Landslide susceptibility mapping using the fuzzy gamma operation in a GIS, Kakan catchment area, Iran

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Abstract

Northwestern Fars province, Iran, is prone to landslides. In order to help the planners for selecting suitable locations to implement development projects a landslide susceptibility map was produced for the Kakan catchment area using the gamma operation of the fuzzy approach. Lithology, slope angle, slope aspect, land cover, weathering depth, proximity to roads, topographical elevation, and soil depth were considered as landslide causal factors for the study area. The factor maps were input into GIS and landslide hazard evaluation factor (LHEF) rating and fuzzy membership functions were assessed for each class of the factor maps. A weighting factor was then considered for each factor map and multiplied to fuzzy membership functions to justify the affect of each data layer on the output fuzzy membership functions due to the expert's opinion. Three values for gamma were examined and output maps were evaluated using the known landslides. A gamma value of 0.94 yielded the most reliable susceptibility for landslides. Comparing the known landslides of the area with the output susceptibility map showed that the identified landslides were located in the high susceptibility zones.

Introduction

Landslide hazard and risk zoning and mapping for urban and rural areas is widely performed around the world (Siddle et al 1991, Lee et al 1991, Hutchinson and Chandler 1991, Hutchinson et al 1991, Morgan et al 1992, Carrara et al 1991, and 1992, Moon et al 1992). A landslide zonation map divides the land surface into zones of varying degrees of stability, based on an estimated significance of casuative factors in inducing instability. Engineers, earth scientists, and planners are interested in assessment of landslide susceptibility and hazard because of two purposes: (1) The landslide hazard maps identify and delineate unstable hazard-prone areas, so that environmental regeneration programs can be initiated adopting suitable mitigation measures; (2) These maps help planners to choose favourable locations for siting development schemes, such as building and road construction. Even if the hazardous areas can not be avoided altogether, their recognition in the initial stages of planning may help to adopt suitable precautionary measures.

The main factors which influence landsliding are discussed in Varnes (1984) and Hutchinson (1995). Normally the most important factors are bedrock geology (lithology, structure, degree of weathering), geomorphology (slope gradient, aspect, relative relief), soil (depth, structure, permeability, porosity), land use and land cover, and hydrologic conditions.

Soeters and van Westen (1996) and Leroi (1996) discuss the methods which can be used to assess probability of landsliding. Traditional methods of landslide hazard mapping have been based on extensive fieldwork by expert geologists in potentially dangerous areas. This is slow, expensive and very labor intensive operation, and as such can not be widely applied. With the increasing availability of high resolution spatial data sets, GIS, and computers with large and fast processing capacity, it is becoming possible to partially automate the landslide hazard and susceptibility mapping process and minimize fieldwork. Several studies have used GIS and statistics for landslide hazard and susceptibility mapping (Wadge 1988, Gupta and Joshi 1990, Wang Shu-Quiang and Unwin 1992, Pachauri and Pant 1992, Binaghi et al 1998, Guzzetti et al 1999, Skellariou and Ferentinou 2001, Gritzer et al 2001), but mapping studies using fuzzy approaches are limited (for example, Juang et al 1992, Davis and Keller 1997, Binaghi et al 1998, Ercanoglu and Gokceoglu 2002).

Northwestern Fars province, Iran, is affected by landslides. The Kakan area, 51˚ 42´ 30″ E to 51˚ 51´ 30″ E, and 30˚ 32´ 30″ N to 30˚ 43´ 00″ N, is mountainous and located in the geological Zagros Folded zone, and is subjected to heavy precipitation during fall and winter. A landslide susceptibility map was required as part of comprehensive detailed investigations for the development plans by local government. The objective of the present study is to generate the landslide susceptibility map of a landslide-prone area of 114 km^2 in the Kakan catchment area, based on fuzzy approach. The study includes four main steps: (1) producing the causal factors maps by field studies and digital data processing; (2) evaluating the fuzzy membership functions for evidence maps using a modified method initially discussed by Anabalgan (1992); (3) the use of GIS to produce the index maps and generating the susceptibility map; (4) controlling the reliability of the susceptibility map.

Theory and Methodology

Quantitative prediction models for landslide hazard are based on a spatial database consisting of several layers of digital maps representing the casual factors of the occurrence of landslides. Three mathematical frameworks used for the models are (1) probability theory; (2) fuzzy set theory; (3) Dempster-Shafer evidential theory. Corresponding to the three theories, the conditional probability function, the fuzzy membership function, or the belief function are used to represent a quantitative measure of future landslide hazard. These functions representing the landslide hazard were termed favourability functions. The favourability functions can be estimated in many different ways depending upon the availability of the input data and upon the assumptions made in the processes of modelling and estimation. All models are based on two basic assumptions: (1) that future landslides will occur under circumstances similar to the ones of past landslides in either the study area or in areas in which the experts have obtained their knowledge on the relationship between the causal factors and the occurrences of the landslides; and (2) that the spatial data representing the causal factors contained in the GIS database can be used to formulate the future landslide.

When producing landslide susceptibility maps, some researchers have employed quantitative methods (Carrara et al 1991; Anbalagan 1992; Juang et al 1992; Maharaj 1993; Gokceoglu and Aksoy 1996; van Westen et al 1997; Atkinson and Massari 1998; Pachauri et al 1998; Guzzetti et al 1999; Gritzner et al 2001; Ercanoglu and Gokceoglu 2002). All the available methods for regional landslide assessment have some uncertainties arising from lack of knowledge and variability. This is because regional landslide assessments require some generalizations and simplifications, although these assessments are complex. For this reason, a perfect assessment method for landslide susceptibility does not exist. The fuzzy logic introduced by Zadeh (1965) is one of the tools to solve these complex problems. The idea of fuzzy logic is to consider the spatial objects on a map as members of a set. In classical set theory, an object is a member of a set if it has a membership value of 1, or not a member if it has a membership value of 0. In fuzzy set theory, membership can take on any value between 0 and 1 reflecting the degree of certainty of membership. Fuzzy set theory employs the idea of a membership function that expresses the degree of membership with respect to some attribute of interest. With maps, generally the attribute of interest is measured over discrete intervals, and the membership function can be expressed as a table relating map classes to membership values.

The idea of using fuzzy logic in landslide susceptibility mapping is to consider the spatial objects on a map as members of a set. For example, the spatial objects could be areas on an evidence map and the set defined as “ areas susceptible to landslide”. Fuzzy membership values must lie in the range (0,1), but there are no practical constraints on the choice of fuzzy membership values. Values are simply chosen to reflect the degree of membership of a set, based on subjective judgment. Anabalgan (1992) introduced a landslide hazard evaluation factor (LHEF) rating scheme for some of the landslide causal factors. The LHEF rating scheme is a numerical system which is based on major inherent causative factors of slope instability such as geology, slope morphometry, relative relief, land use, land cover and groundwater conditions. Numerical ratings suggested by LHEF scheme were modified as fuzzy membership functions for each map class. Those evidence maps not listed in Anabalgan (1992) were classified and rated according to the experiences gained from the study of factors and their impact on landslides with conditions anticipated in the area of study.

Factor Maps Generation

The primary causal factors for landslide susceptibility mapping in the study area including slope angle, topographical elevation, slope aspect, weathering depth, lithology, land use, and distance to roads were obtained from topographic data processing, aerial photographs interpretation, and field surveys. Produced maps were digitized manually using a Calcomp-9100 digitizer. The data were then processed to create evidence layers. Weighting rates due to Anabalgan (1992) were evaluated subjectively for factor maps and fuzzy membership functions were calculated so that each class on the map had a value between 0 and 1.

Susceptibility Map Generation

The input maps were combined after evidence layers were weighted by assigning membership functions. The rock and soil types were combined to generate the lithology factor map showing the same importance for the two evidences in mapping susceptibility of the area to landslides. Eight landslide causal factors (lithology, weathering, distance to road, relative elevation, land cover, slope aspect, slope angle, and soil depth) were combined to generate the final susceptibility map using a fuzzy gamma operator, choosing a value of 0.94 for γ. If a value of 1 was given for γ, the combination operation would have been the same as the fuzzy algebraic sum, which has an increasive effect on the results. When $0 < \gamma < 0.35$, the combination is smaller than the smallest input membership value, and the effect is therefore decreasive (Bonham-Carter 1994).

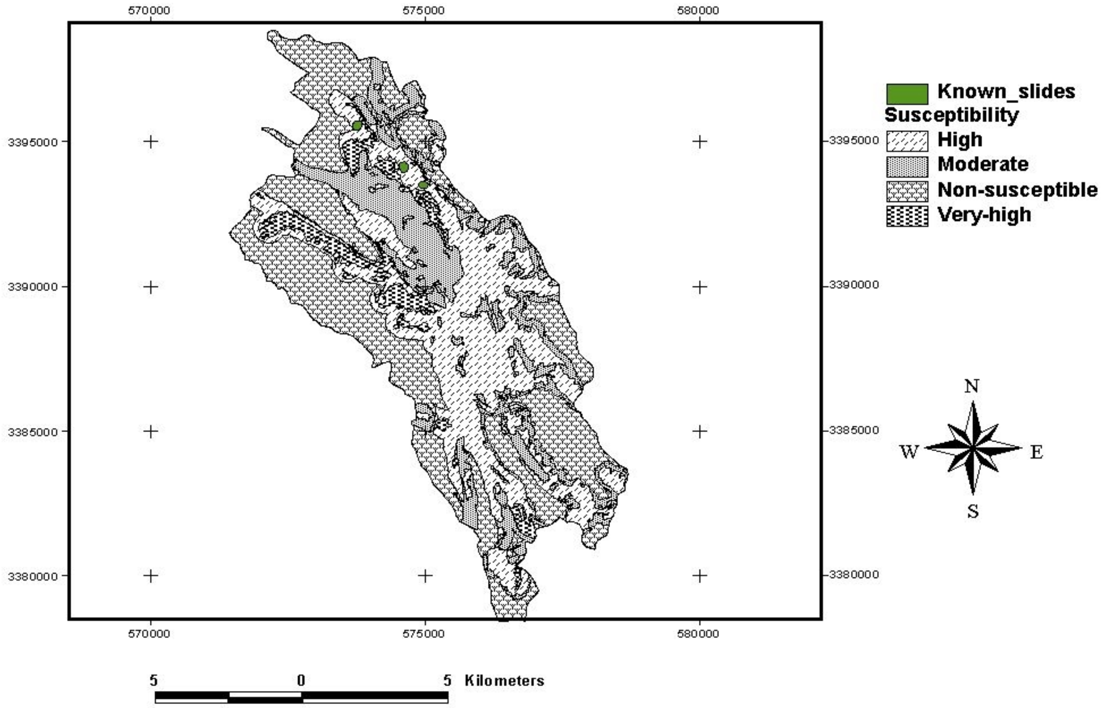
In order to modify the membership values of each factor map and change the influence of each component, an additional “weight factor” (WF) in the range of 0 and 1 was used as a multiplier. This is overall weighting to express the expert’s opinion on the estimated significance of each factor in causing instability, and enables the modeller to make changes interactively with the GIS.

Results and Discussion

Anabalgan (1992) suggested five categories of landslide hazard zones. A modified classification of landslide susceptibility zones on the basis of Anabalgan (1992) was generated and output fuzzy membership functions were classified in order to produce the landslide susceptibility map of the study area.

Different values for gamma were tested on the input fuzzy membership functions to generate the most reliable susceptibility map. Performing fuzzy gamma operation with 0.94 for gamma and classifying the area on the basis of Table 1 yielded an output susceptibility map (Fig. 1) with four zones: non-susceptible, moderate susceptibility, high susceptibility, and very high susceptibility. About 46% of the study area were categorized as non-susceptible. These areas were mainly extended on the hard limestone rocks mostly located on the higher elevations. About 20% of the catchment area was categorized as moderate and 35% as high susceptibility to sliding. Susceptibility zones with fuzzy membership functions > 0.75 make 5% of the area and mostly coincide on the shaly-marly rock units of Pabdeh-Gurpi Formation. Known landslide polygons locate on the high susceptibility zones (Fig. 1).

Figure 1: Landslide susceptibility of the Kakan area .



Results obtained by this model were mostly dependent on data quality, and the gamma values in employed fuzzy combination model. The membership values assigned to each evidence map also play an important role in the final results. The fuzzy operators used in the first or further steps of analyses also affect the possibilities obtained in the final susceptibility map. The effects of choosing different values of gamma (between 0 and 1) is discussed by Bonham-Carter (1994). Choosing a γ value of 0.94 for this study reflects the expert's opinion for giving an increasive possibility value to the final map.

Because of the ease with which the fuzzy sets can be edited with a GIS system, it is easy to try various scenarios to improve the match with known landslides or minimize the effects of overestimated membership values. Multiplying a weighting factor to the factor maps considers the degree of effect of each input map on the landslide susceptibility. The susceptible areas introduced by the fuzzy gamma operation for this case are generally similar to those applying the primary fuzzy values. Assigning a value of 0.6 for gamma decreases the fuzzy membership functions in output map to < 0.3 which is matched only on the low susceptibility zones. In other words, although the gamma value of 0.6 locates between the ranges of increasive (> 0.8) and decreasive (< 0.35) effect of the gamma, it decreases the fuzzy membership functions to low susceptibility zones. Assigning a value of 0.8 for gamma also decreases the fuzzy membership functions to low-to-moderate susceptibility zones (0.1-0.6). An area of about 68 km^2 is covered by these categories. There is lack of fuzzy membership functions of > 0.6 in output susceptibility map. The number of polygons with fuzzy membership functions of 0 were constant in all three cases. An area of about 46km^2 was covered by non-susceptible category. Assigning a value of 0.94 for gamma increases the output fuzzy membership functions to values > 0.8, therefore, locating areas with high and very high susceptibility to sliding (Fig. 1).

Conclusion

The fuzzy logic approach used in this paper provides a flexible method with which to include an expert's opinion in developing an inference network. The variety of fuzzy operators enables the expert to examine different combinations and produce an intermediate map, or add any new data layer to the model and to test its affect on the final possibility map.

Because the fuzzy membership functions assessed for factor maps were mainly extracted from the field data, the procedure followed during the study should find locations of the known landslides. In order to control the performance of the produced susceptibility map, a comparison between the landslide susceptibility class zones on the map and the landslides was carried out. All the three major known landslides were located in the high and very high susceptible zones (Fig. 1). This could be an acceptable result for a medium-scale landslide susceptibility map, and the use of fuzzy gamma operation in the generation of the landslide susceptibility map seems to be a reliable approach.

This landslide susceptibility map can be used as a planning tool but would rather not be recommended for individual site specific evaluation. Areas within the high and very high susceptibility categories should require further study by engineering geologists before development to determine the extent of possibly unstable conditions.

Because the membership function approach has the nature of “fuzzy” rather than present-absent, or binary pattern, it may identify localities which previously have not been recognized by other methods, such as those based on known deposits. The fuzzy maps also have valuable data for other analysis methods, which apply some or all of the quantified factors. The fuzzy logic method is objective and repeatable, and can utilize varying reliability data, which commonly occur in geological descriptions.

Gamma values assigned for each gamma combination operation play the most important role on the output fuzzy membership functions. Owing to the constant value for gamma, the outputs are essentially based on the fuzzy membership functions assessed to factor maps classes. Gamma values > 0.94 moves the output fuzzy membership function values to high and very high landslide susceptibilities and eliminates the moderate susceptible zones. It is suggested to examine different values of gamma and evaluate the results based on the relationship between known landslides and the susceptibility zones.

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Table 1: Landslide susceptibility zonation on the basis of output fuzzy membership functions.

Zone	Fuzzy membership function	**Description**
I	<0.1	Non-susceptible zone
II	0.1-0.4	Low susceptible zone
III	0.4-0.6	Moderate susceptible zone
IV	0.6-0.75	High susceptible zone
V	>0.75	Very high susceptible zone