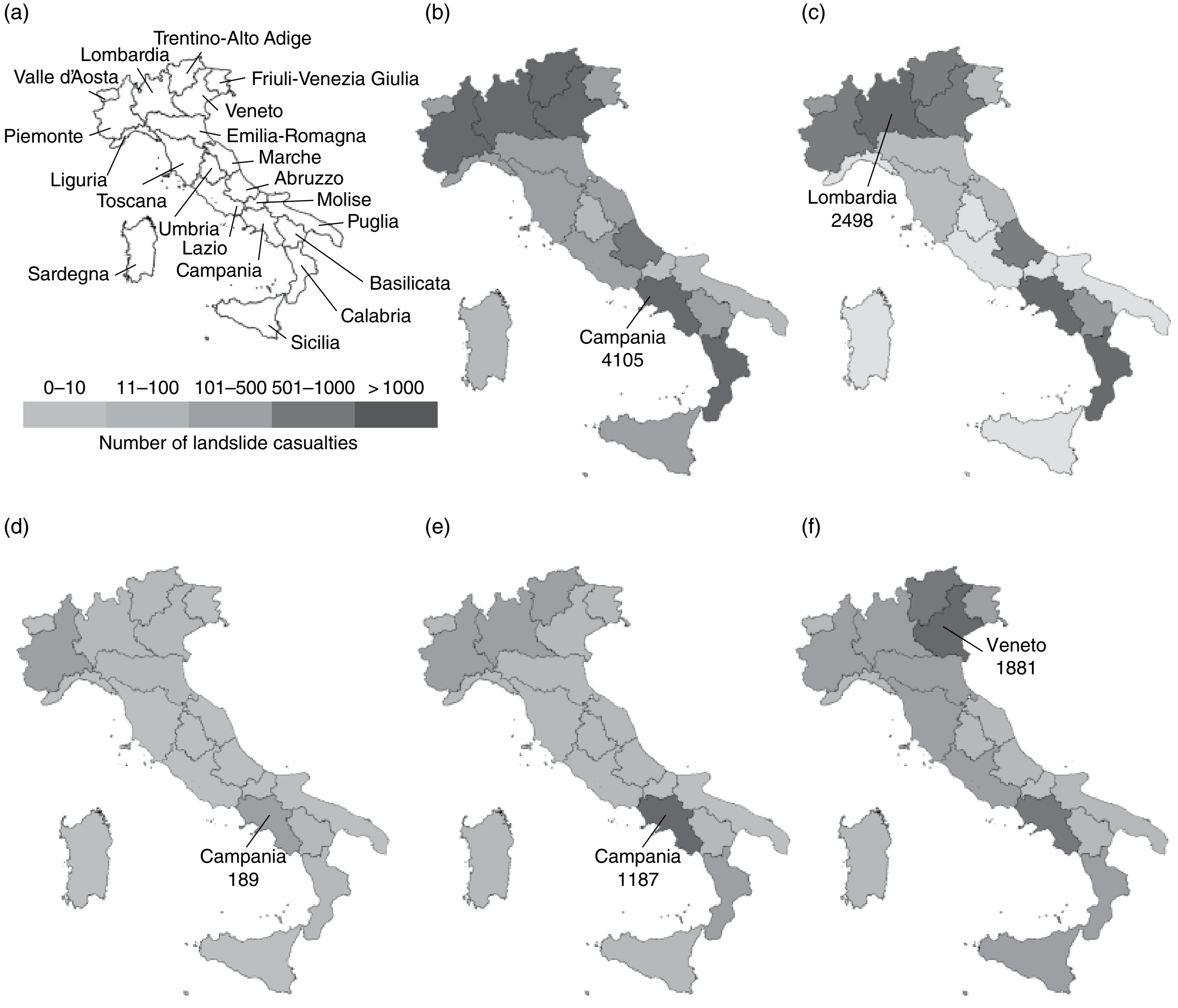

Figure 14.4 Maps of Italy showing the total number of landslide casualties (deaths, missing persons, injured people) in the 20 Italian regions for five periods. (a) Index map showing location and names of the 20 Italian regions. (b) Period 843–2011, (c) Period 843–1860, (d) Period 1861–1909, (e) Period 1910–1959, and (f) Period 1960–2011. Increasing shades of gray show increasing number of casualties.

flow destroyed the village of Gravedona, on the northern shore of Lake Como, completely submerging the village and killing ~1000 residents. The second catastrophic event occurred during the night of 4 September 1618 at Piuro, when 1200 people were buried by a rock avalanche that destroyed the village [*Guzzetti et al.*, 2005a]. Between 1861 and 1959, the Campania region suffered the largest number of casualties (Figure 14.4d and e), the result of destructive events which occurred chiefly in the Salerno area. In the most recent part of the record (1960–2011), the Veneto region, Northern Italy, experienced the largest number of casualties (1881; Figure 14.4f), most of which was caused by the 9 October 1963 Vajont rockslide. In the same period, the Campania region suffered the second largest number of casualties (792). The large number of casualties in Campania, historically and in the recent period, is the result of soil slips, debris flows, and mud flows in areas where a cover of volcanic ash overlies limestone on steep slopes, a highly hazardous geological setting typical of the area surrounding the Vesuvius volcano [*Vallario*, 2001; *Aceto et al.*, 2003; *Guzzetti et al.*, 2005b].

For this work, we have studied the geographical variation in the number of landslide events, and in the number of landslide casualties, in the five subdivisions established by the Italian National Institute of Statistics (ISTAT, web site: www.istat.it): 1, mountain; 2, coastal mountain; 3, hill;

Table 14.2 Number of Landslide Events with Casualties and Number of Landslide Casualties for Each Physiographical Subdivision in Three Main Geographical Areas (North, Center, and South) in Italy in the 151 Year Period 1861–2011

	ISTAT Physiographical Subdivisions	Area		Events		Casualties	
		km^2	%	#	#/100 km^2	#	#/100 km^2
North	1: Mountain	54,958	18.24	550	1.001	3947	7.182
	2: Coastal Mountain	481	0.16	8	1.662	39	8.104
	3: Hill	21,257	7.50	96	0.452	449	2.112
	4: Coastal Hill	1682	0.56	24	1.427	44	2.616
	5: Plain	41,882	13.90	9	0.021	14	0.033
Center	1: Mountain	22,368	7.42	43	0.192	133	0.595
	2: Coastal Mountain	302	0.11	16	5.295	51	16.88
	3: Hill	30,595	10.15	54	0.176	180	0.588
	4: Coastal Hill	10,171	3.38	32	0.315	160	1.573
	5: Plain	5379	1.78	51	0.948	106	1.971
South	1: Mountain	24,087	18.24	56	0.232	235	0.976
	2: Coastal Mountain	3914	1.30	41	1.048	228	5.825
	3: Hill	39,464	13.1	80	0.203	373	0.945
	4: Coastal Hill	22,250	7.38	276	1.240	1972	8.863
	5: Plain	22,547	7.48	55	0.244	249	1.104

4, coastal hill; and 5, plain. The five subdivisions are the result of the aggregation of adjacent municipalities, based on average terrain elevation values, and distance to the seacoast. The subdivisions are therefore based on administrative limits and physiographical conditions. We analyzed the distribution separately in the north, center, and south of Italy. Northern Italy (120×10^3 km^2, 39.9%) encompasses the Italian Alps, the Po, and Veneto plains, and part of the northern Apennines; Central Italy (69×10^3 km^2, 22.9%) comprises the central Apennines, the northern and central Tyrrhenian coast, and the central Adriatic coas; and Southern Italy (112×10^3 km^2, 37.2%) consists of the southern Apennines, the southern Tyrrhenian and Adriatic coasts, the Ionian coast, Sicily, and Sardinia. Table 14.2 shows that the largest number of landslide events with casualties (550) in the record was reported in the mountain subdivision of Northern Italy. In this physiographical subdivision, which includes the Alps, high intensity and prolonged rainfall events, combined with the availability of debris on steep slopes, have resulted in several destructive debris flows. The presence of large relative relief and hard rocks (e.g., granite, metamorphic rocks, massive limestone, and dolomite) has further facilitated the occurrence of rock falls, rock slides, and rock avalanches [*Guzzetti*, 2000], which are particularly hazardous landslide types due to their high mobility [*Cruden and Varnes*, 1996]. In Central Italy, the number of landslide events and landslide casualties is low, with the exception of the coastal mountain zone corresponding to the Apuane Alps in Tuscany. This area, which consists of five coastal mountain municipalities, is characterized by cumulated mean annual rainfall exceeding 3000 mm [*D'Amato Avanzi et al.*, 2004], and exhibits the largest spatial density of landslide casualties (16.9 casualties/100 km^2). In Southern Italy, landslide casualties are most abundant in the coastal hills (1972). In these areas, slopes are steep, relative relief is high, catchments are small, and rocks are highly tectonized and easily erodible [*Esposito et al.*, 2003; *Porfido et al.*, 2009].

We further studied the distribution and the frequency of harmful landslide events in each physiographical subdivision within the 20 Italian regions and results are shown in Tables 14.3 and 14.4. First, for each region, we calculated the percentage of the municipalities that experienced at least one harmful landslide event in each physiographical subdivision (Table 14.3). In the five subdivisions, less than half of the municipalities suffered landslide events, with the exception of the Apuane Alps, where all the municipalities have experienced at least one harmful landslide event. Next, we calculated the density of the harmful landslide events in each physiographical subdivision, and for each region. The density of the harmful events was calculated as the ratio between the total number of events in the considered area, and the total extent of the considered area in square kilometers (Table 14.4). The largest spatial density of events was measured in the coastal hills of Campania (0.18 events per square kilometer).

14.4. RISK EVALUATION

To study the temporal and geographical variations of landslide risk in Italy, we investigated the number of fatalities in relation to the size of the population, and we analyzed the frequency of the damaging events and the severity of the consequences, measured by the number of casualties. We used the former to determine individual

Table 14.3 Percentage of the Italian Municipalities, for Each Region, that Suffered Harmful Landslide Events, in the Five ISTAT Physiographical Subdivisions, for the Period 91 BC to 2011

		Percentage of Municipalities				
		1—Mountain	2—Coastal Mountain	3—Hill	4—Coastal Hill	5—Plain
North	Piemonte	36.89	—	17.21	—	4.32
	Valle d'Aosta	40.54	—	—	—	—
	Lombardia	32.70	—	6.85	—	0.53
	Trentino-Alto Adige	47.45	—	—	—	—
	Veneto	48.72	—	14.17	—	0.58
	Friuli-Venezia Giulia	41.38	—	25.00	—	1.82
	Liguria	14.14	63.64	7.14	32.53	—
	Emilia-Romagna	55.07	—	28.85	10.00	1.21
Center	Toscana	30.26	100.00	20.00	12.50	24.00
	Umbria	58.33	—	27.94	—	—
	Marche	23.25	—	10.75	11.65	—
	Lazio	10.00	—	15.94	38.23	23.53
	Abruzzo	19.28	—	18.18	16.44	—
South	Molise	11.90	—	19.51	18.18	—
	Campania	26.56	—	22.32	58.54	24.07
	Puglia	—	—	21.57	15.79	2.78
	Basilicata	29.33	33.33	34.04	—	66.67
	Calabria	29.79	47.46	25.47	32.81	27.27
	Sicilia	28.81	25.64	20.77	25.81	20.51
	Sardegna	11.76	—	6.14	14.46	3.70

Table 14.4 Density of Harmful Landslide Events for Each Region

		Number of Events/km^2				
		1—Mountain	2—Coastal Mountain	3—Hill	4—Coastal Hill	5—Plain
North	Piemonte	0.0201	—	0.0184	—	0.0025
	Valle d'Aosta	0.0129	—	—	—	—
	Lombardia	0.0288	—	0.0081	—	0.0003
	Trentino-Alto Adige	0.0262	—	—	—	—
	Veneto	0.0233	—	0.0105	—	0.0002
	Friuli-Venezia Giulia	0.0114	—	0.0138	0.0094	0.0007
	Liguria	0.0056	0.0727	0.0048	0.0332	—
	Emilia-Romagna	0.0139	—	0.0117	0.0048	0.0002
Center	Toscana	0.0090	0.0927	0.0033	0.0020	0.0098
	Umbria	0.0093	—	0.0080		—
	Marche	0.0045	—	0.0051	0.0069	—
	Lazio	0.0031	—	0.0059	0.0173	0.0197
	Abruzzo	0.0061	—	0.0145	0.0106	—
South	Molise	0.0061	—	0.0091	0.0036	—
	Campania	0.0117	—	0.0164	0.1837	0.0261
	Puglia	—	—	0.0024	0.0023	0.0005
	Basilicata	0.0075	0.0057	0.0073	—	0.0236
	Calabria	0.0123	0.0273	0.0128	0.0203	0.0066
	Sicilia	0.0043	0.0200	0.0044	0.0077	0.0033
	Sardegna	0.0012	—	0.0015	0.0020	0.0020

Density computed as the ratio of the total number of events in each subdivisions and the total area of the subdivision, in square kilometers, in the five ISTAT physiographical subdivisions, for the period 91 BC to 2011.

risk criteria, and the latter to determine societal risk levels [*Fell and Hartford*, 1997; *Guzzetti et al.*, 2005b; *Salvati et al.*, 2010]. To ascertain the individual and the societal landslide risk levels in Italy, we used the newly updated record of landslide events with casualties in Italy in the 150 year period 1861–2010.

14.4.1. Individual Landslide Risk

Individual risk levels are measured by mortality (or death) rates, which are given by the number of fatalities in a population, scaled to the size of the population, per unit time. In Italy, individual risk levels were first defined by *Guzzetti* [2000], and revised by *Salvati et al.* [2003] and *Guzzetti et al.* [2005b]. To calculate mortality, information on the number of fatalities and on the size of the population per year is required. We obtained (1) the number of landslide fatalities per year from the historical catalog of landslides with human consequences in Italy, and (2) information on the size of the population from general censuses data collected every 10 years by ISTAT, since 1861. For compatibility with previous studies [*Salvati et al.*, 2003, 2010; *Guzzetti et al.*, 2005a, 2005b], in this work mortality is the number of landslide fatalities per 100,000 people in a period of 1 year.

First, we investigated the distribution and the variation of the Italian population in the period 1861–2010. In this 150 year period, the population almost tripled, from 22.2 to 60.3 million. The increase was largest in the plains, moderate in the hills, and lowest in the mountains. From the 1920s, and increasingly in the second half of the 20th century, there was migration from mountainous areas to urban areas, which are generally located in the plains or lowland hills. Consequently, the increase in the size of the population in urban areas was larger than in the rural areas, and some of the hills and the mountains suffered net losses in the number of inhabitants [*Guzzetti et al.*, 2005a]. Analysis of Figure 14.5 reveals that in the ISTAT physiographical subdivisions the largest increase in population occurred in the plains, with a maximum increase of about 13 million in the Po and Veneto plains, in Northern Italy. Minor increases were observed in the hills, more precisely in the inland hills of Northern and Central Italy, and in the coastal hills of Southern Italy.

Using yearly information on the population of each physiographical subdivision, for the three main geographical subdivisions (North, Center, South), we calculated the yearly landslide mortality rates (LMR), and the corresponding average values, in the period 1861–2010 as shown in Figure 14.6. The largest average LMR was

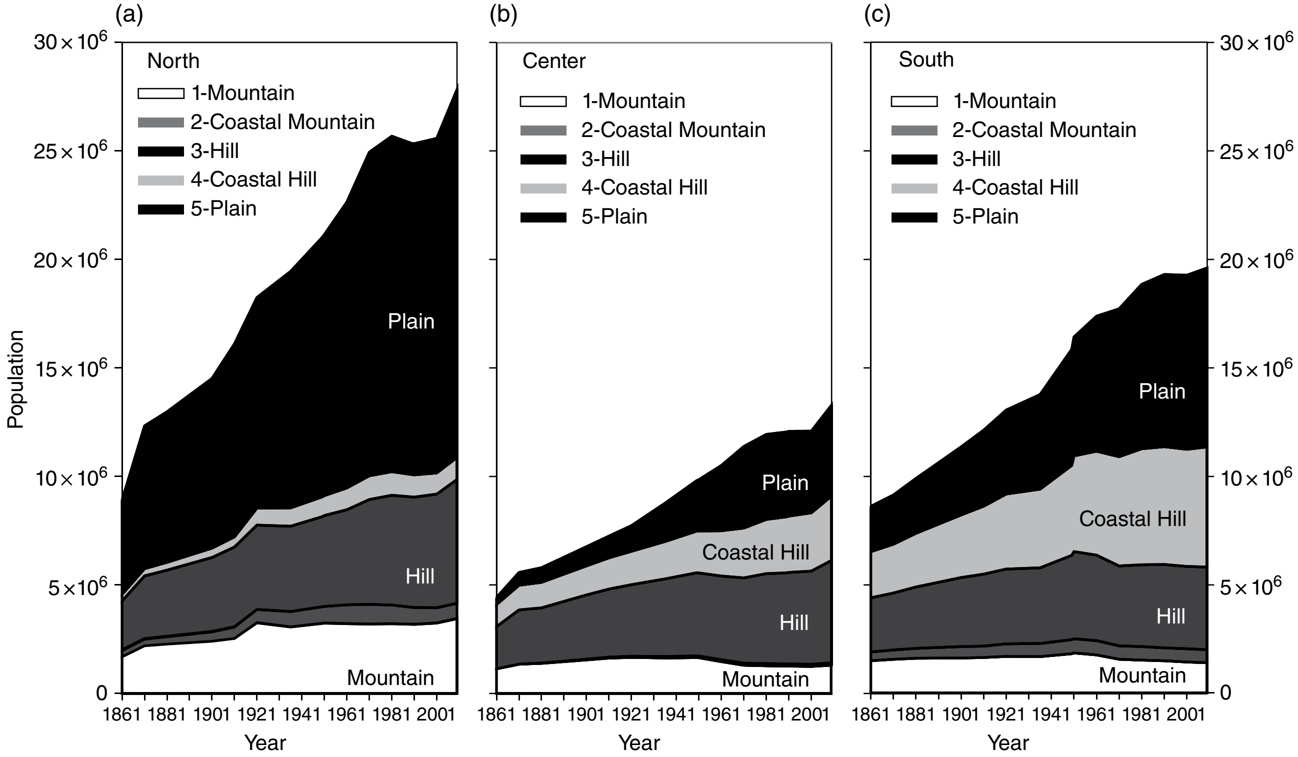

Figure 14.5 Temporal variation of the Italian population in the five ISTAT physiographical subdivisions, in the 150 year period 1861–2010, for the north (a), center (b), and south (c) areas of Italy. Shades of gray show different physiographical subdivisions: 1, mountain; 2, coastal mountain; 3, hill; 4, coastal hill; 5, plain.

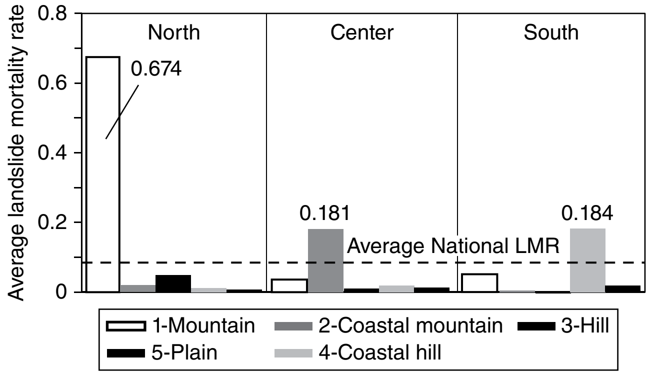

Figure 14.6 Average LMR in the five ISTAT physiographical subdivisions, and in the north, center, and south of Italy, for the 150 year period 1861–2010. Black dashed line shows average LMR for the whole of Italy.

Table 14.5 Average LMR in the Five ISTAT Physiographical Subdivisions, and in the North, Centre, and South of Italy, for Three 50 Year Periods: 1861–1909, 1910–1959, and 1960–2010

		1861–1909	1910–1959	1960–2010
North	1: Mountain	0.222	0.208	1.567
	2: Coastal Mountain	0.005	0.003	0.051
	3: Hill	0.060	0.054	0.032
	4: Coastal Hill	—	0.016	0.021
	5: Plain	8.2E^{-4}	3.9E^{-4}	6.4E^{-4}
Center	1: Mountain	0.014	0.051	0.042
	2: Coastal Mountain	0.067	0.103	0.369
	3: Hill	7.3E^{-4}	0.023	0.014
	4: Coastal Hill	—	0.049	0.009
	5: Plain	—	0.027	0.014
South	1: Mountain	0.012	0.090	0.052
	2: Coastal Mountain	0.004	0.350	0.139
	3: Hill	0.028	0.020	0.034
	4: Coastal Hill	0.048	0.452	0.048
	5: Plain	—	0.010	0.045

recorded in the mountains of Northern Italy (0.674), followed by the coastal hills of Southern Italy (0.184), and by the coastal mountains of Central Italy (0.181). The smallest LMRs, in the range 0.0006–0.002, were measured in the plains. Overall, the national LMR in the observation period was 0.084.

To investigate the temporal variation of landslide mortality, we calculated the average LMR for three subsequent periods: 1861–1909, 1910–1959, and 1960–2010. Results are shown in Table 14.5. In the most recent period (1960–2010), mortality increased in the mountains of Northern Italy and in the coastal mountains of Central Italy. In Southern Italy, mortality decreased slightly in the mountains, and significantly in the coastal hills. The marked increase of mortality in the mountains of the Northern Italy was primarily the result of two high-impact events: (1) the 9 October 1963 Vajont rockslide with 1917 casualties, and (2) the 19 July 1985 Stava mudslide, caused by embankment failure at the Prestavel mine, with 268 casualties. The two disasters are both related to the presence or the failure of man-made structures. Excluding the two events from the analysis, the average landslide mortality in the mountains of Northern Italy in the period 1960–2010 was very similar to the mortality measured in the same area for the previous periods. We conclude that, in Italy, individual landslide risk has not increased significantly in the last 150 years, with the exception of the coastal mountains of Central Italy, corresponding chiefly to the Apuane Alps.

We have further investigated the variation of the LMRs for events of increasing intensity (i.e., an increasing number of fatalities per event), and we have analyzed their temporal variation for the three considered periods 1861–1909, 1910– 1959, and 1960–2010. For the purpose, we divided the historical record into three intensity classes: (1) low intensity (1–5 fatalities), (2) medium intensity (6–50 fatalities), and (3) high intensity (>50 fatalities). We then calculated the average LMR for each intensity class, for the five physiographical subdivisions, in Northern, Central, and Southern Italy, and for the three considered periods. Results are shown in Figure 14.7; since the scarcity of high-intensity data, in the histograms, the high-intensity class are considered together with the medium class. Figure 14.7 allows for the following general considerations: (1) the largest LMR (0.349) was measured in the coastal hills of Southern Italy in the period 1910–1959, and was the result of high-intensity events that each caused more than 50 fatalities; (2) high-intensity events (>50 fatalities) are rare in the record, and those that occurred in the most recent period in the mountains (i.e., the 1963 Vajont rockslide and the 1985 Stava mudflow) were related to the presence or the failure of man-made structures; (3) for medium-intensity events (causing 6–50 fatalities), landslide mortality remained substantially constant in the mountains and the coastal mountains, decreased slightly in the hills of Northern Italy, in the 150 year observation period; and (4) in the most recent period 1960–2010, the risk posed by low-intensity events (causing 1–5 fatalities) increased slightly in the mountains of Central and Southern Italy, in the coastal mountains of Northern and Central Italy, and in the coastal hills.

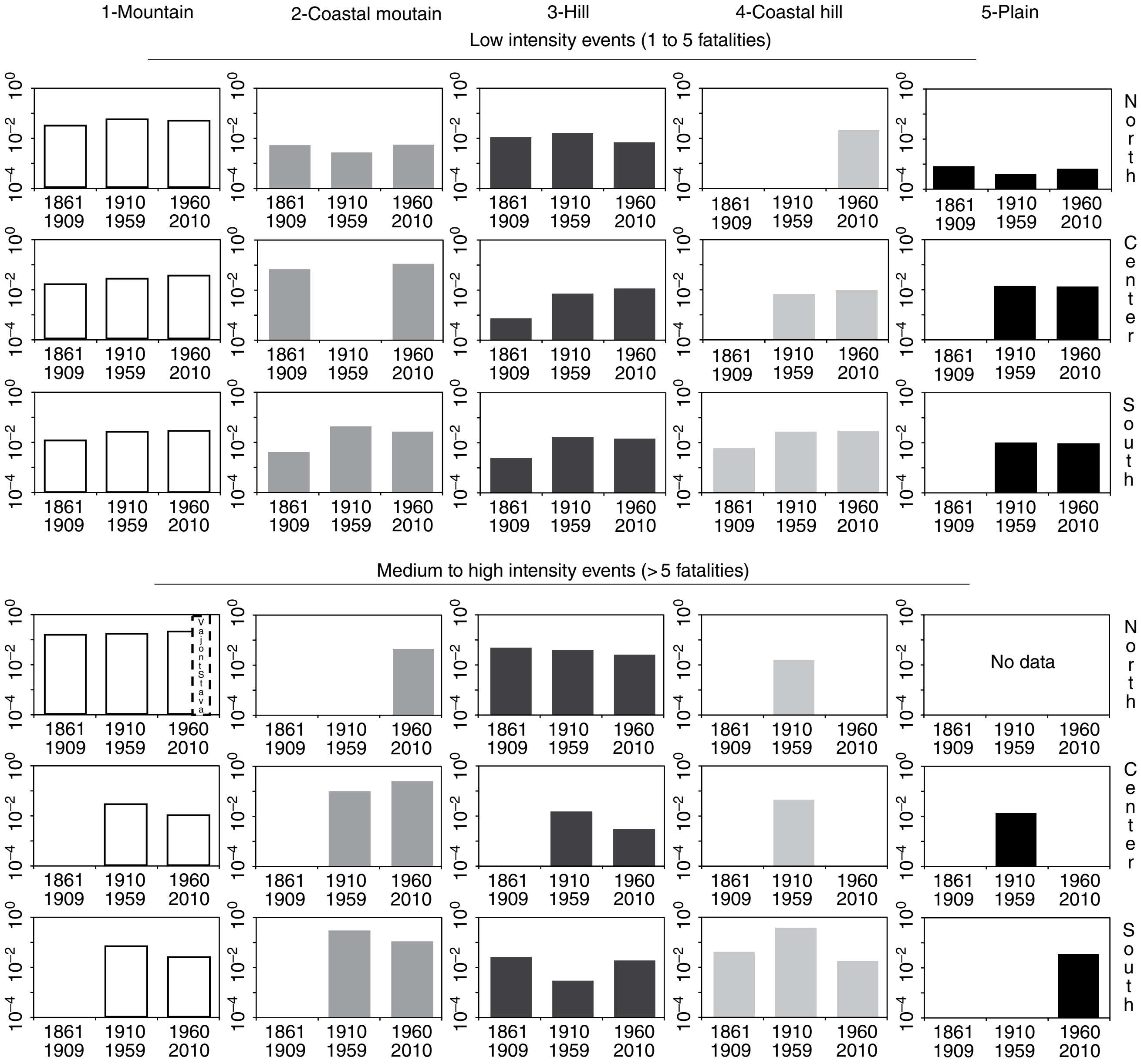

Figure 14.7 Average LMR for different event intensity classes: low-intensity events (1–5 fatalities), medium- to high-intensity events (>5 fatalities) in the five ISTAT physiographical subdivisions, and in the north, center, and south of Italy, for three periods: 1861–1909, 1910–1959, and 1960–2010.

14.4.2. Societal Landslide Risk

To determine societal landslide risk in Italy, we constructed frequency-consequences plots, and we used the plots to investigate the relationships between the (noncumulative) probability of the events and the severity of the consequences, measured by the number of the casualties. To establish societal risk, we adopted the method proposed by *Guzzetti et al.* [2005b], and modified by *Salvati et al.* [2010]. In this method, the empirical probability distribution of the landslide casualties is modeled by a Zipf distribution. The Zipf distribution, defined for a population of finite size, prescribes a power-law probability for the size of an event, given that the size can take an integer value of at least one [*Reed*, 2001; *Newman*, 2005; *Rossi et al.*, 2010]. For a Zipf distribution, the probability mass function (PMF) is given by

$$\mathrm{PMF}\left(c;c,N\right)=\left(c^{s}H_{N,s}\right)^{-1} \tag{14.1}$$

where c is the number of casualties per event, s is the scaling exponent for the Zipf distribution that measures the proportion of small versus large events, N is the largest number of casualties in a single event in the dataset, and

$$H_{N,s} = \sum_{c=1}^{N} C^{-s}$$

with $S \in \mathbb{R}^{+}$; $c \in \{1,2,\ldots,N\}$.

To determine the PMF of the landslide events with casualties from the empirical data, we adopted a maximum likelihood estimation approach [*White et al.*, 2008]. We further adopted a "bootstrapping" re-sampling procedure [*Efron*, 1979; *Davison and Hinkley*, 2006] to estimate the mean value of the Zipf parameter ($s_{\text{mean-boot}}$), and the associated variability (σ_s).

Salvati et al. [2010] used the scaling exponent s of the Zipf distribution to compare societal landside risk at the regional scale in Italy. Regions that exhibited the largest risk levels (largest $s = 2.33$) were Trentino-Alto Adige (Northern Italy) and Campania (Southern Italy), whereas the Emilia Romagna had the lowest value of $s = 1.30$. Interpretation of the geographical variation of the s values was somewhat uncertain, because the analysis of societal risk was based on administrative subdivisions with little relation to the physical settings, and because the standard error ε associated with the estimation of the s value was high for some of the regions, a result of the reduced number of events in the catalog for these regions.

To overcome these limitations, we have performed a new analysis using a topographical (morphometric) subdivision of Italy based on a semi-quantitative, stepwise approach that combined a cluster analysis of four derivatives of altitude, visual interpretation of morphometric maps, and comparative inspection of small-scale geological and structural maps [*Guzzetti and Reichenbach*, 1994]. The classification has divided Italy into eight major physiographical provinces from the aggregation of 30 minor divisions that reflect physical, geological, and structural differences in the Italian landscape (Table 14.6). We used these major physiographical provinces to calculate new landslide societal risk levels. For each physiographical province, the s Zipf parameter was determined for the period 1861–2010. We excluded from the analysis the North Italian Plain province, because of the lack of sufficient data in the historical record. To evaluate the performance of the Zipf model plots [*Wilk and Gnanadesikan*, 1968], we performed 2-sample Kolmogorov–Smirnov tests [*Kolmogorov*, 1933; *Smirnov*, 1933]. In Table 14.7 low values of the ks statistic, and large values of the p-value, indicate a better model fit.

The Zipf models (Figure 14.8 and Table 14.7) give the expected relative proportion of small, medium, and large events, with the total number of casualties in an event measuring the severity of the event. The scaling exponent s (the slope of the Zipf distribution) can be used to compare the proportion of events characterized by different levels of severity in the various provinces. The provinces that exhibit steep Zipf curves (large-scaling exponents s) have a smaller probability of experiencing severe events when compared to those that have less steep curves (small exponents s) and for which the relative proportion of severe events is larger. Table 14.7 shows that, in the considered provinces, s varies between 1.48 and 1.97 (mean, $\mu = 1.71$, standard deviation, $\sigma = 0.15$). We argue that the large variation depends on (1) the physiographical and climatic settings that determine the local susceptibility to harmful landslide events in the different provinces; (2) the frequency and intensity of the triggers, including intense or prolonged rainfall, in the different provinces; (3) the size of the physiographical provinces; and (4) the distribution of the population at risk in the different provinces.

Societal landslide risk depends on the relative proportion of small, medium, and large severity events, which controls the slope of the Zipf distribution, and on the temporal frequency of the events, that is, on the number

Table 14.6 Major Physiographical Provinces in Italy, Obtained from the Topographical Divisions of Italy Proposed by *Guzzetti and Reichenbach* [1994]

	Physiographical Provinces	Abbreviation	Minor Divisions
1	Alpine Mountain System	Alps	Western Alps, Central-Eastern Alps, Carso, Alpine Foothills
2	North Italian Plain	PoPl	Po Plain, Veneto Plain
3	Alpine-Apennines Transition Zone	AlAp	Monferrato Hills, Ligurian Upland
4	Apennines Mountain System	Apen	Northern Apennines, Central Apennines, Molise Apennines, Molise-Lucanian Hills, Lucanian Apennines, Sila, Aspromonte, Sicilian Apennines
5	Tyrrhenian Lowland	Tyrr	Central Italian Hills, Tosco-Laziale Section, Lazio- Campanian Section
6	Adriatic Lowland	Adri	Central Apennine Slope, Murge-Apulia Section, Gargano Upland
7	Sicily	Sici	Marsala Lowland, Sicilian Hills, Iblei Plateau, Etna
8	Sardinia	Sard	Sardinian Hills, Gennargentu Highland, Campidano Plain, Iglesiente Hills

Table 14.7 Societal Landslide Risk in Italy

Parameter	Alps	AlAp	Apen	Tyrr	Adri	Sici	Sard
Number of events (*n*)	624	50	356	300	36	25	30
Largest number of casualties per event (*N*)	1917	19	20	30	33	100	14
Zipf parameter (*s*)	1.972	1.483	1.593	1.729	1.683	1.708	1.796
Standard error *s* (ε)	0.042	0.159	0.042	0.065	0.181	0.187	0.251
KS D-statistic (*ks*)	0.045	0.120	0.070	0.157	0.083	0.120	0.133
KS --value (*p*)	0.556	0.864	0.344	0.001	1.000	0.994	0.952
Mean *s* bootstrap ($s_{\text{mean-boot}}$)	1.965	1.476	1.582	1.721	1.716	1.700	1.823
Standard deviation *s* bootstrap (σ_s)	0.022	0.093	0.019	0.035	0.086	0.080	0.117
N samples bootstrap (n_{boot})	16	200	28	33	278	400	333

Scaling exponent (*s*) and associated standard error (ε) for Zipf models obtained through maximum likelihood estimation of empirical casualty data for the period 1861–2010. KS D-statistic (*ks*) and KS *p*-value (*p*) measure the performance of the Zipf models. Mean *s* bootstrap ($s_{\text{mean-boot}}$) and the standard deviation *s* bootstrap (σ_s) obtained using a bootstrapping resampling procedure.

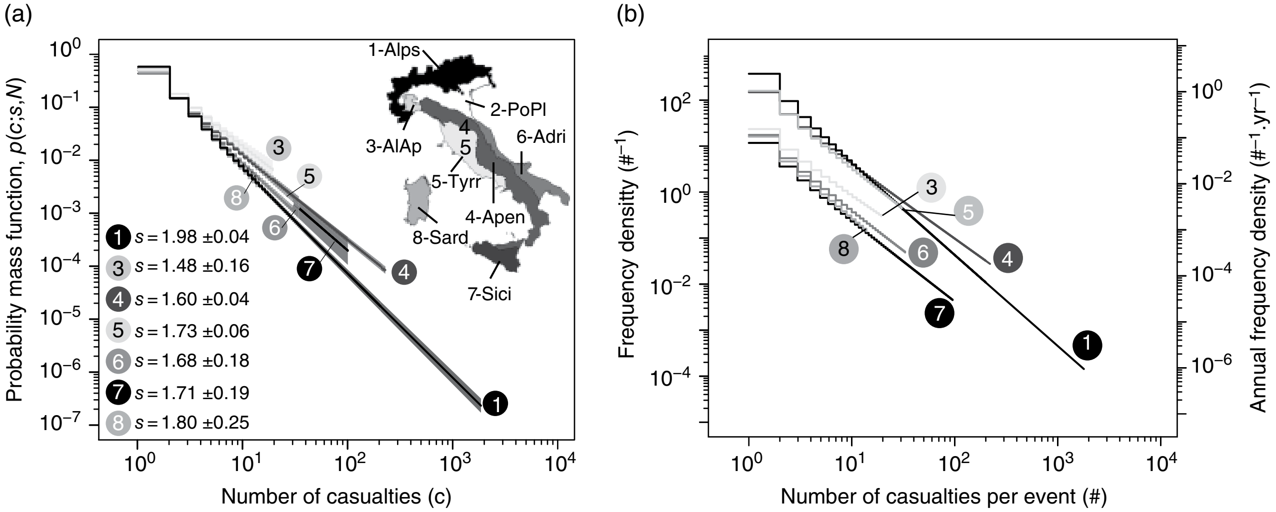

Figure 14.8 Societal landslide risk in the physiographical provinces. For the 150 year period 1861–2010, the plot on the left shows the PMF of landslide events with casualties (a). Map shows location of the physiographical provinces in Italy. Different shades of gray used for different provinces (Table 14.6). The plot on the right (b) shows the frequency density (left *y*-axis) and the annual frequency density (right *y*-axis) of landslide events with casualties in the Italian physiographical provinces against the severity of the landslide events (*x*-axis) measured by the total number of casualties in the 150 year period 1861–2010.

of events in a period, or per unit time (e.g., a year). For each physiographical province, we normalized the PMF to the total number of events with casualties in the province (Figure 14.8b). A close inspection of the plot allows us to comment on the risk levels in the different physiographical provinces, as a function of the severity of the events, measured by the number of casualties. Based on the visual inspection of Figure 14.8b, we have selected three severity classes: low-severity events (landslides that can result in 10 casualties or less), medium-severity events (from 11 to 20 casualties), and high-severity events (more than 20 casualties). The Alpine Mountain System has the highest probability of experiencing low-severity events. The trend changes with the increase in the landslide severity. For medium-severity events, the Apennines Mountain System has nearly the same probability as the Alpine Mountain System of experiencing events. Finally, the Apennines Mountain System has the largest probability of causing high-severity events.

14.5. COMPARISON TO OTHER NATURAL HAZARDS

In Italy, landslides are not the only natural hazard that poses a threat to the population. Floods, earthquakes, and volcanic activity are other types of hazards with

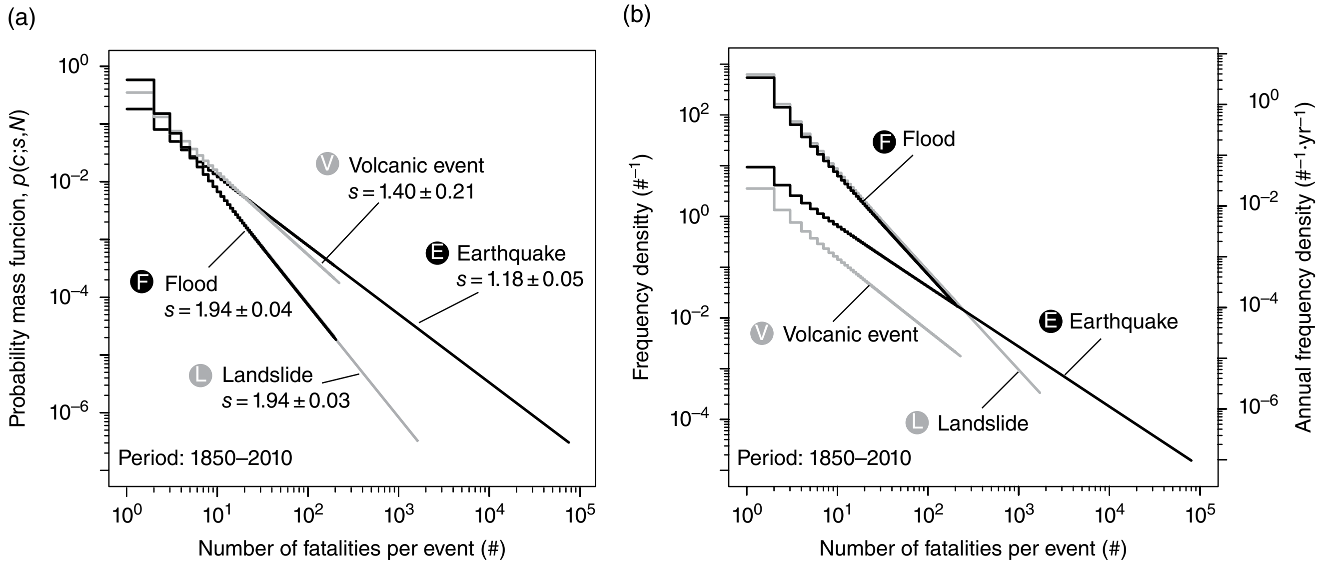

Figure 14.9 Comparison of societal risk levels to the population of Italy posed by earthquakes (E), floods (F), landslides (L), and volcanic events (V) with fatalities (deaths and missing persons) in the period 1861–2010. (a) PMF of events with fatalities (y-axis) against the severity of the events (x-axis), measured by the total number of fatalities. (b) Frequency density (left y-axis) and annual frequency density (right y-axis) of events against the severity of the events (x-axis), measured by the total number of fatalities.

human consequences in Italy [*Guzzetti*, 2000; *Salvati et al.*, 2003, 2012; *Guzzetti et al.*, 2005a]. In this section, using the results of our previous findings [*Salvati et al.*, 2012], we compare levels of societal landslide risk to the risk posed by floods, earthquakes, and volcanic activity in Italy. For the purpose, we used the catalog of floods with human consequences in Italy compiled by *Salvati et al.* [2010], and the catalogs of earthquakes and of volcanic events with human consequences in Italy prepared by *Guzzetti et al.* [2005a]. The updated catalogs cover the periods: (1) AD 589 to 2010 for floods (40,572 fatalities in 1068 events in 1422 years), (2) AD 51 to 2010 for earthquakes (331,560 fatalities in 135 events, in 1960 years), and (3) AD 79 to 2010 for volcanic events (35,340 fatalities in 17 events, in 1932 years).

Details on the approach used for the analysis are given in *Salvati et al.* [2012]. The analysis was performed using the fatalities data (deaths and missing persons), and not casualty data, because for earthquakes and for volcanic events systematic information on injured people was not available. The analysis cover the period 1850–2010.

The slope of the distributions shown in Figure 14.9 allows for a quantitative comparison of the different societal risk posed by floods (F), landslides (L), earthquakes (E), and volcanic events (V). The scaling exponents s for landslides and floods are identical ($s = 1.94$), and the uncertainty in the estimation of the scaling parameter, measured by the standard errors ($\varepsilon = 0.04$ for floods and $\varepsilon = 0.03$ for landslides), indicates that the two distributions are statistically indistinguishable. As *Salvati et al.*, in 2012 found, the relative proportion of large versus small fatal events is the same in Italy for floods and landslides. Further inspection of Figure 14.9a reveals that the scaling exponents of the Zipf distributions for earthquakes ($s = .18$) and volcanic events ($s = 1.40$) are significantly smaller than those obtained for floods and landslides ($s = 1.94$). Even considering the uncertainty associated with the estimates of the scaling parameter s ($\varepsilon = 0.05$ for earthquakes and $\varepsilon = 0.21$ for volcanic events), the proportion of large versus small fatal events caused by geological triggers (i.e., earthquake and volcanic events) is significantly larger than the proportion of fatal events caused by meteorological triggers (floods and for landslides).

To consider the severity (measured by the number of fatalities) and the temporal frequency of the different hazards, we scaled the PMF shown in Figure 14.9a to the total number of harmful events, for the different hazards (Figure 14.9b). Visual analysis of Figure 14.9b allows for the following considerations. For the events with <100 fatalities, the frequency of landslides and floods is significantly larger than the frequency of earthquakes, which is larger than the frequency of volcanic events. In the same period, for events with more than 100 fatalities, harmful earthquakes were more frequent than any of the other hazards. We maintain that the observed differences measure the different ways in which floods, landslides, earthquakes, and volcanic events interact with the built-up environment and the population.

14.6. CONNECTIONS BETWEEN LANDSLIDES AND OTHER HAZARDS

Landslides can be triggered or can cause other hazards. Landslides are triggered by earthquakes [*Keefer*, 1984, 2013; *Fortunato et al.*, 2012] and by primary or secondary volcanic activity [*Moore et al.*, 1994; *Masson et al.*, 2002; *Frattini et al.*, 2004; *McMurtry et al.*, 2004; *De Vita et al.*, 2006]. Landslides can cause tsunamis [*Moore et al.*, 1994; *Locat and Lee*, 2009], and the failure of landslide dams can result in catastrophic flash floods and inundations [*Schuster*, 1986; *Costa and Schuster*, 1988; *Ermini and Casagli*, 2002]. We searched the historical record of harmful landslides in Italy for failures related to (i.e., triggered by or causing) other hazards, and particularly (1) for harmful landslides caused by earthquakes or volcanic activity and (2) for destructive flash floods caused by the collapse of landslide dams.

Although earthquake-induced landslides are one of the most hazardous secondary effects of earthquakes [*Prestininzi and Romeo*, 2000; *Carro et al.*, 2003], the number of events with human consequences in the Italian historical record is limited. The catalog lists 15 earthquake-induced landslides with human consequences, of which 11 landslides caused deaths or injured people and 5 landslides caused evacuees and homeless (Figure 14.10 and Table 14.8). Two of the listed earthquake-induced landslide caused many fatalities as a consequence of landslide tsunamis. On 6 February 1783, the 5.8 M Calabria earthquake triggered a landslide of about $V_L = 5 \times 10^6\,\mathrm{m}^3$ (ID 5 in Table 14.8 and Figure 14.10). The rock avalanche fell from Monte Paci, near the village of Scilla, Southern Calabria, in the Tyrrhenian Sea and produced a tsunami with a 16 m high run-up. The landslide-generated tsunami killed about 1500 people [*Mazzanti and Bozzano*, 2011]. On 28 December 1908, the 7.1 M Messina earthquake produced a large tsunami that killed at least 60,000 people. *Billi et al.* [2008] argued that a submarine landslide (ID 8 in Table 14.8 and Figure 14.10) might have caused the tsunami.

The historical catalog lists eight damaging flash floods related to the failure of landslide dams (Figure 14.8, Table 14.8). The number of fatalities caused by these

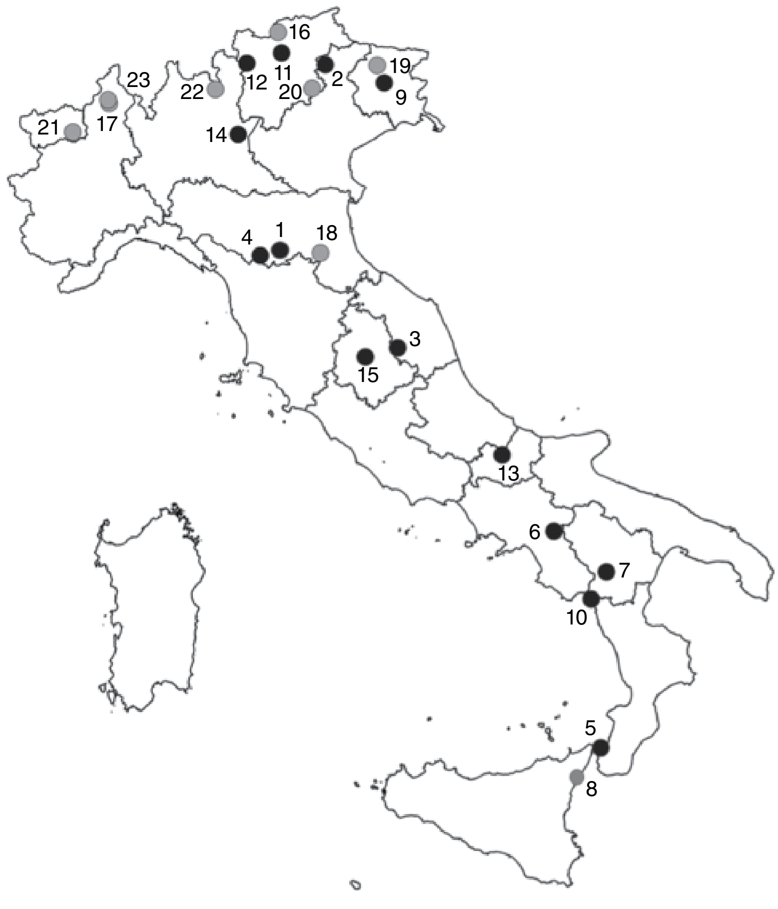

Figure 14.10 Location of harmful historical landslides caused by earthquakes (black dots), and of harmful flash floods produced by the collapse of landslide dams (gray dots) in Italy. See Table 14.8 for further information on the events.

Table 14.8 Harmful Landslide Events Triggered by or Causing Other Hazards, Particularly Harmful Landslides Caused by Earthquakes and Destructive Flash Floods Caused by the Collapse of Landslide Dams

ID	Related Hazard	Location	Date	Damage to the Population
1	Earthquake	Emilia-Romagna	91 BC	Undetermined fatalities
2	Earthquake	Veneto	07/01/1117	Undetermined fatalities and homeless
3	Earthquake	Marche	30/04/1279	Undetermined fatalities
4	Earthquake	Emilia-Romagna	24/12/1779	Undetermined homeless
5	Earthquake	Calabria	06/02/1783	1300 fatalities
6	Earthquake	Campania	09/04/1853	Undetermined fatalities
7	Earthquake	Basilicata	17/12/1857	Tens of fatalities
8	Earthquake	Sicilia	28/12/1908	Undetermined fatalities
9	Earthquake	Friuli-Venezia Giulia	06/05/1976	1 dead
10	Earthquake	Basilicata	09/09/1998	1 dead
11	Earthquake	Trentino-Alto Adige	17/07/2001	2 deaths and 2 injured people
12	Earthquake	Trentino-Alto Adige	17/07/2001	1 dead
13	Earthquake	Molise	31/10/2002	Undetermined homeless
14	Earthquake	Lombardia	25/11/2004	Undetermined homeless
15	Earthquake	Umbria	15/12/2009	Undetermined homeless
16	Landslide dams	Trentino-Alto Adige	22/09/1419	400 deaths
17	Landslide dams	Piemonte	17/10/1610	13 deaths
18	Landslide dams	Emilia-Romagna	11/04/1690	10 deaths
19	Landslide dams	Friuli-Venezia Giulia	15/08/1692	Undetermined fatalities and homeless
20	Landslide dams	Trentino-Alto Adige	31/05/1826	52 deaths and 238 homeless
21	Landslide dams	Valle d'Aosta	31/10/1840	80 deaths
22	Landslide dams	Lombardia	1855	Undetermined homeless
23	Landslide dams	Piemonte	23/08/1900	7 deaths

events varies from a few tens to a few hundreds, confirming that these types of landslide-induced hazards are extremely dangerous to the population.

14.7. CONCLUSIONS

We used a unique historical record of landslide events with human consequences to update the estimates of the individual and the societal landslide risk in Italy [*Salvati et al.*, 2003, 2010; *Guzzetti et al.*, 2005a, 2005b]. Analysis of the geographical distribution of the sites where landslide have caused damage to people, between 91 BC and 2011, has confirmed that landslides with human consequences are most abundant in the mountain zone of Northern Italy, and in the coastal hill of Southern Italy. In Italy, landslide mortality depends on the physiographical setting and the intensity of the events. In the recent period 1960–2010, landslide mortality has increased in the mountains of Northern Italy and in the coastal mountains of Central Italy. In Southern Italy, mortality has decreased slightly in the mountains, and significantly in the coastal hills. In the same period, the individual risk posed by low-intensity events has increased slightly in several areas in Italy.

Studying the frequency and the severity of the landslide events with casualties, we updated the measures of societal landslide risk in Italy. We modeled the historical landslide casualty data in seven physiographical provinces, and we showed that the Alps has the largest probability of experiencing low-severity landslide events. The behavior changes with increasing event intensity, with the Apennines exhibiting the largest probability of experiencing high-severity events.

A comparative analysis of the societal risk posed by landslides, floods, earthquakes, and volcanic events in Italy, confirmed that the frequency and severity of the geological events (earthquakes and volcanic activity) and of the meteorologically induced events (floods and landslides) are different [*Guzzetti et al.*, 2005a]. For the less severe events, the frequency of harmful landslides and floods is larger than the frequency of harmful earthquakes and volcanic events. For catastrophic events (with more than 100 fatalities), earthquakes are more frequent than all the other hazards.

We expect the results of our study to improve the understanding of the risk posed by landslides and the other natural hazards to the population of Italy. The study provides information for comparing the risk levels posed by natural hazards with the risk posed by other societal and technological hazards, and the leading medical causes of death in Italy [*Salvati et al.*, 2003], and with the levels of risk perceived and accepted by society in Italy. Further, the study provides the rationale for establishing insurance, and the design of national and regional landslide risk reduction strategies.

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