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A GIS-based extended fuzzy multi-criteria evaluation for landslide susceptibility mapping

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ABSTRACT

Landslide susceptibility mapping (LSM) is making increasing use of GIS-based spatial analysis in combination with multi-criteria evaluation (MCE) methods. We have developed a new multi-criteria decision analysis (MCDA) method for LSM and applied it to the Izeh River basin in south-western Iran. Our method is based on fuzzy membership functions (FMFs) derived from GIS analysis. It makes use of nine causal landslide factors identified by local landslide experts. Fuzzy set theory was first integrated with an analytical hierarchy process (AHP) in order to use pairwise comparisons to compare LSM criteria for ranking purposes. FMFs were then applied in order to determine the criteria weights to be used in the development of a landslide susceptibility map. Finally, a landslide inventory database was used to validate the LSM map by comparing it with known landslides within the study area. Results indicated that the integration of fuzzy set theory with AHP produced significantly improved accuracies and a high level of reliability in the resulting landslide susceptibility map. Approximately 53% of known landslides within our study area fell within zones classified as having "very high susceptibility", with the further 31% falling into zones classified as having "high susceptibility".

1. Introduction

Landslides are destructive natural hazards that frequently lead to loss of human life and property, as well as causing severe damage to natural resources (Intarawichian and Dasananda, 2010; Feizizadeh and Blaschke, 2013a). Landslide susceptibility mapping (LSM) is considered to be an effective tool for understanding these natural hazards and predicting potential landslide hazard areas (Feizizadeh and Blaschke, 2013a), thereby mitigating their impacts. LSM addresses how likely a terrain is to produce slope failures, with susceptibilities expressed cartographically in maps that portray the spatial distribution of future slope-failure susceptibility (Lei and Jing-feng, 2006; Feizizadeh and Blaschke, 2013a; Feizizadeh et al., 2013a).

LSM requires a multi-criteria approach and high levels of accuracy and reliability in the resulting maps, in order to be relevant for decision making and the design of disaster management plans. The effectiveness of decision making is clearly dependent on the quality of the data used to produce the landslide susceptibility maps, as well as on the method used for decision-making analysis. GIS-based multicriteria decision analysis (MCDA) is considered to be an important spatial analysis method in the decision-making process that allows information derived from different sources to be combined (Feizizadeh and Blaschke, 2001). GIS-based MCDA is an intelligent approach to converting spatial and non-spatial data into information that can, together with the decision maker's own judgement, be used to assist in making critical decisions (Chen et al., 2010; Sumathi et al., 2008; Gbanie et al., 2013). GIS based MCDA provides a collection of powerful techniques and procedures for dealing with decision-making problems and for designing, evaluating, and prioritizing possible alternative courses of action (Feizizadeh and Blaschke, 2013a, 2012; Feizizadeh et al., 2012). GIS integrated with MCDA methods provide a framework within which to handle different aspects of the various elements of a complex decision-making problem, to organize the various elements into a hierarchical structure, and to study the relationships between these different components of the problem (Malczewski, 2006).

Methods of MCDA can be subdivided into Multiple Attribute Decision Making (MADM) and Multiple Objective Decision Making (MODM) (Malczewski, 1999a). Even though the distinction is derived from two specific meanings: attribute and objective, of

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a generic term: criterion (pl. criteria) the dichotomy of MCDM goes beyond the semantics of criterion. The MADM approach requires that the choice (selection) be made among decision alternatives described by their attributes, where criteria are derived from attributes. MADM problems are assumed to have a predetermined, limited number (tens or hundreds) of decision alternatives. Accordingly, in this paper we focus on multiple criteria evaluation of land units and their susceptibility to landslides. Multiple criteria evaluation involves a set of quantifiable spatial criteria, their standardization functions, techniques for expressing preferences regarding the relative importance of the criteria, and aggregation rules combining quantified criterion preferences with standardized criterion values into an overall evaluation score. This procedure makes multiple criteria evaluation especially attractive for integration with GIS for the purpose of solving spatially-explicit land allocation/land use problems (Carver, 1991; Jankowski, 1995; Malczewski, 2004; Chakhar and Mousseau, 2008; Chen and Paydar, 2012).

An analytic hierarchy process (AHP) is one of the GIS-MCDA methods which have been successfully applied to many decision maker systems (Lai, 1995). In spite of AHP's popularity, the method is sometimes criticized for its inability to adequately handle the inherent uncertainties and imprecisions associated with the mapping of a decision-maker's perception to crisp numbers (Chen et al., 2011). The AHP's pairwise matrix is based on expert opinion and thus introduces a degree of subjectivity when used to make comparison judgments. Any incorrect perception of the roles of the different criteria on behalf of the expert can consequently easily be conveyed into the assignment of weightings (Kritikos and Davies, 2011; Feizizadeh and Blaschke, 2013b). AHP can be integrated with fuzzy logic methods in order to deal with this source of uncertainty and to provide a framework for further analysis that makes use of the advantages of fuzzy membership functions (FMFs) to assess criteria and improve the accuracy of the results.

Fuzzy sets have been applied in the context of MCDA in order to standardize criterion maps by assigning to each object a degree of membership or non- membership of each of the criteria (Jiang and Eastman, 2000; Gorsevski and Jankowski, 2010). Combining an AHP with fuzzy set theory permits greater flexibility in the assessment of results and the subsequent decision making. A fuzzy-AHP (FAHP) retains many of the advantages enjoyed by conventional AHPs, in particular the relative ease with which it handles multiple criteria and combinations of qualitative and quantitative data. As with an AHP, it provides a hierarchical structure, facilitates decomposition and pairwise comparison, reduces inconsistency, and generates priority vectors. Finally, an FAHP is able to reflect human thought in that it uses approximate information and uncertainty to generate decisions (Kahraman et al., 2004). These characteristics qualify the use of an FAHP as an appropriate and efficient tool to assist with making complex decisions in environmental management (Vahidnia et al., 2009).

Fuzzy set theory employs a membership function that expresses the degree of membership value with respect to a particular attribute of interest. The attribute of interest is generally measured over discrete intervals and the membership function can be expressed as a table relating map classifications to membership values (Pradhan, 2010; 2011a, b). Fuzzy logic is straightforward to understand and to implement, and has been successfully integrated with GIS-MCDA. GIS-based MCDA can be used together with fuzzy set theory to model imprecise objectives in a variety of research areas (Chang et al., 2008; Yonca Aydin et al., 2013), especially for landslide susceptibility mapping purposes (Akgun et al., 2012; Shadman et al., 2013). Technically, the fuzzy logic method leads to a flexible combination of weighted criteria that can subsequently be implemented through GIS-MCDA, in

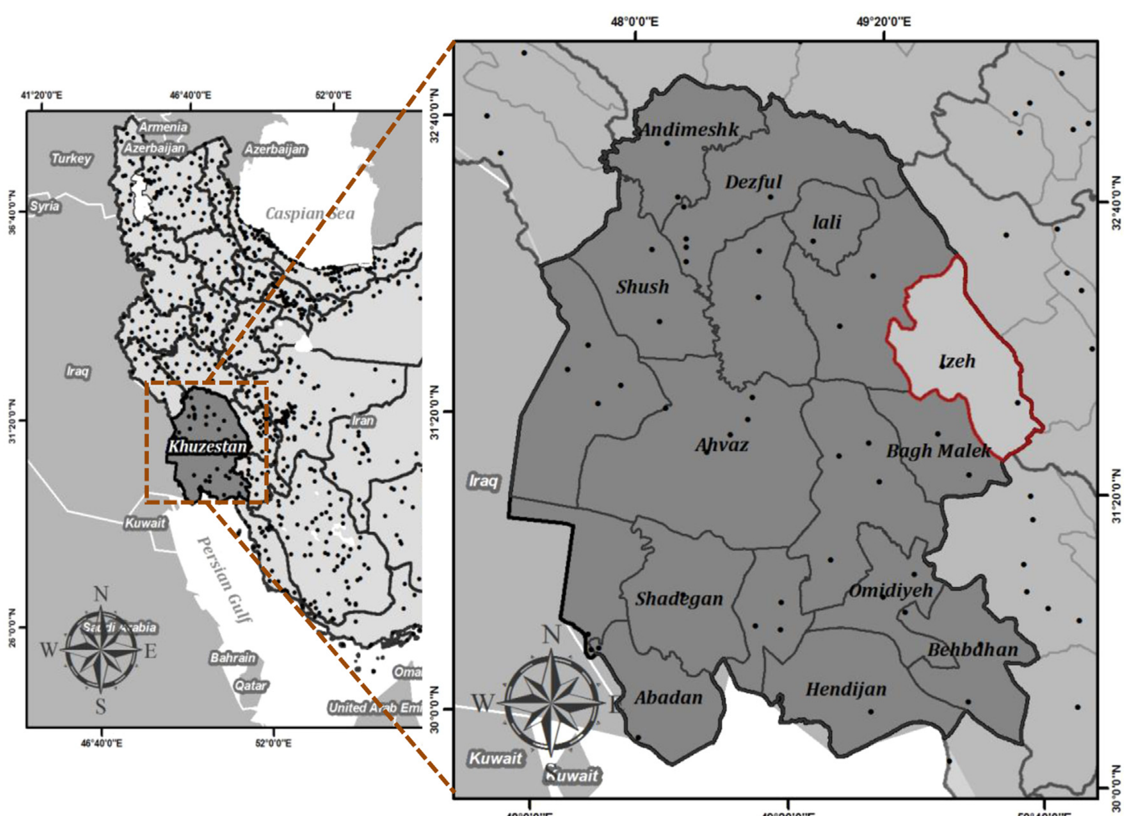

Fig. 1. Location of the study area.