Catena 139 (2016) 250–264

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Susceptibility zoning of shallow landslides in fine grained soils by statistical methods

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ARTICLE INFO

Article history:
Received 6 July 2015
Received in revised form 27 November 2015
Accepted 30 December 2015
Available online 4 February 2016

Keywords:
Landslide
Susceptibility
Zoning
Statistical analysis
Terrain zoning units

ABSTRACT

The paper proposes a methodology, in two successive steps, to zone the susceptibility to shallow landslides in fine grained soils by means of statistical methods. The first step of the methodology, aiming at defining, calibrating and validating the statistical analysis, ends with a landslide susceptibility computational map; the second step of the methodology is employed to produce a susceptibility map for zoning purposes. This structured methodology arises from the need to distinguish, at any given scale of analysis, between the spatial discretization needed to perform the statistical computations (terrain computational units) and terrain units useful for zoning purposes (terrain zoning units). The applicability of the proposed methodology is tested, at two different scales (1:25,000 and 1:5000), in two areas of southern Italy, the test area for the larger scale being a portion of the test area used for the analysis at the smaller scale. This allows for the generalization of the obtained results through the comparison, for the same phenomena in the same geo-environmental context, of the predisposing factors at two scales of analysis. In both analyses, the relevant variables for the susceptibility assessment are: elevation zone, slope gradient, slope curvature and geology; in the analysis at large scale also the weathered rock thickness, available only at this scale, assumes a relevant role. In both cases, the aggregation of multiple terrain computational units (TCU) into a larger terrain zoning unit (TZU) works best when focal statistic techniques are used with a characteristic dimension of the area of influence equal to 16 TCUs.

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1. Introduction

Shallow landslides in fine-grained soils typically involve the upper layer of slopes affected by weathering processes. They generally occur during the wet season and quickly evolve following mechanisms classified as shallow earth slides or earth slides–earth flows (Cascini et al., 2015). The morphometric features of these phenomena mainly depend on the spatial distribution of the weathered rock thickness along the slope, where a diffuse pattern of cracks, due to alternate processes of wetting and drying and insolation and frost, is generally observed. In spite of the small size of these phenomena they usually occur over wide areas, often causing serious economic damages (Crozier, 2005; Glade et al., 2005; Antronico et al., 2013). Susceptibility zoning of these landslides is thus becoming an important topic in the scientific literature (Gullà et al., 2008), especially in relation to land-use planning and management (Soeters and van Westen, 1996; Fell et al., 2008a). Soeters and van Westen (1996) classify the methods employed to derive landslide maps for zoning purposes in three classes: heuristic, statistical and deterministic. Fell et al. (2008a) propose a correlation among the same methods (classified as basic, intermediate and advanced), scales of analysis and zoning purposes to define three zoning levels: preliminary, intermediate and advanced. For instance, when using basic methods exclusively, only a preliminary zoning level can be obtained; while the use of intermediate and advanced methods can allow reaching intermediate or advanced level of zoning (Fell et al., 2008a). The choice on the most appropriate zoning method to adopt, at a given scale for a given purpose, also depend on other factors, such as the characteristics of the phenomena (typology, area and/or volume, etc.), the quality and accuracy of the available data within the area to be zoned, and the know-how and expertise of the analysts. Indeed, depending on their area and/or volume, landslides may be represented by dots with attributes at small scale, by polygons at medium scale, whereas they can be mapped at large scale distinguishing minor and lateral scarps as well as retrogressive deformations such as tension cracks or minor landslides (Cascini et al., 2015). It is also worth stressing that the accuracy of the input data is deeply linked to the accuracy of the obtained results, thus cost–benefit analyses are needed to identify the amount and type of soil investigations which increase the quantity and quality of the available data.

All that considered, we propose a methodology based on statistical analyses in order to identify the most relevant predisposing factors for

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http://dx.doi.org/10.1016/j.catena.2015.12.017
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shallow landslides in fine grained soils. The proposed methodology may be defined, following the terminology introduced by Fell et al. (2008a), an intermediate method pursuing an intermediate level of susceptibility zoning at both medium and large scales. Medium scale zoning should be seen as both an advanced analysis for information and advisory purposes (typically pursued at small scale) and a preliminary analysis for statutory purposes. An application of the proposed methodology is provided with reference to a 136 square kilometers test area, the Catanzaro isthmus in southern Italy, which was already analysed at small scale by Cascini et al. (2015) and is herein analysed at medium scale (1:25,000). To further test the potentiality of the methodology, two hydrological basins within the test area are also analysed and zoned at large scale (1:5000). This allows the comparison, for the same phenomena in the same geo-environmental context, of the identified predisposing factors at each scale of analysis.

2. Materials and methods

2.1. Statistical analyses for landslide susceptibility assessment

The framework for landslide risk analysis proposed by Fell et al. (2005) indicates susceptibility as one of the fundamental ingredients of landslide risk estimation and zoning. Numerous studies exist in the international literature evaluating landslide susceptibility over large areas by means of data driven statistical methods, typically implemented at medium to small scales (Brabb et al., 1972; Carrara et al., 1977; Guzzetti et al., 1999; Dai and Lee, 2002; Chung and Fabbri, 2003; Van Westen, 2004; Thiery et al., 2007; Pourghasemi et al., 2012; Pardeshi et al., 2013; Sarkar et al., 2013; Kavzoglu et al., 2015; among others). Statistical analyses may be classified in two main categories according to whether they employ bivariate and multivariate techniques. The main difference between the two classes of analyses concerns the possible inter-relationships among the causal factors (independent variables of the analyses). Bivariate techniques derive weight values from statistical indicators based on the causal relationship between landslide events (dependent variable of the analyses) and each one of the independent variables, thus assumed as not inter-related. Multivariate techniques employ a statistical model which is able to exploit all the information provided by the set of thematic variables, thus explicitly considering the possible interaction among the independent variables in their causal relationship with the dependent variable. Examples of bivariate statistical models used in landslide susceptibility and hazard studies are: likelihood ratios (Chung, 2006; Lee et al., 2007; Dewitte et al., 2010); weights of evidence (Neuhäuser and Terhorst, 2007; Dahal et al., 2008); information value (Yin and Yan, 1988); favourability functions (Fabbri et al., 2002; Tangestani, 2009). Examples of multivariate statistical models are: discriminant analysis (Carrara et al., 1991; Baeza and Corominas, 2001); factor analysis (Fernandez et al., 1999; Ercanoglu et al., 2004); logistic regression (Atkinson and Massari, 2011; Budimir et al., 2015); artificial neural networks (Ermini et al., 2005; Nefeslioglu et al., 2008).

2.2. The proposed methodology

The multivariate statistical methodology employed herein to zone the susceptibility to shallow landslides in fine grained soils includes two successive steps. The first step includes the definition, calibration and validation of the statistical analysis, and it ends with the production of a landslide susceptibility computational map. The second step is the production of a susceptibility map for zoning purposes. Differently from most of the statistical methods used in the literature to derive landslide susceptibility maps, the proposed approach is based on a clear distinction between landslide susceptibility computational and zoning maps. Indeed, the discretization of the test area employed in the final cartographic product of the statistical analysis, which is perfectly suitable for statistical purposes (e.g., terrain units equal to square cells, whose size is related to the scale of analysis), is not necessarily suitable for zoning purposes. The main conceptual innovation of the proposed procedure is the explicit definition, at the end of the statistical analysis, of a zoning algorithm which deals with this issue.

Fig. 1 shows a flow chart of the proposed two-step procedure. In the first step, the statistical analysis is defined on the basis of a series of spatial variables derived from significant thematic maps (i.e. independent variables of the multivariate analysis) and an inventory of shallow landslides (i.e. dependent variable of the multivariate analysis). During this step, the model is calibrated and validated and the independent variables most relevant for the susceptibility analysis are selected. The first step ends with the production of a landslide susceptibility computational map over the study area. In the second step, the computational map is used as an input for producing the final landslide susceptibility zoning map of the area on the basis of appropriately defined terrain zoning units. Fell et al. (2008a), within their 'Guidelines for landslide susceptibility, hazard and risk zoning for land use planning' define zoning as follows: the division of land into homogeneous areas or domains and their ranking according to degrees of actual or potential landslide susceptibility, hazard or risk. The two-step statistical methodology introduced herein is based on the previous definition as well as on the distinction, proposed by Calvello et al. (2013), between terrain computational units, TCUs, and terrain zoning units, TZUs. The first ones refer to the spatial domains used to define, calibrate and validate a model for landslide analyses, the second ones are spatial domains used to produce a landslide map for zoning purposes. The level of discretization of the area is based, for both spatial domains, on the scale of the analysis. In particular, the size of TCUs is related to the spatial resolution of the map, whereas the size of TZUs is related to the desired informative resolution of the zoning. For instance, when a regular square grid is used in a GIS environment, a common dimension

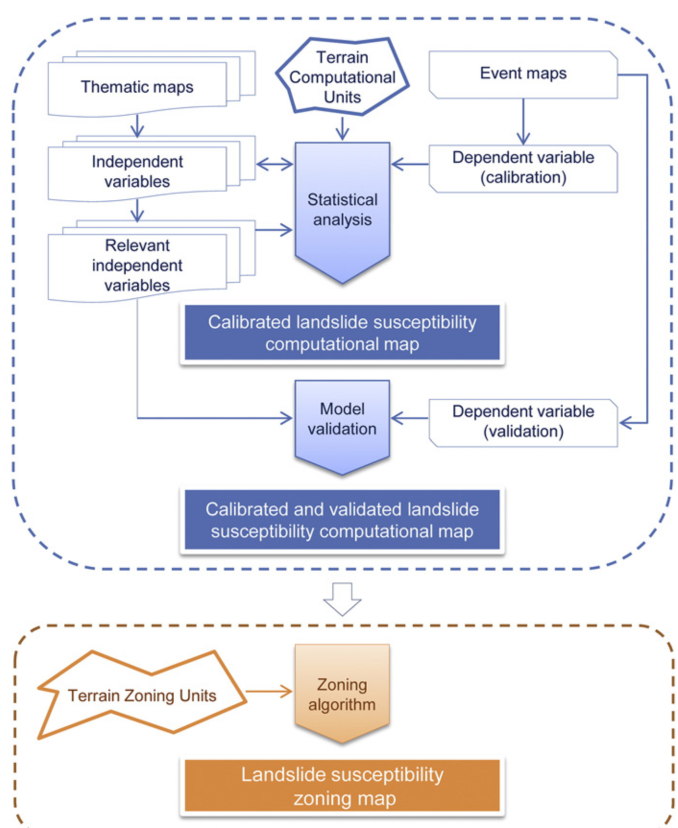

Fig. 1. Procedure to produce landslide susceptibility zoning maps at medium (1:25,000) and large (1:5000) scale.

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