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Landslide susceptibility mapping by using fuzzy logic: a case study of Cham-gardalan catchment, Ilam, Iran

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Abstract Landslides are introduced as regional movements, which influence different engineering structures such as roads, railways, and dams and cause the person's death. Identification of landslide zones may decrease the financial losses and human injuries or deaths. This study tries to achieve a landslide susceptibility mapping in Cham-gardalan catchment by weighting the main criteria and the membership functions of fuzzy logic. For this, we applied the best relationship function between the presence and absence of landslides as well as a collection of the elements. At first, the landslide points were identified by the means of some components those of satellite images, topographical (1:50,000) and geographical (1:100,000) maps, field visits, and Google Earth software followed by the preparation of landslide distribution maps. Then, all effective landslide factors such as percentage of slope, slope aspect, height, geology, land uses, distance from roads, distance from drainages, distance from breakage, and precipitation map have been utilized in order to conduct the fuzzy analyses. Landslide susceptibility map was performed by fuzzy operators (Gamma, Product, Sum, Or, And) in the study area. After fuzzificating and weighting, the effective criteria of landslides were determined through fuzzy Gamma operators with the landaus of 0.2, 0.5, 0.8, and 0.9 and by comparing final maps for making an appropriate model of landslide susceptibility mapping. The regional susceptibility map represents the landslide-prone areas in five categories those of very low, low, moderate, high, and very high. Our results indicated that among the applied operators, Gamma with landau of 0.9 can be used as an appropriate method for mapping the landslide susceptibility due to the suitable fuzzification of given criteria based on landslide distribution maps. In addition, the elements of road, percentage of slope, distance from drainage, and geology were recognized as the most important factors for occurring the landslides.

Keywords Fuzzy operators · Membership function · Geographic information systems · Fuzzificating · Weighting

Introduction

The impacts of natural disasters on the socio-economic statues were resulted in considerable financial and environmental damages worldwide every year. Landslides are regarded as the specific types of natural disasters and range processes resulting from geomorphologic, hydrological, and geological conditions (Karam 2001). These conditions along with the geodynamical processes, vegetation, land use, human activities, rainfall rate and intensity, and earthquake create this phenomenon (Sefidgari 2002). Although the economic damages of landslides have been significant in the developed country, these damages constitute almost 1 or 2 % of their gross domestic product (GDP) according to the studies done by Reflifeco-Ordinary United Nation Disaster (Hansen 1984). The financial damages were calculated about 500 billion annually due to the landslides in Iran (Komak Panah and Farhangfar 1994). Studying the range instabilities like most of geo-environmental issues is very complicated because of the variety of effective factors. Uncertainties resulting from

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Fig. 1 Location of the study area
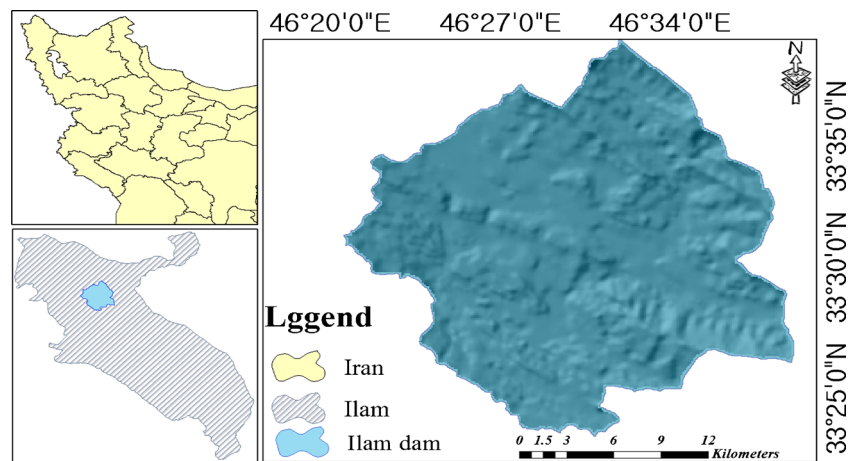
the ambiguities of conditions and concepts related to the parameters such as geology, hydrology, tectonics, vegetation, precipitation, and erosion necessitate the application of suitable and accurate method in order to examine the regional instabilities but most of the above information may be unwritten so that they are not exact and valid. Such limitations are the main bases for the fuzzy theory (Fatemi et al. 2005). The fuzzy theory was introduced by Lotfizadeh in 1965 in his essay entitled "Fuzzy Collections" in Information and Control Journal (Tanka 2004). The fuzzy theory includes all of the theories, which apply the fundamental concepts of fuzzy collections or membership functions which the aim is to present a new method to express the daily uncertainties and ambiguities (Ashghali Farahani 2004). Considering that lots of methods are developing based on this theory, it is possible to formulate the indefinite, ambiguous, and undetermined reasoning of human mind mathematically by providing new methods concerning the concepts of fuzzy collection assumptions (Shariat Jafari 2008). Fuzzy models applied to the studies to solve the problems of the earth sciences, especially the landslide hazards, are limited involving the studies of Mahdavifar in Khorsh Rustam region in the southwest of Khalkhal for zoning the landslide-prone areas (Mahadvifar 1997). In this research, this region was divided into 5071 units of 500 m by the help of a regular system; afterwards, the required units were examined with respect to various landslide elements such as geology, percentage of slope, land-use types, distance from the fault, and landslide deposits.

Results show that using fuzzy collections removes the limitations of quantitative methods because of taking the possibilities into consideration instead of numbers and analyzes the roles of natural events more accurately as compared to the other quantitative methods. Fatemi Aghda et al. (2005) investigated the landslide hazards using fuzzy logic in Roodbar, Gilan. In this paper, information layers of slopes, lithology, and distance from fault, current land uses, rainfall, and maximum earthquake acceleration are regarded as the effective parameters of regional instabilities. Zoning the landslide hazards was done by fuzzy multivariable decision-making method and both experimental and theoretical weighing ones. Furthermore, hazard rating was computed through two triangle and trapezoid fuzzification functions. As well, analytical hierarchical process (AHP) has been introduced as a suitable method for mapping landslide (Jamali 2009).

In the last decades, the considerable increase of mass movements, particularly landslides, has been observed. In our study area, different mass movement forms such as landslip exist in most of the watershed areas, especially in the road across the dam. This region is one of the recreation areas within the city because of the lake and beautiful nature. Forest park construction plan is implemented there while constituting the most important source of drinking water of Ilam and the surrounding villages; therefore, it is necessary to provide the map of mass movements and also to investigate the effective factors regarding this fact that it is located on the sensitive and loose geological structures. This study aims to (a) recognize the most important factors on the landslides, (b) present the regional model by using the decision making techniques of the model of fuzzy logic, (c) classify and prioritize the effective elements to predict the sensitive regions and find the suitable solutions, and (d) provide the maps of landslide susceptibility.

Table 1   Weight of the effective landslide factors in the region using the AHP method of the expert judgment

Element	Road	Slope aspect	River	Geology	Land use	Precipitation	Fault	Percentage of slope	Elevation
Weight	0.271	0.239	0.157	0.127	0.072	0.035	0.034	0.030	0.030

Table 2 Fuzzy membership functions types (Klir and Yuan 1995; Liu et al. 2010; Yager and Zadeh 2012)

Function type	Function definition
Gaussian	This function defines the membership function with regard to the normal or Gaussian distribution and a midpoint (the fuzzy membership of midpoint is 1)
Small	It is used when the small amounts in the map have a membership close to 1. It is based on a midpoint defined by the user (the membership of midpoint is 0.5)
Large	It is used when the large amounts in the map are close to 1. This function is defined concerning the midpoint by the user (the membership of midpoint is 0.5)
Near	It specifies the function according to the specific amounts defined by a midpoint by a special user (the midpoint membership is 1)
MS-small	This function defines fuzzy membership function based on the mean and standard deviation. Smaller amounts are of the membership near to 1
MS-large	This function defines fuzzy membership function based on the mean and standard deviation. Larger amounts are of the membership near to 1
Liner	It defines fuzzy membership function based on the maximum and minimum fuzzy memberships of 1 and 0

Study area and data analysis

Cham-gardlan catchment is located in the southeast of Ilam province in western Iran (32° 45′ 48″ to 33° 7′ 20″ N and 47° 6′ 13″ to 47° 32′ 55″ E), with an area of 476.5 km^2 (Fig. 1). The region is a mountainous area which the highest elevation is about 2400 m in the north of the region (Ghalarang Mountain), and the altitude at the drainage point is 640 m in the southwest of the catchment.

Data description

Identifying the effective factors of landslide is the most important stage of its susceptibility mapping. For mapping landslide susceptibility, we used a number of datasets those of elevation, percentage of slope, slope aspect, distance from fault, geographical units, distance from river as well as roads, land uses, and precipitation. The layers of elevation, percentage of slope, and slope aspect were created from a high-resolution digital elevation model (DEM). As well, the geological information, e.g., distance from fault and geographical units, were obtained from the geological map at 1:100,000 scale which was provided by the Geological Survey and Mineral Explorations of Iran (GSI). We also applied 20-year meteorological information for preparing the precipitation layer. In addition, the Landsat ETM+ (2007) satellite image was used for creating the land-use

map. Distances from both river and road were produced by a 1:50,000 scale topographic map by the National Cartographic Center of Iran.

Weighting factors and criteria

The generated landslide mapping was based on the comparisons of the previous landslide map, and the effective landslide factors map where the first step was to provide the distribution map of previous landslides. Therefore, the potential landslide areas and previous landslides were recognized by aerial photography (1:50,000). Most of the landslides cannot be distinguished in the images due to the small dimensions and similarity to the adjacent areas. Thus, 64 landslide points were sampled for collecting the collect the required information in the field. Then, all layers were converted to mapping landslides by using satellite imagery and Google Earth software. Combining the distribution map and the measured factors gives the number of pickles in every layer. For fuzzification of criteria, the fuzzy membership functions have been utilized (Table 1). These functions were applied as the basis of midpoint and spread parameters. Fuzzification function has been selected with regard to each factor's nature, importance, and relation with the target one. Because the application of the fuzzy logic model is based on the network analyses, therefore, each pixel has to get the membership value from 0 to 1 regarding the ideal function. After providing all the layers, which influence the landslides in the given region and fuzzificating

Table 3 Fuzzy membership function types of the landslide elements

Parameter	Slope aspect	Land use	Fault	Road	River	Precipitation	Percentage of slope	Elevation	Geology
Applied function type	Gaussian	Gaussian	Small	Small	Small	Large	Large	Large	Large

them, they are weighed by the expert judgment with respect for their importance and effects.

The highest weight belongs to the layers which play the most important roles in the landslides (LLC. 1998). After choosing the weight of layers, it is multiplied by the layers in raster calculate and the special analysis; as a result, the overlapping maps will be ready.

Fuzzy operators

Different fuzzy operators in the below were used for mapping landslide susceptibility (Wang 1999); those are including algebraic operators (AND, OR, Product, and SUM) and Gamma operator.

1. Fuzzy intersection or AND operator

It uses the minimum function for the overlaying, and it corresponds to the intersection defined as follows:

$$\mu_{Combinatia} = \text{MIN}(\mu_A, \mu_B, \mu_c, \dots) \tag{1}$$

In Eq. 1, μ_A, μ_B, μ_c show the fuzzy membership values of existing pixels in the specific situations on the maps of different factors. The operator of "AND" should be used for the dependent parameters and some evidences that are necessary to approve the hypothesis.

2. Fuzzy union or OR operator

This operator uses the maximum function and corresponds to the union which is defined by Eq. 2.

$$\mu_{Combinatian} = \text{MAX}(\mu_A, \mu_B, \mu_c, \dots) \tag{2}$$

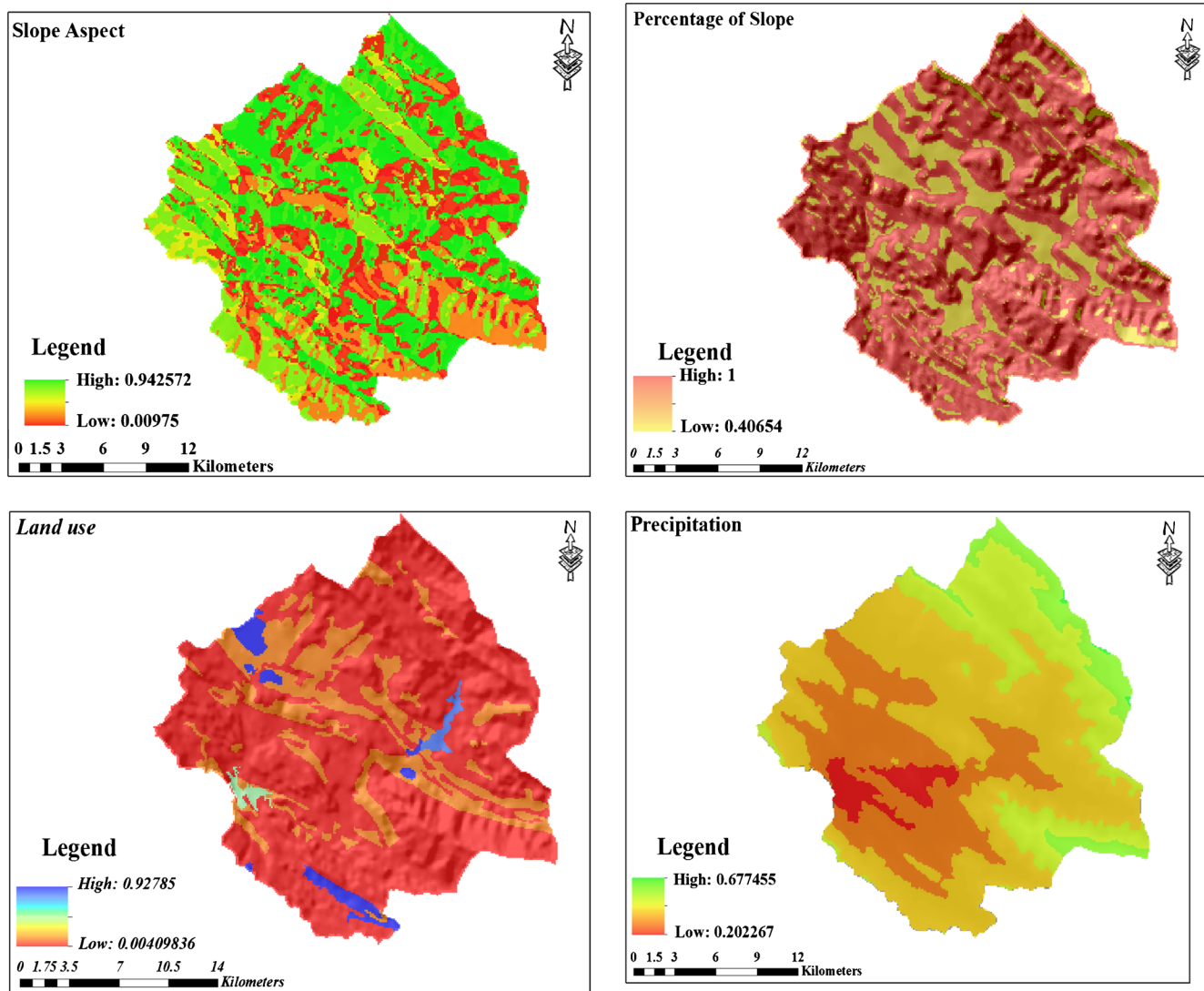Fig. 2 Fuzzificating the effective elements in the landslide susceptibility using fuzzy membership function
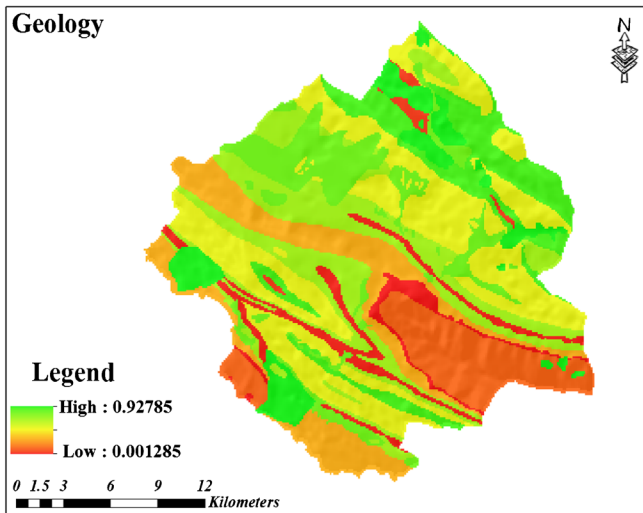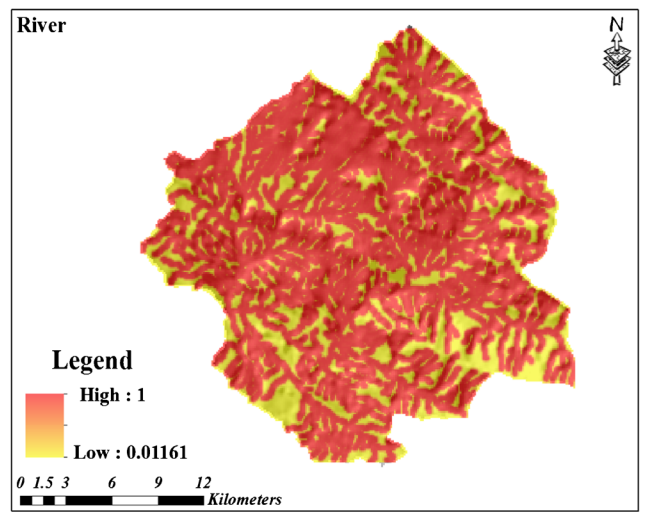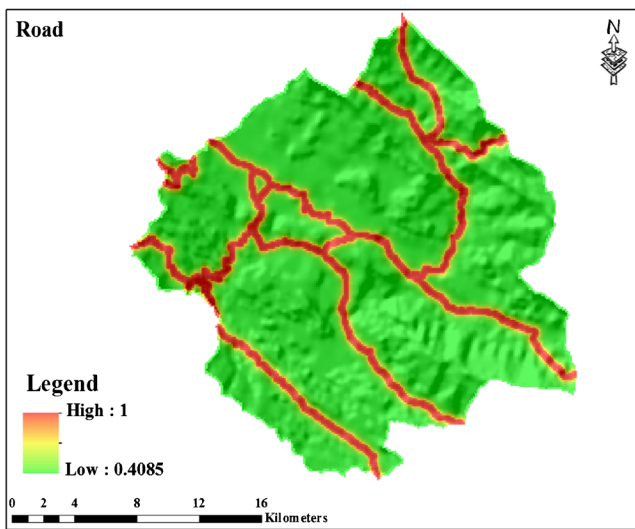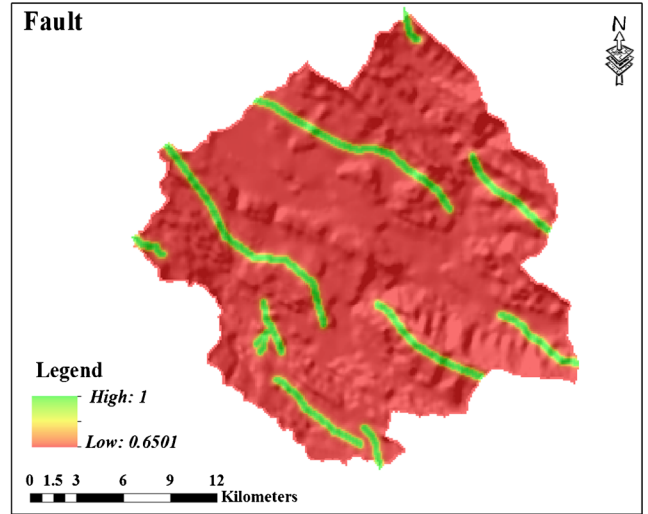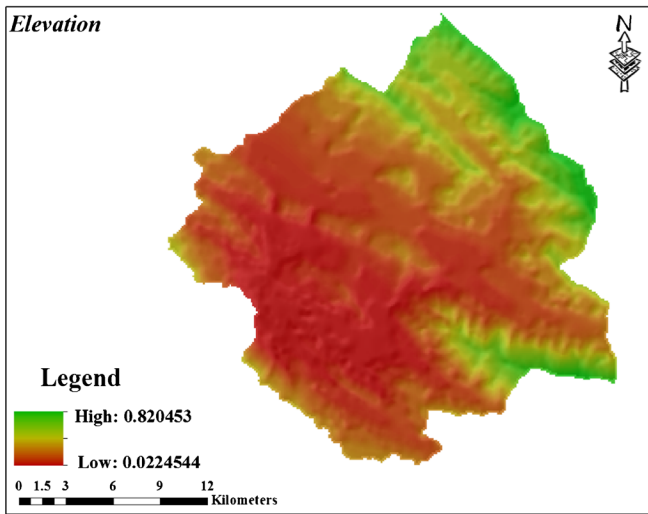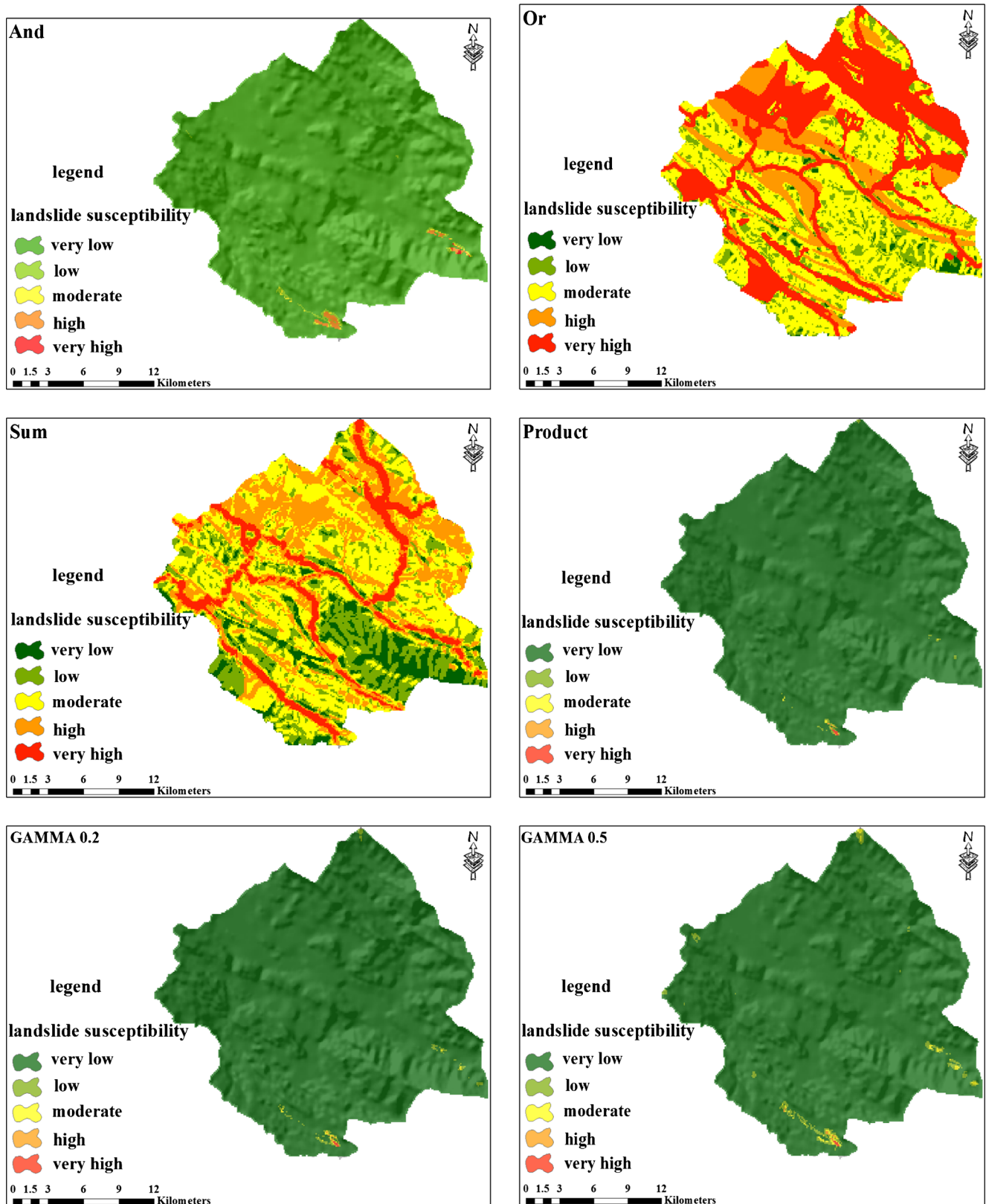
Fig. 2 (continued)

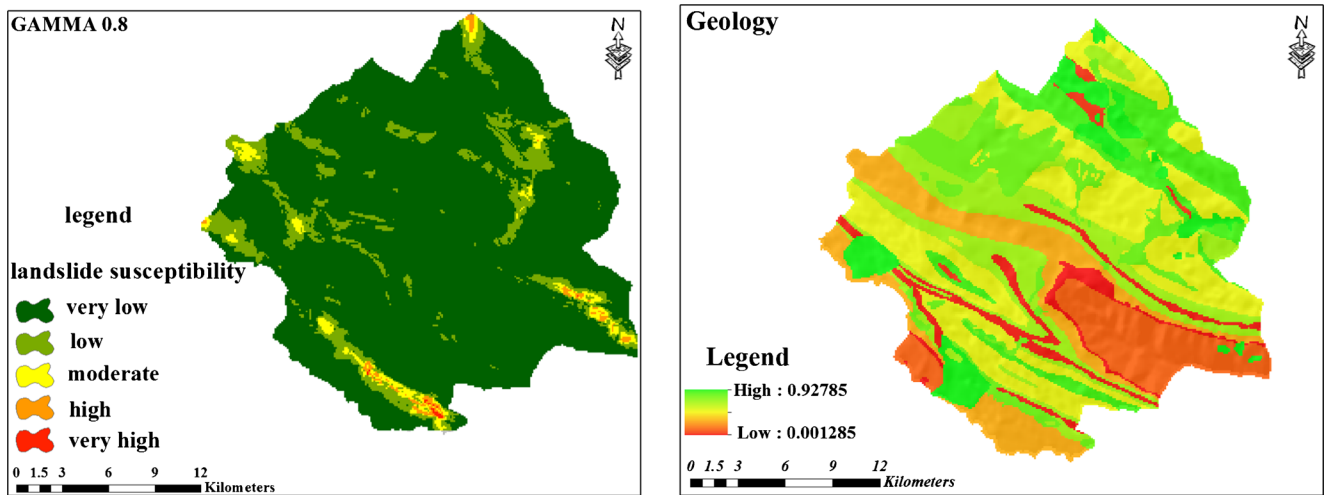Fig. 3 Results of layers overlapping by using different fuzzy operators

Fig. 3 (continued)

If this operator is used, the maximum function value will be selected out of two membership functions.

3. Fuzzy multiplication or product operator (minimization)

Fuzzy multiplication operator is defined as follows.

$$\mu_c(x) = \prod_{i=1}^{n} \mu_i(x) \tag{3}$$

Here, μ_i is the membership value in the map of the ith factor (Eq. 1). Using this function, the fuzzy membership values are more likely to be reduced in the output map. They move toward 0 because of multiplying some numbers which are less than 1; therefore, the combination of elements will have the decreasing impacts. In other words, they decrease each other.

4. Fuzzy addition or SUM operator (maximization)

This operator is defined by Eq. 4.

$$\mu_c(x) = 1\prod_{i=1}^{n}(1-\mu_i) \tag{4}$$

where μ_i means the membership value in the map of the ith factor. The fuzzy membership values are more likely to be increased in the output map, when this operator is used. They move toward 1; consequently, the combination of elements will have the increasing impacts so that due to the increasing impacts of fuzzy mathematical addition, there will be the maximum risk. In other words, they augment each other. Unlike fuzzy union and intersection, all the membership values of the input map influence the output 1 for all the fuzzy multiplication and addition operators of values.

5. Fuzzy Gamma operator

It is defined by fuzzy multiplication and addition in the equation 5.

$$\mu_{combination} = (\text{Fuzzy algebraic Summ})^{\gamma}$$
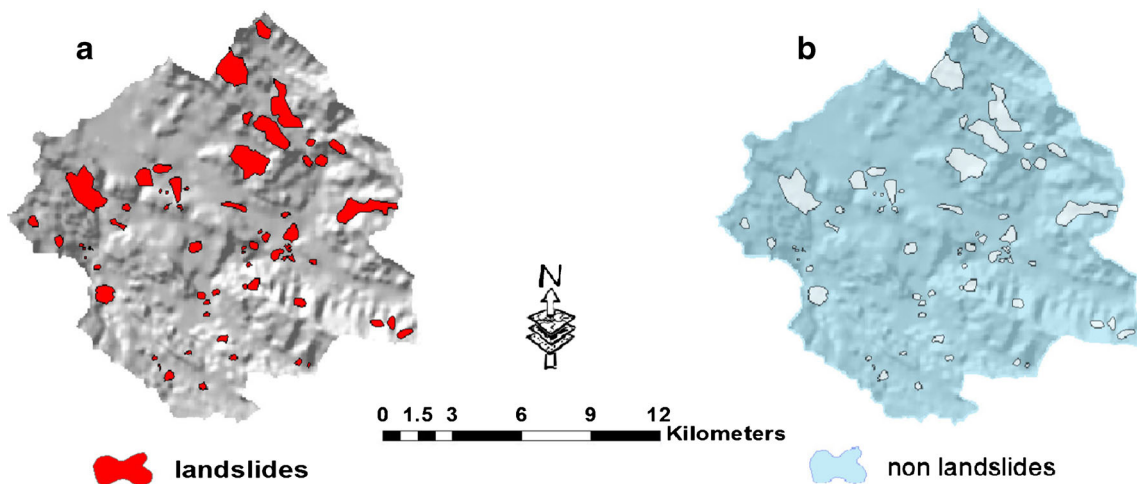$$\times (\text{Fuzzy algebraic Product})^{1-\gamma} \tag{5}$$

Fig. 4 Landslide regions (*a*) and those with no landslide (*b*)

where γ in Eq. (5) is between 0 and 1. It equals 1 and 0, when γ is the same fuzzy addition and multiplication, respectively. Correct selection of γ between 0 and 1 produces some values of the output which shows the flexible adaptation of all the decreasing and increasing tendencies of fuzzy multiplication and addition, respectively.

Results

Fuzzificating and mapping

Function for the fuzzification was selected as the basis of the criteria importance, nature, and relation with the target 1. Since the use of the fuzzy logic model was based on the raster analysis (network) for mapping the landslide susceptibility, each pixel should be taken a membership value from 0 to 1 with regard to the ideal function. At first, all parameters have to be weighed by the means of fuzzy membership function (the functions in the Table 2) in the environment of geographic information systems (GIS) technology.

Fuzzy membership function types which have been used for fuzzification in each factor concerning all measured parameters were presented in Table 3.

Fuzzification for each factor through fuzzy function showed that the choice of one function should be done

according to the target (mapping landslide susceptibility), criterion nature in the study area, and the relationship between the criterion and target. For example, since the distance from breakage is important and the least distance has the highest value, small function is more likely to be used for the fuzzification in this paper. According to Table 3, this function is used when the small inputs are of the highest membership values. Hence, the breakage criterion can be defined as follows regarding the landslide susceptibility mapping; as the distance from breakage decreases, instability and as a result the landslide susceptibility increase. Fuzzification of other factors will be performed on the same basis. Figure 2 shows the maps of the effective elements in the landslide susceptibility by using the fuzzy membership functions.

Weighting

After fuzzification of different measured layers by using membership function, they have been weighed by the AHP method of the expert judgment (Table 1). Accordingly, the layers are weighed with regard to their importance and effects. Afterwards, using the fuzzy operators and Gamma with landaus of 0.2, 0.5, 0.8, and 0.9, specific layers were combined
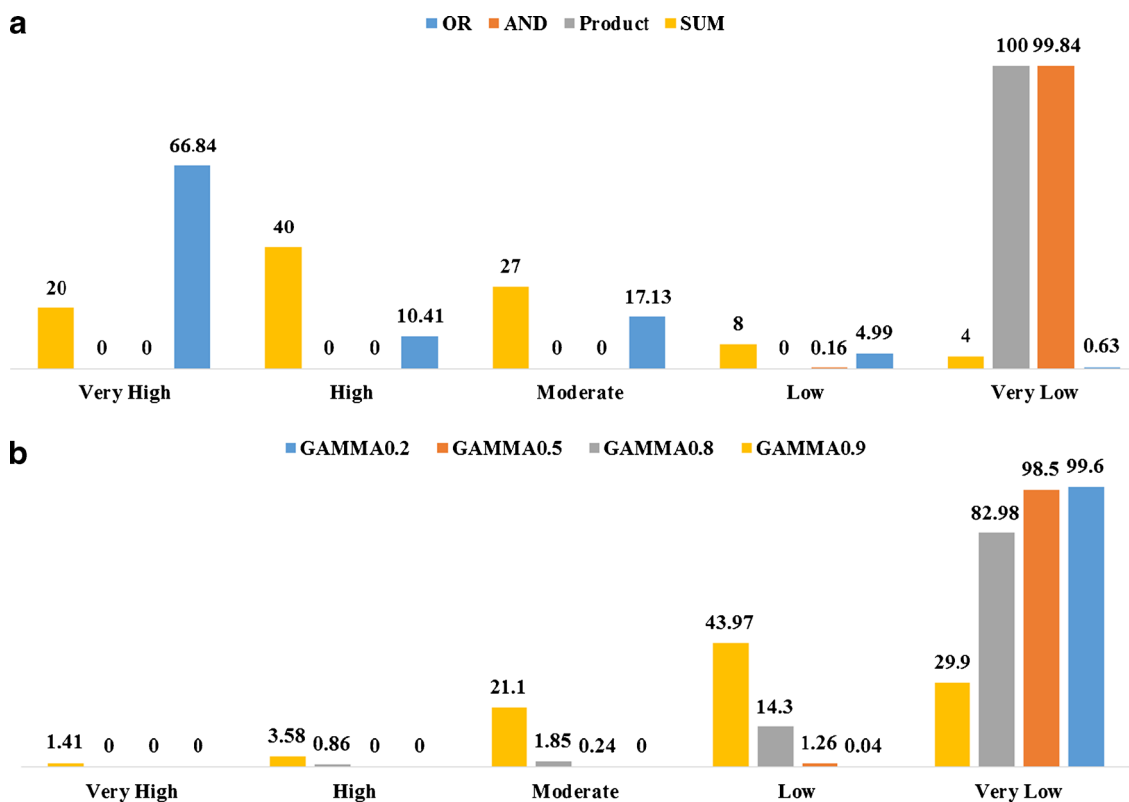

Fig. 5 Number of pixels inside the landslide regions by **a** algebraic operators and **b** Gamma operator

and the maps of landslide susceptibility were provided by different applied functions (Fig. 3).

After providing the maps of landslide susceptibility by using the fuzzy operators, different layers were compared with the landslide maps to determine the accuracy of the operators for finding the maps which do not have the landslide. At first, the maps of landslide areas and those with no landslide were specified through the satellite imagery and field visits (Fig. 4).

Landslide susceptibility mapping was designed by two layers of landslide regions and those with no landslide in order to recognize the number of pixels in the inside all categories those of very low, low, moderate, high, and very high (Fig. 4a) and outside the landslide region (Fig. 4b). Then, the number of pixels in the inside the landslide regions was produced by algebraic operators (OR, AND, Product, Sum) (Fig. 5a) and by Gamma operator (Fig. 5b) and also in the outside the landslide regions (Fig. 6a, b). As well, the ratio of the pixel frequencies inside the region as compared with the outside were calculated by each operator in all levels of very low, low, moderate, high, and very high by algebraic operators (Fig. 7a) and Gamma operator (Fig. 7b).

Discussion

In this study, landslide susceptibility mapping was presented a number of fuzzy operators using different landaus. The produced map showed that the landslide mapping prepared by the "And" operator makes the region into very low hazardous class. But, the application of "Or" operator leads to the classification of most regions as high and very high hazardous classes. It should be stated that the operators of "And" and "Or" are the operators of Boolean logic indicating the absolutely pessimistic and absolutely optimistic results by 0 and 1 numbers, respectively (Zhang and Kandel 2003). The operator "Sum" produced a low sensitive map, because the pixel value tends toward the right in this operator whom more pixels may be put into very high and high hazardous categories (Chung and Fabbri 2001). As well, the landslide hazard maps were presented by the fuzzy "Product" operator. Since all the information layers are multiplied, this operator leads to the smaller outputs which tend to 0. Consequently, fewer pixels are put in very high and high hazardous classes. In order to decrease very high sensitivity of fuzzy multiplication and low accuracy of addition
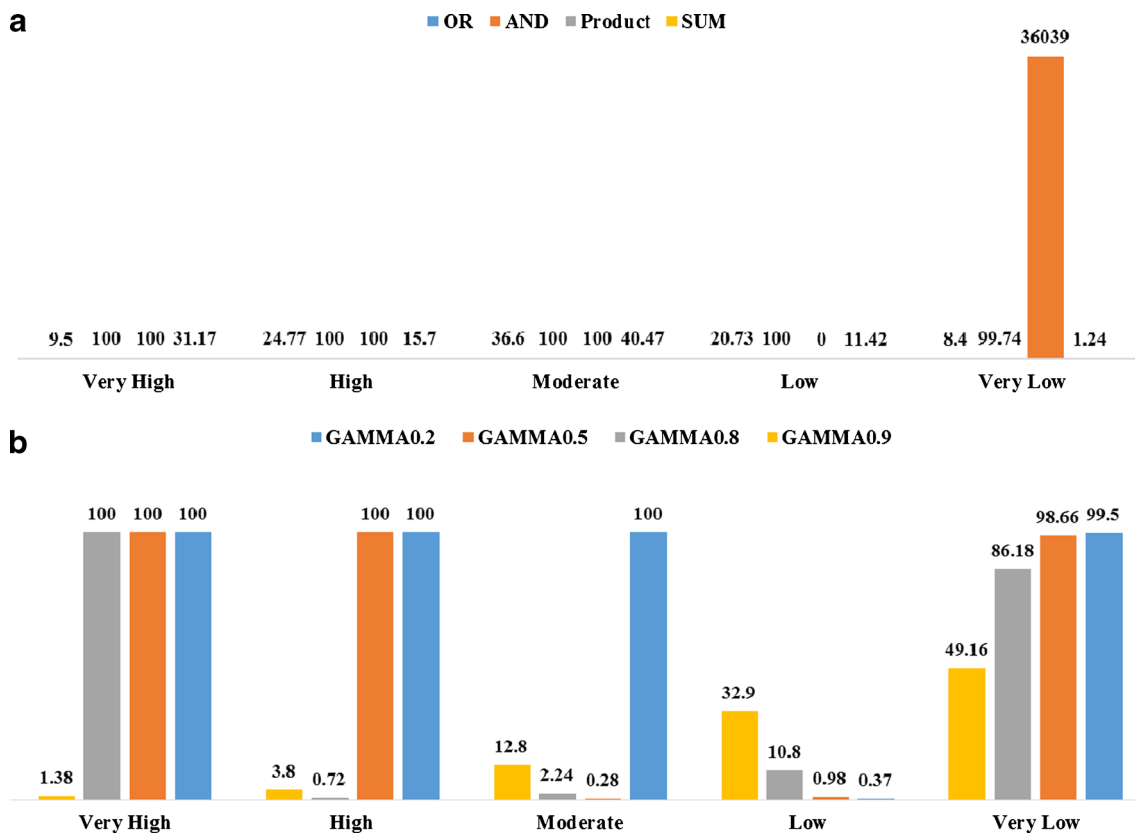

Fig. 6 Number of pixels outside the landslide regions by **a** algebraic operators and **b** Gamma operator
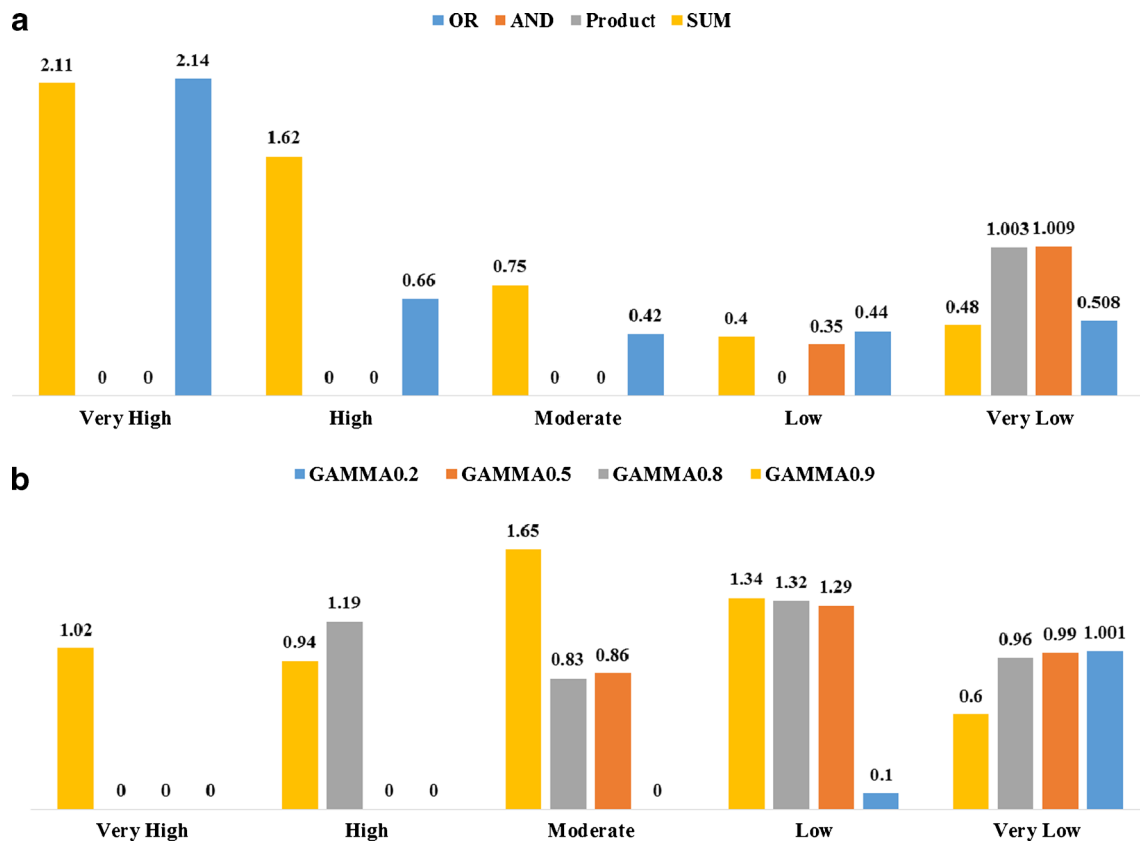
Fig. 7 Comparisons of pixel frequencies of landslide regions and those with no landslides by **a** algebraic operators and **b** Gamma operator

operators, another operator named fuzzy "Gamma" is applied. A variety of Gamma values (0.2, 0.5, 0.8, and 0.9) are more likely to be used (Lee 2007) which the outputs of the "Gamma" operator map were presented with different values. It indicates that as Gamma value tends from 0.2 to 0.9, the resultant maps have different categories so that the categories can be appropriately separated, and the accuracy of the maps is more likely to be enhanced (Chi et al., 2002; Hampati-ray et al. 2007; Lee 2007; Tangestani 2003;). The results of statistical descriptions of different fuzzy operators are shown by the fuzzy membership function in Fig. 7. It indicates that if we move from the fuzzy "AND" operator to Gamma computed as 0.9, it can be concluded that Gamma operator is of more accuracy in the region with regard to the variation coefficient and its gradual decrease. Comparison of fuzzy operator maps shows that "Gamma" operator presents more accurate landslide maps with the accuracy value of 0.9. Our results are in the line of the previous studies those introduced the gamma operator with the best accuracy (Lee 2007; Pradhan et al. 2009; Pradhan 2010). Therefore, it is suggested that it is necessary to consider the resultant maps as a basis in order to take the operational measures in the region. Accuracy of

mapping landslide is directly related to the fuzzification method and the choice of method.

The fuzzy membership function was applied for weighting of the landslide map by using the AHP method of the expert judgment to find their importance and effects. Finally, five landslide intensities of very low, low, moderate, high, and very high were recognized in the study area.

Conclusion

In the current study, the landslide map was determined by weighting the main criteria and the membership functions of fuzzy logic. For this, the most important f factors were applied for mapping landslide susceptibility, e.g., percentage of slope, slope aspect, height, geology, land uses, distance from roads, distance from drainages, distance from breakage, and precipitation. These factors were weighted for fuzzificating by using the AHP method of the expert judgment. As well, our results illustrated that the fuzzy operator of "Gamma" has been recognized an inappropriate model for mapping landslide susceptibility. Five classes those of very low, low, moderate, high, and very high were identified by using this function in the final landslide maps.

References

Ashghali Farahani A (2004) Hazard examination of instable natural regions in Roodbar by fuzzy theory, M. A. thesis in engineering geology, Tarbeiat Molam University

Chi, KH, Park NW, Chung CJ (2002) Fuzzy logic integration for landslide hazard mapping using spatial data from Boeun, Korea, Symposium Geospatial Theory, Processing and Aplications, Ottawa, pp: 6

Chung CF, Fabbri AG (2001) Prediction models for landslide hazard zonation using a fuzzy set approach. Geomorphology and Environmental Impact Assessment Balkema, Lisse, The Netherlands, pp. 31–47

Fatemi Aghda S, Ghayomian JM, Ashghali Farahani A, Teshnehlab M (2005) Zoning of landslide hazards by fuzzy multiple items of making decision (case study of Roodbar, Gilan 56–57: 67–80

Hampati-ray PK, Dimri S, Lakhera RC, Sati S (2007) Fuzzy-based method for landslide hazard assessment in active seismic zone of Himalaya Landslides. 4: 101–111

Hansen A (1984) Landslide hazard analysis, slope instability, Eds., Brunsden, D. Prior, D.P., John Wiley and Sons Ltd, pp: 523–602

Jamali AA (2009) Application of GIS, classification of landslide hazards and comparison of effective factors to produce landslide (case study: Menshad watershed, Yazd).Geometric national conference. 88, 20 & 21th Ordibehesht

Karam A (2001) Quantitative modeling of landslide hazard zoning in Zagrous (case study: Sarkhoon-Charmahal Bakheteiari reigon), PhD. Thesis of natural geography, Tarbiat Modares University, p: 354

Klir G, Yuan B (1995) Fuzzy sets and fuzzy logic (Vol. 4). Prentice hall, New Jersey

Komak Panah A, Farhangfar R (1994) Instability Zonation of Rock Slopes on Seismic Areas. Proceedings of the First National Workshop on the Strategies for Landslide Damage Reduction, Tehran, Iran, pp 415–434

Lee S (2007) Application and verification of fuzzy algebraic operators for landslide susceptibility mapping. Environ Geol 52:615–623.17

Liu, H., Gu, D., Howlett, R. J., & Liu, Y. (2010). Robot Intelligence. Springer

Mahadvifar M (1997) Zoning of landslide hazards in Khoresh Roustam region in Khalkhal, the collection of assays in the second seminar on landslide and damages decrease, the international institute of earthquake and engineering, 1: 148

Pradhan B, Lee S, Buchroithner MF (2009) Use of geospatial data and fuzzy algebraic operators to landslide-hazard mapping. Applied Geomatics 1(1–2):3–15

Pradhan B (2010) Landslide susceptibility mapping of a catchment area using frequency ratio, fuzzy logic and multivariate logistic regression approaches. Journal of the Indian Society of Remote Sensing 38(2):301–320

Sefidgari R (2002) Investigation of landslide hazard zoning in 1: 50000 (case study: Damavand Watershed), M.A thesis of geological engineering, Tarbeiat Modares University, p: 159

Shariat Jafari M (2008) Landslide (stability principles of natural landslide), Sazeh press

Tanka K (2004) Introduction to Fuzzy zoning on the pragmatic use (translated by Ali Vahidian and Kamyad Hamed Tareghian), Ferdousi University press, p: 213

Tangestani MH (2003) Landslide susceptibility mapping using fuzzy gamma operator in GIS, Kakan catchment area, Iran; Proceedings of the Map India Conference (2003), copyright GIS Development

Wang LX (1999) A course in fuzzy systems. Prentice-Hall press, USA, pp. 258–265

Yager, R. R., & Zadeh, L. A. (eds). (2012). An introduction to fuzzy logic applications in intelligent systems (Vol. 165). Springer Science & Business Media

Zhang YQ, Kandel A (2003) Fuzzy moves using compensatory granular reasoning. Int J Comput Intell Appl 3(03):249–263