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Gerardo Herrera · Rosa María Mateos · Juan Carlos García-Davalillo · Gilles Grandjean · Eleftheria Poyiadji · Raluca Maftei · Tatiana-Constantina Filipciuc · Mateja Jemec Auflič · Jernej Jež · Laszlo Podolszki · Alessandro Trigila · Carla Iadanza · Hugo Raetzo · Arben Kociu · Maria Przyłucka · Marcin Kułak · Michael Sheehy · Xavier M. Pellicer · Charise McKeown · Graham Ryan · Veronika Kopačková · Michaela Frei · Dirk Kuhn · Reginald L. Hermanns · Niki Koulermou · Colby A. Smith · Mats Engdahl · Pere Buxó · Marta Gonzalez · Claire Dashwood · Helen Reeves · Francesca Cigna · Pavel Liščák · Peter Pauditš · Vidas Mikulėnas · Vedad Demir · Margus Raha · Lídia Quental · Cvjetko Sandić · Balazs Fusi · Odd Are Jensen

Landslide databases in the Geological Surveys of Europe

Abstract Landslides are one of the most widespread geohazards in Europe, producing significant social and economic impacts. Rapid population growth in urban areas throughout many countries in Europe and extreme climatic scenarios can considerably increase landslide risk in the near future. Variability exists between European countries in both the statutory treatment of landslide risk and the use of official assessment guidelines. This suggests that a European Landslides Directive that provides a common legal framework for dealing with landslides is necessary. With this long-term goal in mind, this work analyzes the landslide databases from the Geological Surveys of Europe focusing on their interoperability and completeness. The same landslide classification could be used for the 849,543 landslide records from the Geological Surveys, from which 36% are slides, 10% are falls, 20% are flows, 11% are complex slides, and 24% either remain unclassified or correspond to another typology. Most of them are mapped with the same symbol at a scale of 1:25,000 or greater, providing the necessary information to elaborate European-scale susceptibility maps for each landslide type. A landslide density map was produced for the available records from the Geological Surveys (LANDEN map) showing, for the first time, 210,544km² landslide-prone areas and 23,681 administrative areas where the Geological Surveys from Europe have recorded landslides. The comparison of this map with the European landslide susceptibility map (ELSUS 1000 v1) is successful for most of the territory (69.7%) showing certain variability between countries. This comparison also permitted the identification of 0.98Mkm² (28.9%) of landslide-susceptible areas without records from the Geological Surveys, which have been used to evaluate the landslide database completeness. The estimated completeness of the landslide databases (LDBs) from the Geological Surveys is 17%, varying between 1 and 55%. This variability is due to the different landslide strategies adopted by each country. In some of them, landslide mapping is systematic; others only record damaging landslides, whereas in others, landslide maps are only available for certain regions or local areas. Moreover, in most of the countries, LDBs from the Geological Surveys co-exist with others owned by a variety of public institutions producing LDBs at variable scales and formats. Hence, a greater coordination effort should be made by all the institutions working in landslide mapping to increase data integration and harmonization.

Keywords Landslides · Europe · Legal framework

Introduction

Landslides are one of the most widespread geohazards in Europe, responsible for significant social and economic impacts. A report of the European Environment Agency reveals that landslides in Europe caused—for the decade 1998–2009—about 312 fatalities, and direct average costs were evaluated to reach up to €48 billion (Spizzichino et al. 2010). Moreover, a present study (Haque et al. 2016) reveals that in 27 European countries (including Turkey), during the 20-year period 1995–2014, 1370 deaths and 784 injuries were recorded from 476 deadly landslide events. In the last decades of the twentieth century, with the expansion of settlements and the development of different activities, the pressure to build on less suitable and unfavorable areas in terms of landslides greatly increased. Rapid population growth in urban areas throughout many countries in Europe and extreme climatic scenarios can considerably increase the landslide risk in the near future.

Landslides in Europe are mostly concentrated in the mountainous areas and coastal cliffs, but many of them are strongly controlled by unfavorable geological conditions consisting of weak clay layers in gently tilted strata and the local hydrological setting (Crosta 1998), e.g., landslides triggered in argillaceous formations in low-slope areas in the river basins. Italy is the most landslide-prone country in Europe where landslides are the most frequent and disperse natural hazards, causing after earthquakes the great number of fatalities and damage to urban area infrastructures and cultural heritage (Trigila et al. 2015). The series of major earthquakes which struck central Italy since August 2016 have caused hundreds of disrupted landslides. Among them rockfalls, rockslides, and debris slides are distributed widely from the mainshock epicenters, and some of them severely affected the road network of the region (CERI 2016). Furthermore, many documented cases in other European countries exist and refer to long rainy periods which triggered a large number of landslides extending over large areas. An example of this abnormal situation took place in the Island of Mallorca (Spain) from the period 2008–2010 when a combination of persistent precipitations and low temperature caused an unusual number of slope failures; they produced a great impact on the regional economy of the island which revolves exclusively around tourism (Mateos et al. 2012).

The Geological Surveys of Europe analyzed the integration of geohazards into urban and land-use planning in 19 European countries (Mateos et al. 2017, Poyiadji et al. 2017). They found that, for example, Czech Republic, Estonia, and Slovenia do not include geohazards in their land legislation; others still do not officially require geohazard maps in their urban and land-use planning, and most of them lack official methodological guidelines to produce maps such as that recently published by the Swiss Federal Office for the Environment (FOEN 2016). Moreover, there is scarce knowledge about real social and economic impacts of geohazards and the transboundary nature of impacts is unevenly understood. Additionally, data fragmentation and data ownership restrictions in landslide inventories militate against data integration and the development of strategies to understand and, by prescribing appropriate measures, reduce landslide risk in Europe. This is especially relevant with regard to landslide hazard since there are no common guidelines and practices similar to the Directive 2007/60/EC on the assessment and management of flood risk. Therefore, it is essential to develop a European Landslides Directive that provides a common legal framework for dealing with landslides.

The starting point for the integrated management of landslides is the landslide database (LDB). Even where there are national and global LDBs and catalogues, they suffer from incompleteness and their statistics greatly underestimate actual occurrences. In Europe, many countries have created or are creating landslide databases, but there is currently not a European LDB. The Joint Research Centre took the first steps in this direction, creating in 2007 the European Landslide Expert Group. This group, formed by landslide experts from European universities, research institutions, and Geological Surveys, produced guidelines for mapping areas at risk of landslides in Europe using harmonized approaches and common thematic datasets (Chacón 2007; Günther et al. 2007, 2008, 2012, 2013; Hervás 2007; Hervás and Montanarella 2007; Hervás et al. 2007; Hobbs 2007a, b; Malet et al. 2007; Panagos and van Liedekerke 2007; Pasuto and Tagliavini 2007; Poyiadji 2007; Reichenbach et al. 2007; Schmidt-Thomé 2006; Trigila et al. 2007). The state of the art of landslide databases in Europe presented by Van Den Eeckhaut and Hervás (2012) analyzed LDBs in 28 countries that account for 633,700 landslides. These authors recognize significant differences among the LDBs concerning the accuracy of the landslide location, the classification of landslide types, the completeness of the database, or how impacts are evaluated. They suggest enhancing interoperability proposing a minimum set of features that European countries should try to collect and include in LDBs. Taking into account that the Geological Surveys provided updated information on 14 out of 22 national LDB for the previous review, we present an extended review of the LDBs of the Geological Surveys analyzing their completeness and interoperability.

The Geological Surveys of Europe, EuroGeoSurveys (EGS), is a not-for-profit organization representing 37 National Geological Surveys and some regional surveys in Europe, an overall workforce of several thousand experts, sharing their expertise and knowledge in geosciences through expert groups. In this work, the joint effort of 30 Geological Surveys members of the Earth Observation and Geohazards Expert Group (EOEG) has made this review possible. Landslides are present in all the considered countries, and they are of great importance in their safety and economy. Figure 1 shows some examples from the EOEG photogallery of landslides affecting urban areas/infrastructures during the past 10 years; a wide range of typologies can be observed which reflects the large variety of geographical and geological contexts existing in Europe.

This works analyzes the landslide databases of the Geological Surveys of Europe focusing on their completeness and their interoperability. Based on this, the following objectives have been set: (1) to provide an extended and updated review of the LDBs in the Geological Surveys of Europe, (2) to elaborate a landslide density map (LANDEN) based on the available records from the Geological Surveys of Europe, (3) to compare the landslide density map with the European landslide susceptibility map (ELSUS 1000 v1), and (4) to provide a quantitative approximation to the completeness of the landslide databases of the Geological Surveys of Europe.

Methodology

The review of the LDBs from the Geological Surveys of Europe is based on five questionnaires circulated to gather the available information for every landslide type according to the classification proposed by Cruden and Varnes (1996). This builds on work already undertaken by Van Den Eeckhaut and Hervás (2012). In this work, numeric information was only provided for the number of landslides, date of creation, and scale. Information regarding the completeness, history, trigger, or impact was reported by landslide national experts in four classes (i.e., < 25, 25–50, 50–75, and > 75%). Finally, the information regarding the type, the size, the activity, or the lithology was evaluated with two classes (optionally yes or no).

The five questionnaires circulated among the Geological Surveys in Europe include information on their LDBs during 2015. The first one (Table 1) gathers numeric information on the number of landslides and types according to Cruden and Varnes (1996): slides, falls, flows, complex, and unclassified or others. In order to make the first questionnaire comparable with that from Van Den Eeckhaut and Hervás (2012), the information about the size, activity, history, trigger, or impact was collected according to the proposed four classes. The other four questionnaires gather information, for every landslide type, on the number of records with information on the symbol, area, volume, activity, lithology, trigger, and impact. Information about the scale, and the date of the first and last record, is also provided for all of them. Symbol information provides the number of records that are mapped as points, lines, or polygons, or combinations of same. Area and volume provide the number of records with information on the areal extent or volume for every landslide type. Activity provides the number of records where the state of activity (active, reactivated, dormant, and inactive) is available according to Cruden and Varnes (1996). The number of records with information available on the lithology of the landslide, the identification of the trigger, and the consequences or impacts produced by every landslide type has also been gathered.

The landslide density map of recorded landslides (LANDEN map) aims to show where landslides have been mapped by the Geological Surveys. Hence, the LDBs available from 17 Geological Surveys were combined together. For this purpose, the available landslide records where transformed into a point layer. Landslides mapped as polygons were converted into points calculating their centroids. The 1-km reference grid from the European Environment Agency (EEA) was used to calculate the landslide density for every 1 km^2. A color scale was used to depict landslide density per

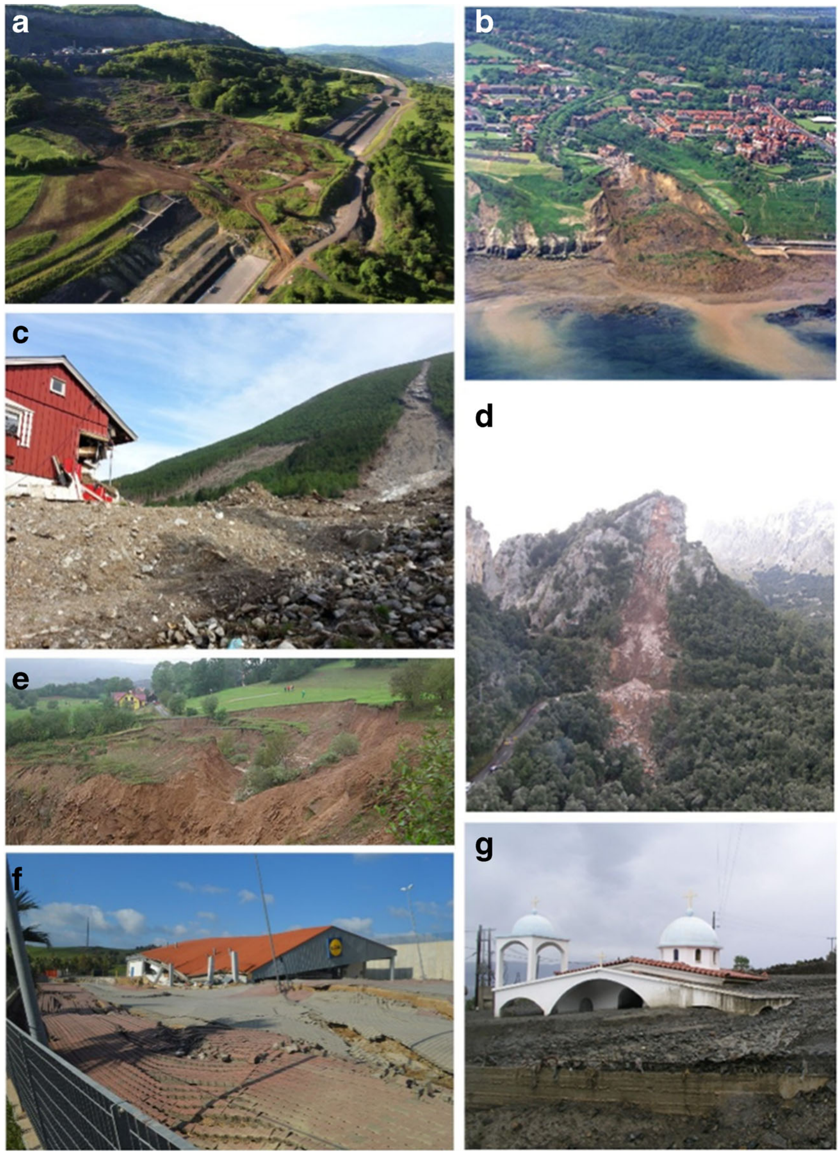

Fig. 1 Some examples of landslides in Europe that occurred during the last decade: **a** Litochovice landslide (Czech Republic), **b** Scarborough landslide (UK), **c** debris flow in Norway, **d** rockfall in Mallorca (Spain), **e** Tenczyn landslide (Poland), **f** Montescaglioso landslide (Italy), **g** Vamvakes landslide (Greece)

1 km^2 varying from 1 to 100. The average landslide density per administrative area is calculated using the municipal administrative boundaries provided by 10 Geological Surveys, and for the other 7, the lowest administrative level available from the Global Administrative Areas (GADM 2015) is used.

The comparison of the LANDEN map with the European landslide susceptibility map ELSUS v1 was made through a confusion matrix. The ELSUS v1 map is the result of a climate-physiographically differentiated pan-European landslide susceptibility assessment using spatial multi-criteria evaluation and transnational landslide information (Günther et al. 2014). For this purpose, the ELSUS v1 has been reclassified into two classes: low to very low susceptibility as referred to hereafter as not susceptible and moderate to very high susceptibility classes as susceptible. Based on the results of the confusion matrix, a quantitative approximation of the completeness of the LDBs for each of these countries is estimated.

Description of the landslide databases from the geological surveys

General overview

In this work, we provide information on 34 LDBs from 29 geological surveys of 24 countries (Table 1 and Fig. 2). From this total, there are 14 regional LDBs from 6 countries (Croatia, Denmark, Estonia, Germany, Romania, Spain). LDBs are not owned by the geological surveys of four countries (Belgium, Bulgaria, Iceland, and Portugal). Therefore, even if in most of the countries geological surveys usually own and maintain a LDB, there are also other institutions holding different LDBs both at national and regional levels. The lack of integration of the existing LDBs in

Table 1 Landslide DBs in the Geological Surveys of Europe

Nº.	Country	Acron.	GS	Type	Num.	Slides	Falls	Flows	Complex	Unclass/other
1	Austria	AUS	GBA	N	26,500	17,210	2445	4250	1173	1422
2	R. Sparska, Bosnia & Herzeg.	BIH	GSRS	N	1225					1225
3	Croatia (SB)	CRO	CGS	R	67					67
4	Croatia (ZA)	CRO	CGS	R	800					800
5	Cyprus	CYP	GSD	N	1879	929	106	322	522	
6	Czech Republic	CZE	CZS	N	17,552	15,224	258	47	2023	
7	Denmark	DEN	GEUS	R	10	8	2			
8	Estonia	EST	EGK	R	26	26				
9	France	FRA	BRGM	N	42,300	12,690	8460	2538	18,612	
10	Germany (BW)	GER	BGR	R	9305					9305
11	Germany (HE)	GER	BGR	R	3999					3999
12	Germany (MV)	GER	BGR	R	570	570				
13	Germany (NI)	GER	BGR	R	438	335	76	27	0	
14	Germany (SN)	GER	BGR	R	546	113	414	18		1
15	Greece (H)	GRE	IGME GR	N	2498	1729	146	162	378	83
16	Greece (IGC)	GRE	IGME GR	N	306	182	14	16	35	59
17	Hungary	HUN	MFGI	N	1554	1214	152	188		
18	Ireland	IRE	GSI	N	3000	16	160	166	3	2655
19	Italy	ITA	ISPRA	N	528,903	162,019	24,363	153,742	60,496	128,283
20	Lithuania	LIT	LGT	N	165	144	2		19	
21	Norway (H)	NOR	NGU	N	51,161	103	28,588	6397	364	15,709
22	Norway (U)	NOR	NGU	N	250					250
23	Poland	POL	PGI	N	49,330	45,800	550	580	2400	
24	Romania	ROM	GIR	R	2345	1500	300	45	500	
25	Serbia	SER	GZS	R	1855	218	4	6	25	1602
26	Slovakia	SLK	SGUDS	N	22,742	13,590	127	207	2288	6530
27	Slovenia	SLO	GEOZS	N	7273	7264	8	1		
28	Spain (GR)	SPA	IGME ES	R	5665	1765	1038	2862		
29	Spain (ICGC)	SPA	ICGC	R	2755	1156	1410	189		
30	Spain (MOVES)	SPA	IGME ES	N	2379	814	1021	271	155	118
31	Spain (MU)	SPA	IGME ES	R	889	51	794	44		

Table 1 (continued)

Nº.	Country	Acron.	GS	Type	Num.	Slides	Falls	Flows	Complex	Unclass/other
32	Sweden	SWE	SGU	N	3351					3351
33	Switzerland	SWI	FOEN	N	40,000	30,000	10,000			
34	United Kingdom	UK	BGS	N	17,915	3811	687	437	944	12,036

Nº.	First	Last	Scale	Symbol	Size	Activity	Geology	History	Trigger	Impact
1	8500 BP	2015	1:2000–1:200,000	All	A	N	Y	25	100	25
2	2014	2014	1:25,000	Pt		N	N		100	100
3	2007	2010	1:5000	Pg	A	Y	Y	25	25	25
4	1911	2015	1:5000	Pg	A	Y	Y	25	25	25
5		2015	Variable	All	A	Y	Y	25	25	50
6	PH	2015	1:10,000–1:25,000	All	A	Y	Y	50	50	25
7	1904	2007	1:25,000	All	AV	Y	Y	75	50	25
8	1905	2009	1:50,000		AV	N	Y	75	100	25
9	1900	2015	1:25,000	Pt	AV	V	N	75	50	50
10			1:50,000	Pg	A	N	Y	25	25	25
11	1901	2015	1:25,000	All	A	Y	Y	50	25	25
12	1500	2015	1:10,000	All	AV	N	Y	25	50	25
13	PH	2013	Variable	Pt	AV	Y	Y	50	50	25
14	1681	2015	Variable	Pt	V	N	Y	50	100	25
15	1925	2011	1:1000–1:500,000	All	A	Y	Y	75	75	75
16	1929	2010	1:50,000	Pg	A	N	Y	100	100	100
17	1848	2014	1:4000–1:25,000	All	AV	Y	Y	75	100	75
18	1697	2013	1:500,000	All	AV	Y	Y	75	50	50
19	1116	2014	1:10,000–1:25,000	Pg	AV	Y	Y	25	25	25
20	1840	2015	Variable	Pt		N	Y	25	25	100
21	900	2015	Variable	All	A	N	N	25	25	100
22			1:5000	Pg	V	Y	Y	25		
23	PH	2014	1:10,000	All	A	Y	Y	75	100	100
24	1916	2015	0	All	A	Y	N	25	75	75
25	2015	2015	0	Pt					100	100
26	1961	2015	1:50,000; 1:10,000	All	V	Y	Y	25	100	25

Table 1 (continued)

Nº.	First	Last	Scale	Symbol	Size	Activity	Geology	History	Trigger	Impact
27	1954	2014	1:25,000–1:250,000	Pt			Y	25	25	25
28			1:25,000	All	A	N	Y	25	25	25
29	1881	2015	1:25,000	All	AV	Y	Y		0	0
30	1620	2015	1:25,000		AV	Y	Y	25	75	75
31		2011	1:25,000	All		N	Y	25	25	25
32			0	L	N	N	Y	25	25	25
33	PH	2015	0	All	A	Y	Y	25	25	25
34	PH	2015	0	Pt	A	Y	Y	25	25	25

Type definition: *N* national LDB, *R* regional LDB; *PH* pre-Holocene; *Pt* point; *Pg* polygon; *L* line; *A* area; *V* volume; *Y* yes; *N* no

the different countries requires that their interoperability is improved. With this aim, the Geological Surveys of Europe present a review of their LDBs in order to identify common landslide features that make them interoperable in their current formats. From now on, when we refer to the LDB of a country, we only refer to those owned by the geological surveys and not to all the existing LDBs. For instance, in Norway, landslide databases are filled by different organizations: the Geological Survey of Norway (NGU), the Norwegian Geotechnical Institute, and road and railroad, water, and energy authorities. The historical landslide database was compiled by NGU, but nowadays, it is maintained by the Norwegian Water and Energy Directorate (NVE) (Hermanns et al. 2012). Currently, NGU holds the Unstable Rock Slope database that identifies critical areas where catastrophic events may occur. In fact, the LDBs from NGU and most of the GSs reflect the location of landslides causing life loss, damages, or traffic interruption rather than the complete picture of all the landslides in the country.

The 34 LDBs contain a total number of 849,543 landslides (Table 1 and Fig. 2) that represent a 34% increase over the landslide records reported by Van Den Eeckhaut and Hervás (2012). This is due to the inclusion of new LDBs and recent updating activities made by several geological surveys. Most of the landslide records (62%) are concentrated in Italy; another 35% of them are distributed across 10 countries (Austria, Czech Republic, France, Germany, Norway, Poland, Slovakia, Spain, Switzerland, and the UK), whereas the remaining 3% is distributed across 13 countries (Fig. 2). Analysis of the type of landslides reveals that 36% are slides, 10% are falls, 20% are flows, 11% are complex slides, and 24% either remain unclassified or correspond to another typology. The Republic of Srpska—Bosnia and Herzegovina, Croatia, Sweden, and two regional LDBs from Germany do not provide landslide typology information. In the UK and in the Republic of Ireland, the majority of the landslides (> 88%) remain unclassified, whereas in Italy, 24% of the records correspond to other classes. This is because the landslide inventory of Italy (IFFI) takes into account 11 landslide types.

The time span of the LDBs is variable (Table 1); usually, the oldest landslide dates from the past two centuries. There are 16 LDBs with landslides dated in the period 1800–2015 AD (Anno Domini), 6 with landslides from 900 to 1800 AD, 6 with pre-Holocene (PH), and 6 with no information on the date. The date of the last landslide record provides an indicator of LDB updating. Most of these databases are updated annually (17) or every 2 years (5), whereas for 8 of them, the last landslide record dates from 2007 to 2013. In the geological surveys from Poland (PGI), Switzerland (FOEN), Spain (IGME and ICGC), Sweden (SGU), and Ireland and in several state geological surveys (SGS) of Germany, the LDBs are under construction. A draft version of the national LDB from FOEN will be ready in 2019, and in 2023, PGI will finish mapping the Polish part of the Carpathian Mountains, which is expected to contain 95% of landslides in Poland (Mrozek et al. 2014). In Germany, the 16 state geological surveys (SGS) are responsible for the elaboration of their LDBs following a common INSPIRE compliant methodology that includes integration of pre-existing data, remote sensing, and fieldwork. However, data integration and the full spatial coverage of the landslide inventories are yet not achieved due to different resource allocation and working priorities in the different federal states. In 2015, 5 SGS

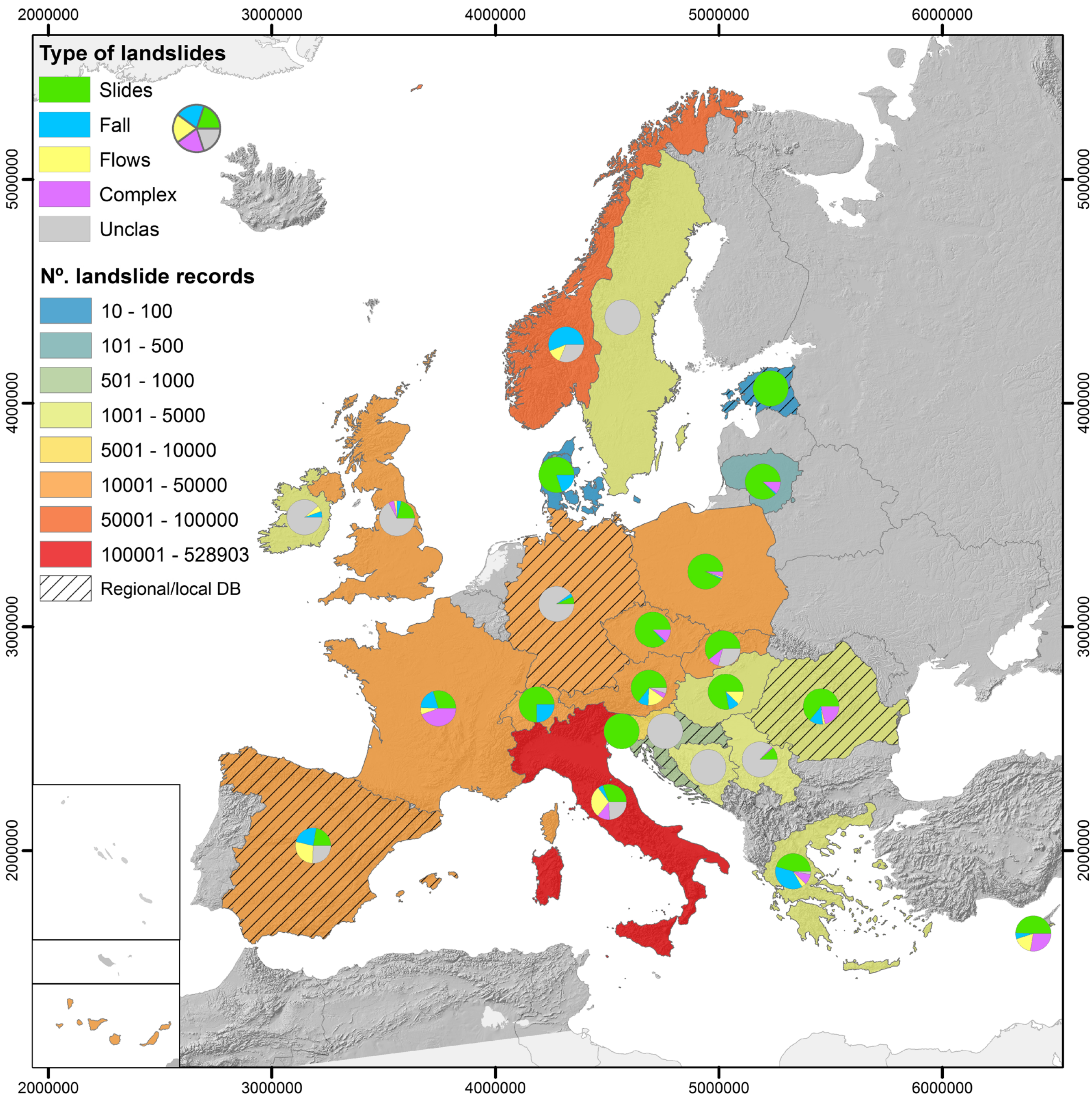

Fig. 2 Number of landslide records gathered by the Geological Surveys of Europe. Coordinate reference system ETRS89-LAEA Europe

reported 14,858 landslide records mapped at variable scales from 1:10,000 to 1:50,000. In Spain, the geological survey (IGME) has worked since 2014 for the integration of pre-existing LDBs and new landslide records into an INSPIRE compliant national LDB (MOVES). IGME-Spain mapping or updating of landslide records follows standardized procedures that include the collection of historical documents, photo-interpretation, and field surveys. In 2015, MOVES accounts for 2379 landslide records mapped at 1:25,000 or larger, and 6554 landslides in the process of integration. The design of MOVES ensures the interoperability with the LDBs of the Geological Survey of Catalonia (ICGC) that includes 2755 landslide records. In the near future, the LDBs from other regions of Spain (e.g., Asturias, Cantabria, or Basque Country) owned by other institutions will be assessed to ensure their interoperability. In Sweden and Ireland, the LDBs cover at least 50% of both countries. In other countries with consolidated national LDBs like Italy (Trigila and Iadanza, 2008; Trigila et al., 2010), Norway, Austria, Slovakia, the UK, Czech Republic, or Greece, the LDB updating activity follows similar standardized procedures that usually include collection of pre-existing data, remote sensing, and fieldwork. Taking into account that a great proportion of the LDBs are constructed based on these methods, little information on landslide history is available. The landslide history refers to the initiation and reactivation dates. According to Table 1, this information is available for more than 25% of the landslide records of 12 LDBs from 9 countries, which account for 121,559 landslide records.

Following standardized procedures for landslide mapping or updating would improve the spatial accuracy of the landslide location. Most of the LDBs (17) include landslides mapped with polygons or points at 1:25,000 or greater. Other geological surveys (10) report variable mapping scales ranging between 1:1000 and 1:500,000. This is the case of the LDBs from countries like Austria (GBA), Slovenia (GEOZS), or Greece (IGME GR), where their national LDBs integrate different landslide inventories mapped at different scales in different epochs, or by different public institutions in different formats. Consequently, the quality of the location data (resolution) and the information describing the event (literature, reports, maps) is also very different. In order to obtain records of comparable quality, the GBA applies a standardized procedure to integrate landslide information into its LDB. This is still not the case for the LDB from Slovenia (GeoZS). It contains 7273 landslide events mapped at variable scales (1:25,000–1:250,000) by different institutions. In the frame of the national project MASPREM 2 (Šinigoj et al., 2015; Jemec Auflič et al., 2016), a web application (e-Plaz) to collect landslides and other types of slope mass movements has been developed. This application is intended to homogenize and centralize the collection of landslide data with a minimum set of indicators (date, location type, and damage).

Landslide classes

Slides

Slides are the most frequently mapped landslide type by the geological surveys; they account for 305,865 records in 24 LDBs from 20 countries (green color on pie charts in Fig. 2 and Table 1). They represent 36% of the total amount of reported landslides. Most of the landslide records (53%) are concentrated in Italy (ISPRA), 45% are distributed in 8 countries: Poland (PGI), Switzerland (FOEN), Austria (GBA), Czech Republic (CGS), France (BRGM), Slovenia (GEOZS), and Spain (IGME-ICGC), whereas the remaining 2% are distributed in 11 countries (Fig. 3a).

Most of the slides are mapped with polygons (71%) indicating a higher spatial accuracy than points (Fig. 3b). However, a higher spatial accuracy is expected at least for some of the point records for certain geological surveys that evaluate the spatial accuracy on the position of the slide. For instance, BRGM distinguishes three accuracy levels, while BGS expresses the accuracy in meters. Area information of the slides is provided in 11 countries, but only 9 countries account for more than 1000 slides with areal extent (Fig. 3c).

The information of the slide volume is rare (2%), but the state of activity is more frequent (Fig. 3c). The state of activity is related to the date when the landslide information was compiled. Therefore, some slides indicated as active could now be inactive or vice versa. This information is available in 14 LDBs from 13 countries (Fig. 3c), which represent 35% of the total number of slides (106,896). However, there are only 6 countries with more than 1000 slides which include activity information. The information on the lithology and the trigger is most frequent than the impact (Fig. 3d). Impacts are available for 11% of the total slides (33,039) in 18 LDBs from 16 countries.

Falls

Falls represent 10% of the total number of reported landslides. There are 81,238 falls in 25 LDBs from 19 countries (blue color in pie charts in Fig. 2 and Table 1). The majority of the falls (65%) are concentrated in Norway (NGU) and Italy (ISPRA); 31% is distributed between Switzerland (FOEN), France (BRGM), Austria (GBA), and Spain (IGME and ICGC), and the remaining 3.5% in 13 countries (Fig. 4a). In Norway, it is the most frequent recorded type due to the impact they produce in society. The Norwegian historical LDB accounts for 51,161 landslide records from which 56% are falls (Kalsnes et al. 2016). The unstable rock slope LDB accounts for 250 records with postglacial deformation that can potentially result in rock avalanches (Oppikofer et al. 2015). They are extremely slow rockslides or rock flows that can result in catastrophic falls and extremely fast flows; thus, the "events" would be complex.

In most of the LDBs, falls (76%) are mapped as points (Fig. 4b). Depending upon the mapping scale, points or polygons can represent the location of the fall impact, the source area, or both of them. As in the case of the NGU databases, they can also represent unstable slope areas that can result in falls. Volume information is more frequently provided than in the slides, being available for 33% of the records in 8 LDBs (Fig. 4c). The state of activity information is available in the LDBs from 11 countries (Fig. 4c) that account for 30% of the total falls (24,036).

Information on the lithology is available for 20% of the records on the LDBs of 12 countries, whereas information on the trigger is less frequent (15%) for 11 countries (Fig. 4d). Impact information is available for 46% of the total fall records (37,689) in 16 LDBs from 14 countries (Fig. 4d).

Flows

Flows represent 20% of the total number of reported landslides. There are 172,308 flows in 19 LDBs from 16 countries (yellow color in pie charts in Fig. 2 and Table 1). Most of the flow records (89%) are concentrated in Italy (ISPRA), 10% are distributed in 4 countries (Austria, GBA; France, BRGM; Norway, NGU; and Spain, IGME and ICGC), and the remaining 1% is distributed across 11 countries (Fig. 5a) The type of flow depends on the lithology, i.e., earth and mud flows are more frequent in areas where marl and clay units domain, whereas debris flows are more abundant in rocky mountainous areas. More importantly, further subdivision of flow types according to their velocity seems to be necessary for susceptibility, hazard or risk assessment. In order to do so, the Italian Landslide Inventory (IFFI) from ISPRA divides flows into two classes: extremely rapid debris-mud flows and slow earth flows.

Flows mapped as polygons represent 56% of the records providing information on the areal extent from the LDBs of 9 countries. Flows mapped as lines constitute 30% and as points 14% (Fig. 5b). Area information is mostly available in Italy (95,795). In other 11 countries, this information is scarce, i.e., less than 580 records each (Fig. 5c). Volume information is only available for 3% of the flows (4666), mainly in the LDBs of Norway, Italy, and Spain (Fig. 5c). The state of activity (Fig. 5c) is available in the LDBs from

8 countries, which represents 36% of the flows, but they are mainly located in Italy (58,658) and Spain (1904). The information on the impact is available in 12 countries for 22% (38,460) of flows, but again is mainly concentrated in Italy (32,432), Norway (3600), and Spain (1269). In the rest of the countries, information on the state of activity or the impact does not exceed 500 flow records (Fig. 5d).

Complex landslides

There are 87,649 complex landslides in 14 LDBs from 15 countries representing 10% of the total number of reported landslides (pink color in pie charts in Fig. 2 and Table 1). They are concentrated in Italy (69%) and France (21%) whereas the remaining 10% is distributed across 12 other countries (Fig. 6a). Complex landslides are mass movements which are characterized by a combination of two or more principle types of movement. In Norway (NGU), records for 364 complex landslides describe large rock avalanches or large rock falls (volume > 10,000 m^3), whereas in other countries like in Spain, complex landslides can be large roto-translational mass movements that smoothly grade into flows in the lower parts of the slopes.

Complex landslides featured as polygons reach 72% (Fig. 6b) providing area information for more than 2000 records in Italy, Poland, Czech Republic, and France, and for less than 615 records in other 5 countries. In the case of France (BRGM), complex landslides are mapped as points but the spatial accuracy is expected to be higher in at least 38% of their records (7927) that include volume information (Fig. 6c). The state of activity is available in the LDBs from 8 countries, which represents 35% of the total number of complex landslides (30,147), but they are mainly concentrated in France (14,276) and Italy (13,389).

The information on complex landslide impact is available for 17% of the records in 8 countries (15,283), being mostly located in Italy (12,777) and France (1008) and 6 other countries with less than 550 records each (Fig. 6d).

Analysis of landslide spatial distribution

Landslide density map of the available records (LANDEN)

In this section, we analyze the spatial distribution of landslide records from the LDBs from the Geological Surveys of 17 countries in Europe. For this purpose, we calculate the landslide density of the available records for every square kilometer following the methodology described in the "Methodology" section. As a result, the landslide density map of the available records from 17 Geological Surveys of Europe (LANDEN) is produced. The surficial extent of these countries is 3.65 million km^2 from which approximately 6% constitute landslide-prone areas (0.21 million km^2), where at least one landslide occurred for every square kilometer. A landslide density of 1–3 landslides/km^2 is found for 69% of this area, 4–10 landslides/km^2 for 24%, and 11 or more landslides/km^2 for the remaining 6% (Fig. 7). Hereafter, we refer to landslide-prone areas or landslide mapped areas as every square kilometer where at least one landslide record is available in the LDBs. Hence, more than 35% of the Italian territory are landslide-prone areas, and more than 10% of the territories of Czech Republic, Slovenia, and Slovakia. In large countries like the UK, Poland, France, or Spain landside records only represent 1–4% of the territory. This first analysis is helpful to understand where landslides have been mapped and will permit evaluating the completeness of the available LDBs in the next section.

In the next part, the spatial distribution of landslides per administrative area is analyzed. For this purpose, the available landslide records gathered by the geological surveys of 17 countries are combined with the smallest administrative boundaries available for each country. These administrative areas are municipalities for 10 countries and for the other 7 (Austria, Norway, Hungary, Romania, Croatia, Greece, and Cyprus), the lowest available unit from the Global Administrative Areas (GADM, 2015). Overall, there are 86,083 administrative areas with an average area of

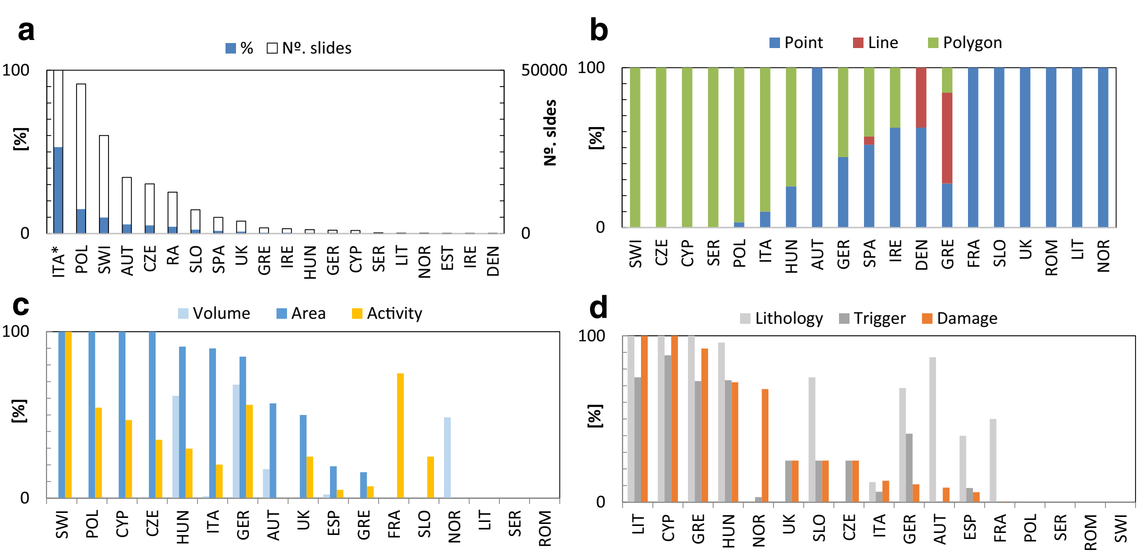

Fig. 3 **a** Number of slide records gathered by the Geological Surveys of Europe. ITA* refers to the number of slides in Italy (162019) which is out of the range of the *Y*-axis; **b** percentage of slides mapped as points, lines, or polygons; **c** percentage of slides with information available on the area, the volume, and the activity; **d** percentage of slides with information available on the lithology, the trigger, and the impact

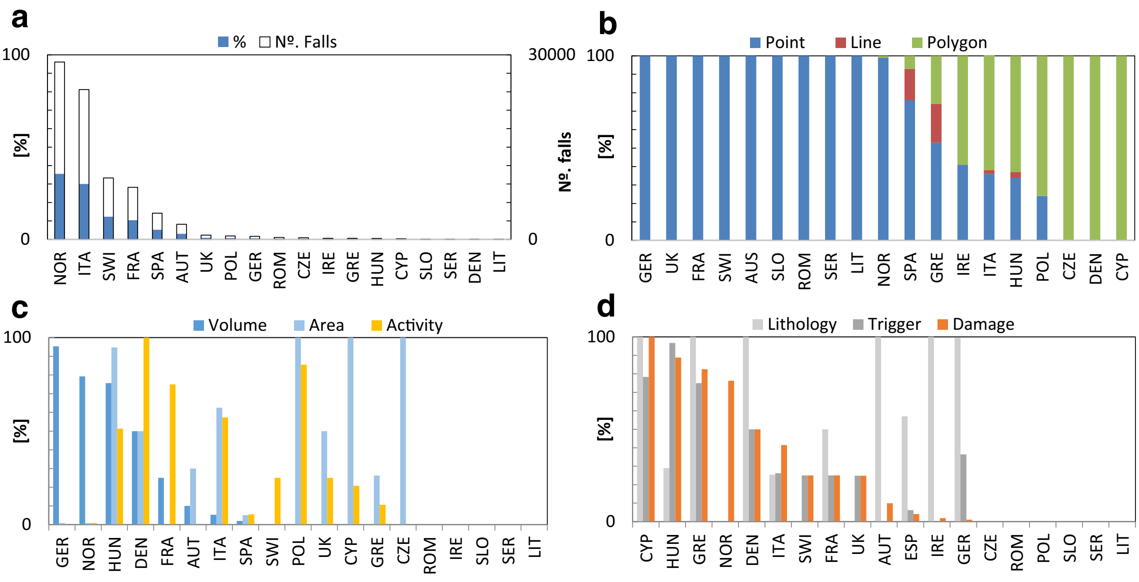

Fig. 4 **a** Number of fall records gathered by the Geological Surveys of Europe; **b** percentage of falls mapped as points, lines, or polygons; **c** percentage of falls with information available on the area, the volume, and the activity; **d** percentage of falls with information available on the lithology, the trigger, and the impact

40 km². However, there is certain variability in the extent of the municipalities between countries. The average size of the municipalities of Czech Republic, Slovakia, and France is below 15 km², whereas in Sweden the average area is 1550 km². Note that in countries like Norway, Sweden, and the UK, larger municipalities are found in the north where there is a smaller population density, and smaller municipalities are located in the south coinciding with the greatest population density. However, the administrative boundaries available from GADM are larger (146 km² on average) than those provided by the geological surveys (33 km² on average); therefore, the number of landslides per municipality is not directly comparable. For this reason, in Fig. 8, we present the average landslide density (per km²) for each administrative area.

From the total amount of 86,090 administrative areas, 72% of them do not coincide with recorded landslides and 23,523 administrative areas with an average area of 69 km² that account for 32 landslides each (0.5 landslide per km²). From this number, 17% of the administrative areas account for 7 landslides on average (0.16 landslides per km²), and 10% of them 75 landslides on average (2.6 landslides per km²). The average landslide density of each country can be observed in the bar plot from Fig. 8. More than 70% of the administrative areas from Norway, Slovenia, and Italy (bar plot in

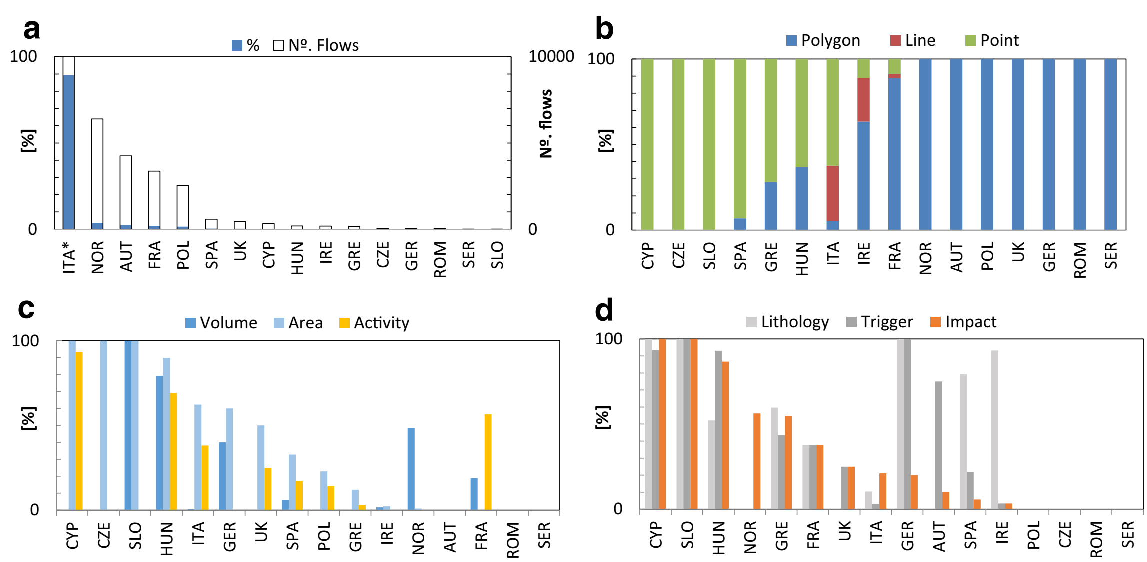

Fig. 5 **a** Number of flow records gathered by the Geological Surveys of Europe. ITA* refers to the number of slides in Italy (153,742) which is out of the range of the *Y*-axis; **b** percentage of flows mapped as points, lines, or polygons; **c** percentage of flows with information available on the area, the volume, and the activity; **d** percentage of flows with information available on the area, the volume, and the activity the lithology, the trigger, and the impact

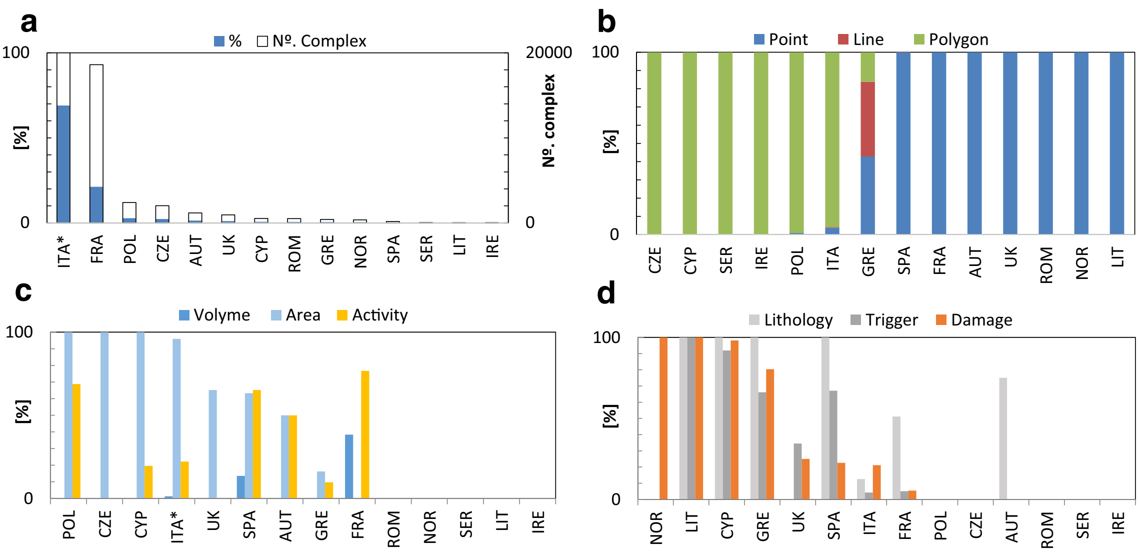

Fig. 6 **a** Number of complex landslide records gathered by the Geological Surveys of Europe; **b** percentage of complex landslides mapped as points, lines, or polygons; **c** percentage of complex landslides with information available on the area, the volume, and the activity; **d** percentage of complex landslides with information available on the lithology, the trigger, and the impact

Fig. 8) account for landslide records. In the latter, the average area of the municipalities is 37 km^2 and the majority of them have 60 landslides per administrative area (average landslide density over 1 landslide/km^2). Something similar occurs in Slovakia where 64% of the municipalities (average area 14 km^2) have 11 landslides per administrative area. Landslides affect more than 45% of the administrative areas in 6 other countries, and less than 25% in 8 of them. In large countries like UK and France, landside records are only available for 24% of their administrative areas and in Spain for only 9% of them. In Spain, the average landslide density is 0.02 landslide/km^2 with less than 1 landslide per administrative area. The same average landslide density is found in Romania, Ireland, Sweden, Croatia, Greece, and Hungary. In countries like Poland or Czech Republic, even if the number of administrative areas with landslides represents less than 13% for each country, the average landslide density is over 0.2. If we focus on the administrative areas with the greatest landslide density, there are 8 countries (Czech Republic, Norway, Cyprus, Poland, Slovenia, Austria, Slovakia, and Italy) that account for 6736 administrative areas with an average landslide density of over 0.5 landslide/km^2. This map could be useful to identify landslide-prone administrative areas according to the geological survey records. However, it could also be misleading as the previously presented landslide density map, due to the variable completeness of the LDBs.

Comparison with ELSUS v1 map

The previously presented landslide density map (LANDEN) is compared with the European landslide susceptibility map (ELSUS v1) proposed by Günther et al. (2014), in order to provide a first approximation of the incompleteness of the landslide databases (LDBs) from the geological surveys. This comparison is made using a confusion matrix following the methodology described in the "Methodology" section.

The LANDEN map covers an area of 3.65 Mkm^2 from 17 countries and accounts for 0.21 Mkm^2 of landslide-prone areas with landslide records from the geological surveys (as it is described in the previous section). ELSUS v1 does not cover Cyprus, and therefore, the comparison with the LANDEN map is restricted to 16 countries. In these countries, ELSUS v1 landslide-susceptible areas covering 1.14 and 2.27 Mkm^2 are not susceptible landslide areas (Fig. 9a).

In the confusion matrix, landslide-susceptible areas according to ELSUS v1 that coincide with landslides recorded in one of the databases are true positives (TP) and not susceptible areas where no landslides are recorded are true negatives (TN). Areas not susceptible to landslides that coincide with recorded landslides are false negatives (FN), whereas false positives (FP) indicate landslide-susceptible areas that do not coincide with any landslide records. It could be due to several reasons: (1) an overestimation of ELSUS v1; (2) the existence of landslide records in LDBs owned by other institutions; (3) the existence of unmapped landslides; and (4) the absence of landslides in a susceptible area where new landslides could occur in the future. Taking into account that any of these possibilities could be correct, FP is used as an indirect indicator of the incompleteness of the LDBs from the geological surveys.

The cell-to-cell comparison of the ELSUSV1 with the LANDEN map reveals a successful comparison for 69.7% of the area, with 0.15 Mkm^2 of TP and 2.22 Mkm^2 of TN. ELSUS v1 comparison was unsuccessful (FN) for 1.4% of the area (0.05 Mkm^2), whereas FP occupies 28.9% of the area (0.98 Mkm^2). The FP indicates that there is an area of 0.98 Mkm^2 susceptible to landslides that does not coincide with any record from the LDBs of the geological surveys. In Fig. 9b, c, ELSUSv1 is compared with landslide-prone areas mapped by the geological surveys in each country. Note that ELSUS v1 is not available for Cyprus and the Canary islands, and therefore, the comparison is not possible there (NA in Fig. 8). Similarly, ELSUS v1 is not available along certain coastlines due to the resolution of the DEM used for its calculation (Günther et al. 2014). For instance, in Norway, 21% of the landslide mapped areas

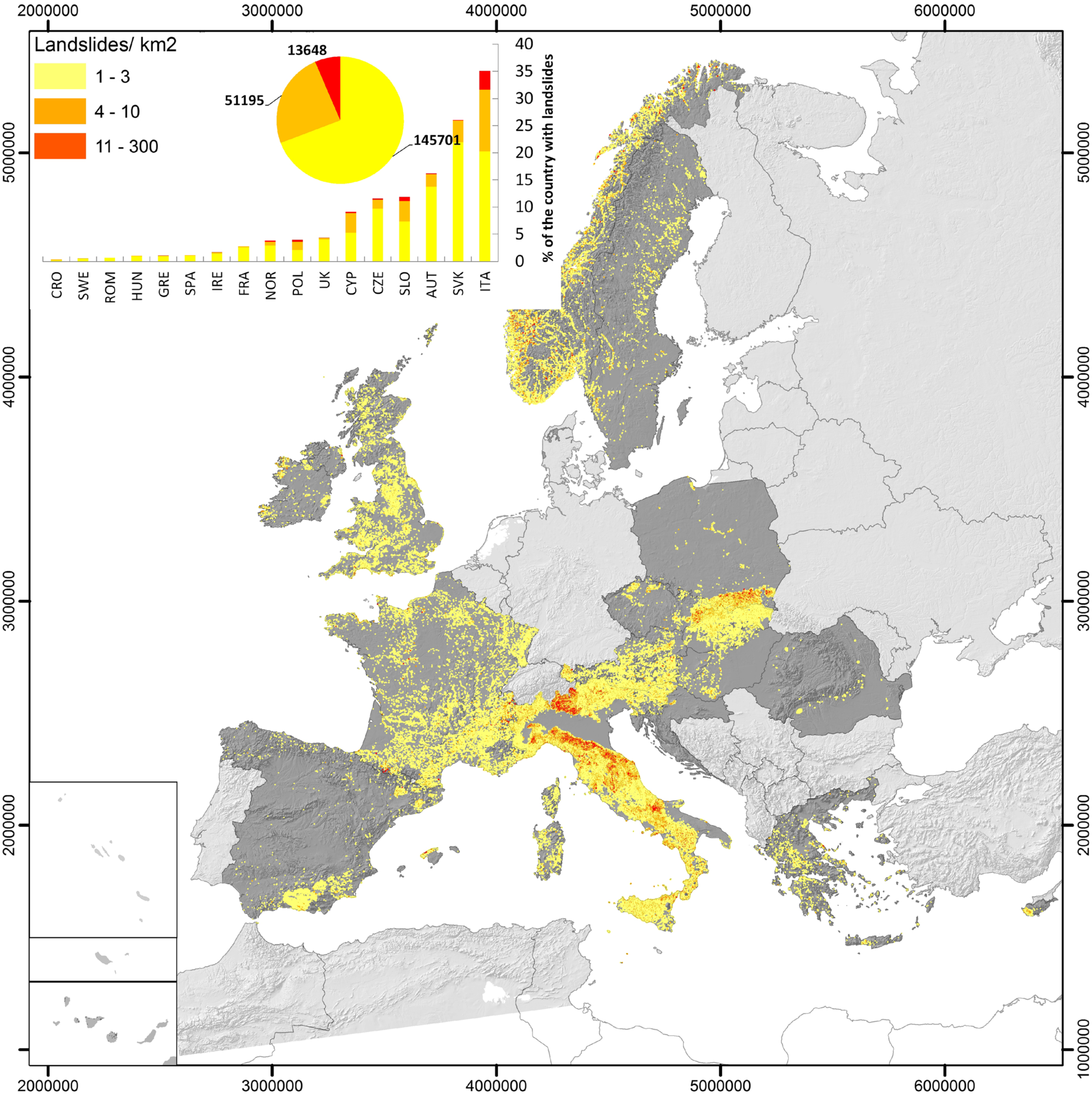

Fig. 7 Landslide density per square kilometer from the available landslide records gathered by 17 Geological Surveys of Europe. Coordinate reference system ETRS89-LAEA Europe

located along the coastline cannot be compared with ELSUS v1 estimations. All such areas were marked as NA. Focusing on those landslide mapped areas that are comparable with ELSUS v1, we observe that in Italy TP represent 88% of the landslide mapped areas by the geological survey (ISPRA), FN represent 11%, and the remaining 1% are landslide mapped areas where ELSUS v1 was not estimated. On the other end, there is Sweden, where TP only represent 16% of the landslide mapped areas by the geological survey (SGU) whereas FN represent 80%. Note that in this country only 405 out of 2563 landslide mapped areas coincide with ELSUS v1 susceptible areas. This underestimation is due to the poor performance of ELSUS v1 reported in some countries like Sweden or Romania by Günther et al. (2014). This mismatch is probably due to the presence of quick clay landslides (actually flows) in southwest Sweden. They occur at very low angles that continent-scale models may fail to account for. The same problem occurs in other countries like Spain, where many landslides develop in low-slope areas related to the river basins. A very significant example is the riverbank of the Guadalquivir, where highly plastic clays display an expansive behavior (Tsige et al., 1994; Alonso et al., 2010)

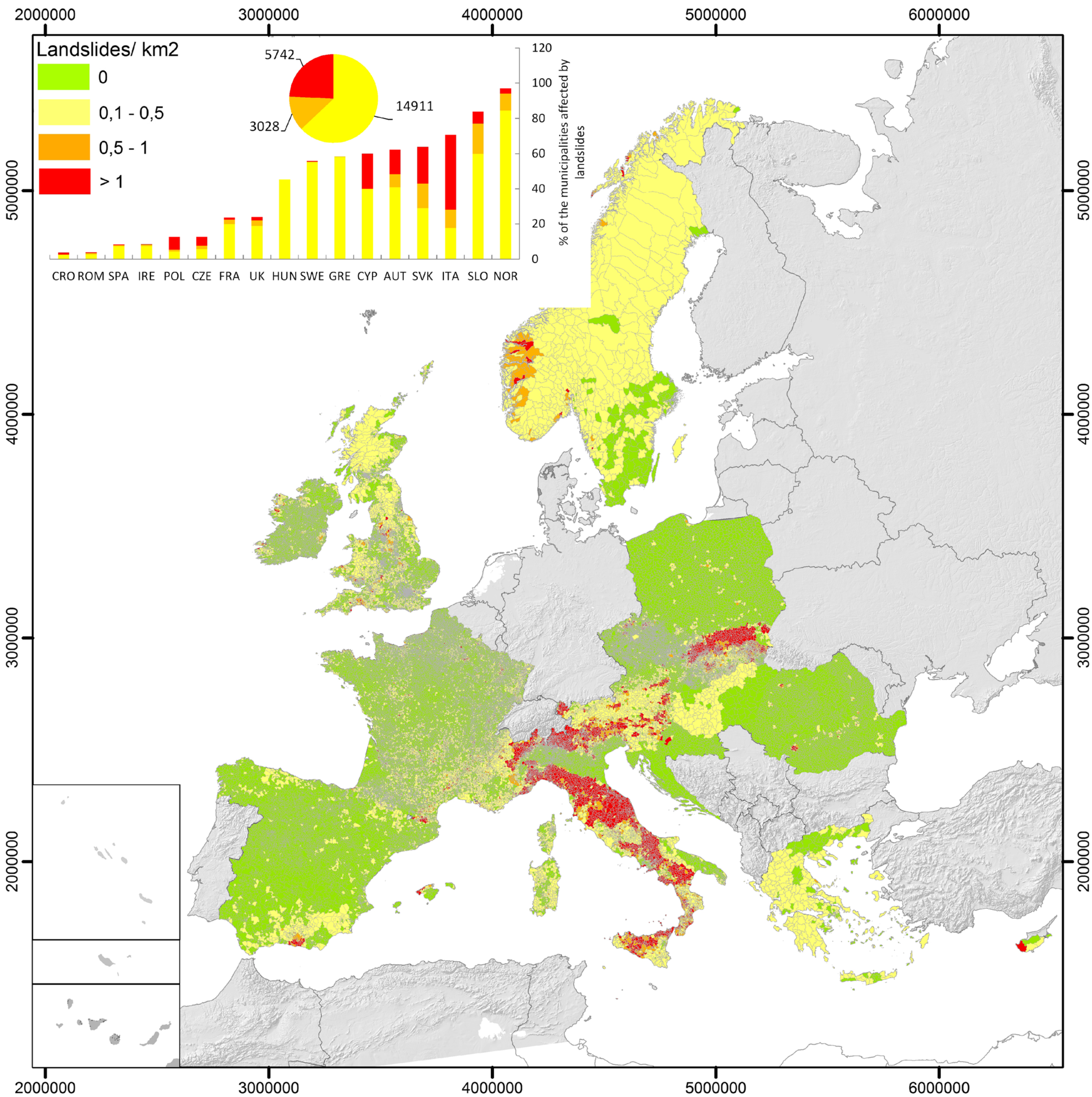

Fig. 8 Landslide density (landslide per km^2) for each municipality. The graph indicates the percentage of administrative areas classified by landslide density. Green represents the absence of landslides records in the GSs (no data). Coordinate reference system ETRS89-LAEA Europe

and undergo serious landslide problems affecting smooth slopes (< 12°) and generating multiple damages in the region. These areas located in the main river basins of the country are not contemplated as susceptible zones in the Spanish ELSUS map, but they really are.

Assuming these limitations, we estimate the average values obtained for the 16 countries and we obtain an average success of 65%, the unsuccessful comparison of 2.1 and 33.4% of the landslide-susceptible areas without records from the geological surveys (FP). The FP is greater than 50% of the extent of Greece, Austria, and Slovenia (Fig. 9c) where there is 0.14 Mkm^2 of landslide-susceptible areas with no landslide records in their LDBs. On the other end, there are countries like Poland, Hungary, and Sweden with an FP below 10% of their national extent (0.07 Mkm^2). For the rest of the countries, FP ranges between 25 and 50% of the area of every country and accounts for 0.77 Mkm^2, from which France, Spain, Italy, and the UK already account for 0.48 Mkm^2.

In the next part, the ELSUS v1 is compared with the LANDEN map for each administrative area. For this purpose, the median

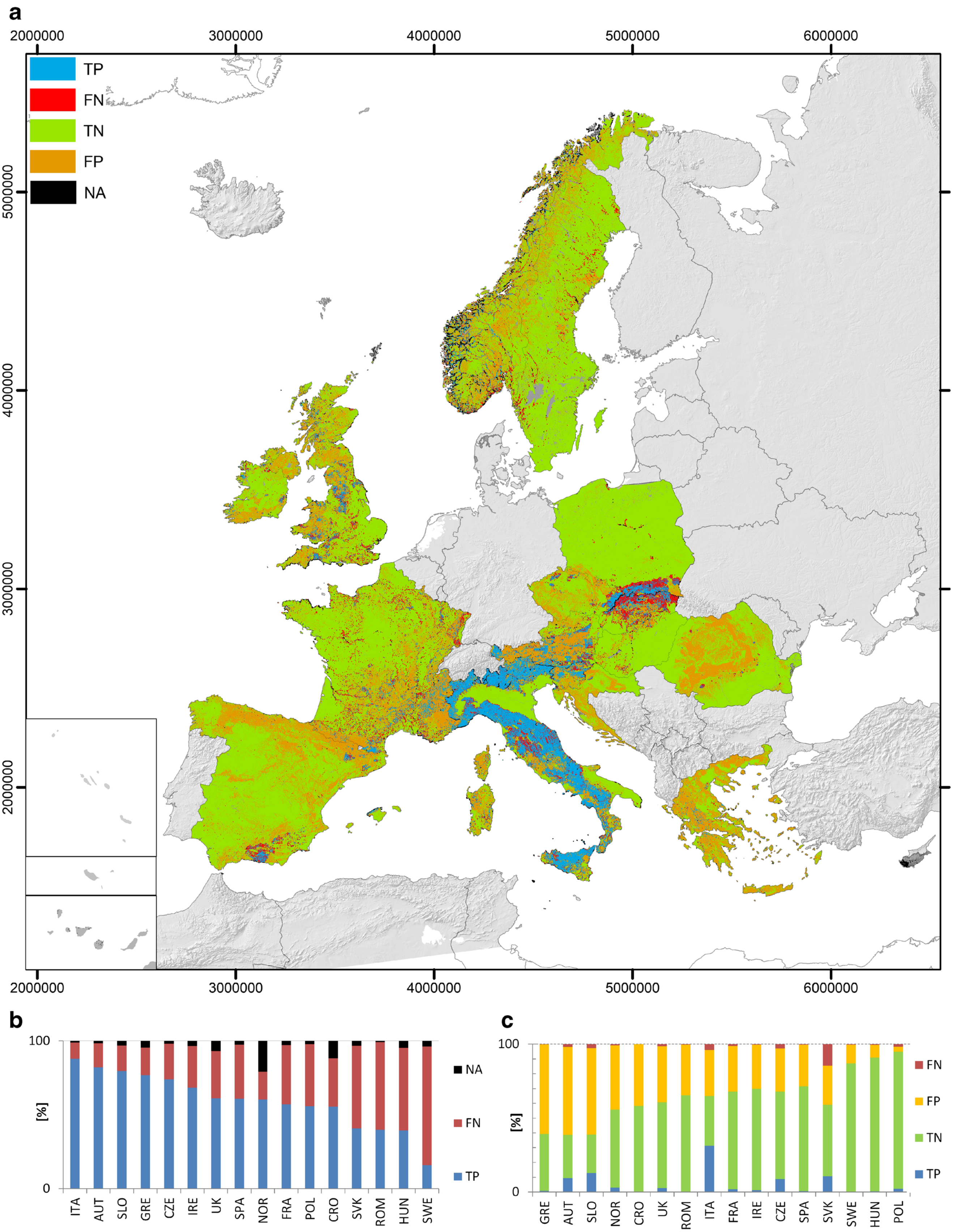

Fig. 9 **a** LANDEN map derived from the LDBs of 16 geological surveys superimposed over the ELSUS v1 susceptibility map classified in susceptible or not susceptible areas; **b** confusion matrix obtained for every country classified by % of the total area; **c** areal extent of the TP and FN. Coordinate reference system ETRS89-LAEA Europe

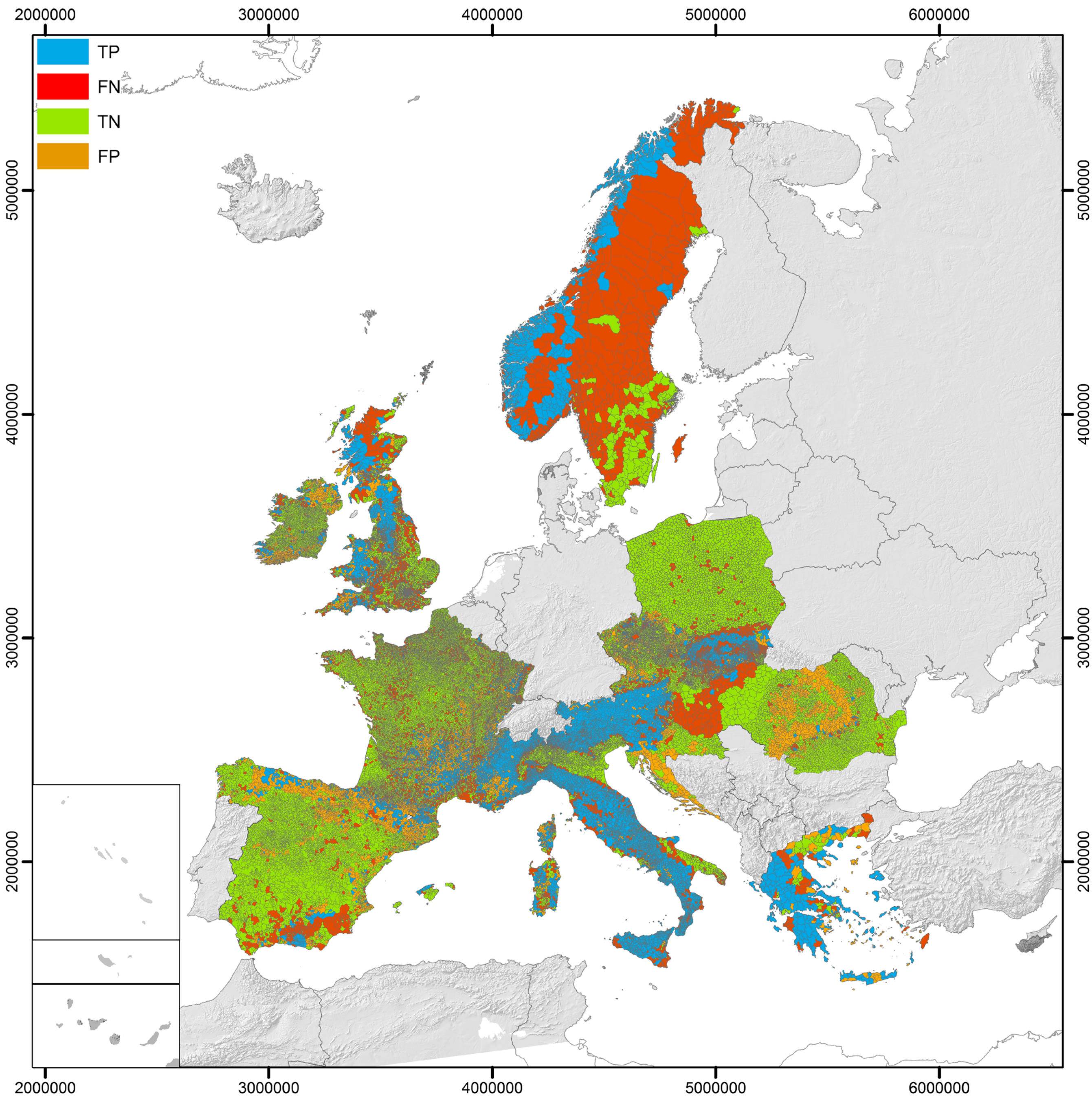

Fig. 10 Comparison between the LADEN map with the ELSUS map for each administrative area. Coordinate reference system ETRS89-LAEA Europe

value of the ELSUS v1 susceptibility is calculated for each administrative area and then compared to the total number of recorded landslides. This calculation is constrained by the great variability of the area of the administrative areas, and it will probably not be representative in those countries were administrative areas are very large (e.g., Sweden). From the total number of administrative areas that coincide with ELSUS v1 (85,156), 58% represent not susceptible administrative areas with no LDBs (TN) and 15% of the administrative areas are susceptible and account for landslide records (TP). Therefore, ELSUS v1 estimation is successful for 74% of the administrative areas, it is unsuccessful for 12% of them (FN), whereas the remaining 14% represent susceptible administrative areas with no LDBs (FP). Therefore, there are 11,924 administrative areas susceptible to landslides with no landslide records in the geological surveys (Fig. 10). As it is expected, the confusion matrix analysis applied to the administrative areas yields a greater error (4.5 times) than the previous analysis applied at 1 km^2. Despite this limitation, it still provides a valuable indicator on the LDBs' incompleteness for the administrative areas available for each country.

LDBs' completeness analysis

According to Van Den Eeckhaut and Hervás (2012), the European landslide DBs' completeness is less than 50% of all the landslides that have ever occurred in every country based on the opinion of national landslide experts. The incompleteness of the LDBs is due to different reasons. Landslide mapping in most of the countries only targets impacted areas or areas with a high exposure and risk. In other countries, LDBs are available at regional and local levels, being not always included into common national LDBs.

In order to provide a quantitative approximation of the completeness of the LDBs for each of these countries, we calculate the relationship between landslide mapped areas (TP + FN + NA) and the sum of ELSUS susceptible areas (TP + FP) and landslide mapped areas that do not coincide with ELSUS (FN + NA). This value is obtained through the following equation:

$$completeness = \frac{\mathrm{TP} + \mathrm{FN} + \mathrm{NA}}{\mathrm{TP} + \mathrm{FP} + \mathrm{FN} + \mathrm{NA}}$$

According to this relationship, the completeness of the LDBs from Poland, Italy, and Slovakia is over 50%, whereas for seven countries the completeness varies from 10 to 30%. The completeness from the rest of the countries is between 6 and 1% (Fig. 11). Note, that these numbers represent an indirect estimation of the LDB completeness, since the 100% completeness would require one landslide record for every square kilometer susceptible to landslides. However, they are useful to highlight the gaps and the needs of the LDB from the geological surveys to be completed.

The LDBs of the geological survey of Poland are the most complete. According to ELSUS v1, there are 17,384 km^2 of landslide-susceptible areas (6% of the Polish territory). The LANDEN map coincides with ELSUS v1 on 6991 km^2 (TP) whereas 5234 km^2 of landslide mapped areas do not match with susceptible areas (FN). Consequently, there are 10,393 km^2 landslide-susceptible areas with no LDB records (FP). Considering the mapped landslide-prone areas (6991 + 5234 km^2) over the landslide-susceptible areas plus landslide mapped areas in not susceptible areas (17,491 + 5234 km^2), we obtain that the estimated completeness of the LDB from PGI is 55%. Landslide-susceptible areas in countries like Romania, Greece, Spain, or Croatia cover wide areas, 0.32 Mkm^2 all together, that represent 28 to 60% of their territory. However, the completeness of the LDBs available from these geological surveys is less than 5%. This is because (1) the LDBs from the geological surveys of Greece and Spain are limited to damaging landslides and (2) the LDBs from Romania or Croatia are local and regional landslide databases. These countries still lack a systematic landslide mapping strategy as in other countries like Italy, Poland, or Slovakia.

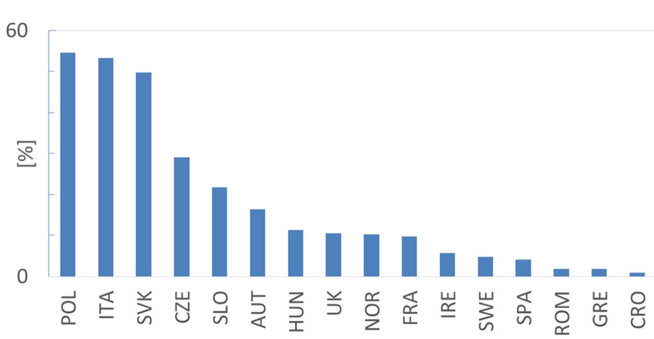

Fig. 11 Percentage of the LDBs' completeness estimation for 16 geological surveys

Discussion

Review of the geological survey landslide databases

This review of landslide databases (LDBs) of the Geological Surveys of Europe provides information on 34 LDBs from 29 geological surveys of 24 countries, from which 20 are national and 14 regional LDBs. These LDBs co-exist with others owned by a variety of institutions: road and railroad authorities, water and energy authorities, regional or municipal authorities, universities, etc. The 34 LDBs contain 849,543 landslides, from which 36% are slides, 10% are falls, 20% are flows, 11% are complex landslides, and 24% either remain unclassified or correspond to other typology. Most of them are located in Italy (62%) and 10 other countries. The majority of the LDBs (17) include landslides at 1:25,000 or greater, but others (10) report variable mapping scales ranging between 1:1000 and 1:500,000. This is because their national LDBs integrate different landslide inventories mapped by different public institutions in different formats and scales. In order to obtain records of comparable quality, the geological surveys apply standardized procedures to integrate different source LDBs into theirs.

Among all type of movements, slides are the most frequently mapped landslide type by the geological surveys; they account for 305,865 records from 20 countries. They are usually mapped as polygons and provide information on the areal extent, permitting to perform European-scale slide susceptibility analysis. The information necessary for hazard and risk analysis is less frequent (impact for 11% of the records) and not homogeneously distributed in all the countries. Further subdivision should be made, regarding shallow- and deep-seated slides due to the different methodologies and approaches in local geotechnical studies and also in susceptibility, hazard, and risk mapping and assessment. However, our experience tells us that the depth of the sliding surface is known only for a small percentage of landslides in a national inventory.

Falls represent 10% of the total number of landslide records (81,238) from 20 countries, with the majority of them located in Norway and Italy (65%) and 4 other countries. They are usually mapped as points (76%) providing information on the volume and state of activity for more than 30% of the records. European-scale fall susceptibility analysis seems to be possible for most of the countries, but only for 5 of them is volume information available for hazard analysis. Impact information is only significant (> 2500 records) in 4 countries (Norway, France, Italy, and Switzerland) and below 200 records for other six countries. Therefore, local-scale hazard and risk analysis seems to be more adequate, and continuous monitoring of those unstable rock slopes, which are extremely slow rockslides that can result in catastrophic falls and extremely fast flows.

Flows represent 20% of the total amount of reported landslides (172,308) from 16 countries with most of them located in Italy (89%). The type of flow depends on the lithology; earth and mud flows are more frequent in areas where marl and clay units dominate, whereas debris flows are more abundant in rocky mountainous areas. They are usually mapped as polygons or lines and provide information on the areal extent, permitting European-scale flow susceptibility analysis. Similarly to what occurs in the slides, the information necessary for hazard and risk analysis is less frequent and not homogeneously distributed in all the countries. For instance, impact information is only significant in Italy, Norway, and Spain. Moreover, further subdivision of flows is necessary according to their velocity (rapid debris-mud flows and slow earth flows), in order to perform susceptibility, hazard, and impact models.

Complex landslides account for 87,649 records from 15 countries with most of them concentrated in Italy (69%) and France (22%). They are featured as polygons (72%) and provide extensional information permitting complex landslide susceptibility analysis. However, due to the reduced number of records available for the rest of the countries (10,000) and the heterogeneity of the landslides involved in this typology makes the European-scale approach not very realistic.

Landslide density map of the geological surveys

The landslide density map of the geological surveys (LANDEN map) elaborated for 17 countries in Europe provides the first picture of the spatial distribution of the landslides recorded by the geological surveys in 3.65 million km^2 of the European surface. This map reveals that approximately 6% are landslide-prone areas, i.e., 1 km by 1 km cells with one or more landslide records. Note that they do not represent the real extent of mapped landslides (landslide area) but are an indicator of where landslides have been mapped. For instance, in Italy, the country with the greatest density of landslides, landslide-prone areas represent 35% of the Italian territory whereas the landslide area represents the 7.3%. Taking this aspect into account, landslide-prone areas occupy more than 10% of Czech Republic, Slovenia, or Slovakia. In large countries like UK, Poland, France, or Spain, landside-prone areas only represent 1–4% of the territory.

The average landslide density map has been calculated for the available administrative areas of these 17 countries, permitting the identification of those administrative areas affected by landslides that were recorded by the geological surveys. From a total number of 86,090 administrative areas, 28% account for landslide records, from which the average density for 8612 administrative areas is more than 0.5 landslide/km^2. Italy, Slovakia, Austria, Slovenia, Cyprus, and Norway account for more than 60% of the administrative areas with landslide records and an average landslide density greater than 0.2 landslide/km^2. In fact, these six countries account for 6059 administrative areas with more than 0.5 landslide/km^2. On the other hand, 10% of the administrative areas from Croatia, Spain, Ireland, and Romania account for landslides with an average landslide density below 0.03 landslide/km^2, indicating that their LDBs are probably incomplete.

It is worth noting that the landslide density analysis presented in this paper was carried out purely using landslide point data and not mapped landslide extents (polygons). Even if a landslide is several kilometers in length or several hundreds of meters wide, it was only represented by 1 point, either its centroid or, for instance in the case of the national landslide database of the UK, the highest point on the landslide head scarp. The use of point data for the estimation of landslide density per square kilometer or per municipality therefore means that a single point will fall within a single kilometer grid or a single municipality, despite the size and shape of the corresponding landslide. While this is an unavoidable issue due to the processing method and use of point data, it creates landslide density maps (and consequent estimates of their completeness) that look as though the inventories of several countries were not as well developed as they actually are.

LANDEN map comparison with ELSUS v1 map

In this work, we present the first independent assessment of ELSUS v1 map through its comparison with the LANDEN map, using a confusion matrix. The successful comparison covers 70% of the area (2.37 Mkm^2), 1.4% the unsuccessful comparison (0.05 Mkm^2), whereas 28.9% of the area (0.98 Mkm^2) represents landslide-susceptible areas without records from the geological surveys. The variable success of the comparison appreciated among countries (between 13 and 88%) can be explained by the poor performance of ELSUS v1 in some countries (Günther et al. 2014). Several geological aspects were not taken into account such as the development of clay landslides in smooth slopes. However, the average success obtained for each country is similar to that of the cell to cell comparison, being the landslide-susceptible areas without records from the geological surveys (FP) an indicator of the completeness of each database. The comparison for the administrative areas available for each country provides a similar result; it is successful for 74% of the administrative areas and unsuccessful for the 12%, indicating that there are 11,924 administrative areas susceptible to landslides with no landslide records in the geological surveys.

LDBs' completeness analysis

Taking into account the results from the previous comparison, the LDBs' completeness has been evaluated. As a result, it is over 50% for Poland, Italy, and Slovakia; for another five countries (Slovenia, Austria, Hungary, UK, and France), the LDBs' completeness varies from 10 to 30%, whereas for the rest of the countries, it is between 6 and 1%. In Romania, Greece, Spain, or Croatia, the LDBs' incompleteness represent 28 to 60% of their territory, which is explained by the fact that the LDBs of Spain or Greece focus mainly on damaging landslides, whereas in Romania and Croatia, there are only local and regional landslide databases.

Conclusions

In this work, the review of 34 LDBs from 29 geological surveys of 24 countries permitted the classification of 849,543 landslide records in slides (36%), falls (10%), flows (20%), complex slides (11%), and others (24%). The majority of the records for each landslide type are mapped with the same features at a scale of 1:25,000 or greater, permitting the elaboration of European-scale maps for each landslide type. However, the spatial accuracy on the position of every landslide should be evaluated using the same procedure (e.g., those from BRGM, BGS, or ISPRA).

Based on the landslide additional information available for most of the LDBs, the elaboration of European scale susceptibility assessment for each landslide type seems reasonable. The information necessary for hazard and risk analysis is scarce (below 40%) and not homogeneously distributed in all the countries; therefore, European-scale assessments seem difficult. However, the comparison of local-scale hazard and risk assessments performed in different countries would be helpful to harmonize procedures and define standards for each landslide type. In order to do so, further subdivision of landslide types seems to be necessary needing so different methodologies and approaches in susceptibility, hazard and risk mapping, and assessment, e.g., rapid debris/mud flows, slow earth flows, rock fall-prone areas, and unstable rock slopes that can result in catastrophic rock fall avalanches.

The landslide density map of the geological surveys (LANDEN map) shows, for the first time, 210,544 km² landslide-prone areas where 17 geological surveys from Europe have recorded more than 1 landslide for each square kilometer. Landslide-prone areas represent 35% of Italy and between 3 and 26% in 9 other countries. Overall, there are 23,681 administrative areas with landslide records from which 8612 account for 2.5 landslides/km² on average. Most of these administrative areas are located in Italy, Slovakia, Austria, Slovenia, Cyprus, and Norway. In the future, a greater coordination effort should be made by different institutions in order to produce an improved version of the landslide density map of Europe including LDBs from missing countries, a greater spatial resolution, a map for every landslide type, and the landslide damaging events that occurred every year. Additionally, in countries with high seismic hazard (Italy, Greece, Albania, etc.) both static and dynamic conditions should be taken into account. Hence, the resulting maps could certainly help landslide hazard management at European, national, and regional scales, being also useful to perform multi-hazard analysis in areas with high seismic hazard.

Additionally, this work provides an independent evaluation of the European landslide susceptibility map (ELSUS 1000 v1) performed with the LANDEN map. The comparison is successful for most of the territory (69.7%) even if it shows certain variability between countries. The unsuccessful comparison of 1.4% is due to geological aspects that this continent-scale model did not take into account. On the other hand, there is 0.98 Mkm² (28.9%) of landslide-susceptible areas without records from the geological surveys that have been used to evaluate the LDBs' completeness.

The proposed method to evaluate the landslide database completeness from the geological surveys yields that the average LDBs completeness is 17%, being between 10 and 50% for 8 countries, and between 6 and 1% for the rest. These numbers represent an indirect estimation of the LDB completeness, since the 100% completeness would require one landslide record for every square kilometer susceptible to landslides. However, these numbers are useful to highlight the gaps of the existing LDB and the variable landslide strategies adopted by countries across Europe. In some of them, landslide mapping is systematic; others only record damaging landslides, whereas in others, landslide maps are only available for certain regions or local areas. Moreover, in most of the countries LDBs from the Geological Surveys co-exist others owed by a variety of public institutions producing LDBs at variable scales and formats.

A greater coordination effort should be made by all the institutions working in landslide mapping to increase data integration and harmonization. In order to do so, a European Landslides Directive should be promoted, in order to provide a common legal framework addressing one of the most widespread and damaging geohazards in Europe.

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Dirk Kuhn, on behalf of the participating SGS

G. Herrera (✉) · **R. M. Mateos** · **J. C. García-Davalillo** · **G. Grandjean** · **E. Poyiadji** · **R. Maftei** · **T.-C. Filipciuc** · **M. Jemec Auflič** · **J. Jež** · **L. Podolszki** · **A. Trigila** · **H. Raetzo** · **A. Kociu** · **M. Przyłucka** · **M. Kułak** · **M. Sheehy** · **X. M. Pellicer** · **C. McKeown** · **G. Ryan** · **V. Kopačková** · **M. Frei** · **D. Kuhn** · **R. L. Hermanns** · **N. Koulermou** · **C. A. Smith** · **M. Engdahl** · **P. Buxó** · **M. Gonzalez** · **C. Dashwood** · **H. Reeves** · **F. Cigna** · **P. Liščák** · **P. Pauditš** · **V. Mikulėnas** · **V. Demir** · **M. Raha** · **L. Quental** · **C. Sandić** · **B. Fusi**
Earth Observation and Geohazards Expert Group (EOEG),
EuroGeoSurveys, the Geological Surveys of Europe,
Brussels, Belgium
Email: g.herrera@igme.es

R. M. Mateos
e-mail: rm.mateos@igme.es

J. C. García-Davalillo
e-mail: jc.garcia@igme.es

G. Grandjean
e-mail: g.grandjean@brgm.fr

E. Poyiadji
e-mail: kynpo@igme.gr

R. Maftei
e-mail: mafteir@yahoo.com

M. Jemec Auflič
e-mail: mateja.jemec@geo-zs.si

J. Jež
e-mail: jernej.jez@geo-zs.si

L. Podolszki
e-mail: laszlo.podolszki@hgi-cgs.hr

A. Trigila
e-mail: alessandro.trigila@isprambiente.it

H. Raetzo
e-mail: hugo.raetzo@bafu.admin.ch

A. Kociu
e-mail: arben.kociu@geologie.ac.at

M. Przyłucka
e-mail: maria.przylucka@pgi.gov.pl

M. Kułak
e-mail: marcin.kulak@pgi.gov.pl

M. Sheehy
e-mail: michael.sheehy@gsi.ie

X. M. Pellicer
e-mail: Xavier.Pellicer@gsi.ie

C. McKeown
e-mail: Charise.McKeon@gsi.ie

G. Ryan
e-mail: Graham.Ryan@gsi.ie

V. Kopačková
e-mail: veronika.kopackova@geology.cz

M. Frei
e-mail: Michaela.Frei@bgr.de

D. Kuhn
e-mail: d.kuhn@bgr.de

R. L. Hermanns
e-mail: reginald.hermanns@ngu.no

N. Koulermou
e-mail: nkoulermou@gsd.moa.gov.cy

C. A. Smith
e-mail: Colby.Smith@sgu.se

P. Buxó
e-mail: Pere.Buxo@icgc.cat

M. Gonzalez
e-mail: Marta.Gonzalez@icgc.cat

C. Dashwood
e-mail: cfoster@bgs.ac.uk

H. Reeves
e-mail: hjre@bgs.ac.uk

F. Cigna
e-mail: fcigna@bgs.ac.uk

P. Liščák
e-mail: pavel.liscak@geology.sk

P. Pauditš
e-mail: Pere.Buxo@icgc.cat

V. Mikulėnas
e-mail: vidas.mikulenas@lgt.lt

V. Demir
e-mail: vedad.demir@fzzg.gov.ba

M. Raha
e-mail: margus.raha@egk.ee

L. Quental
e-mail: lidia.quental@lneg.pt

C. Sandić
e-mail: c.sandic@geozavodrs.com

B. Fusi
e-mail: fusi.balazs@gmail.com

G. Herrera · R. M. Mateos · J. C. García-Davalillo
Geohazards InSAR Laboratory and Modeling Group, Geohazards Unit,
Geological Survey of Spain (IGME),
Madrid, Spain

G. Grandjean
Risk and Prevention Division,
BRGM,
Orleans, France

E. Poyiadji
Engineering Geology Department,
Institute of Geology and Mineral Exploration,
Athens, Greece

R. Maftei · T.-C. Filipciuc
GeoHazard team,
Geological Institute of Romania,
Bucharest, Romania

M. Jemec Auflič · J. Jež
Geological Survey of Slovenia,
Ljubljana, Slovenia

L. Podolszki
Croatian Geological Survey,
Zagreb, Croatia

A. Trigila · C. Iadanza
ISPRA, Geological Survey of Italy,
Rome, Italy

C. Iadanza
e-mail: carla.iadanza@isprambiente.it

H. Raetzo
Swiss Federal Office for the Environment,
Bern, Switzerland

A. Kociu
Geological Survey of Austria,
Vienna, Austria

M. Przyłucka · M. Kułak
Polish Geological Institute – National Research Institute,
Warsaw, Poland

M. Sheehy · X. M. Pellicer · C. McKeown · G. Ryan
Geological Survey of Ireland,
Dublin, Ireland

V. Kopačková
Czech Geological Survey,
Prague, Czechia

M. Frei · D. Kuhn
Federal Institute for Geosciences and Natural Resources (BGR),
Hanover, Germany

R. L. Hermanns
Geological Survey of Norway,
Trondheim, Norway

N. Koulermou
Cyprus Geological Survey,
Strovolos, Cyprus

C. A. Smith · M. Engdahl
Geological Survey of Sweden,
Goteborg, Sweden

P. Buxó · M. Gonzalez
Institut Cartogràfic i Geològic de Catalunya,
Barcelona, Spain

C. Dashwood · H. Reeves · F. Cigna
British Geological Survey,
Nottingham, UK

P. Liščák · P. Pauditš
Geological Survey of Slovakia,
Bratislava, Slovakia

V. Mikulėnas
Geological Survey of Lithuania,
Vilnius, Lithuania

V. Demir
Federalni zavod za geologiju,
Ilidža, Bosnia and Herzegovina

M. Raha
Geological Survey of Estonia,
Tallinn, Estonia

L. Quental
Laboratório Nacional de Energia e Geologia,,
Amadora, Portugal

C. Sandić
Geological Survey of the Republic of Srpska,
Zvornik, Bosnia and Herzegovina

B. Fusi
Geological Survey of Hungary,
Budapest, Hungary

O. A. Jensen
Norwegian Water and energy Directorate of Norway,
Oslo, Norway