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Landslide zoning over large areas from a sample inventory by means of scale-dependent terrain units

Michele Calvello *, Leonardo Cascini, Sabrina Mastroianni

Dept. of Civil Engineering (DICIV), Università degli Studi di Salerno, Via Ponte Don Melillo, 84084 Fisciano, SA, Italy

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ABSTRACT

A procedure is proposed to produce landslide distribution zoning maps to be considered preparatory to susceptibility, hazard and risk zoning maps, based on 1) the results from a statistical multivariate analysis of a landslide inventory, which must be available for only a portion of the territory to be zoned, and 2) the use of appropriately defined terrain mapping units. The units are divided into terrain computational units (TCUs) and terrain zoning units (TZUs), whose size is related to the scale of zoning. The procedure comprises three phases: calibration, validation and prediction. The purpose of the prediction phase is the application of a calibrated and validated statistical model in a territory, previously recognized as viable on the basis of 'a-priori applicability maps,' for which no information is available regarding the distribution of landslides or where the information provided by the landslides inventory is unreliable or heterogeneous. The proposed procedure is applied to two case studies in southern Italy for the analysis and zoning of slow-moving landslides at 1:25,000 and 1:100,000 scales, respectively. The first case study illustrates the applicability of the procedure. The aim of the second case study is to address the part of the procedure related to the evaluation of the computational maps at the end of the calibration and validation phases.

1. Introduction

The "Guidelines for Landslide Susceptibility, Hazard and Risk Zoning for Land Use Planning" (Fell et al., 2008a) define landslide zoning as the division of land into homogeneous areas or domains and their ranking according to degrees of actual or potential landslide susceptibility, hazard or risk or based on the applicability of certain hazard-related regulations. Within this process, the analysis of past events, i.e. the use of an inventory including the location, classification, volume, activity, date of occurrence and other characteristics of landslides in an area (Fell et al., 2008a), is essential to the calibration and validation of any model leading to landslide susceptibility assessment, which is the first step in the landslide risk management framework proposed by Fell et al. (2005).

The existing literature offers many definitions and interpretations of landslide susceptibility (e.g., Brabb, 1984; Soeters and Van Westen, 1996; Guzzetti et al., 1999; Dai and Lee, 2002; Remondo et al., 2003; Santacana et al., 2003; Guzzetti, 2005; Fell et al., 2008a). The most useful definitions of the term seem to be the ones proposed by Brabb (1984) and Fell et al. (2008a), as they clearly highlight the significant and relevant aspects related to landslide susceptibility zoning. Particularly, Brabb's (1984) definition stresses the forecasting nature of susceptibility maps on the basis of the following principle introduced by Varnes (1984): the past and present are keys to the future. As a consequence, the application of this concept implies that future landslides are likely to occur in the same geological, geomorphological and hydrological processes that have led to instability in the past till the present. Based on this principle, it is also apparent that the susceptibility is a feature on a territory that could be considered "homogeneous" with respect to landslide occurrences in both space and time. On the other hand, Fell et al. (2008a) highlight the need to select landslides to be considered for the creation of susceptibility maps, both in terms of size and type. Therefore, reliability, completeness and resolution must be considered when preparing and using a landslide inventory map.

When reliable and complete landslide inventories are not available for landslide zoning, two alternative approaches may be employed: (i) producing a new reliable landslide inventory over the entire area to be zoned, or (ii) producing a new landslide inventory over a portion of the area and developing a model to identify the relationship between landslides and other available thematic information; then using the model to export the results to the remaining area. Herein, following the second approach, a procedure is proposed that facilitates the production of landslide distribution zoning maps over large areas of a territory using appropriately defined terrain mapping units or TMUs (e.g., Hansen, 1984; Guzzetti, 2005), and the results of statistical multivariate analyses (e.g., Carrara, 1983; Guzzetti et al., 1999) of a landslide inventory that is available only for a portion of the territory to be zoned. The maps, which are to be considered preparatory to susceptibility, hazard and risk zoning maps, infer the expected occurrence of landslides in any part of the

* Corresponding author. Tel./fax: +39 089 963439.
E-mail address: mcalvello@unisa.it (M. Calvello).

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Table 1
Mapping scales for landslide inventories and susceptibility zoning in relation to landslide zoning methods, levels and purposes (modified from Fell et al., 2008a and Cascini, 2008).

Purpose	Scale		Applicability of zoning methods	Examples	Typical area
Regional zoning – information	Small	<1:100,000	Basic (applicable) Intermediate (inapplicable) Advanced (inapplicable)	Landslide inventory and susceptibility zoning to inform policy makers and the general public	>10,000 km^2
Regional zoning – information – advisory	Medium	1:100,000 to 1:25,000	Basic (applicable) Intermediate (may be applicable) Advanced (inapplicable)	Landslide inventory and susceptibility zoning for regional development; or very large scale engineering projects.	1000 to 10,000 km^2
Local zoning – information – advisory – statutory	Large	1:25,000 to 1:5000	Basic (applicable) Intermediate (applicable) Advanced (applicable)	Landslide inventory, susceptibility and hazard zoning for local areas	10 to 1000 km^2

investigated area, i.e. without leaving unclassified areas. These maps are hereafter called ‘landslide distribution zoning maps’ because they are used for zoning purposes and employ terrain subdivisions related to topography at the scale of the analysis, rather than to landslide spatial features.

2. Terrain units for landslide zoning maps at different scales

Reference scale is a key aspect of any landslide analysis including landslide density zoning, because the aims and objectives of such analyses and the methods used differ as a function of spatial scale. Fell et al. (2008a) indicate that landslide zoning maps should be prepared at a scale appropriate for displaying necessary information at a particular zoning level and the scale should be selected by considering the objectives of the map. Cascini (2008) observes that: (i) input data used to produce landslide zoning maps must have appropriate resolutions and quality, and (ii) the inventory used should be mapped at a larger scale than susceptibility zoning maps. Table 1 summarizes relationships among purposes, zoning methods and mapping scales for landslide inventory and susceptibility zoning. Fell et al. (2008a) and Cascini (2008) group zoning methods into three categories: 1) basic methods — heuristic and empirical procedures that process essentially topographic, geological and geomorphological data; 2) intermediate methods — procedures based on statistical analyses; and 3) advanced methods — deterministic or probabilistic procedures using hydrogeological and geotechnical data. Depending on the scale and methods to be adopted, three different purposes are defined for regional and local zoning over large areas, i.e. information, advisory and statutory. Table 1 also provides typical examples of zoning as a function of the scale of analysis.

All zoning is based on the discretization of a territory into map units. As Hansen (1984) defines, a TMU is a portion of land surface that contains a set of ground conditions that differ from the adjacent units across definable boundaries. At the analysis scale, a TMU represents a domain that maximizes internal homogeneity and between-units heterogeneity (Guzzetti, 2005). Several methods have been proposed in the literature for the identification of map units for landslide analyses (e.g., Meijerink, 1988; Carrara et al., 1995; Soeters and van Westen, 1996; Guzzetti et al., 1999). Choosing the most appropriate mapping unit depends on a number of factors, including the type of landslide phenomena to be studied; the scale of the investigation; the quality, resolution, scale and type of the thematic information required; and the availability of adequate information management and analysis tools.

According to the previously discussed issues, it is evident that the selection of an appropriate terrain subdivision, which must be defined by considering both the scale of the analysis and landslide types, is mandatory for the reliability of any landslide zoning procedure. There are two aspects related to landslide analyses that make this choice relevant: computation and zoning. To address this issue, a distinction is proposed between terrain computational units, or TCUs, which refer to territorial domains used to define, calibrate and/or validate a model for landslide analyses, and terrain zoning units, or TZUs, which are units used to produce a landslide map for zoning purposes. This distinction introduces the following principle: when dealing with geo-statistical analyses developed for zoning purposes at a given scale, the terrain units that are suitable to be used within a geostatistical model (TCUs) are not necessarily suitable for the discretization of the zoning map derived from the results of that model (TZUs). Indeed, at a given scale, a map classifying the portions of a territory that result from the discretization of the spatial model used within a landslide analysis of that territory, i.e. a computational map, does not necessarily need to be equal to the discretization of the territory appropriate for a landslide map for zoning purposes at that scale, i.e. a zoning map. The latter, for instance, could be the useful result of a manipulation of the computational results, such as the aggregation of multiple computational terrain units into a single zoning unit.

A very important issue, when dealing with such units, is the definition of their appropriate size, which must be related to the scale of analysis. The minimum area of terrain units for computational purposes at a given scale (minimum area of TCUs) is smaller than the minimum area of terrain units for zoning purposes at that scale (minimum area of TZUs), because the minimum area of a TCU is related to the ‘spatial resolution’ of the map, i.e. the measure of the smallest area identifiable on the map as a discrete separate unit, whereas the minimum area of a TZU is related to the desired ‘informative resolution’ of the zoning. For instance, when a regular square grid is used, such as for raster files in a GIS environment, a commonly used dimension of cell size is 1/1000 of the scale factor, such that the area covered by each elementary pixel increases as the scale of analysis decreases whereas, regardless of the scale, the size of each square cell on paper is always 1×1 mm. This criterion is surely adequate for defining terrain units for computational purposes (TCUs); however, it is inappropriate for a zoning map at that scale because the dimensions of the terrain units (TZUs) would be too small for zoning purposes.

Table 2
Suggested dimensions of the terrain zoning units (TZUs) at different scales.

Reference scale	Elementary pixel dimension		Minimum and maximum TZU dimensions	
	Side length (m)	Area (m^2)	Number of elementary pixels	Area (km^2)
1:X	X 10^{-3}	$X^2\ 10^{-6}$	16–1600	16 X^2–1600 X^2
1:250,000	250	62,500	16–1600	1–100
1:100,000	100	10,000	16–1600	0.16–16
1:25,000	25	625	16–1600	0.01–1
1:5000	5	25	16–1600	0.004–0.4