Synoptic Pan-European Landslide Susceptibility Assessment: The ELSUS 1000 v1 Map

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Abstract

In order to identify areas in Europe susceptible to landslides in the context of the EU Soil Thematic Strategy and the associated Proposal for a Soil Framework Directive, a harmonised approach encompassing geographically-nested susceptibility assessments ("Tiers") and, where possible, the use of comparable datasets as input criteria for susceptibility modelling was devised. The first version of the 1 km grid size European Landslide Susceptibility Map (ELSUS 1000 v1), covering the EU and neighbouring countries, is derived from "Tier 1" assessment. The mapping approach employed includes first a climate-physiographic regionalisation of the study area. For each region, a spatial multi-criteria evaluation model is established to evaluate landslide susceptibility using commonly available pan-European datasets on slope angle, lithology and land cover, which are considered as the main conditioning factors for all types of landslides at this scale. Factor weights are assigned through pairwise comparisons using analytical hierarchy processes for each region, while region-specific factor class weights are initially established by computing landslide frequency ratios using more than 102,000 landslide locations across Europe. For each model region, a pixel-based susceptibility index is calculated by linear summation of conditioning factor weights and factor class weights. Each index map is then evaluated and classified into five susceptibility levels using true positive ratio breaks derived from receiver operating characteristics curves obtained with the landslide inventory. Finally, the region-specific classified susceptibility maps are spatially combined into the synoptic

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K. Sassa et al. (eds.), *Landslide Science for a Safer Geoenvironment*, Vol. 1,
DOI 10.1007/978-3-319-04999-1_12,

ELSUS 1000 v1 map. The map is available from the European Soil Data Centre (ESDAC), hosted by the Joint Research Centre, together with ancillary datasets, including a reliability evaluation of the susceptibility map. Further work is in progress to improve the accuracy of the map, mainly by integrating into the assessment a new pan-European lithological dataset and further landslide locations for areas not represented in the current inventory.

Keywords
Landslides • Soil thematic strategy • Landslide susceptibility assessment • ELSUS 1000 • Europe

Introduction

Small-scale, harmonised assessment of landslide susceptibility over the territory covered by EU member states and adjacent countries is needed to identify areas at risk of landslides, as required by the UE Thematic Strategy for Soil Protection (EC 2006a) and the associated proposal for a Soil Framework Directive (EC 2006b).

Following recommendations by the European Soil Bureau Network for common criteria to evaluate soil threats, including landslides, and geographically-nested ("Tier"-based) approaches (Eckelmann et al. 2006), the European Landslide Expert Group promoted by the Joint Research Centre (JRC Ispra) proposed specifications for landslide susceptibility zoning, including pan-European thematic datasets and common approaches for the various "Tiers" (Hervás et al. 2007). Specific datasets for landslide conditioning factors and approaches for susceptibility assessment for "Tier 1" (continental- or nation-wide, heuristic) and "Tier 2" (nation-wide, statistical) were further presented by Günther et al. (2008, 2013a) and Hervás et al. (2010).

In this work, we outline the "Tier 1" spatial multi-criteria evaluation approach used to produce the first version of the European Landslide Susceptibility Map (ELSUS 1000 v1). Unlike other approaches for landslide susceptibility mapping at a European scale (e.g. Van Den Eeckhaut et al. 2012; Jaedicke et al. 2013) or global scale (e.g. Nadim et al. 2006; Hong et al. 2007), our method includes a prior subdivision of the study area into climate-physiographic modelling regions and accounts for a large number of landslide locations for susceptibility modelling and evaluation of the resulting map.

Materials and Methods

Regionalisation of the Study Area

The European Landslide Susceptibility Map ELSUS 1000 v1 is prepared by first differentiating the study area (27 EU member states and neighbouring countries) into seven climate-physiographic model zones (0 to 6) by combining climate regions according to the Köppen-Geiger classification (Peel et al. 2007) and physiographic regions (mountain/plain) based on Nordregio (2004), and adding a 1 km-wide zone inland from coastlines to account for specific conditions for coastal landslides (Günther et al. 2014, Fig. 1).

Susceptibility Criteria

Three main geo-environmental criteria (landslide conditioning factors) derived from common pan-European datasets were selected for susceptibility evaluation, as specified for a "Tier 1" assessment (Hervás et al. 2007, 2010; Günther et al. 2008, 2013a, b, 2014; Malet et al. 2013, 2014). They include terrain gradient (slope angle) from the EU27 DEM (Reuter 2009), shallow subsurface lithology from the Soil Geographical Database of Europe 1:1 M (Panagos et al. 2012), and land cover from the ESA's GlobCover (http://ionia1.esrin.esa.int). These criteria are chosen because they reflect basic terrain conditions related to susceptibility to all kinds of landslides. The three criteria are classified and further aggregated (Table 1) using information on the distribution of more than 102,000 landslides provided by national or regional mapping agencies or collected by the Joint Research Centre (JRC) and Federal Institute of Geosciences and Natural Resources (BGR).

Spatial Multi-criteria Evaluation

The susceptibility analysis is carried out individually for each model zone using a 1 km × 1 km pixel as the terrain unit at a scale of 1:1 Million.

Since the collected landslide inventory must be considered incomplete and heterogeneous throughout the model zones, quantitative data-driven (statistical) susceptibility modelling techniques are difficult to apply. A semi-quantitative, index-based heuristic assessment scheme is thus employed, consisting of a spatial multi-criteria evaluation technique. In this evaluation technique, first the weights

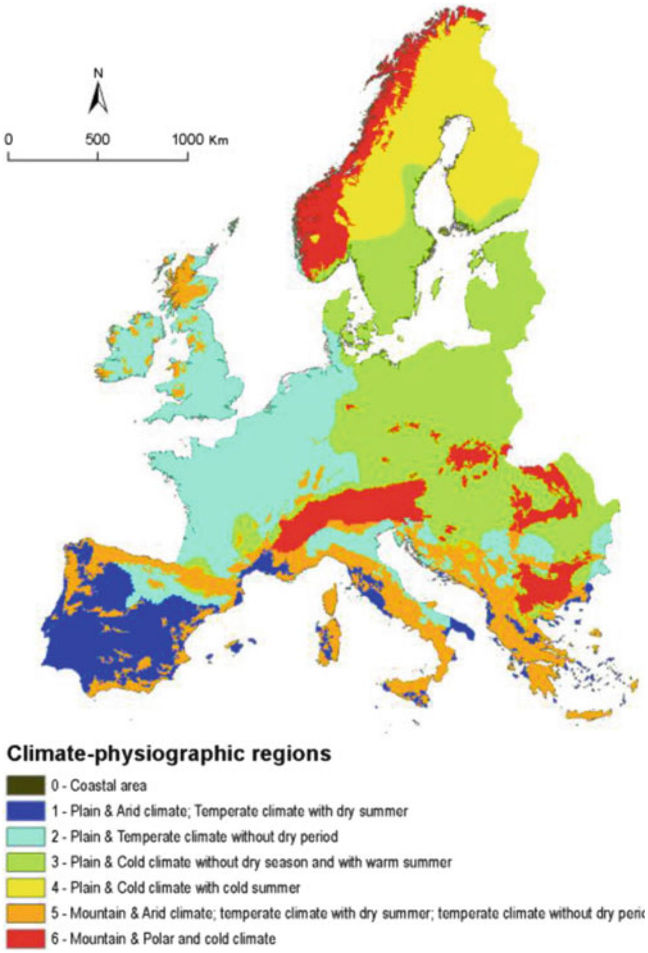

Fig. 1 Climate-physiographic regions used for separate landslide susceptibility modelling (from Günther et al. 2014)

of the hierarchically ordered criteria, or parameters (in the succession slope angle, lithology, and land cover) are assigned through pairwise comparisons using analytical hierarchical processes (Saaty 1980). For the three different physiographic settings (i.e. "coastal areas" 0, "plains" 1-4, and "mountains" 5-6), different pairwise comparisons are established, resulting in different criteria weights (Table 1). For the "coastal areas", the land cover criterion is discarded, since no evidence was found that it exerts a significant control on landslide susceptibility at the given analysis scale and terrain unit size. It should also be noted in this context that ELSUS 1000 v1 has great limitations for correct assignment of coastal landslide susceptibility because the criteria datasets used have mismatching coastlines.

The second step in the applied spatial multi-criteria evaluation is the assignment of parameter class weights, which are allocated directly. For this, landslide frequency ratios (FR) of the criteria classes are computed for each model region using:

$$FR = \frac{LS_{ji}/LS}{A_{ji}/A} \quad (1)$$

where LS_{ji} is the number of pixels affected by landslides in class i of criterion (parameter) j, LS is the total number of pixels affected by landslides, A_{ji} is the number of pixels of class i of criterion j, and A is the total number of pixels of a model zone. The normalized frequency ratio values serve as the initial starting points for the assignment of parameter class weights. They are further modified by expert knowledge to obtain the final parameter class weights listed in Table 1, considering regional and class-specific bias in the landslide inventory, and the regional quality of the criteria data (especially related to lithology).

The pixel-specific landslide susceptibility index (LSI) is then determined by a weighted linear summation of the criteria- and criteria-class weights (Voogd 1983) with

$$LSI = \sum_{j=1}^{n=3} w_j \times x_{ji} \quad (2)$$

where w_j is the weight of criterion j and x_{ji} is the weight of class i in criterion j.

Landslide Susceptibility Classification and Evaluation

The zone-specific continuous pixel landslide susceptibility index values are classified into susceptibility levels using true positive ratio breaks deduced from analysis of receiver operating characteristics (ROC) curves obtained with the landslide inventory (Günther et al. 2014). For this instance, four susceptibility levels ("high", "moderate", low", and "very low") are used for the "plain" model zones (1-4) to respect the overall lower landslide intensity when compared to "mountains" and "coasts" (5-6, 0), where five levels ("very high", "high", "moderate", "low", and "very low") are used. The four susceptibility classes in the "plain" model zones (from "high" to "very low") are defined by occupancy of 50 %, 25 %, 15 %, and 10 % of the landslide-affected pixels in each zone; the five levels in "mountains" and "coasts" (from "very high" to "very low") render 50 %, 25 %, 15 %, 7 %, and 3 % of the landslide-affected pixels, respectively.

The compound classified ELSUS 1000 v1 map (Fig. 2) is derived by spatial merging of the zone-specific classified susceptibility maps. The five susceptibility levels of the map ("very high", "high", "moderate", "low", and "very low") occupy 6 %, 12 %, 13 %, 17 %, and 53 % of the analysed area and contain 20 %, 30 %, 22 %, 15 %, and 13 % of the landslide-affected terrain elements, respectively.

Table 1 Criteria class weights and analytical hierarchical processes-derived criteria weights (in brackets) used for susceptibility analysis for the seven climate-physiographic zones (Z0–Z6)

Slope angle (°)	Z0 (0.75)	Z1 (0.64)	Z2 (0.64)	Z3 (0.64)	Z4 (0.64)	Z5 (0.58)	Z6 (0.58)
0	0.030	0.049	0.021	0.006	0.012	0.081	0.089
1–3	0.049	0.050	0.057	0.028	0.023	0.095	0.101
4–6	0.085	0.095	0.117	0.078	0.055	0.108	0.101
7–10	0.110	0.140	0.154	0.119	0.075	0.122	0.102
11–15	0.121	0.151	0.163	0.160	0.195	0.128	0.116
16–20	0.153	0.189	0.174	0.188	0.202	0.135	0.140
21–30	0.217	0.169	0.158	0.217	0.236	0.155	0.161
31–90	0.237	0.156	0.154	0.204	0.202	0.176	0.189
Lithology	Z0 (0.25)	Z1 (0.26)	Z2 (0.26)	Z3 (0.26)	Z4 (0.26)	Z5 (0.28)	Z6 (0.28)
Alluvium/Colluvium	0.140	0.115	0.066	0.044	0.342	0.066	0.100
Glaciofluvial materials	0.106	0.104	0.127	0.031	0.158	0.118	0.055
Calcareous rocks	0.058	0.093	0.057	0.100		0.085	0.115
Marls	0.009	0.022	0.137	0.127		0.047	0.160
Clayey materials	0.170	0.120	0.137	0.055	0.092	0.114	0.085
Sandy materials	0.085	0.091	0.046	0.012	0.197	0.095	0.165
Sandstone/Flysch/ Molasse	0.063	0.109	0.153	0.064	0.066	0.114	0.070
Loamy/Silty materials	0.182	0.104	0.040	0.075		0.026	0.015
Detrital formations	0.009	0.005	0.014	0.111		0.039	
Crystalline rocks	0.053	0.010	0.051	0.080		0.071	0.070
Schists	0.087	0.005	0.023	0.177		0.060	0.150
Volcanic rocks	0.037	0.219	0.082	0.118	0.000	0.118	0.010
Other/Organic	0.002	0.002	0.066	0.005	0.145	0.047	0.005
Land cover	Z0	Z1 (0.10)	Z2 (0.10)	Z3 (0.10)	Z4 (0.10)	Z5 (0.13)	Z6 (0.13)
Cropland	–	0.285	0.102	0.107	0.024	0.143	0.143
Open forest	–	0.085	0.153	0.156	0.134	0.119	0.304
Closed forest	–	0.103	0.129	0.162	0.147	0.107	0.232
Shrub	–	0.044	0.027	0.071	0.024	0.036	0.036
Pasture/Meadow	–	0.044	0.259	0.164	0.152	0.238	0.107
Bare	–	0.156	0.071	0.176	0.367	0.119	0.071
Artificial	–	0.285	0.259	0.164	0.152	0.238	0.107

ELSUS 1000 v1 is evaluated on an administrative terrain unit level basis (Eurostat NUTS 3 regions). The resulting confidence level map (Fig. 3) provides reliability information on NUTS 3 units where sufficient landslide information is available to rank ELSUS 1000 v1 as having "good", "moderate" or "poor" confidence. 38 % of the area covered by the map cannot be evaluated in this respect due to missing landslide information.

Accessibility to ELSUS 1000 v1

The map, accompanied by explanatory metadata, can be downloaded in raster (ESRI GRID) format from the European Soil Data Centre (ESDAC, Panagos et al. 2012) through the European Soil Portal (http://eusoils.jrc.ec.europa.eu/library/themes/Landslides/#ELSUS).

Additional downloadable datasets include the confidence level map of ELSUS 1000 v1, a NUTS 3-aggregated map of ELSUS, which was used by ESPON to outline NUTS 3 units with landslide hazard (ESPON 2013), and the climate-physiographic regions, classified slope angle, soil parent material (lithology proxy) and land cover datasets used for landslide susceptibility modelling.

Conclusions

The method used to identify landslide priority areas in Europe for EU soil protection policies can be considered more robust than previously developed approaches, mainly because it uses distributed landslide data and different susceptibility weights can be estimated using spatial multi-criteria evaluation for the same criteria classes depending on their climate-physiographic setting (Günther et al. 2014).

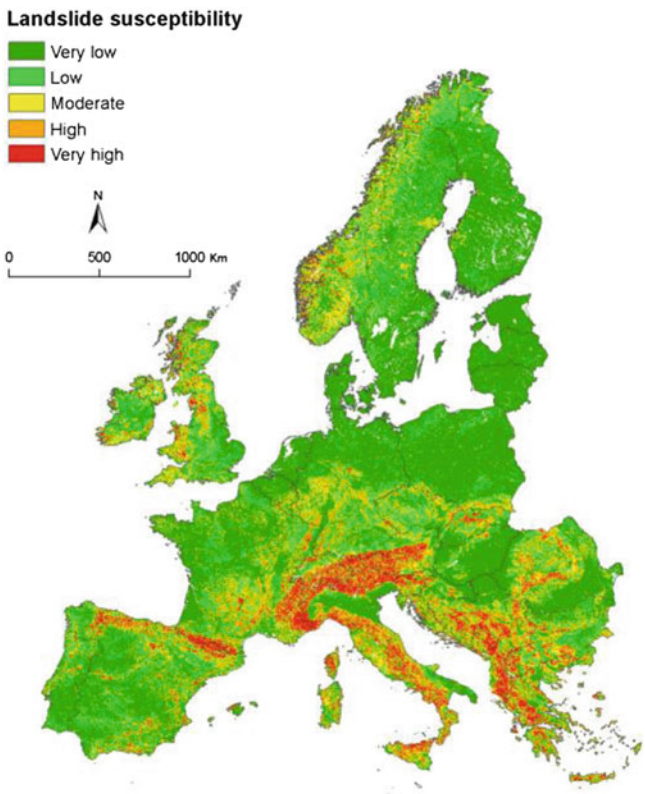

Fig. 2 Classified European landslide susceptibility map (ELSUS 1000 v1) (from Günther et al. 2014)

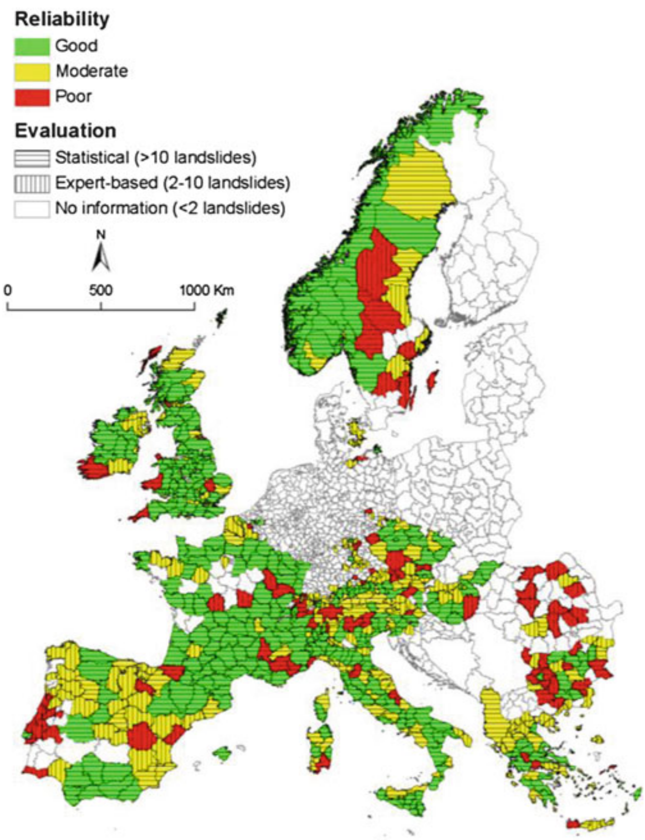

Fig. 3 NUTS 3 territorial units-referenced reliability map of ELSUS 1000 v1 (updated from Günther et al. 2014)

However, as shown by the confidence level map at NUTS 3 territorial unit level, the first version of ELSUS 1000 has some constraints on correctly assessing landslide susceptibility in regions where landslide data was not provided or are scarce, and also because the soil parent material dataset used in the model does not ideally represent the lithology susceptibility criterion.

Work is in progress to further evaluate, validate and eventually improve the accuracy of the map by using a new harmonised lithological dataset derived from the International Hydrogeological Map of Europe at 1:1,500,000 scale (IHME 1500, Gilbrich et al. 2001) in the assessment and by collecting additional landslide inventory data in some regions. In addition, it is envisaged that landslide susceptibility will be evaluated separately for major landslide types in countries where the necessary landslide information can be provided.

Acknowledgements This work has been carried out in the framework of the Joint Research Centre-coordinated European Landslide Expert Group's support to the EU Soil Thematic Strategy. It also forms part of the International Programme on Landslides project IPL-162 "Tier-based harmonised approach for landslide susceptibility mapping over Europe" and of the Council of Europe's EUR-OPA project "Pan-European and nation-wide landslide susceptibility assessment", coordinated by the European Centre on Geomorphological Hazards (CERG).

We are grateful for the support of the following institutions and persons providing basic information on landslides from their national or regional databases: Albanian Geological Survey (AGS, M. Jusufati) Geologische Bundesanstalt, Austria (GBA, N. Tilch), British Geological Survey (BGS, C. Dashwood), Environment, Nature and Energy Department, Flemish Government, Belgium (LNE, L. Vandekerckhove), Czech Geological Survey (CGS, D, Čápová), Bureau de Recherches Géologiques et Minières, France (BRGM, G. Grandjean), Sächsisches Landesamt für Umwelt, Landwirtschaft und Geologie, Germany (LfULG, P. Dommaschk), Bayerisches Landesamt für Umwelt (LFU, A. von Poschinger and T. Gallemann), Landesamt für Umwelt, Naturschutz und Geologie MV (LUNG, K. Schütze), Institute of Geology and Mineral Exploration, Greece (IGME, E. Poyiadji), Hungarian Office for Mining and Geology (BMFH, T. Oszvald), Geological Survey of Ireland (GSI, R.

Creighton), Instituto de Geografia e Ordenamento do Território, University of Lisbon, Portugal (IGOT, J.L. Zêzere), Geological Survey of Norway (NGU, T. Oppikofer and R. Hermanns), Swedish Geotechnical Institute (SGI, M. Öberg and C. Cederbom), and Federal Office for the Environment, Switzerland (FOEN/BAFU, H. Raetzo and B. Loup).

We also thank P. Panagos and M. Van Liedekerke (JRC Ispra, Italy) for publishing the maps on ESDAC.

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