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GIS-based multicriteria evaluation with multiscale analysis to characterize urban landslide susceptibility in data-scarce environments

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A B S T R A C T

Landslides can have a severe negative impact on the socio-economic and environmental state of individuals and their communities. Minimizing these impacts is dependent on the effective identification of risk areas using a susceptibility analysis process. In such a process, output maps are generated to determine various levels of threat to human populations. However, the reliability of the process is controlled by critical factors such as data availability and data quality. In data-scarce environments, susceptibility analysis done at multiple interlocking geographic scales can provide a convergence of evidence to reliably identify risk areas. In this study, multiscale analysis and fuzzy sets are combined with GIS-based multicriteria evaluation (MCE) to determine landslide susceptibility levels for areas of the Metro Vancouver region, British Columbia, Canada. Landslide-conditioning parameters are chosen based on their relevance and effect on a particular scale of analysis. These parameters are derived for three geographic scales using digital elevation models, drainage networks and road networks. An analytical hierarchy process (AHP) analysis provides relative weights of importance to combine variables. The landslide susceptibility analysis is done for regional, municipal and local scales at resolutions of 50 m, 10 m, and 1 m respectively. At each scale, susceptibility models are validated against real inventory data using the seed cell area index (SCAI) method. The strong inverse correlation between the map classes and the SCAI adds to confidence in the results. The developed approach can enable analysts in data-scarce environments to reliably identify susceptible areas thereby improving hazard mitigation, emergency services targeting, and overall community planning.

Introduction

Landslides are described as the mass movements of slope-forming materials comprising rocks, soils, artificial fill, or a combination of these (Sidle & Ochiai, 2006). Causal factors such as slope and erosion accumulate in an area and the onset of a rapid trigger event releases the landslide. These trigger events include rainfall, weathering, surface fractures, and earthquakes. The landslide evolves swiftly and can have devastating impacts on the well-being of humans and communities, especially in regions where urban residential areas coincide with mountainous terrains. The economic costs include relocating communities, repairing physical structures, and restoring water quality in streams and rivers (Yalcin, 2007).

The Joint Technical Committee on Landslides and Engineered Slopes characterizes landslide susceptibility zoning as the spatial distribution and classification of terrain units according to their predisposition to result in landslides (Fell et al., 2008). Landslide susceptibility assessments are important to engineers and city planners because the susceptibility maps provide an additional tool to support the selection of areas for development. In order to plan for the adverse effects of landslides, since the 1970s landslide susceptibility and hazard zoning techniques have been developed by manually delineating susceptibility zones using aerial photographs (Blesius & Weirich, 2010; Brabb, Pampeyan, & Bonillia, 1972; Drennon & Schleining, 1975). In recent decades, there was improved progress in preparing hazard zoning maps because of the rapid development of Geographical Information Systems (GIS) that

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greatly advanced the susceptibility mapping process in both efficiency and accuracy (Weirich & Blesius, 2007). GIS facilitated large volumes of data to be managed and quickly analyzed for use in various landslide mapping studies (Yalcin & Bulut, 2007). Despite the advances in GIS capabilities, landslide susceptibility studies are still mostly being conducted at a single spatial scale. The objectives of this study are to (i) develop a multiscale approach to model landslides, (ii) implement the approach at regional, municipal and local spatial scales, and (iii) test the approach using inventory data from the Metro Vancouver area, District of North Vancouver (DNV), Canada; and locally on the Berkley Escarpment in the DNV. The spatial resolutions of the Metro Vancouver, DNV, and Berkley Escarpment data are 50 m, 10 m, and 1 m respectively.

There are many techniques available to produce landslide susceptibility maps and these can be categorized generally into quantitative methods, semi-quantitative methods, and qualitative methods. Further, within each of these categories research efforts are being made to use multiple approaches to improve the susceptibility map outputs.

Quantitative methods such as deterministic models (Gomes et al., 2008; Gorsevski, Gessler, Boll, Elliot, & Foltz, 2006; Klimes, 2008; Luzi & Pergalani, 1996; Mergili, Schratz, Ostermann, & Fellin, 2012; Santini, Grimaldi, Nardi, Petroselli, & Rulli, 2009; Van Westen & Terlien, 1996; Wan, Lei, & Chou, 2012; Wu & Sidle, 1995) and probabilistic and statistical models (Ayalew & Yamagishi, 2005; Dai & Lee, 2003; Ercanoglu, 2005; Kia et al., 2012; Ohlmacher & Davis, 2003; Piacentini et al., 2012; Thapa, 2011; Xu, Xu, Lee et al., 2012; Yilmaz, 2009; Yilmaz & Keskin, 2009; Yilmaz, Topal, & Suzen, 2012) have minimal dependence on human judgment and expert opinion to produce the output maps. These quantitative techniques also require large volumes of detailed data derived from laboratory tests and field surveys making them highly unsuitable for regional scale studies (Van Westen, Van Asch, & Soeters, 2006) or use in data-scarce environments (Demoulin & Chung, 2007). These quantitative methods have also been integrated with GIS and multicriteria evaluation (MCE) techniques to better represent the spatial character of the problem situation.

Heuristic methods, including both qualitative and semi-quantitative, range from direct field mapping methods to complex logical and computer-based systems that incorporate human judgment and expert opinions (Castellanos Abella & Van Westen, 2008; Lai & Dragicevic, 2011; Lee & Choi, 2004; Pavel, Nelson, & Fannin, 2011; Reis et al., 2012; Van Westen, Rengers, & Soeters, 2003; Wang, Guo, Fang, & Chang, 2012). A common heuristic approach linking GIS and multicriteria evaluation (Jankowski, 1995) uses expert opinions on multiple criteria with the resulting landslide maps categorized into zones of “very low”, “low”, “medium”, “high”, and “very high” categories of susceptibility. A mixture of criteria weighting tools such as the Analytical Hierarchy Process (AHP) and criteria integration tools such as Weighted Linear Combination (WLC) are used to combine the factors and generate landslide susceptibility maps (Akgun & Bulut, 2007; Akgun & Turk, 2010; Gorsevski, Jankowski, & Gessler, 2006; Pourghasemi, Pradhan, & Gokceoglu, 2012; Thanh & De Smedt, 2012; Wu & Chen, 2009; Yalcin, 2008). Heuristic analysis is shown to be a cost-effective approach for large study areas having limited accessible data (Van Westen et al., 2006).

Recently, a combination of methods has been pursued. The comparison of multiple susceptibility mapping methods is useful because it provides an indication of the reliability range of the results (Lee et al., 2012; Regmi, Giardino, Vitek, & Dangol, 2010; Rossi, Guzzetti, Reichenbach, Mondini, & Peruccacci, 2010; Sterlacchini, Ballabio, Blahut, Masetti, & Sorichetta, 2011; Xu, Xu, Dai, & Saraf, 2012). However, limitations include the dependency on large volumes of data and the inability of generalizing the comparison results outside the data context.

In addition to data availability, scale is also an important factor. Selecting the appropriate analysis scale is a challenge when producing susceptibility maps because it is often a compromise between a desired scale and data availability. Nevertheless, landslide susceptibility studies mostly generate a single map at a fixed scale determined by data convenience. However, the scale of observation will affect the analysis, outputs and interpretation. For example, at a country level scale topography will explain the broad patterns of slope, aspect, and flow accumulation but mask local finer scale variations. As the scale changes, so do associated patterns of spatial processes and this has implications for understanding any phenomena and the applicability of methods and results from one scale to another (Hay, Marceau, Dube, & Bouchard, 2001). Thus, understanding the behavior of a phenomenon at multiple scales is imperative to determine the effect of scale on the spatial patterns and processes (Wu, Jelinski, Luck, & Tueller, 2000).

The research literature has indicated only one analysis using a multiscale MCE approach to evaluate landslides. The authors developed a national landslide risk index map for Cuba with additional analyses at provincial and municipal levels (Castellanos Abella & Van Westen, 2007). One challenge was the lack of available data for the entire country and hence the authors were forced to exclude deterministic landslide hazard assessment methods from their analysis. They compromised by using MCE and AHP methods to produce a qualitative landslide risk index. Further, with this national level risk map they identified areas of high risk at the provincial and municipal levels for additional statistical analysis once relevant data becomes available. While the authors have produced a useful representation of landslides at the national level, it is clear the methods used and the scale of analysis were conditioned on the available data.

In this study, we have integrated a multiscale analysis and fuzzy sets into a GIS-based multicriteria evaluation (MCE) approach to determine landslide susceptibilities in the Metro Vancouver region, British Columbia, Canada. The focus is on shallow landslides triggered by rainfall events typical of the study sites. This focus allows for the generalization of the results to other study areas susceptible to shallow landslides. The ability to model landslide susceptibility across multiple scales allows various levels of decision makers to identify susceptibility hotspots and effectively allocate resources and services. The next sections give background to the theory, outline the multiscale GIS-based MCE approach, and present results from three scales of analysis. The implications of the work are then discussed and conclusions stated.

Material and methods

GIS-based multicriteria evaluation

Geographic information systems (GIS) have evolved from preforming functionalities such as geographic database management to geovisualization analysis and are now able to provide advanced scientific and mathematical analysis between multiple map layers (Eastman, Jin, Kyem, & Toledano, 1995). Consequently, GIS is well-suited and extensively applied to the design and development of robust decision support systems capable of evaluating choices from advanced spatial data analysis techniques at various scales of analysis (Lai, 2011).

The goal of multicriteria evaluation (MCE) or multicriteria analysis (MCA) is to assess choice possibilities when there are multiple criteria and conflicting objectives (Carver, 1991; Jankowski, 1995; Voogd, 1982). The MCE procedure integrates information from various standardized criteria to produce a single