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A comparative study of fuzzy logic approach for landslide susceptibility mapping using GIS: An experience of Karaj dam basin in Iran

Maryam Ilanloo*

Islamic Azad University, Tehran, Iran

Abstract

Preparation of landslide susceptibility maps is important for engineering geologists and geomorphologists. However, due to complex nature of landslides, producing a reliable susceptibility map is not easy. For this reason, many procedures have been used to produce such maps .Among various models ، this paper discusses the effectiveness of fuzzy logic approach for landslide hazard mapping. In this study ، a new attempt is tried to produce landslide susceptibility map of Karaj Dam Basin in Iran. To obtain the fuzzy relations for producing the susceptibility map, a landslide inventory database is compiled by both field surveys and airphoto studies. The factor maps were input into a GIS and a modified landslide hazard evaluation factor (MLHEF) rating and fuzzy membership functions as well as belief function values were assessed for each class of the factor maps. According to this map, 10% of the study area is classified as very high susceptibility, 23% as high susceptibility, 38% as moderate susceptibility, 4.5% as low susceptibility and 0.5% as very low susceptibility or nonsusceptible areas .the results show that the fuzzy set theory can integrate effectively various spatial data for landslide hazard mapping, and it is expected that some suggestions in this study are helpful to further real applications including integration , and interpretation stages in order to obtain a decision – supporting layer .

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1. Introduction

In recent years, regional- and medium-scale landslide assessments have become an important topic of interest for specialists of different disciplines such as engineering geologists, planners, local administrations, decision makers, etc. This situation can be considered as a consequence of increasing in the interference of landslide occurrence with urbanisation, engineering activities and other socioeconomic activities in landslide

* Corresponding author. Tel. : +98-93-7484-0448; fax: 062-5235-7876.
E-mail address: maryamilanloo@yahoo.com.

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prone areas. Landslide cause extensive damage to property occasionally resulted in loss of life throughout most areas of country .so it is necessary to declineate the area that will be likely to be affected by the future landslides.

The assessment of landslide hazard and risk has recently become a topic of interest for both geoscientists and the local administrations (Carrara et al., 1991, [19], Parise, 2001, Krejci et al., 2002; Demoulin and Chung, 2007; Nefesliogluet al., 2008).Many techniques have been proposed in literature for landslide hazard mapping [13], Van Westen, 1993, Soeters and Van Westen, 1996). Van Westen et al. (1999) divided these techniquesinto two groups: 1- Direct hazard mapping, in which the degree of hazard is determined by the mapping geomorphologist, based on his experience and knowledge of the terrain condition; 2- Indirect hazard mapping, in which either statistical models or deterministic models are used to predict landslide prone areas ,based on information obtained from the interrelation between landscape factors and the landslide distribution. With the increasing availability of high-resolution spatial data sets, GIS, remotesensing, and computers with large and fast processing capacity, it is becoming possible to partially automate the landslide hazard and susceptibility mapping process and thus minimize fieldwork [17, Van Lynden and Mantel, 2001, Gritzner et al., 2001, Ayalew and Yamagishi, 2005; Guinau et al.,2005; Fallet al., 2006; [25], Yalcin, 2008). Quantitative prediction models for landslide hazard are based on a spatial database consisting of several layers of digital maps representing the casual factors for occurrence of landslides.

The purpose of the present study is to produce the landslide susceptibility map of a landslide prone area In the Karaj Dam basin area in Iran by using fuzzy relations. These functions representing the landslide hazard were termed favorability functions. this model is based on two basic assumptions: (1) future landslides will occur under circumstances similar to those 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) the spatial data representing the causal factors contained in the GIS database can be used to formulate future landslide. For this purpose, firstly, a detailed landslide inventory map of the study area is prepared by means of extensive field and air photography studies. Landslide conditioning parameter maps are prepared from Digital Elevation Model (DEM) and from existing thematic maps of the study area. Finally, landslide susceptibility map of the study area is produced, and performance of the produced map is discussed.

2. The study area

The study area is located at the Alborz Center Mountain which is known as one of the most landslide prone areas in Iran. Karaj Dam basin has an area of approximately 764km². A simplified geological map of the study area is shown in Fig. 1. Upper Cambrian sillty slate, sandstone, shale, minor dolomite Formation, are the oldest geological unit in the region and covers 49 km in the study area. Tertiary has a great extent in the region (600.7 km). Tertiary units are mainly composed of shale, tuff, and marl. There are also limestones and quartzites forming especially the steep slopes and higher elevations in the study area. The Tertiary is highly susceptible to landsliding due to weathering. Quaternary (alluvium) formations have a lower extent in the region (30 km).

The topography of the study area varies between 1676 and 4347 m, and the dominant range in elevation is 2200–3300 m. The higher elevations occur in the East. The drainage pattern is dendritic. The main stream is the Karaj River, which flows from North to the Southweast and is used for agricultural activities.There are also many subsidiary intermittent streams flowing .Most of the area (62%) is covered by pasture, 9% is utilized for agricultural activities and 3% for settlement purposes. Approximately 26% of the area contains rocky barren lands.annual precipitation of the area ranges 400–880 mm, and the mean annual temperature is between 5 and 13 ^{o}C.

In order to develop a method for the assessment of landslide susceptibility, determination of the conditioning factors for the landslides is crucial. The first step in every susceptibility assessment consists of collecting all available information and data for the study area and this stage may be the most important part of landslide hazard mitigation efforts.

Their liability and accuracy of the collected data also influence the success of the applied methodology. Furthermore, analysis of cause–effect relationships is not always simple, however, as a landslide is seldom linked to a single cause. Evaluating the relationship between the landslide occurrence and the conditioning parameters becomes very important for the landslide susceptibility mapping.

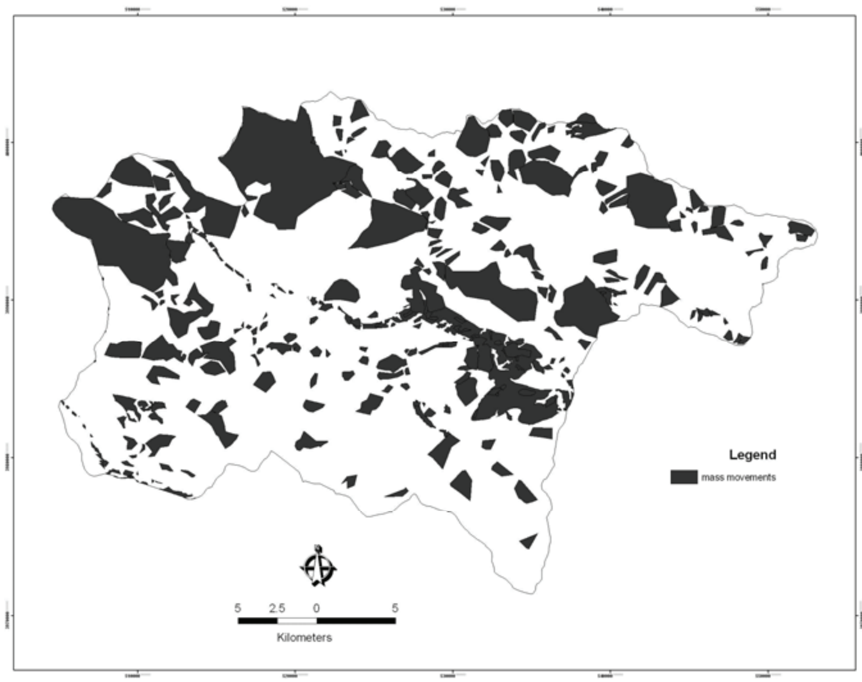

Fig. 1. Landslide inventory map of the study area

For a landslide susceptibility assessment, several spatial data layers (i.e., parameters) are necessary to evaluate the zones susceptible to sliding. When applying any model to landslide susceptibility evaluation, it is very important to define criteria controlling the degree of susceptibility. Although any parameter may be important with respect to the landslide occurrence for a region, the same parameters may not be important for another region. Hence, different parameters are used and ranked subjectively or objectively to produce a landslide susceptibility map.

Similarly to the most of the procedures for landslide susceptibility assessment, the methodology applied in this study is based on the well-known principle of ‘‘today and past are keys to the future’’.

Considering the characteristics of the existing landslides, to identif the possible areas of future landslides is the fundamental principle of landslide susceptibility mapping studies. For this reason, a detailed landslide Inventory map of the study area (Fig. 1) is prepared by means of 1:15,000-scaled airphoto interpretations and extensive field studies. The landslides determined from the airphotos were also checked and mapped during field studies with the aid of a Global Positioning System (GPS) apparatus having a 3- to 10-m accuracy.

Parameter maps that are used in the landslide susceptibility analyses can be divided into five groups such as geological, topographical, landuse, climatological and hydrological parameters.

The input data for test consist of several layers of map information (Table 1). The slope, aspect and altitude were calculated from the 1:50000 scale DEM. The lithology and fault maps were obtained 1:100000 scale geological map. After preprocessing, all data sets were built on a cell – based database.

The aerial photographs taken in 1958 and 2002 were used to detect landslide location, and the location was verified by fieldwork. In total, 421 Mass movements were mapped.

In this study, faults and folds in the study area are considered as the structural elements and the distances of 0, 100, 250,400 and 500 m to the faults and folds based on the study of Luzi and Pergalani (1999) are buffered and limited for 1 km. The other geological parameter used for the analyses is the relationship between discontinuities and slopes. The main reason for the utilization of this parameter is to investigate the areas susceptible to transportational or planar failure conditions which may occur along the contact surfaces between the regolith masses and the bedding planes in the shale unit. Then, the areas providing failure conditions are evaluated using both slope angle and the slope aspect maps of the study area, and assuming the internal friction angle (Ø) as 28j, equals the smallest major bedding dip value because translational or planar failure is kinematically possible, where Ø value is smaller than the dip values of major discontinuities and slopes. Different topographical parameters, such as slope angle, drainage network, slope aspect, etc., are widely acknowledged in the literature in different works.

In this study, slope angle (Fig. 2a), land cover (Fig. 2b), aspect slope (Fig. 2c) topographical elevation (Fig. 2d). And Annual precipitation.

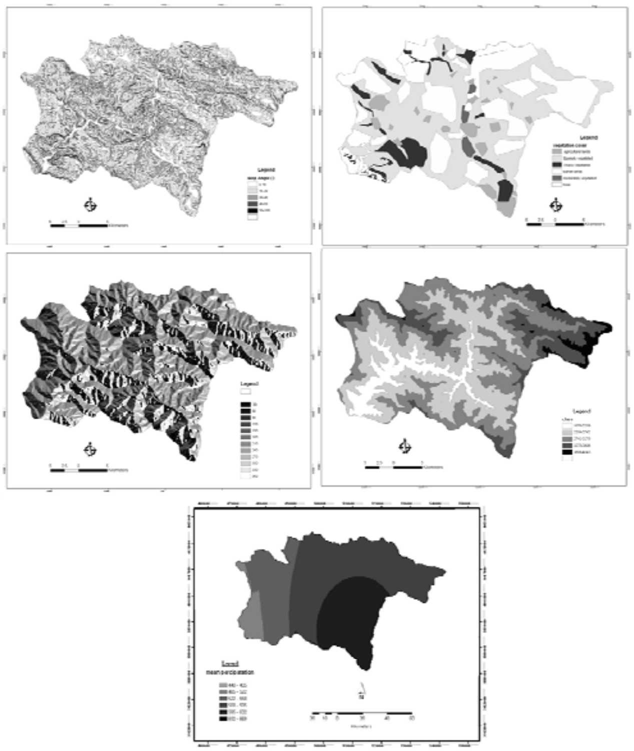

Fig. 2. Topographical parameter maps: (a) slope angle; (b) Land cover; (c) slope aspect; (d) topographical elevation. (e) Annual precipitation.

Parameters are considered as topographical parameters in the landslide susceptibility analyses and are prepared by using Surfer (Ver.7.0; 1999). Slope angle, topographical elevation, shape of slope and slope aspect maps are obtained from the DEM of the study area. Similarly, in the closeness to the faults and folds parameter, there is not a consensus on which distances can be considered for the distance to drainage network parameter. It should be noted that the same procedure cannot be applied to closeness to the faults and folds parameter due to the non spatial distribution of this parameter.

Before evaluating the buffering distances, the streams forming the drainage network are classified as three groups considering connection features of the streams such as main rivers, second- and third- or higher-order streams. There are one main rivers, namely Karaj, in the study area (see Fig 2b). The. To evaluate the buffering distances for main rivers, second- and third- or highe rorder streams, distances between the crest of the landslides related with the drainage network and the river or streams are measured. Taking the average values of these distances for each group, buffering distances are calculated as 165 m for the main rivers, 75 m for the second-order streams and 40 m for the third- or higher-order streams. Vegetation cover (VEC; Fig.3a) and main roads (MRO; Fig. 3b) are considered as the environmental parameters. The vegetation cover and main road maps are obtained from General Directorate of Forests and General Directorate of Rural Services Of Iran, respectively. These maps are converted to digital format by digitizing of existing maps. In addition to the main roads, there are also many secondary roads connecting the small villages to each other, but they are not considered in the analyses because it is very difficult to map them, and during their construction, road cuts are considerable shallow.

3. Methodology

The idea of fuzzy logic [23] 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. Working in GIS with map layers, 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.

Fuzzy logic is attractive because it is straightforward to understand and implement. It can be used with data from any measurement scale and the weighting of evidence is controlled by the expert. Fuzzy logic method allows for more flexible combinations of weighted maps, and can be readily implemented with a GIS modeling language. When using fuzzy logic in landslide susceptibility mapping the spatial objects on a map are considered as members of a set. For example, the spatial objects could be areas on an evidence map (map of causative factors for land sliding) and the set defined as ‘‘areas susceptible to landslide”. A variety of operators can be employed to combine the membership values when two or more maps with fuzzy membership functions for the same set are available. An et al. [5] discussed five operators, namely the fuzzy AND, fuzzy OR, fuzzy algebraic product, fuzzy algebraic sum and fuzzy gamma operator. This study uses the fuzzy algebraic sum, the fuzzy algebraic product, and fuzzy gamma operator for combining the fuzzy membership functions.

Photographs interpretation, and the field surveys as well. The generated evidence maps were processed and analyzed in ArcGIS, Arcview, and Idrsi software packages.

4. Evidence maps

The primary causal factors for landslide hazard mapping in the study area include altitude, slope angle, slope aspect, lithology, fault , plant cover ,road ,river , annual precipitation, produced from topographical data processing, satellite images and aerial data layers were geo-referenced in the Universal Transverse Mercator (UTM) geographic reference system.

In fuzzy model, the spatial objects on each map were evaluated according to the proposition ‘‘susceptible locations to land sliding”, and fuzzy membership functions were assigned to each map layer which was used as evidence in support of this proposition

The fuzzy membership values were chosen based on subjective judgment about the relative importance of the map classes. Anabalgan [2] proposed a numerical rating scheme based on an empirical approach for the landslide causative factors including geology, slope morphometry, relative relief, land use and land cover and groundwater conditions. He assigned the maximum rating of 2 or 1 for a variety of subcategories of each causative factor [2], (Table 2). Since most of the factors introduced by Anabalgan were inherently causative for slope instability at the area and because of the similarities of subcategories, a modified rating scheme was proposed for the study area.

Weighting rates based on the author’s knowledge were evaluated and assigned to factor map classes in a way that each class on the map had a value between 0 and 1 (Table 2).

The geological units were reclassified into five rock types due to their relationship to the landslide susceptibility; limestone, shaly-marly, congolomera, dolomite and the sandstone exposures. The Quaternary alluvial deposits cover the remaining AMIRKABIR catchment area. Ratings of rock types based on Anabalgan [2] were assigned to each class and the fuzzy membership functions were evaluated based on the expert knowledge.

Table 1. fuzzy membership functions assigned for factors classes

No	class	Fuzzy
Lithology	Limestone	0.7
	Shale-marl	1.0
	congolomera	0.6
	dolomite	0.5
	sandstone-tuff	0.4
Fault(m)	o- 100	1.0
	100-200	0.75
	250-400	0.5
	400-600	0.25
	600-1000	0
Slop angle (°)	0-15	0
	15-30	0.75
	30-40	1
	40-50	0.50
	50<	0.25
Slop aspect	North – facing	0.2
	South- facing	0.9
	East- facing	1
	West- facing	0.3
altitude	1600-2200	0.5
	2200-2700	0.6
	2700-3200	0.8
	3200-3800	1.0
	3800-4400	0.9
Land cover	Sparsely vegetated area	0.9
	moderately vegetated area	0.7
	Thickly vegetated area	0.2
	agricultural lands	0.5
	barren lands	1
Road	0-200	1.0
	200-400	0.8
	400-600	0.5
	600-800	0.1
	800<	0
river	0-100	1.0
	100-200	0.9
	200-400	0.6
	400-600	0.1
	600<	0
wells	530>	0.1
	530-620	0.4
	620-700	0.6
	700-800	0.8
	800<	1.0

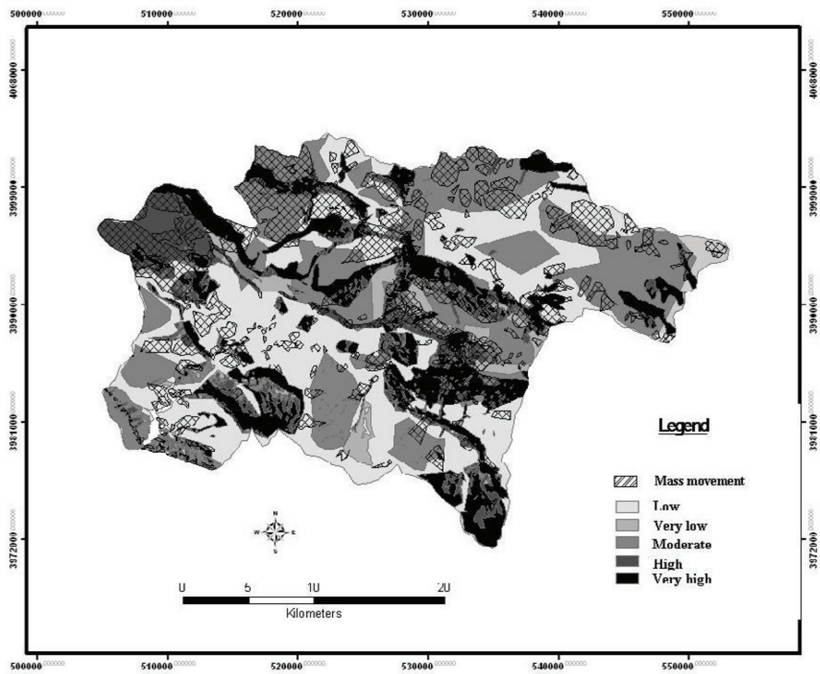

Fig. 3. Landslide hazard map generated by fuzzy gamma 0.98

The slope angle map was produced automatically in IDRISI using the digital elevation model (DEM) of topographical data at a scale of 1:50,000, with contour intervals of 100 m, and a30 m_ 30 m grid sizes. Anabalgan [2] introduces a subjective scheme for slope angle rating. The area has slope angles varying in the range 0_–70_. (Table 1) shows the slope angle classes and the fuzzy membership assigned to each map class. The slope aspect map for fore main slope directions was also produced from the DEM. In fact the slope aspect is mostly related to the physiographic trends and/or the receiving precipitation due to the prevailing winds [11]. It is observed that the south- and eastern-facing Slopes retain higher moisture content in a longer time, causing higher landslide susceptibility. The fuzzy membership for different slope directions was evaluated based on the fact that the northern- and western-facing aspects have an increase sliding susceptibility (Table 2). Land cover acts as a protection and reduces the susceptibility of soil erosion, landslides and the splash action of the rainwater.Aerial photographs and Landsat ETM+ data interpretation along with field observations were used to delineate the land cover types in the area. Five classes of land use were identified: sparsely vegetated area, moderately vegetated area , thickly vegetated area , agricultural lands, and barren lands, including rocky exposures, urban areas, and river bed , Although Anabalgan [2] assigns the highest rating to the barren lands, field observations at the study area showed that these areas were mostly the limestone units with low susceptibility to landslides. This leds to a modified fuzzy membership functions, which were evaluated on the basis of modified ratings.

5. Results and discussion

The input layers were processed after fuzzy membership was assigned for each map class. The rock and soil types were combined to generate the lithology factor map showing the same importance for the two evidences. Five primary causal factors including lithology, land cover, slope aspect, slope angle, and river of distance were integrated to generate the final output maps using fuzzy sum, product, and gamma operators as well.

The classification scheme suggested by Anabalgan [2] was used for landslide hazard zonation in the study area, based on the fuzzy model (Table 2).

Table 2. 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

The fuzzy sum, and product combination rules were run on 9 main causal factor maps, and each output layer was classified according to the intervals of 0.1 for membership function. The known landslides were then overlaid the landslide susceptibility maps to examine the degree of coincidence of susceptibility with land sliding. . According to this map, 12% of the study area is classified as very high susceptibility, 41% as high susceptibility, 42% as moderate susceptibility, 4.5% as low susceptibility and 0.5% as very low susceptibility or no susceptible areas.

One of the most important advantages of fuzzy gamma is the inexpensive fast application by combining few available information. Different scenarios can be examined by GIS operators, because of the flexible combination of input maps. The production of intermediate maps and the flexible integration of new data layers into the model allow testing effects on the final susceptibility map. Because of the membership function approach, areas susceptible to landslides have found, that previously have not been found using other methods (index overlay for example). The fuzzy logic method is subjective and depends on expert knowledge. Data of varying reliability was used in the analyses, however the relative weight of the input data can be controlled, and the importance of each condition can be assessed.

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