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Climate-physiographically differentiated Pan-European landslide susceptibility assessment using spatial multi-criteria evaluation and transnational landslide information

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ABSTRACT

With the adoption of the EU Thematic Strategy for Soil Protection in 2006, small-scale (1:1 M) assessments of threats affecting soils over Europe received increasing attention. As landslides have been recognized as one of eight threats requiring a Pan-European evaluation, we present an approach for landslide susceptibility evaluation at the continental scale over Europe. Unlike previous continental and global scale landslide susceptibility studies not utilizing spatial information on the events, we collected more than 102,000 landslide locations in 22 European countries. These landslides are heterogeneously distributed over Europe, but are indispensable for the evaluation and classification of Pan-European datasets used as spatial predictors, and the validation of the resulting assessments. For the analysis we subdivided the European territory into seven different climate-physiographical zones by combining morphometric and climatic data for terrain differentiation, and adding a coastal zone defined as a 1 km strip inland from the coastline. Landslide susceptibility modeling was performed for each zone using heuristic spatial multicriteria evaluations supported by analytical hierarchy processes, and validated with the inventory data using the receiver operating characteristics. In contrast to purely data-driven statistical modeling techniques, our semi-quantitative approach is capable to introduce expert knowledge into the analysis, which is indispensable considering quality and resolution of the input data, and incompleteness and bias in the inventory information. The reliability of the resulting susceptibility map ELSUS 1000 Version 1 (1 km resolution) was examined on an administrative terrain unit level in areas with landslide information and through the comparison with available national susceptibility zonations. These evaluations suggest that although the ELSUS 1000 is capable for a correct synoptic prediction of landslide susceptibility in the majority of the area, it needs further improvement in terms of data used.

1. Introduction

In the past three decades, various approaches to determine the degree of landslide susceptibility (e.g., Brabb, 1984; Guzzetti et al., 1999; Fell et al., 2008) have been proposed and applied employing empirically and physically based techniques for various types of landslides at different observation scales. However, data-driven statistical modeling techniques require robust spatial information on the prior probability of landslides to occur from complete landslide inventories, and conceptual process-oriented susceptibility mapping approaches need detailed geo-mechanical data to be properly calibrated. Therefore, the application of such quantitative susceptibility modeling techniques at very small observation scales for entire nations or continents prove difficult. Several landslide susceptibility maps at European (Van Den Eeckhaut et al., 2012; Günther et al., 2013a; Jaedicke et al., 2014) or global (Nadim et al., 2006; Hong et al., 2007) scales are available, but none of these make use of distributed landslide information that is available in many European areas (Van Den Eeckhaut and Hervás, 2012) for model calibration and map validation. Additionally, all previous small-scale assessments do not consider regional differences in landslide setting, as expressed by specific climate-physiographical conditions over Europe.

This study focuses on the production of a first version of a synoptic-scale (1 km resolution) European landslide susceptibility map (ELSUS

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1000) based on common Pan-European landslide conditioning factors that is calibrated and validated with landslide information, and that builds on a climate-physiographical regionalization of the area. The aim of the ELSUS 1000 is solely the representation of the propensity of the terrain to generate landslides. It does not attempt to provide information on the temporal frequency of landslide susceptibility, or the delineation of hazardous areas using information on dynamic spatial landslide triggering data. Therefore, we selected only very reduced static (or quasi-static) environmental information from available Pan-European datasets for susceptibility modeling. According to the specifications for continental-level landslide susceptibility evaluations formulated by the European Landslide Expert Group, these consist of slope gradient, shallow subsurface lithology and land cover (Hervás et al., 2007; Günther et al., 2013a). More dynamic environmental data that may be used for general landslide hazard zoning (e.g., soil moisture, precipitation, and seismicity) were discarded since they reveal a higher temporal dependence than the three parameters used and therefore should be considered in a future stage to produce hazard scenario maps based on the ELSUS 1000.

This paper first describes i) the landslide data collected, ii) the method we applied for a climate-physiographical terrain delineation resulting in seven individual model zones over the study area, and iii) the environmental data we used to map landslide susceptibility for the European territory covering 27 EU member states plus additional Balkan countries, Norway and Switzerland (Cyprus and Iceland have not been considered because data were not available to us). We present a methodological framework for index-based modeling of zone-specific landslide susceptibility that is based on a heuristic spatial multicriteria evaluation (SMCE) utilizing the analytical hierarchy process (AHP; Saaty, 1980). Such approaches have shown very successful for small and medium-scale analyses where inventory information is highly incomplete, biased or even absent, and only a few low-resolution spatial factors can be used to model generic landslide susceptibility (e.g., Barredo et al., 2000; Castellanos Abella and van Westen, 2008; Yalcin, 2008; Malet et al., 2013; Pellicani et al., 2013). In contrast to purely data-driven multivariate classification techniques, expert knowledge can be applied to account for bias in the inventory information and deficits in the susceptibility factor data used. The quantification of expert knowledge to assign weight coefficients for the index-based modeling through the use of AHP allows an advanced control in the heuristic assessment. The susceptibility indices resulting from the evaluation are validated through the analysis of receiver operating characteristics (ROC) curves (e.g., Fawcett, 2006). We present the resulting model-zone susceptibility maps and the method we used to combine them into one classified landslide susceptibility map for the whole study area. We then discuss an approach to produce a confidence level map based on common European administrative mapping units represented by the EUROSTAT NUTS (*Nomenclature des Unités Territoriales Statistiques*) level 3 (NUTS 3) areas, and compare the ELSUS 1000 with selected national-level susceptibility maps of European countries that were available for our study. We conclude with a critical discussion on the ELSUS 1000 Version 1 and future approaches for improvements.

2. Materials and methods

2.1. Landslide information

The main prerequisite for any kind of landslide susceptibility assessment is information on spatial occurrence of landslide events, even if incomplete (e.g., van Westen et al., 2009). For this study, a pioneering attempt has been undertaken to gather basic spatial information of landslides over the European territory, i.e. landslide location points. Although for many European countries regional or national landslide inventories or maps are available with different degrees of completeness and information (Dikau et al., 1996; Van Den Eeckhaut and Hervás, 2012), so far almost no attempt has been made to explore these data for continental-level landslide zonings at small spatial scales. We collected location information on landslide events on national and regional levels throughout Europe from inventories, literature, published maps, and through Google Earth imagery (Table 1). The collected landslide information consists of more than 102,000 records reflecting solely

Table 1
Landslide data collected for this study. "Quality" only refers to relative average accuracy of location information, not completeness of the inventory, "published map" sources were scanned and georeferenced from Jelinek et al. (2007). "Ad. Info" refers to databases where information on typology, size, or date of the events is available (not collected for this study). For provider acronyms, please refer to Acknowledgements.

National-level data						
Country	*n*	Provider	Source	Quality	Access	Ad. Info
Norway	32,886	NGU	Inventory DB	Good	Restricted	Yes
France	17,935	BRGM	Inventory DB	Good	Open	Yes
United Kingdom	15,897	BGS	Inventory DB	Good	Restricted	Yes
Italy	15,499	CNR-IRPI	Inventory DB	Good	Open	Yes
Czech Republic	9257	CGS	Inventory DB	Good	Restricted	Yes
Greece	2321	IGME	Inventory DB	Medium	Restricted	No
Slovenia	1234	GeoZS	Published map	Low	Open	No
Spain	973	JRC	Inventory DB	Good	Restricted	Yes
Austria	654	BGA	Overview DB	Good	Restricted	Yes
Sweden	543	SGI	Inventory DB	Good	Restricted	Yes
Bulgaria	419	BAS	Published map	Low	Open	No
Hungary	342	BMFH	Inventory DB	Low	Restricted	No
Albania	309	AGS	Inventory DB	Medium	Restricted	No
Switzerland	284	BAFU	Overview DB	Good	Restricted	Yes
Portugal	162	IGOT	Inventory DB	Medium	Restricted	No
Ireland	157	GSI	Inventory DB	Good	Restricted	No
Romania	77	JRC	GoogleEarth™	Good	Restricted	No
Denmark	39	JRC	GoogleEarth™	Good	Restricted	No
Regional-level data						
Region	*n*	Provider	Source	Quality	Access	Ad. Info
Bavaria (Germany)	2222	LFU	Inventory DB	Good	Restricted	Yes
Flanders (Belgium)	291	LNE	Inventory DB	Good	Restricted	Yes
Mecklenburg-Vorpommern (Germany)	75	LUNG	Inventory DB	Good	Restricted	Yes
Saxony (Germany)	73	LFULG	Inventory DB	Good	Restricted	Yes