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Pan-European landslide susceptibility mapping: ELSUS Version 2

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ABSTRACT
We present an updated version of the European landslide susceptibility map ELSUS 1000 released through the European Soil Data Centre in 2013. The ELSUS V2 map shows the landslide susceptibility zonation for individual climate-physiographic zones across Europe. ELSUS V2 covers a larger area of Europe than ELSUS 1000 at a higher spatial resolution (200 × 200 m). The updated map was prepared using the same semi-quantitative method as for ELSUS 1000, combining landslide frequency ratios information with a spatial multi-criteria evaluation model of three thematic predictors: slope angle, shallow subsurface lithology and land cover. However, the new map was prepared using also: (i) an extended landslide inventory, containing 30% of additional locations for model calibration, map validation and classification and (ii) a new lithological data set derived from the International Hydrogeological Map of Europe (IHME). The new version of the map increases the overall predictive performance of ELSUS by 8 %.

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ELSUS; landslide susceptibility mapping; Europe; heuristic model

1. Introduction

Landslide susceptibility is the likelihood of a landslide occurring in an area controlled by local terrain conditions (e.g. Fell et al., 2008; Guzzetti, Carrara, Cardinali, & Reichenbach, 1999). Susceptibility does not consider the temporal probability of a failure (i.e. when or how frequently landslides occur), or the magnitude of the expected events (i.e. how large or destructive possible failures may be) (Committee on the Review of the National Landslide Hazards Mitigation Strategy, 2004). Evaluating landslide susceptibility at small scales (<1:200,000) over large areas (entire nations or continents) generally suffers from high generalization, low resolution of spatial input data and incomplete landslide inventory information, making data-driven statistical modelling very difficult. Therefore, landslide susceptibility mapping at global (Hong, Adler, & Huffman, 2007; Nadim, Kjekstad, Peduzzi, Herold, & Jaedicke, 2006), continental European (Günther et al., 2013; Jaedicke et al., 2014) and national scales (e.g. Sakkas, Misailidis, Sakellariou, Kouskouna, & Kaviris, 2016) are often performed without landslide information. Only a few studies utilize such data for continental (Günther, Van Den Eeckhaut, Malet, Reichenbach, & Hervás, 2014; Van Den Eeckhaut et al., 2012) or national-level assessments (e.g. Castellanos Abella & van Westen, 2008; Gaprindashvili & van Westen, 2016; Malet, Puissant, Mathieu, Van Den Eeckhaut, & Fressard, 2013).

In this contribution, we present the updated version of the continental European Landslide Susceptibility map ELSUS 1000 reported in Günther et al. (2014). The methodological approach for the elaboration, validation and classification of ELSUS V2 is the same as the previous version, but the new map is prepared with new thematic data sets. In particular, ELSUS V2: (i) covers a larger area (including Iceland, Cyprus, the Faroe Islands and the Shetland islands) with a higher spatial resolution (200 × 200 m cell size in contrast to the 1 × 1 km resolution of ELSUS 1000); (ii) uses an extended landslide inventory; and (iii) exploits the newly available digital information on shallow subsurface lithology, derived from the International Hydrogeological Map of Europe (IHME) at a 1:1.5 Mil. scale (Duscher et al., 2015), replacing the data set on soil parent material from the European Soil Database (ESDB) (Heineke et al., 1998; Panagos, Van Liedekerke, Jones, & Montanarella, 2012) previously used as a proxy for shallow subsurface lithology.

The map shows a harmonized overview of European landslide susceptibility at the 1:5 Mil. scale. It thus provides a synoptic zonation of landslide susceptibility and cannot be used for detailed and local visualization. The map can be viewed at scales up to 1:200,000 as determined by the cell size of 200 × 200 m and should not be enlarged to greater scales.

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2. Materials and methods

2.1. Landslide information

To prepare ELSUS V2, we used a landslide database containing 149,117 generic landslide locations, considerably extended with respect to the 102,182 data points used for ELSUS 1000. The additional data were mainly gathered from national-level landslide inventories for Romania and Slovakia (Table 1). In Cyprus, landslide locations were collected from published documents and corrected through visual interpretation of Google Earth imagery (Hervás, 2016). These countries were only fairly (Romania) or not at all (Slovakia) represented with landslide information in ELSUS 1000, or were not covered by the assessment (Cyprus). In France, the inventory was completed for the mountain territories with the integration of the database of RTM (http://rtm-onf.ifn.fr) and extensively quality-checked. For Ireland, an update on the national inventory was provided by GSI. For Spain and Andorra, the landslide information was enlarged through the incorporation of the ALISSA inventory (Hervás, 2016). The landslide locations of this data set extracted from maps, papers, reports and media news were verified and validated using mainly Google Earth imagery. The complete synoptic landslide database was entirely filtered for duplicate locations and was corrected along the coastline on the Vector Map Level 0 (VMAP; NIMA, 2001) topography rejecting locations positioned more than 200 m offshore the VMAP coastline. The updated landslide data set is summarized in Table 1. No landslide locations for ELSUS are available in the North and Northeast (Iceland, Finland, Estonia, Latvia, Lithuania and Poland) and the Southeast of Europe (Croatia, Bosnia–Herzegovina, Montenegro and Macedonia), even though regional or national-level inventories do exist in some of these countries (Herrera et al., 2017; Van Den Eeckhaut & Hervás, 2012).

2.2. Controlling factors: environmental data

As recommended for Pan-European landslide susceptibility evaluations in the context of the European Union's Soil Thematic Strategy (EC, 2006), ELSUS is based on the use of three data sets related to relief information, shallow subsurface lithology and land cover (Hervás et al., 2007). The landslide susceptibility evaluation for ELSUS V2 was performed for the same seven climate-physiographic zones as delineated for ELSUS 1000 (Günther et al., 2014), derived from GTOPO 30 data according to Nordregio (2004) and Köppen climate zone information (Peel, Finlayson, & McMahon, 2007). The climate-physiographic regions defining the ELSUS model zones are shown as an inset in the main map.

The EU 27 DEM information (Reuter, 2009) used for ELSUS 1000 was extended to Cyprus incorporating elevation information derived from the Shuttle Radar Topography Mission (SRTM 90 data, Farr et al., 2007). For Iceland, the Faroes and the Shetlands, DEM data compatible with the EU 27 DEM were downloaded from http://viewfinderpanoramas.org and merged with the data on a 100 × 100 m grid cell. The terrain gradient was calculated using the slope algorithm of Horn (1981) (Figure 1(A)) and classified into eight classes. In contrast to ELSUS 1000, different classifications of the continuous slope map were performed for the different climate-physiographic zones based on the zone-specific landslide frequency analysis (Table 2).

A new data set representing shallow subsurface lithology, derived from the IHME at the 1:1.5 Mil. scale (IHME 1500; Duscher et al., 2015), was used in ELSUS V2. This map displays harmonized digital information on the distribution of consolidated, partly consolidated and unconsolidated geologic materials over Europe. The data have a high degree of semantic consistency, an excellent spatial accuracy at the 1:1.5 Mil. scale and a uniform outcrop depth throughout the majority of the analyzed area. We consider these data more relevant for landslide susceptibility evaluation than the unsystematic soil parent material data of the ESDB (Heineke et al., 1998; Panagos et al., 2012) used for ELSUS 1000. As discussed in Günther et al. (2014), soil parent material descriptions over Europe, as derived from the ESDB, are only partly lithological but also genetical and therefore hard to be spatially evaluated. In contrast, IHME 1500 class descriptions are more strictly related to lithological/petrographical material properties. Additionally, the IHME 1500 data reveal a higher degree of Pan-European harmonization since its geometry was elaborated on a supra-national European basis. The IHME 1500 lithology information was grouped into 19 classes considering landslide density information, class sizes and distributions, and semantic compatibility (Figure 1(B), Table 2).

The land cover information derived from the global GlobCover data set (ESA, 2010), spatially extended to the new countries, was reclassified into seven classes as in ELSUS 1000 (Table 2, Figure 1(C)).

2.3. Landslide susceptibility evaluation

As detailed in Günther et al. (2014), the ELSUS methodology used Analytical Hierarchy Process (AHP, Saaty, 1980) combined with spatial multi-criteria evaluations (SMCE) to compute a landslide susceptibility index (LSI) for each model zone. In the SMCE-based AHP, the specific weight of the three environmental parameters (slope gradient, shallow subsurface lithology and land cover) was obtained for 'plain' and 'mountainous' model zones using the same pairwise comparisons as for ELSUS 1000 (Table 2). The model zone-

Table 1. Landslide data collected for this study (gray: substantial extensions of inventory data used for ELSUS 1000).

Country	Number	Provider	Source	Quality	Ad. Info
National-level data					
Albania	235	AGS	Inventory DB	Medium	No
Andorra	55	JRC	Inventory DB	Good	Yes
Austria	658	BGA	Overview DB	Good	Yes
Bulgaria	420	BAS	Published map	Low	No
Cyprus	375	JRC	Inventory DB	Good	No
Czech Republic	9319	CGS	Inventory DB	Good	Yes
Denmark	39	JRC	GoogleEarth™	Good	No
France	21991	BRGM/RTM	Inventory DB	Good	Yes
Greece	2310	IGME	Inventory DB	Medium	No
Hungary	359	BMFH	Inventory DB	Low	No
Ireland	3017	GSI	Inventory DB	Good	Yes
Italy	14641	CNR-IRPI	Inventory DB	Good	Yes
Norway	26884	NGU	Inventory DB	Good	Yes
Portugal	125	IGOT	Inventory DB	Medium	No
Romania	29604	IGAR	Inventory DB	Good	Yes
Slovakia	16236	SGUDS	Inventory DB	Good	Yes
Slovenia	1235	GeoZS	Published map	Low	No
Spain	2611	JRC	Inventory DB	Good	Yes
Sweden	535	SGI	Inventory DB	Good	Yes
Switzerland	290	BAFU	Overview DB	Good	Yes
United Kingdom	15023	BGS	Inventory DB	Good	Yes
Regional-level data					
Bavaria (Germany)	2222	LFU	Inventory DB	Good	Yes
Flanders (Belgium)	291	LNE	Inventory DB	Good	Yes
Mecklenburg-Vorpommern (Germany)	75	LUNG	Inventory DB	Good	Yes
Saxony (Germany)	73	LFULG	Inventory DB	Good	Yes

Note: 'Quality' only refers to relative average accuracy of location information, not completeness of the inventory. 'Published map' as source was scanned and georeferenced from Jelínek, Hervás, and Wood (2007). 'Ad. Info' refers to databases where information on typology, size, date or damage of the events is available (not collected for this study). For the landslide data provider acronyms, please refer to the Acknowledgements section.

specific parameter class weights (Table 2) were initially assigned using normalized parameter class landslide frequency ratio (FR) values. To account for missing or biased landslide information in specific parameter classes of the individual model zones, these initial weights were modified by expert knowledge in the SMCE to obtain an LSI satisfying both expert knowledge and landslide signal indicated by Receiver Operating Characteristics (ROC) metrics (Günther et al., 2014). The expert knowledge-based modifications also consider comments and inputs from regional experts collected during the evaluation of the ELSUS 1000 map. These comments mainly refer to areas without landslide information, and to deficits in the soil parent material information used as a spatial proxy for shallow subsurface lithology in ELSUS 1000. The model zone-specific LSI was computed through a combination of parameter- and parameter class weights obtained with the SMCE procedure using a weighted linear summation (Voogd, 1983).

2.4. Map classification and evaluation

The LSI map for each climate-physiographic zone was classified in five susceptibility levels in the 'coastal' (Z0) and 'mountainous' (Z5 and Z6) model zones using sensitivity rates from ROC metrics of 3%, 7%, 15%, 25% and 50%, in order to delineate 'very low', 'low', 'moderate', 'moderate to high' and 'high to very high' landslide susceptibility classes. For the 'plain' model zones (Z1, Z2, Z3 and Z4), four susceptibility levels defined by sensitivity rates of 10%, 15%, 25% and 50% were used to classify the LSI as 'very low', 'low', 'moderate' and 'moderate to high' landslide susceptibility. The classification was performed following the same scheme as proposed for ELSUS 1000 (Günther et al., 2014). To obtain the final susceptibility zonation, the classified susceptibility outputs were mosaicked into a single map, which was filtered using a circular majority filter with a one-pixel radius to eliminate singular grid cell values.

The performance prediction of the ELSUS V2 map was evaluated using ROC curves (e.g. Fawcett, 2006) and the extended landslide inventory data (Figure 2). It can be observed from the ROC curves that in all model zones ELSUS V2 is performing significantly better than ELSUS 1000. As indicated by area-under-ROC-curve (AU_{ROC}) values, ELSUS V2 presents a significant increase in model performance in the mountainous zones Z5 and Z6 (Figure 2). The overall prediction rate of ELSUS V2 has increased about 8% to that of ELSUS 1000 (Figure 2(C)).

As for ELSUS 1000, a reliability assessment was performed based on EUROSTAT NUTS (Nomenclature des Unités Territoriales Statistiques) Level 3 (NUTS 3) units, as detailed in Günther et al. (2014). The resulting map is shown as an inset in the main map. Due to the enlarged spatial extent of the updated landslide inventory, the areal percentage of NUTS 3 units classified with 'no information' decreases from 41% to 35% even though the spatial coverage of ELSUS V2 is extended by 2%. The updated reliability

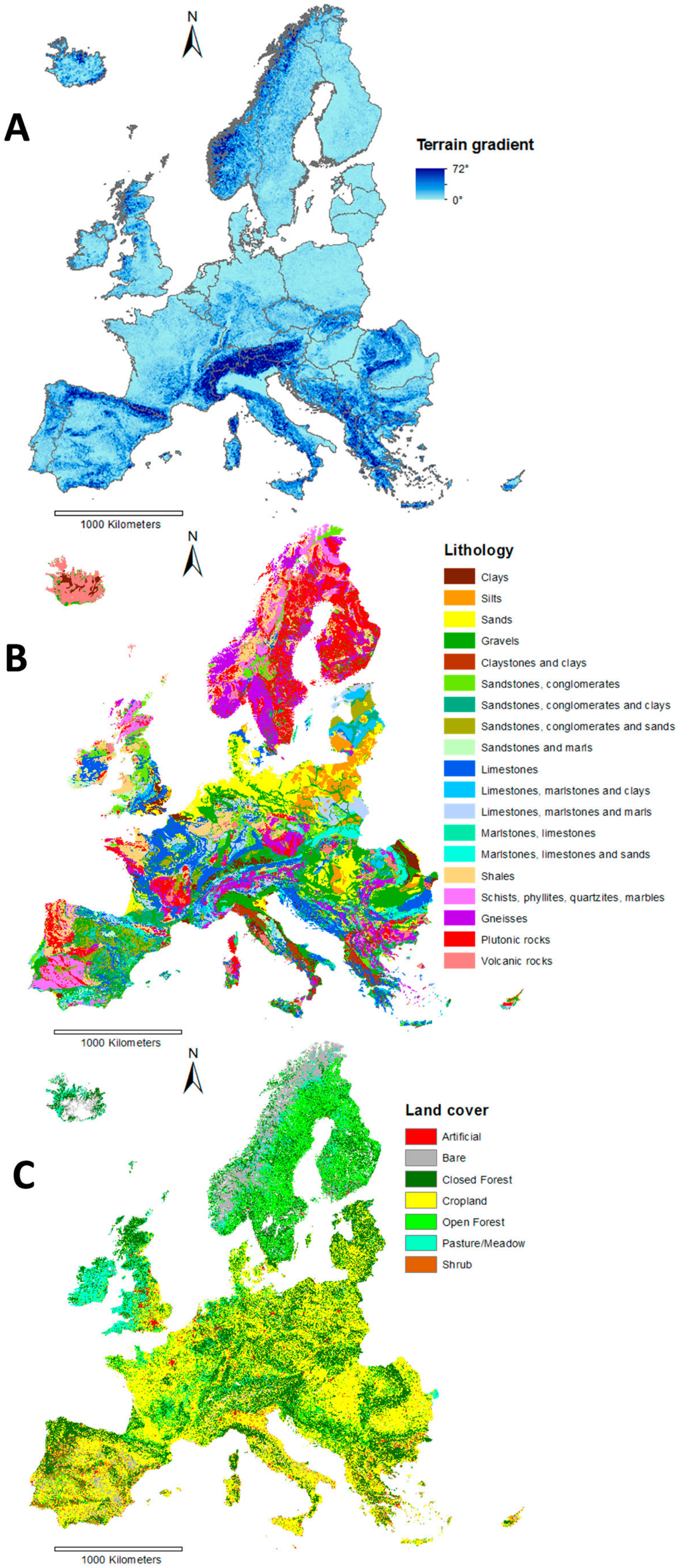

Figure 1. Thematic information used for ELSUS V2. (A) Terrain gradient from EU27 DEM; (B) Lithology from IHME; (C) Land cover from GlobCover.

Table 2. Established normalized weights of parameters (in bold in specific heading) and parameter classes used for susceptibility analysis for the seven climate-physiographic zones (Z0–Z6).

Slope angle

Zone Class	Z0 (.75)	Zone Class	Z1 (.64)	Z2 (.64)	Z3 (.64)	Z4 (.64)	Zone Class	Z5 (.58)	Z6 (.58)
0°	0.007	0°	0.019	0.006	0.001	0.016	0°	0.037	0.026
1–8°	0.034	1–4°	0.035	0.034	0.019	0.032	1–3°	0.067	0.073
9–12°	0.080	5–8°	0.101	0.102	0.072	0.057	4–7°	0.097	0.141
13–20°	0.100	9–12°	0.132	0.132	0.162	0.087	8–12°	0.101	0.151
21–26°	0.156	13–16°	0.141	0.151	0.171	0.169	13–17°	0.134	0.141
27–34°	0.180	17–20°	0.152	0.159	0.181	0.202	18–25°	0.147	0.126
35–41°	0.217	21–30°	0.184	0.206	0.197	0.235	26–37°	0.191	0.151
42–90°	0.225	31–90°	0.235	0.210	0.197	0.202	38–90°	0.227	0.189

Land cover

Zone Class	Z0 (-)	Z1 (.10)	Z2 (.10)	Z3 (.10)	Z4 (.10)	Z5 (.13)	Z6 (.13)
Cropland	–	0.112	0.259	0.078	0.159	0.235	0.313
Open Forest	–	0.174	0.136	0.086	0.169	0.219	0.084
Closed Forest	–	0.161	0.165	0.205	0.124	0.231	0.111
Shrub	–	0.044	0.031	0.047	0.040	0.012	0.046
Pasture/Meadow							
Meadow	–	0.237	0.159	0.055	0.221	0.109	0.027
Bare	–	0.068	0.117	0.293	0.140	0.034	0.151
Artificial	–	0.205	0.134	0.235	0.147	0.160	0.270

Lithology

Zone Class	Z0 (.25)	Z1 (.26)	Z2 (.26)	Z3 (.26)	Z4 (.26)	Z5 (.29)	Z6 (.29)
Schists, quartzites and marbles	0.061	0.006	0.031	0.089	0.096	0.034	0.034
Shales	0.092	0.003	0.041	0.024	0.096	0.056	0.022
Plutonic rocks	0.031	0.007	0.027	0.013	0.030	0.037	0.018
Gneisses	0.031	0.020	0.042	0.024	0.097	0.039	0.026
Sandstones and conglomerates	0.035	0.031	0.056	0.082	0.122	0.090	0.063
Sandstones, conglomerates and sands	0.021	0.017	0.013	0.035		0.046	0.056
Limestones	0.073	0.049	0.041	0.031	0.185	0.028	0.054
Sandstones, conglomerates and clays	0.070	0.044	0.083	0.037		0.033	0.083
Gravels	0.025	0.052	0.044	0.053	0.173	0.049	0.052
Sands	0.026	0.105	0.028	0.030	0.038	0.005	0.038
Sandstones and marls	0.091	0.101	0.078	0.030		0.085	0.053
Limestones, marlstones and clays	0.073	0.019	0.122	0.037		0.106	0.088
Clays	0.060	0.109	0.097	0.141	0.860	0.070	0.088
Marlstones and limestones	0.034	0.018	0.031	0.039		0.047	0.053
Marlstones, limestones and sands	0.045	0.091	0.067	0.134		0.042	0.088
Limestones, marlstones and marls	0.036	0.094	0.060	0.027		0.103	0.064
Volcanic rocks	0.094	0.101	0.031	0.094	0.077	0.058	0.057
Silts	0.042	0.003	0.028	0.011		0.006	0.014
Claystones and clays	0.061	0.128	0.080	0.067		0.067	0.049

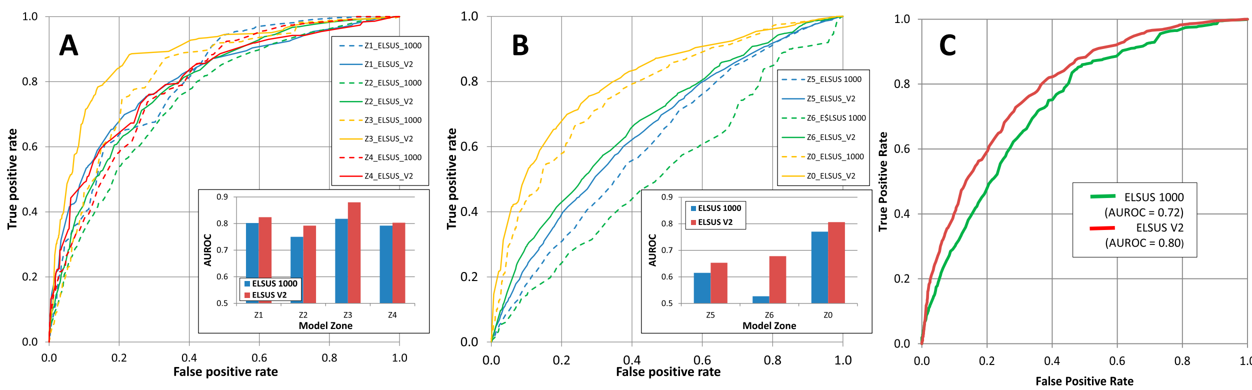

Figure 2. ROC curves and AU_{ROC} values (insets in A and B) detailing the predictive model performance of ELSUS V2 compared to ELSUS 1000 using the updated landslide inventory. (A) Results for 'plain'; (B) Results for 'mountainous/coastal' model zones; (C) Overall prediction model performance of the composite ELSUS 1000 and ELSUS V2 maps.

assessment reveals 62%, 32% and 6% of the NUTS 3 terrains with landslide information (65% of the total area) as having 'good', 'moderate' and 'poor' map reliability in ELSUS V2, respectively (ELSUS 1000: 54% 'good', 30% 'moderate' and 16% 'poor', Günther et al., 2014).

3. Conclusions

The updated version of ELSUS performs better than ELSUS 1000 since it is based on more landslide information and utilizes qualitatively better data on shallow subsurface lithology. These factors allowed for an increase in the spatial resolution from 1 × 1 km pixel size to 200 × 200 m. Additionally, the assessment covers all 28 EU Member States and several neighboring countries, and coastal landslide susceptibility can be evaluated with a higher spatial completeness since a unique topographical information was used for all three spatial predictors. However, some general drawbacks of the ELSUS assessment in terms of map reliability prevail as there are still extensive areas without landslide information, and the landslide data used for model calibration and map validation comprise information of different completeness, spatial accuracy and size that cannot be harmonized at this stage of the assessment (Günther et al., 2014).

ELSUS aims to display a harmonized picture of the terrain susceptibility to generic landslides over Europe. Since landslides must be considered highly diverse and localized geomorphological phenomena, a continental map based on harmonized Pan-European data sets can possibly never properly ascertain landslide susceptibility for all terrains covered by the assessment. Additionally, a harmonized landslide inventory over Europe is not available and at present, a complete evaluation of the map is not possible. In this context, it is important to use the map always with the reliability map, and to keep in mind that the spatial resolution of the assessment (a pixel size of 200 × 200 m) may make enlargements of the map to scales larger than 1:200,000 to deduce local landslide susceptibility inadmissible.

The ELSUS V2 map should be further validated quantitatively with higher spatial resolution inventory information and susceptibility maps at regional and national levels over Europe. An attempt will be made distributing the ELSUS data and evaluation tools to interested organizations maintaining such information. From these evaluations, regional drawbacks of ELSUS V2 can be specified and strategies to improve the quality of the ELSUS assessment can be designed.

Future progress in ELSUS should focus on the production of typologically differentiated landslide susceptibility maps and the adoption of quantitative susceptibility modelling strategies to operate at small scales. For these purposes, the landslide inventory information should incorporate additional information on typology (at least 'slides/flows' versus 'falls/topples') and spatial accuracy of the locations. With these data available, it will be possible to perform statistical modelling within pilot areas in the specific ELSUS model zones covering all parameter classes where the inventory information can be considered complete and accurate enough to produce valid negative/positive samples for binary statistical evaluations (Jurchescu, Günther, Malet, Reichenbach, & Micu, 2016; Van Den Eeckhaut et al., 2012). Additionally, statistical modelling will allow the delineation of areas where further landslide and non-landslide information is required, depending on the spatial class distribution of the predictor data.

Software

The computations of the landslide susceptibility indices through SMCE were performed with the open-source GIS software ILWIS. Map classifications and evaluations through ROC curves were performed with Avenue scripts written for ArcView GIS 3 software (ESRI). Filtering of the final raster map was done with the open-source GIS software SAGA (Conrad et al., 2015). The map layout and cartography was done with ArcGIS software (ESRI). Final map layout was designed with Adobe Illustrator.

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Disclosure statement

No potential conflict of interest was reported by the authors.

Underlying research materials for this article can be accessed at https://esdac.jrc.ec.europa.eu/themes/landslides (European Soil Data Centre, Panagos et al., 2012).

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