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Landslide susceptibility zonation using the fuzzy algebraic operators in GIS, Iran

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Abstract
The evaluation of land surface and its properties in order to identify and zone of natural hazard areas, especially landslide hazard, are subjected to researches of geomorphologists. The aim of this study was to investigate and zone of landslide susceptibility in Iran with respect to the factors affecting landslide, based on the theory of fuzzy logic approach and GIS containing thirteen information layers, including annual temperature, soil erosion, land use, slope, aspect, climate, elevation, distance from the streams, geology, annual precipitations, soil and distance from the fault and 4037 cases of landslide events occurred until 2007, in Iran. After analyzing landslides and the other layers, the effect of each twelve information layers (previously mentioned) was determined on landslide occurrence and the classification and fuzzification of layers were done based on the occurrence percent of landslides and also by expert studies in different classes, then fuzzy functions of SUM, PRODUCT & GAMA, AND, OR were used to prepare the final zoning map. In order to control the verification of the output susceptibility map, the landslide susceptibility class zones on the map and the known landslides were compared. Overlay of the known landslides with the landslide susceptibility map revealed that 0.9 GAMA has provided a better susceptibility zonation map; accordingly, 35.38% of the areas of the country are in the range of moderate susceptible zone and 33.09% in high susceptible zone.

Keywords: Landslide hazard, Fuzzy Logic, GIS, Landslide Susceptibility Zonation, Iran

1. Introduction
Hazard is a naturally occurring or human-induced process with the potential to create loss, (a potential threat to humans and their welfare). Risk is the actual exposure of something of human value to a hazard and is often measured as the product of probability and loss (the probability of a hazard occurring and creating loss)[1]. Landslide hazard refers to the probability of occurrence of landslides of a particular type and magnitude (volume and velocity) in a given location within a reference period of time. Landslide susceptibility refers to the tendency of an area to landslide occurrence. Briefly, it is defined as the probability of occurrence of landslides of a particular type in a given location. Susceptibility assessments commonly depict an important first step in hazard and risk assessment. Unfortunately, the terms susceptibility and hazard are often incorrectly used as synonyms, and therefore many so-called landslide hazard maps are actually susceptibility maps, as they do not consider the temporal dimension along with the spatial aspects in the evaluation of future landslide occurrence [2].

Susceptibility can be determined by a range of techniques, including geomorphic mapping, stability analysis, or even expert opinion. Several methods have been applied for landslide susceptibility zonation so far, which some of them are as follows: ANN (artificial neural network), AHP (analytic hierarchy process), FR (frequency response) and LR (logistic regression)[3]. The applied model in this study is based on fuzzy logic theory, which acts in uncertainty conditions and analyzes imprecise and somewhat vague variables mathematically and seems appropriate for phenomena such as landslide affected by several factors with probability and uncertain properties.

Some studies carried out on landslide zoning by fuzzy method are as follows:

Xie et al. 2004[4]; Tangestani 2004[5]; Sezer et al. 2011[6]; Schernthanner 2007[7]; Saboya et al. 2006[8]; Pradhan et al. 2009[9]; Pradhan 2011a[10]; Pradhan 2010[11]; Pradhan 2011b[12]; Pourghasemi et al. 2012[13]Pistocchi et al. 2002[14] Lee and Choi 2003[15] Lee 2007[16] Lee and Juang 1993[17]Juang and Huang 1996[18]; Gorsevski et al. 2006[19]; Gomez and Kavzoglu 2005[20]; Gemitzi and Falalakis 2011[21]; Ercanoglu and Gokceoglu 2004[22]; Ercanoglu and Gokceoglu 2002[23]; Chi et al. 2002[24]; Catani et al. 2005[25].

2. Materials and methods

2.1. Study Area

Iran is generally prone to a wide range of landslide hazards due to natural conditions such as mountainous topography, tectonic activity and high seismicity, various geographical and climatic conditions. Landslide as a natural disaster in Iran creates huge life and economic losses. Based on the information of landslide database for Iran, about 4584 landslides have been recorded by the end of 2007 and two tectonic belts of Zagros and Alborz have the greatest records for landslides (Figure 1) (National Geoscience Database of Iran website archive: http://www.ngdir.ir) [26].

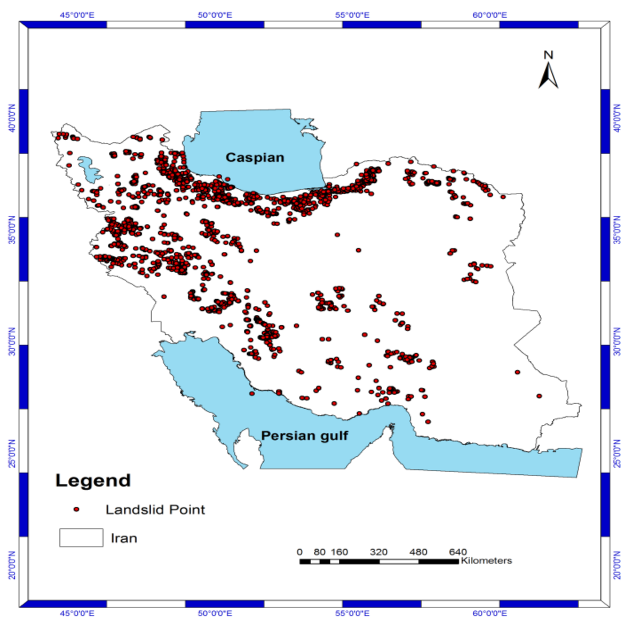


Fig 1: Landslides recorded in Iran

In this study, the data contains isothermal lines, isohyets, land use, climate, soil, erosion classes and distance from streams taken from the Forests, Range and Watershed Management Organization website archive (http://frw.org.ir/00/En) [27]. The data contains geology, fault map and landslides layer include 4584 cases (recorded by the end of 2007) taken from National Geoscience Database of Iran website archive (http://www.ngdir.ir) [26]. A digital elevation model (DEM) with a resolution of 9 m (ASTER global DEM: http://gdex.cr.usgs.gov/gdex)[28] was applied for preparing the digital maps of elevation, slope and aspect. This review contains 12 layers including: isothermal lines, isohyets, land use, climate, soil, geology, elevation classes, slope, aspect, distance from the fault, erosion classes and distance from streams. After the investigation of the frequency of landslide occurrence in each layer by raster analysis approach (Figure 2). Then each layer was valuated based on the occurrence percent of landslides and also by expert studies in different classes, then they fuzzified by membership function of (membership type) in GIS and finally, Landslide Susceptibility Zoning was done in Iran by applying of different fuzzy functions.

2.2. Fuzzy logic and Geographical Information System (GIS)

The theory of fuzzy logic as a mathematical theory for mathematical modeling can perform in uncertainty conditions and at the first time was introduced by Dr. Lotfi Zadeh in 1965 [29]. In fact, the fuzzy method is understandable for wide range of subjective, objective and quantitative information. In fuzzy model, each member is membership in different sets, but the membership degree is different. If we consider the set of A, if a member belongs to this set we will give number (1) and if not, we will attribute number (0) to it (equation 1).

$$\mu_A(X) = \begin{cases} 1 & IF \quad X \in A \\ 0 & IF \quad X \notin A \end{cases} \qquad (1)$$

Fuzzy technique is performed by functions such as OR, AND, SUM, Product and Gamma [30] briefly discussed below:

A) OR function: this function is the union of sets and extracts the maximum membership degree of the members and has no high accuracy in location. The fuzzy or is like the Boolean OR (logical union) in that the output membership values are controlled by the maximum values of any of the input maps. The fuzzy or is defined as:

$$\boldsymbol{\mu_{combination} = MAX(\mu_A \mu_B \mu_C \ldots)} \qquad (\mathbf{2})$$

B) AND function: is the interception of the sets and extracts the minimum membership degree, meaning minimum weight or value of each pixel among all the informational layers; in other word, only the pixel which has a value equal to 1 in all base maps would have a value equal to 1 in the final map. It is defined as:

$$\boldsymbol{\mu_{combination} = MIN(\mu_A \mu_B \mu_C \ldots)} \qquad (\mathbf{3})$$

where $\boldsymbol{\mu_{combination}}$ is the calculated fuzzy membership function, $\boldsymbol{\mu_A}$ is the membership value for map A at a particular location and $\boldsymbol{\mu_B}$ is the value for map B, and so on.

C) Fuzzy algebraic product function: all information layers are multiplied in each other and due to being between 0 and 1 of fuzzy, the numbers became smaller and close to 0 in the output map. The fuzzy algebraic product is defined as:

$$\boldsymbol{\mu_{combination} = \prod_{i=1}^{n} \mu_i} \qquad (\mathbf{4})$$

where $\boldsymbol{\mu_I}$ is the fuzzy membership function for the i-th map, and i=1, 2, …, n maps are to be combined

D) Fuzzy algebraic sum function: is considered as the multiply complement of the set complement, due to this reason in contrary to fuzzy algebraic product, the value of pixels close to 1 and due to this reason, this function has a much lower susceptibility in location [9].

The fuzzy algebraic sum is defined as:

$$\boldsymbol{\mu_{combination} = 1 - \prod_{i=1}^{n} (1 - \mu_i)} \qquad (\mathbf{5})$$

E) Fuzzy gamma function: has balancing role as compared with fuzzy product and sum functions and it balances the high susceptibility of fuzzy product and the low susceptibility of fuzzy sum, indeed closer to reality. The gamma equal to 0 is equivalent to fuzzy product and the gamma equal to 1 is equivalent to fuzzy sum. The gamma operation is defined in terms of the fuzzy algebraic product and the fuzzy algebraic sum by:

$$\boldsymbol{\mu_{combination}} = (\boldsymbol{Fuzzy\ algebraic\ sum})^{\boldsymbol{\lambda}} * (\boldsymbol{Fuzzy\ algebraic\ product})^{\boldsymbol{1-\lambda}} \quad (\boldsymbol{6})$$

Where λ is a parameter chosen in the range (0, 1)

2.3. Determination of fuzzy membership function

Membership functions of fuzzy method are presented in various forms in Arc Map software that concerning the relation of studied variables in this research, the used layers in landslide model were firstly reclassified with respect to the frequency of landslide occurrence, effectiveness percent and decreasing or increasing effect and then became fuzzy with linear function, these layers are including: annual temperature, soil erosion, land use, slope, aspect, climate, elevation classes, distance from the streams, geology, annual precipitation, soil and distance from the fault.

The fuzzy maps of considered layers have been shown in Figure 3. The landslide susceptibility map was prepared using the introduced functions. Concerning gamma function, since considered values create some results for gamma in the output, so it is consistent with increasing effect of algebraic sum and decreasing effect of algebraic product, therefore different values of gamma should be tested in choosing its value to enhance the accuracy of the created map. In this study, gamma was tested in two values of 0.9 and 0.7. The frequency of landslides occurrence in each class of landslide susceptibility zoning was investigated to evaluate the accuracy of the model and choosing the best zoning map and the best zoning map was identified; accordingly the area percent graph was calculated in each landslide susceptibility class.

3. Results and discussion

Evaluation of landslides percentage in each layer shows that areas with annual precipitation of 500-650 mm and annual temperature of 10-15^{o}C have the higher percentage of landslide occurrence. Also wet lithosol soils are the susceptible type for landslides due to having fine particles and discontinuity. The investigation of erosion classes indicates that seventh class of erosion has the highest landslide and definitely in higher classes of erosion landslides would not happen due to lack of soil. Geological formations have the highest percentage of landslide occurrence in the country, four priorities are including:

1- Low level piedmont fan and valley terrace deposits

2- Marl, calcareous sandstone, sandy limestone and minor conglomerate

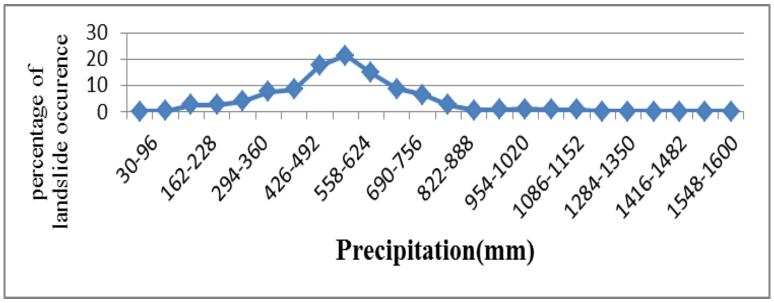
3- Dark grey shale and sandstone (SHEMSHAK FM.)

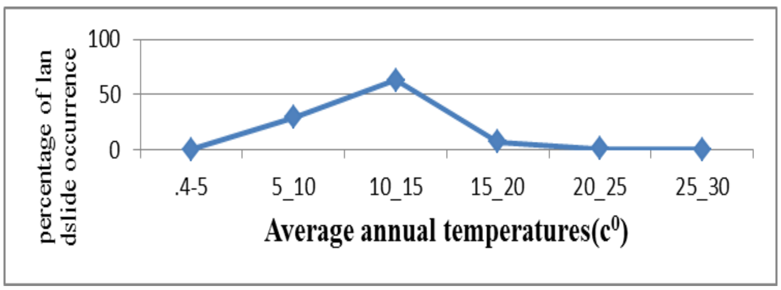
4-Undivided Bangestan Group, mainly limestone and shale, Albian to Companian, comprising the following formations: Kazhdumi, Sarvak, Surgah and Ilam

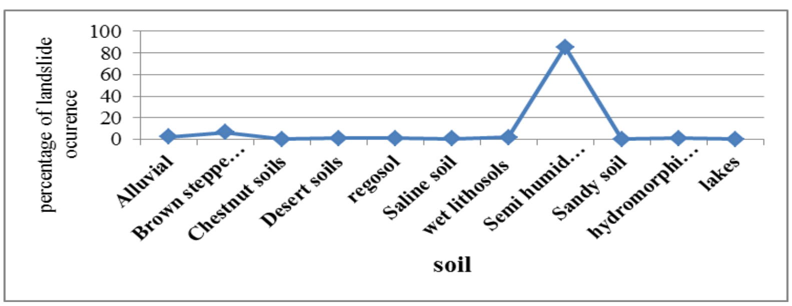
The study of slope layer shows that the highest percentage of landslides occurrence had been in class of 10 to 20 percent and had a decreasing trend in higher percentages. Also the study of aspect layer demonstrates that orientations of South, West South and East North have the highest percentage of landslide occurrence, because South and West South hillsides are prone to landslide occurrence due to receiving more humidity. Also in East North hillsides, the differences in receiving daily heat is higher and weathering activities are more active, because humidity and weathering are as main factors in landslide occurrence. The study of landslide occurrence as compared to distance from the fault and distance from the streams specifies that landslide occurrence had a decreasing trend by distancing from the streams and the fault.

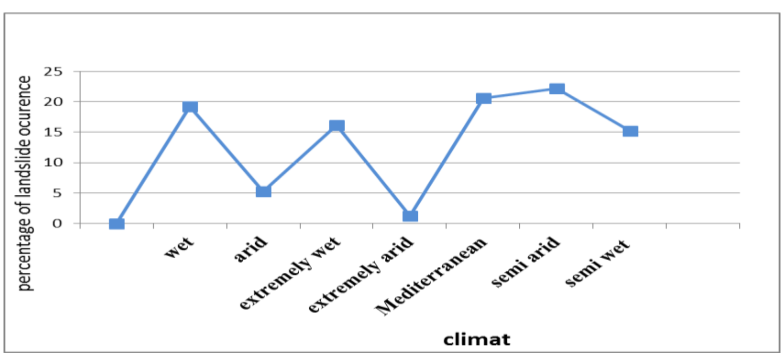
In a similar study, Tangestani [5] used the fuzzy method for landslide susceptibility zonation in the southwestern region of Iran, and the results showed that landslide zones coincides with the Zagros folded belt in the region. Geological formations present in the region include limestone, shale and marl, and most landslides have occurred on slopes of between 15-25% with the north and west aspects, the elevation class of 2400- 2600 meters, and in areas with good vegetation and forest cover. Also, landslide occurrence showed a decreasing trend with the increase of distance from streams and faults. In another research carried out by Pourghasemi et al. [31] using fuzzy and AHP method in northern parts of Iran, it was found that landslide occurrence zones coincide with the

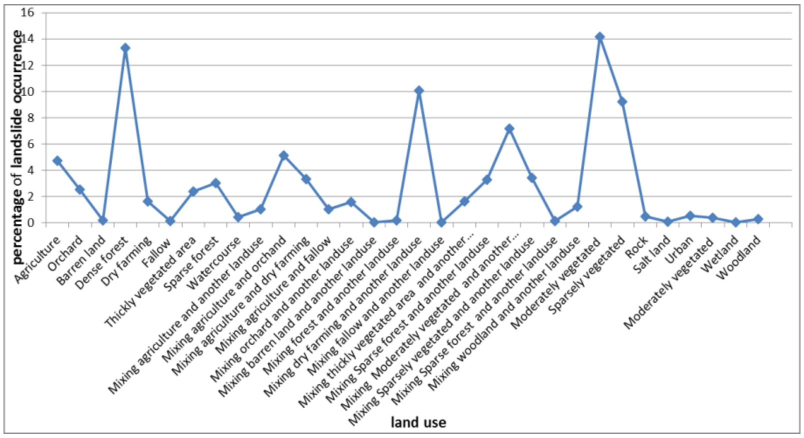
Alborz mountain belt in northern Iran, and in terms of lithologic features, they coincide with old and new terraces and volcanic rocks. Also, the most landslides have occurred in the elevation class of 1500 -1800 meters and on slopes of 30 to 50° with aspects of northeast, southeast and southwest, and with moderate to good vegetation cover. The results obtained from both investigations in the Alborz and Zagros mountain belt confirm the main results of the present research. Overall, landslides occur mostly in young mountains with neo-tectonic activities and along active faults. Tectonic activity can be a direct cause of slope movements in the case of regional tilting or uplift; also, Tectonic activity can increase the slope gradient.

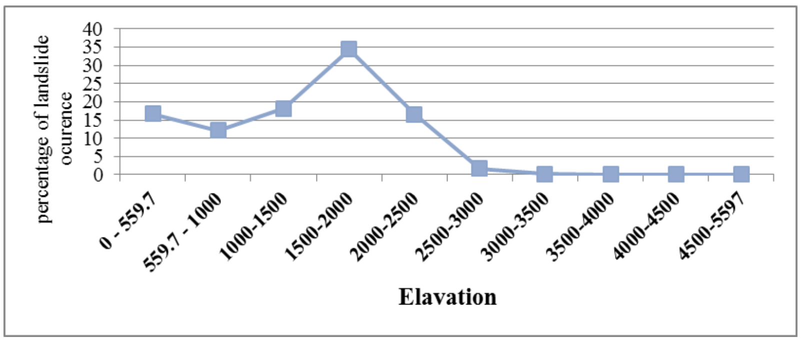


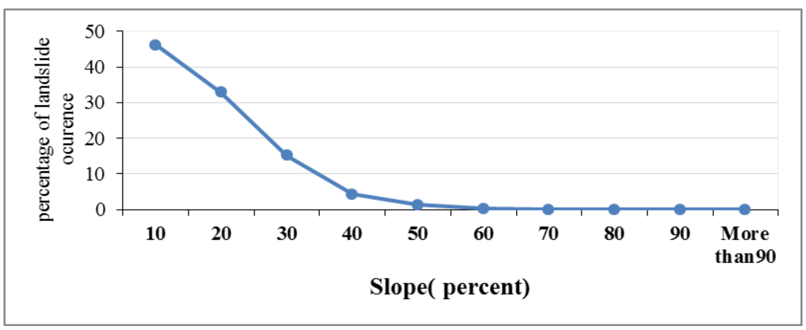


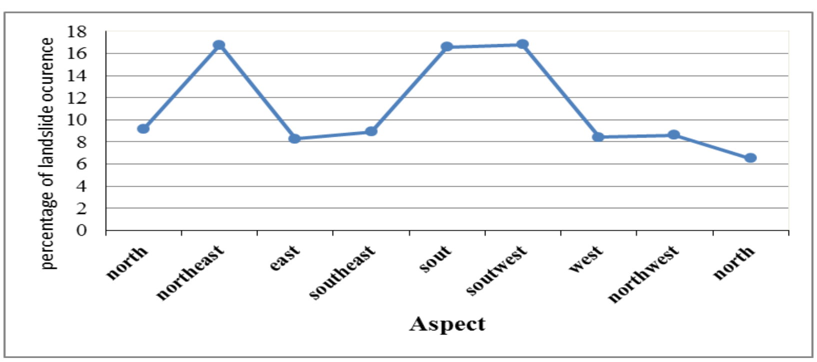





percentage of landslide occurrence
16
14
12
10
8
6
4
2
0
Agriculture
Orchard
Barren land
Dense forest
Dry farming
Fallow
Thickly vegetated area
Sparse forest
Watercourse
Mixing agriculture and another landuse
Mixing agriculture and orchand
Mixing agriculture and dry farming
Mixing agriculture and fallow
Mixing orchard and another landuse
Mixing barren land and another landuse
Mixing forest and another landuse
Mixing dry farming and another landuse
Mixing fallow and another landuse
Mixing thickly vegetated area and another...
Mixing Sparse forest and another landuse
Mixing Moderately vegetated and another...
Mixing Sparsely vegetated and another landuse
Mixing Sparse forest and another landuse
Mixing woodland and another landuse
Moderately vegetated
Sparsely vegetated
Rock
Salt land
Urban
Moderately vegetated
Wetland
Woodland
land use


percentage of landslide ocurence
40
35
30
25
20
15
10
5
0
0 - 559.7
559.7 - 1000
1000-1500
1500-2000
2000-2500
2500-3000
3000-3500
3500-4000
4000-4500
4500-5597
Elavation


percentage of landslide ocurence
50
40
30
20
10
0
10
20
30
40
50
60
70
80
90
More than90
Slope(percent)


percentage of landslide ocurence
18
16
14
12
10
8
6
4
2
0
north
northeast
east
southeast
sout
soutwest
west
northwest
north
Aspect

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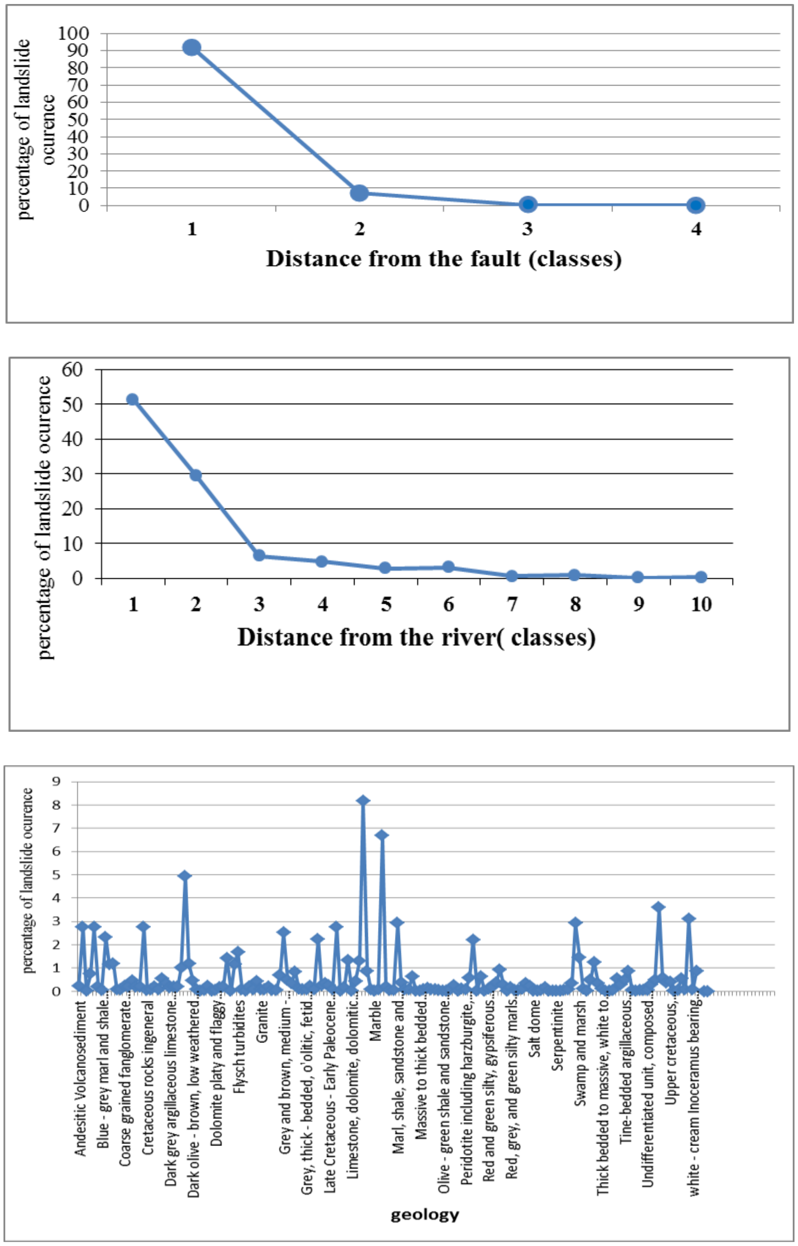

Fig 2: The percentage frequency of landslide occurrence in each studied layers

Other factors that may affect the probability of landslide occurrence include the type of soil material, slope, climate and vegetation cover. Important material characteristics include mineral composition, degree of cementation or consolidation, the presence of zones of weakness. In arid and semiarid climates, vegetation tends to be sparse, soils are thin, and bare rock is exposed [32]. In such conditions, slopes are subject to extreme mechanical weathering, which leads to formation of fine-grain and unconsolidated materials on the slopes. Most mountain slopes in Iran have various alluvial fans with surfaces covered with week and unconsolidated materials as the results of intense weathering and erosion; Furthermore, the steep slopes intensify instability. Some materials of alluvial fans such as clays have blended with soluble cements that can be dissolved during heavy rainfalls and leave unconsolidated materials. Also, Weak zones can be especially hazardous if the weakness zone intersects or parallels the slope of a mountain.

Another important factor is the vegetation cover. Vegetation allows the water to infiltrate the slope while plant roots increase the resistance of a slope; also, vegetation adds weight to a slope. In the results of this study, most landslides have occurred in areas with moderate to good vegetation cover. Thus, this factor seems to add an extra weight to the slopes, which in combination with other factors, has a negative effect on the occurrence of landslides in Iran. Investigation of slope factor indicates that in general, slopes of 15-30% are critical, as in higher slopes the insufficient thickness of soil leads to lower frequently of landslides. In addition, in presence of unconsolidated geological formations under integrated limestone strata, landslides have occurred in limestone outcrops at higher elevations.

After classifying the layers based on landslide occurrence and expert studies, fuzzy maps of the layers was prepared in GIS and with linear membership function presented in Figure 3.

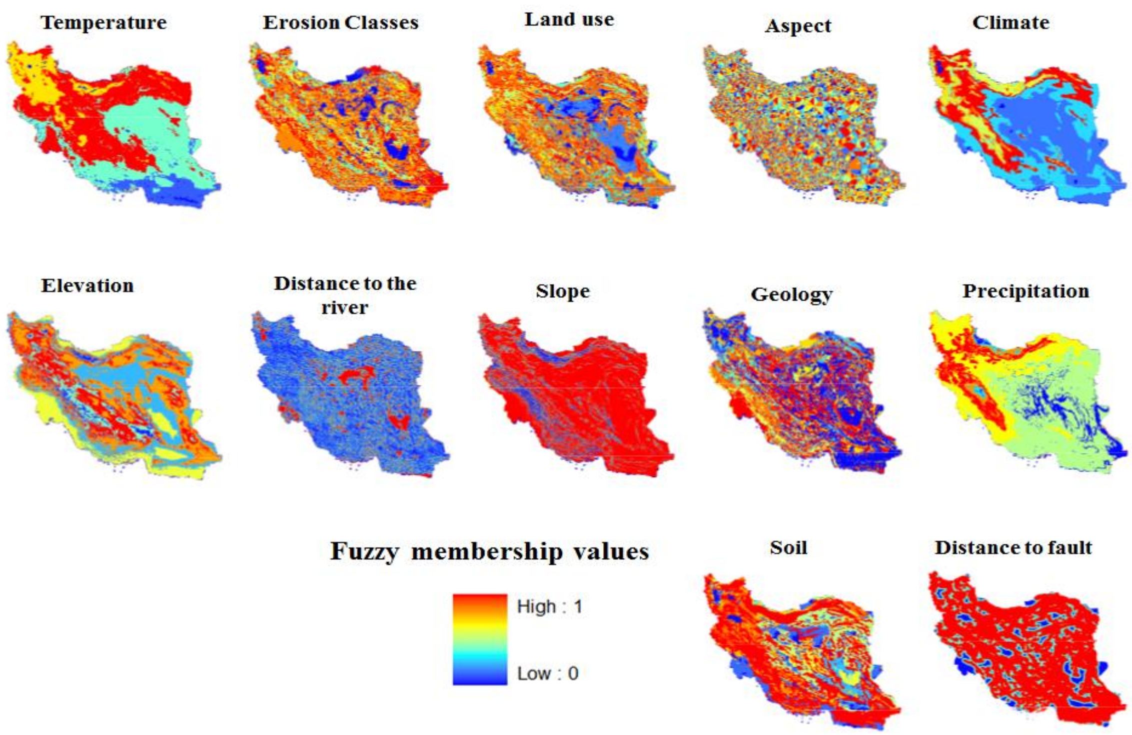

Fig 3: Map of fuzzy layers

Fuzzy maps of zoning based on 5 introduced functions in Figure 4 show that two functions of SUM and OR have classified the entire zone in low susceptibility class and are not appropriate to analyze and also two functions of (AND) and (PRODUCT) have not appropriate classification. It seems that GAMMA function has provided more appropriate results in the fuzzy method. The percentage frequency of landslides occurrence in different susceptibility zones were compared to test the accuracy of the results. The results of this comparison are presented in Table 1 and shows that Gamma of 0.9 has provided better results in zoning, so that in the average and high susceptibility zones the frequency of landslides has been 33.57 and 52.35 percent, respectively. Figures 5 and 6 present the graph and map related to the percentage of landslide occurrence based on gamma of 0.9, we can conclude that 33.9 percent of Iran is exposure to high susceptibility and 35.38 percent is exposure to medium susceptibility of landslide occurrence. Also the map of zoning shows that two mountainous belts of Zagros and Alborz have high to very high susceptibility zones, this matter indicates that tectonic has an effective role in the occurrence of landslides in Iran.

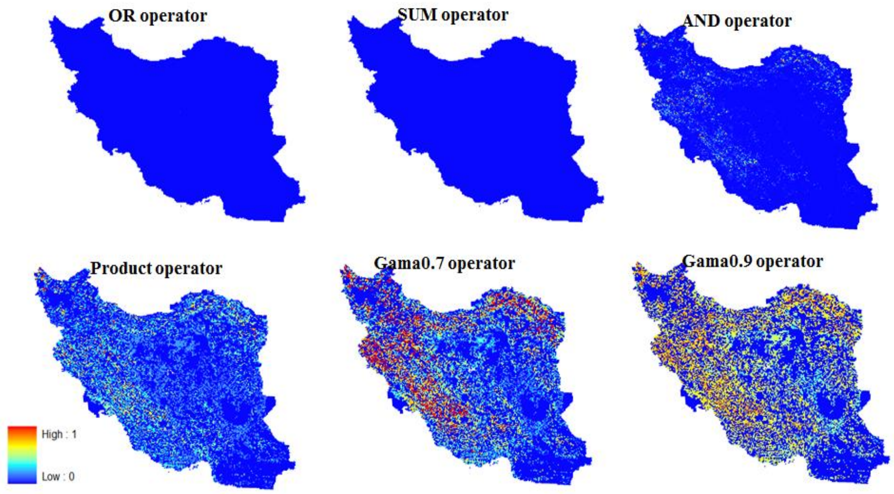

Fig 4: Fuzzy maps of zoning based on five functions

Table 1: The frequency of landslides occurrence in each level of Landslide susceptibility based on four functions

Susceptibility	AND Operator	Product Operator	Gama0.7	Gama0.9
Very Low	79.56034	98.36181	17.86635	7.771777
Low	10.00935	1.263749	19.60141	0.093919
Moderate	9.354537	0.234028	36.76436	33.57596
High	0.912067	0	25.48652	52.35971
Very High	0.163704	0.140417	0.28136	6.198638

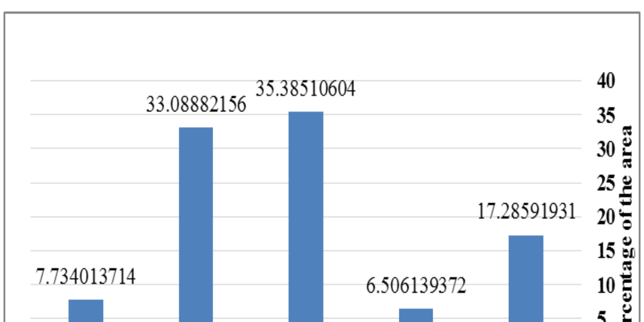

Fig 5: percentage of the area in each levels of Landslide susceptibility zonation based on 0.9 gamma function

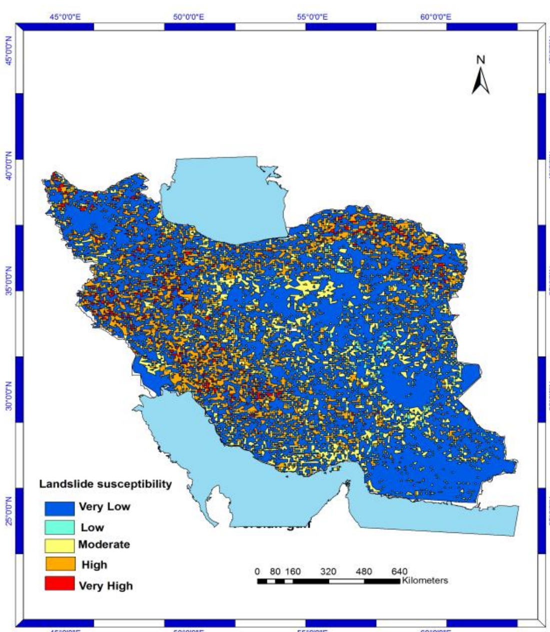

Fig 6: Landslide susceptibility zoning based on 0.9 gamma function

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Conclusions

The investigation of the results of fuzzy method for landslide susceptibility zoning in Iran based on 12 variables affecting landslides shows that applying of gamma function prepared better results in zoning rather than other functions. Accordingly, 35.38 percent of Iran is located in the range of average susceptibility and 33.09 percent in the range of high susceptibility. Also study of landslides occurrence in slope layers and elevation demonstrate that the highest percentage of landslide occurrence occurs in elevation range of 1500 to 2000 m and in the slope range of 20 percent where is the hillside of mountainous areas. Since Iran is a country with mountainous topography and the greatest habitats are located in hillsides and alluvial fans, the need for effective measures to identify susceptibility areas and planning to reduce landslide hazard is more evident.

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