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Landslide Susceptibility Mapping for Shirin-darreh Dam's Reservoir using Fuzzy Analytical Hierarchy Process and GIS

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ABSTRACT

Landslides are one of the most important natural hazards that occur widely in the dam's sites as well as dam's reservoirs. In this regard, the landslides susceptibility assessments for dam's reservoirs can be utilized to estimate the floods risks, dam failures due to slope instabilities in reservoir. Additionally, obtain the hazard risk potential in dam's reservoir capable to investigate the risk-able zones and categorized prone areas to land-sliding. For this purpose, the present study has tried to use a combined computational model based on fuzzy-hierarchical approach (FAHP) and geographic information system (GIS) to assessment of landslides susceptibility and hazard zonation in Shirin-darreh Dam's Reservoir (North Khorasan) to provide the hazard risk potential maps. Methodologically, after identifying the effective factors in landslides' occurrence (including 6 main factors as morphological, geological, climatic, seismic, in-field and susceptible and human parameters), these factors are weighted by FAHP model and layered Information has entered GIS, which has led to estimates of areas with high to low landslide risk sensitivity. Based on the results of the evaluation, it has been determined that in the peripheral margin of the southern and upstream part of Shirin-darreh dam, it has a high slip sensitivity, which can be considered as a dangerous point for dam destruction and flooding downstream of the dam.

1. Introduction

Landslide is considered as movement of sedimentary layers (non-compact to compact); Broken and aerated rocks; soil and rock mixture on steep slopes that have become unstable. Landslides can occur on a variety of scales under simple to complex failure mechanism that are generally recognizable as the slippery mass moving downstream of the slope (Anbalagan, 1992). Various studies have shown that landslides are the second leading natural disaster which causing catastrophic financial and human damage worldwide, as reported by the United Nations Development Program, UNDP (Azarafza et al., 2018). Landslides (depending on the areas affected) can cause extensive damage to people who that cost of reconstruction or compensation concerning about billions of dollars in different countries (Peethambaran et al., 2020). However, the landslides hazards in Iran brought financial damage more than 1866 billion tomans (IRS) since 1999 which caused destruction of 6763 hectares of forest, 170 km of roads and facilities (Pourghasemi et al., 2018). Apart from the issue of financial and costs that landslides inflict on communities, damages to the

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infrastructures such as tunnels, dams, communication roads and railway lines have doubled the disaster and have wider secondary consequences (Pourghasemi et al., 2018). Regarding to the nature of landslides, it can be said that these geological phenomena are always influenced by several triggering factors that can be divided into different effective groups such as earthquakes, heavy rains, soil looseness, geometric change of slopes, road construction, structural degradation, downstream lightening, fluid porosity, surface and deep weathering, vegetation loss, volcanic activity, groundwater level changes, separation, tidal waves (coastal areas), etc. (Highland and Bobrowsky, 2008). By considering these factors as well as identifying landslide patterns, landslide-susceptible areas can be identified and classified which will greatly help categorize the prone high-risk areas for landslides. On the other hand, identifying high-risk areas in urban planning, land use planning, infrastructure project implementation and crisis management is considered efficient (Cascini, 2008; Attapoor et al., 2014). This classification of susceptible areas, in addition to reducing financial and human losses in the short term, provides the possibility of sustainable development planning for different countries at national, regional and local scales (Lee and Jones, 2006). In order to achieve this goal, experts use various susceptibility methods that can be generally classified into three categories of quantitative, semi-quantitative and qualitative approaches. These groups can be subdivided into a variety of different methods (Castellanos Abella and Van Westen, 2007). In another more common classification, landslide susceptibility assessments gathered in groups including deterministic, statistical, inventory, heuristic, and geostatistical and knowledge-based methods (Jing et al. 2015; Shihabudheen et al., 2017; Azarafza et al. al., 2017; Harrison et al., 2017; Moharrami et al., 2020). However, application each of these approaches to landslide risk zoning has some advantages and disadvantages. The knowledge-based methods has achieved significant successes which widely considered by researchers in recent years (Shihabudheen et al., 2017). Based on knowledge-based methods, the computational tools such as artificial intelligence are used to improve the accuracy and performance of susceptibility assessments (high-risk) in terms of landslides. generally, the knowledge-based methods can be classified into the fuzzy logic, artificial neural network, supervised machine learning, support vector machine, decision tree, random forest, bayesian network, etc. (Peethambaran et al., 2020; Nanehkaran et al., 2021). With the development of computer applications and computational intelligence over the years, it has become clear that knowledge-based approaches have comprehensively replaced conventional methods (Pourghasemi et al., 2018).

In the present study, the combined method of fuzzy logic and hierarchical analysis system as one of the knowledge-based approaches to identify, evaluate and susceptibility assessments for landslides in Shirin-darreh dam reservoir (one of the largest dams in North Khorasan Province) has been considered. This dam was built with the aim of controlling floods, and supplying drinking water to the surrounding areas. The destruction of the dam caused by any landslide in the upstream reservoir of the dam can widespread flooding in the area and lead to huge damages and life lost. Therefore, the importance and necessity of implementing an appropriate model for landslide susceptibility assessment in the dam reservoir area is an executive priority.

2. Background

In line with landslide susceptibility assessments, extensive studies have been conducted by researchers and experts on natural hazards, which can include various aspects that have been implemented for different parts of the world. In these studies, it has been tried to prepare landslide maps for their study areas by using different evaluation methods. In this regard, at the first by identifying the landslide triggers in the study area, the role of each factor is estimated by decision-making processes and entered as information layers in the Geographic Information System (GIS). The result of implementation process has been the prepared for susceptibility mapping and the extraction of vulnerable and risk-able areas (Pourghasemi et al., 2018).

Saffari and Hashemi (2016) used entropy model and fuzzy logic to landslide susceptibility analyze in the urban area of Kermanshah. By identifying and categorizing 9 groups of landslide triggering factors for their study area, the researchers stated that the fuzzy logic model is 90% more efficient in preparing zoning maps than the entropy model. Vahabzadeh et al. (2017) have used logistic regression and probability statistical methods along with decision-making models to assess landslide susceptibility for the Cheshmidar watershed in Kurdistan province. The authors by identifying 17 landslide triggering factors in the study catchment, stated that the northern parts of the catchment are more prone to landslides than other parts. Kuhpeyma and Faiznia (2018) by using the Mahalanobis distance method in Latian catchment with satellite information, field data and decision making model attempted to the susceptibility assessment of landslide in this basin. The results showed that more than 80% of the basin is located in a high and very high risk range which indicates the possibility of various landslides in the area. Heidari et al. (2020) used a random forest machine learning algorithm to identify and classify landslide susceptibility in Raeisali Delvari's dam reservoir. The researchers used a total of 279 historical landslides to prepare their database and used to investigate the susceptibility mapping for the dam area. Mossafaei et al. (2020) is used fuzzy-hierarchical approach (FAHP) and gamma fuzzy model to susceptibility assessment of the landslides in the Taleghan catchment in Qazvin Province. The scholars by identifying and classifying the landslide triggers in this watershed attempted to develop FAHP-based susceptibility maps of the catchment. The results indicated that the FAHP is 70% more efficient than the traditional models.

Azarafza et al. (2018) try to prepare landslide risk-able maps for Assaluyeh and South Pars regions using an integrated approach including weighted FAHP model, neighborhood rate, multi-criteria decision making system (MCDM). The authors by classifying 7 groups of landslide triggers in the region extracted the risk map of the region. Ozer et al. (2020) by implementing a comprehensive framework for landslide susceptibility analysis regarding FAHP and the expert system for the Reef Mountains in Morocco; 5 triggering groups was identified as independent and dependent factors. Authors stated that the FAHP application has significant advantages in classifying multiple effective factors. Moharrami et al. (2020) conducted a study of the integrated approach of FAHP, the best-worst decision model (BWM) and the MCDM system for the preparation of landslide susceptibility maps on a national scale in Austria. The researchers categorized 10 landslide triggers including topographic conditions, slope conditions, slope aspect, lithological features, land-cover, precipitation, historical slides, distance from faults and distance from roads for assessments. The susceptibility map estimated landslide risk-able areas at the national level. Based on the results, it has been shown that applying the FAHP approach in combination with other decision-making methods can significantly improve spatial analysis and identification of landslide prone areas. Berhane et al. (2020) conducted a study on landslide susceptibility analysis for the Adavo-Adgat mountain range in Ethiopia and prepared a landslide risk zoning map for the study area. The researchers used the FAHP model to identify and classify the influencing factors and prepare susceptibility maps in regional and national levels. Peethambaran et al. (2020) in a study attempted to assess landslide susceptibility and risk analysis in the eastern part of the Himalayas by using knowledge-based analysis approaches such as machine learning, FAHP, decision tree, support vector machines, neural networks, etc. The researchers aimed to apply different types of knowledge-based approaches to identify the capability and performance of each of these methods. Based on the results of this evaluation, the FAHP model is in a good category for landslide susceptibility analysis.

3. Case Study

The study area related to the reservoir area of Shirin-darreh dam. The dam as one of the large earth-fill dams located on the Atrak River. The construction of the dam started in 1996 and ended in April 2005. Shirin-darreh dam with 65,800 thousand cubic meters is introduced as one of the largest dams in North Khorasan, which has been constructed with the aim of controlling floods, supplying drinking water to Bojnourd city and its water requirements for industries and agricultures nearby the dam's site. The location of the dam is shown in Fig. 1.

Figure 1. Location of the Shirin-darreh dam site

Although it has not been more than a decade since the operation of dam; the experts are worried about the reduction useful life of dam due to continuous sedimentation and high erosion. With regard to this issue, it can be seen that the water inflows of the rivers feeding the dam reservoir always have the ability of sufficient kinetic force in geometric deformation, transport of bed sediments, structural degradation, continuous stylization of the mass, pore-wate pressure, surface and deep weathering in the area. Such events can be considered as a sign of landslide prone areas upstream and the Shirin-darreh dam's reservoir. In this regard, the concern of floods on the dam site due to a possible landslide in the dam reservoir is added, which is a natural crisis and lead the dam's failure. Thus, the preparation of landslide susceptibility maps in the reservoir area and upstream of the dam is a priority that has been considered in this article.

4. Material and Methods

In order to analyze landslide susceptibility in the study area, three categories of studies including desk studies (referring to documental sources to review the literatures in landslide susceptibility assessment), remote-sensing studies (evaluation of data and satellite images), and field surveys (investigation of landslide prone areas) have been performed. During these stages, information and study framework have been prepared, which is presented as process flowchart in Fig 2. Regarding to landslides which can be identified in a wide range of instabilities that categorized by Varnes (1978) where shown in Table 1. Chung and Fabbri (2003) stated that preparing a database of different type of historical landslides can be effective in improving the performance of susceptibility mapping. So, due to the high sensitivity of the assessment for the study area, landslide susceptibility for all these groups will be considered as land-slides to be able to have a more comprehensive view of the different types' condition of ground movements in the area. As can be seen in Fig. 2, the processing stages in this study are based on the FAHP application to investigate the landslide susceptibility in Shirin-darreh dam's reservoir. The implementation methodology is presented as follow:

4.1. Data and Information

For the first stage of landslide susceptibility analysis, it is necessary to prepare a database of information reference to the influencing factors regarding landslide occurrence. These triggering factors can be obtained based on desk studies on maps, remote sensing surveys and field surveys. In this regard, the presented study used all type of evaluation to prepare comprehensive triggering factors in Shirin-darreh dam's site. The remote sensing surveys is established on atellite imagery such as Landsat TM8, ETM^{+}, altitude data (DEM), and climate information. In this regard, the 2020 data of Landsat TM8 satellite and DEM data dated 2019 have been used for the quality of 12.5 meter data (updated from NASA-Alaska site). Also, climatic information of the region has been prepared from the Iran Meteorological Organization. These information layers are extracted as evaluation databases and analysis by FAHP in GIS. Field studies have been used to measure the accuracy of remote sensing assessments as well as impressions related to historical landslides in the upstream Shirin-darreh dam's reservoir.

4.2. Landslide Triggering Factors

Based on studies that has led to the preparation of input databases in the landslide susceptibility assessment for the upstream and dam's reservoir, there are 6 group of triggering factors which each of these groups has different sub-factors. Table 2 illustrated the identified triggering factors in the study area. According to this Table, it can be stated that triggering factors concluded morphological, climatic, geological, seismic, field and human factors are involved in landslides occurrence in the region. These factors and their sub-factors are considered as dataset used for FAHP model to evaluate impact coefficients of each factor and sub-factors. The coefficients are used to create information layers in GIS which lead to digitalize data and prepare landslide susceptibility maps.

Figs. 3 to 7 show maps prepared of landslide triggers for the study area. This information is provided by measuring satellite imagery, field survey and documental studies. The output of this assessment will be used as landslide susceptibility maps for Shirin-darreh dam's reservoir. It should be noted that although no seismicity has been reported in the upstream area of the dam in terms of seismicity, the seismicity of the area has been considered as areas of high susceptible.

Table 1. Landslide classification based on sliding mechanism (Varnes, 1978)

Sliding type	Material type		
	Rock	Soil	
		Coarse	Fines
Falls	Rock fall	Debris fall	Earth fall
Topples	Rock topple	Debris topple	Earth topple
Rotational slide Translational slide	Rock slide	Debris slide	Earth slide
Lateral spread	Rock spread	Debris spread	Earth spread
Flows	Rock flow	Debris flow	Earth flow
Creeps	Deep creep	Soil creep	
Complex	Composite movements		

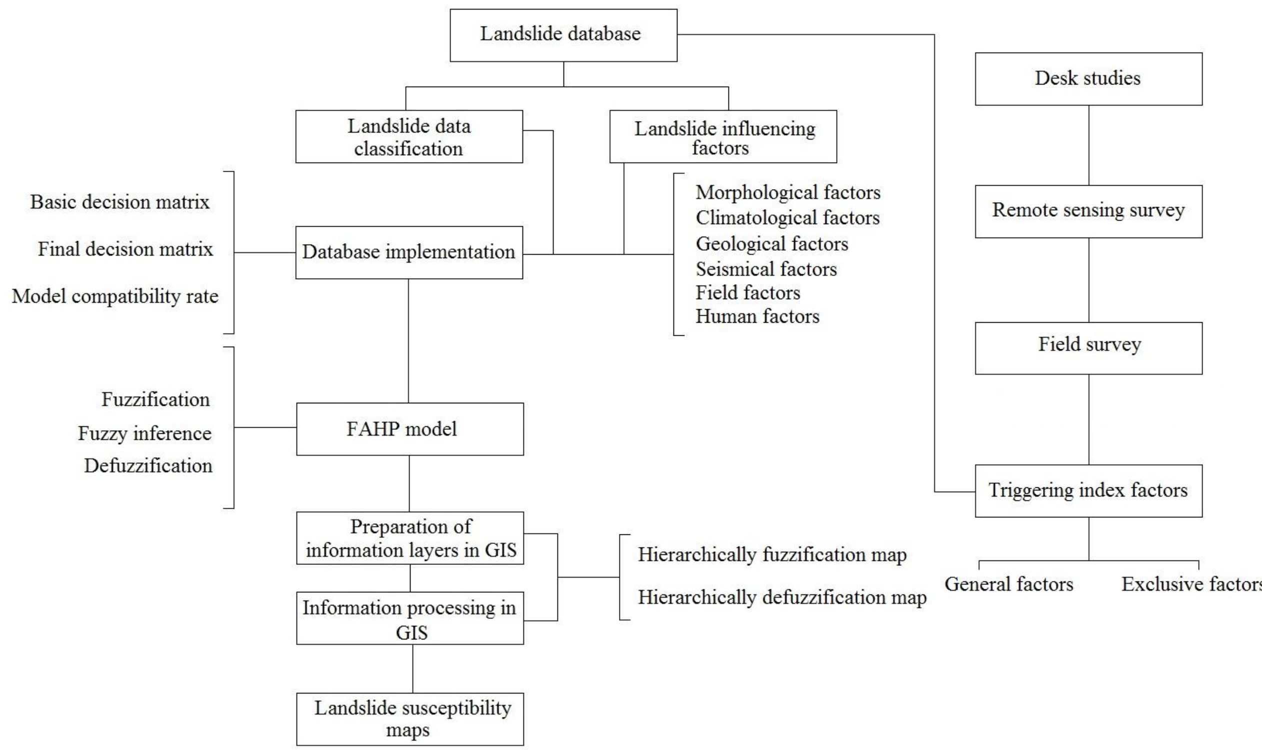

Figure 2. The flowchart of the methodology

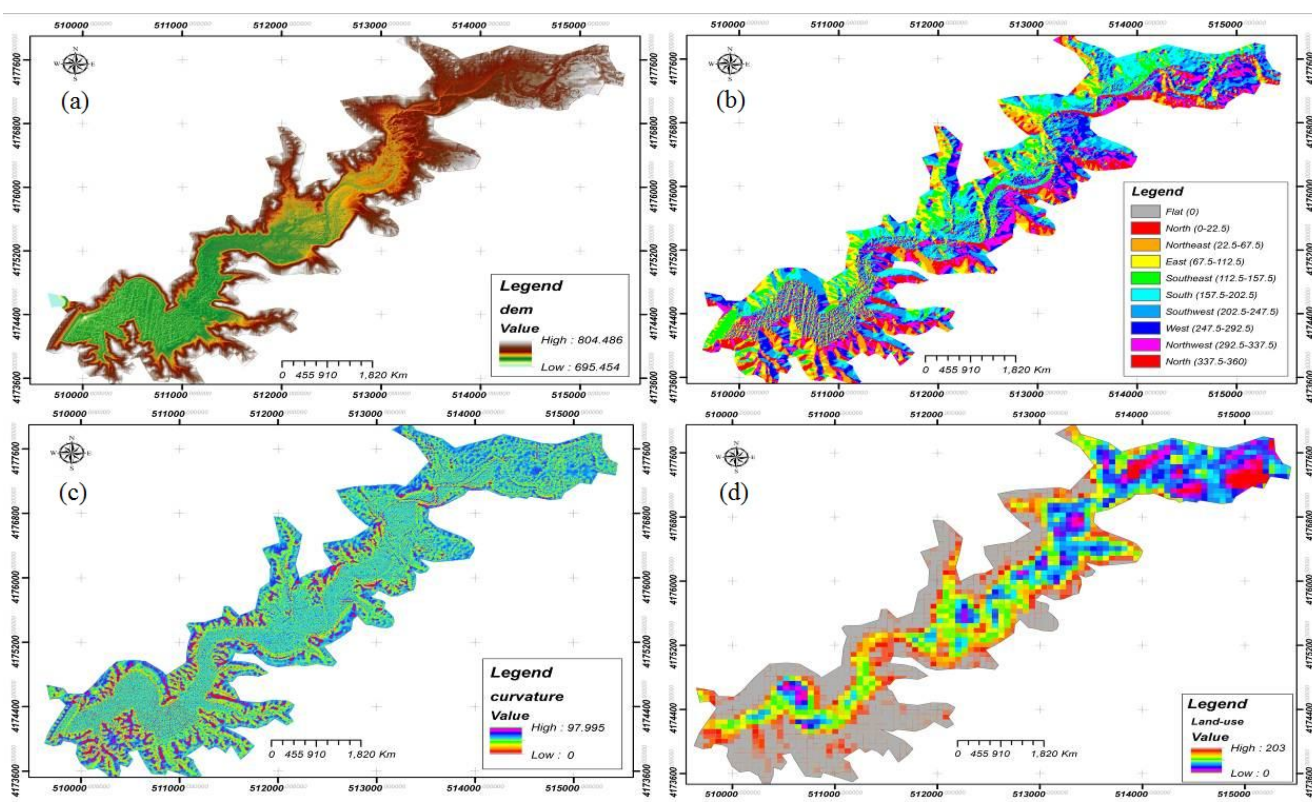

Figure 3. Maps prepared from the morphological factors: (a) altitude change, (b) sloping aspect, (c) morphological curvature status and slope of the area, (d) land cover

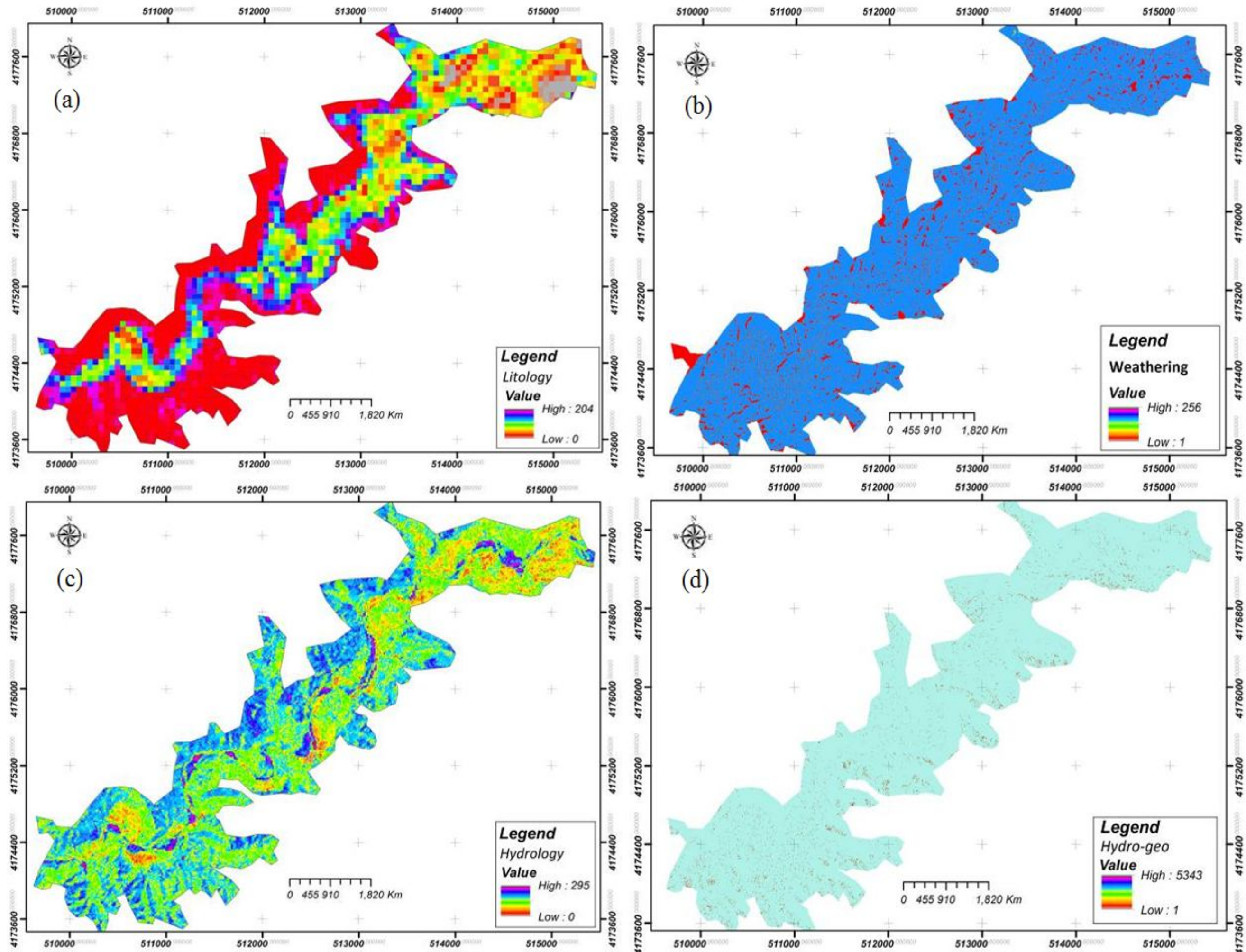

Figure 4. Maps prepared from the geological factors: (a) lithology, (b) weather condition of the catchment area, (c) hydrological conditions, (d) hydrogeological conditions

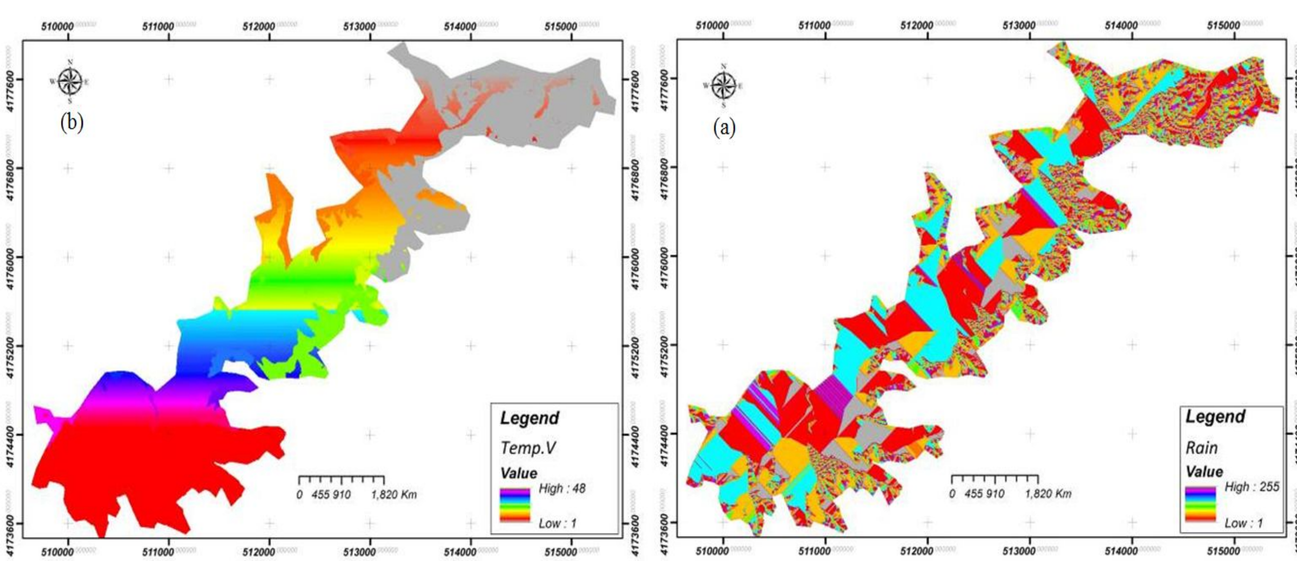

Figure 5. Maps prepared from the climate factors: (a) precipitation, (b) temperature

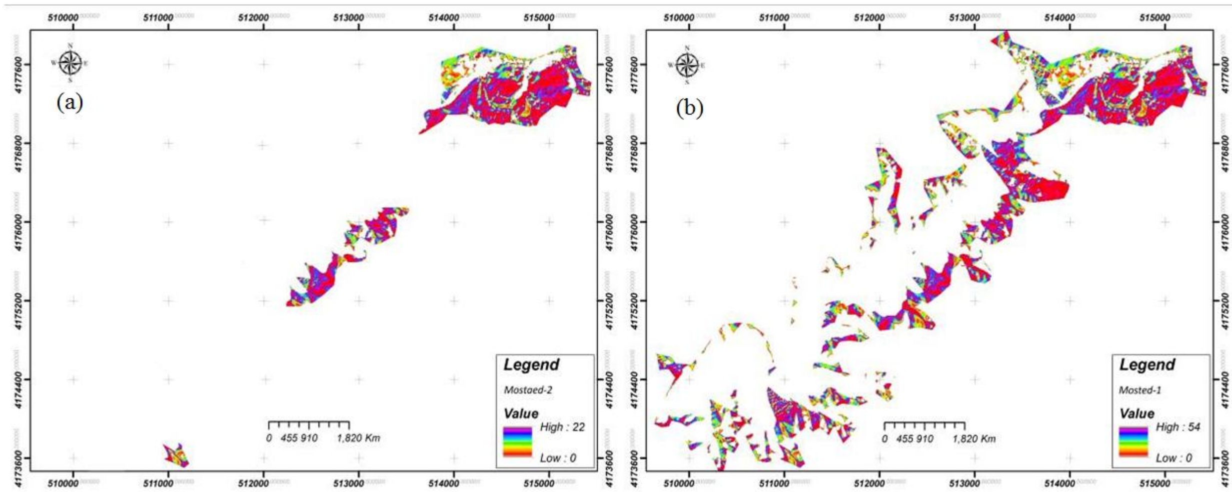

Figure 6. Maps prepared from the field factors: (a) Location of landslides, (b) Location of sensitive areas for landslides

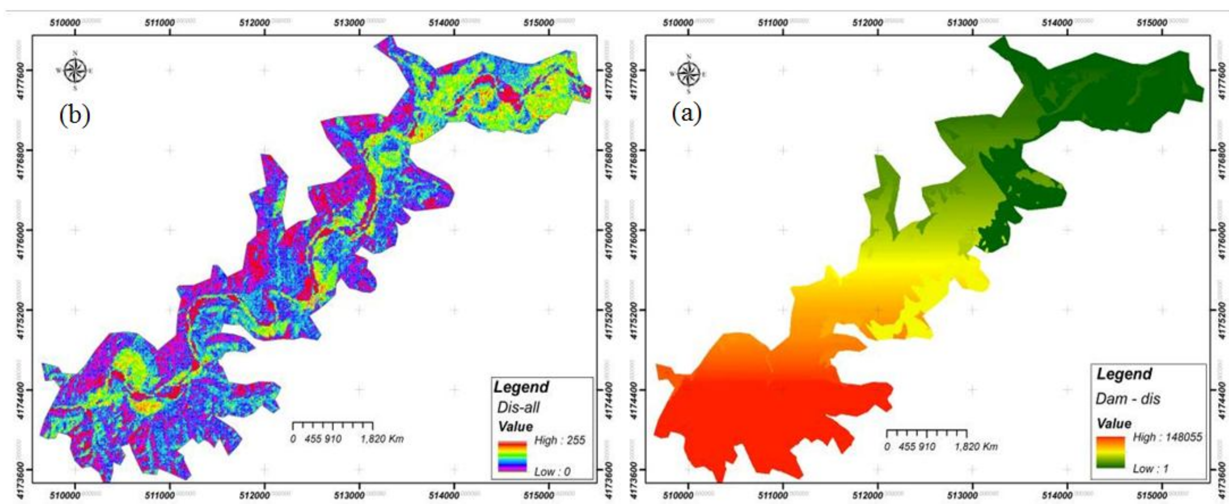

Figure 7. Maps prepared from the human factors: (a) distance to the dam, (b) distance to human land use areas

Table 2. Factors affecting landslide occurrence identified for Shirin-darreh dam's site

No.	Triggering factors	Description
1	Morphology	Altitude variation
		Slope aspect
		Morphological curvature status and slope of the area
		Land cover
2	Geology	Lithology
		Weather condition of the catchment area
		Hydrological conditions
		Hydrogeological conditions
3	Climatology	Precipitation
		Temperature
4	Seismicity	All seismic activities around the site
5	Field elements	Location of landslides
		Location of sensitive areas for landslides
6	Human work	Distance to the dam
		Distance to human land use areas

4.3. Fuzzy-hierarchical Model (FAHP)

In order to provide landslide susceptibility maps for the upstream area and the Shirin-darreh dam's reservoir, after preparing the basic database, this information is classified by hierarchical and decision-making approaches using experts. Each factor and sub-factors are weighted by FAHP and provide the fuzzification – defuzzification maps. Fig. 8 shows the implementation process of the FAHP model on the landslide database. As shown in this figure, the input data is first retrieved as fuzzy data (fuzzification). This stage of the evaluation operation is performed by defining fuzzy sets and fuzzy membership functions for each factor. The information is then inferred based on the knowledge of the expert system (role database) and then converted into non-fuzzy sets (defuzzification). Fig. 9 presents the fuzzy sets for the landslide factors as well as the membership functions defined for them. Using this implementation approach, fuzzy-hierarchical impact coefficients are prepared. Table 3 shows the weights prepared based on fuzzy pair-decision matrices for each of the factors causing the landslide event. These coefficients are implemented as triggering factor's effects based on FAHP at GIS as information layers. The fuzzy information layers can't used directly to landslide susceptibility analyzes. These fuzzification maps become defuzzification after fuzzy inference. A defuzzification map is used to prepare main landslide susceptibility maps.

4.4. Landslide susceptibility analysis

After estimating the fuzzy membership functions and extracting the fuzzy coefficients as sensitivity factors for each of the factors and sub-factors; these coefficients enter the GIS environment as information layers. These layers are representation of input information and FAHP coefficients which used in the preparation of risk maps.

5. Results and Discussions

Landslide susceptibility assessments are performed to identify prone areas to probability of landslides occurrence, which can provide a good view of assessed high-risk area by preparing maps. Based on these results, a strategy can be considered in hazard management to prevent any possible future events and take the necessary measures in advance.

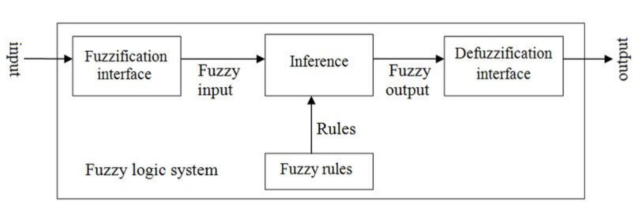

Figure 8. Scheme of fuzzy analysis process

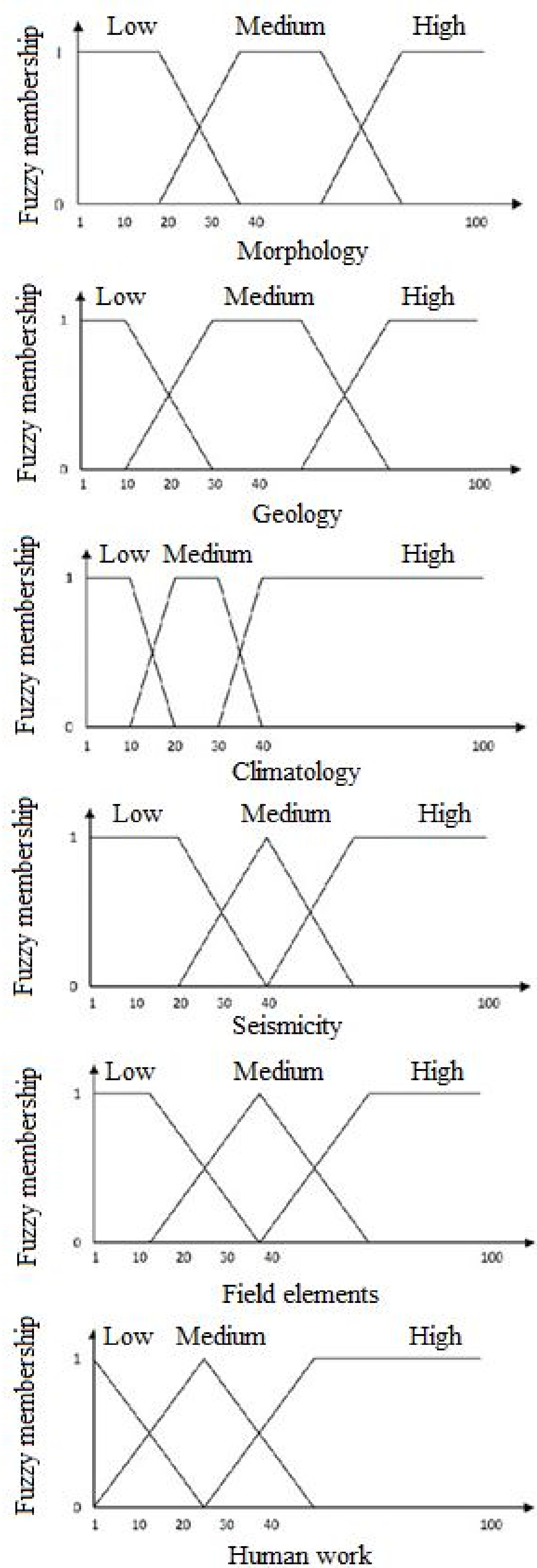

Figure 9. Fuzzy membership functions for triggering factors in the study area

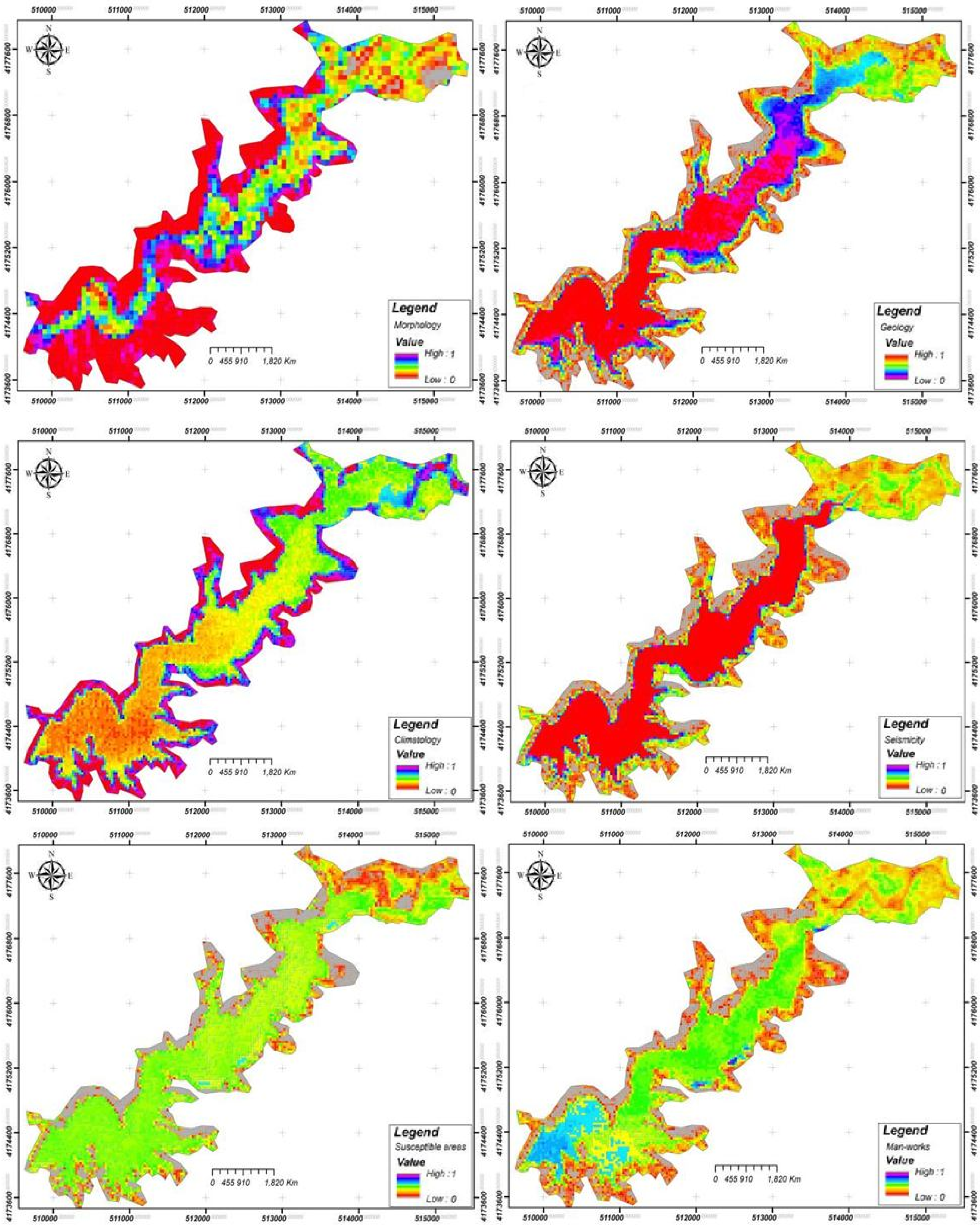

Figure 10. Fuzzified index maps prepared for the study area

Table 3. Factors affecting landslide occurrence identified for Shirin-darreh dam's site

Main factors	Impact	Sub- factors	Impact
Morphology	0.193	Altitude	0.336
		Slope aspect	0.275
		Curvature	0.209
		Land cover	0.180
Geology	0.169	Lithology	0.124
		Weathering	0.247
		Hydrology	0.318
		Hydrogeology	0.311
Climatology	0.116	Precipitation	0.678
		Temperature	0.322
Seismicity	0.225	Seismic activities	1.00
Field elements	0.181	Historical landslides	0.527
		Sensitive locations	0.437
Human work	0.116	Distance to the dam	0.779
		Distance to land use	0.221

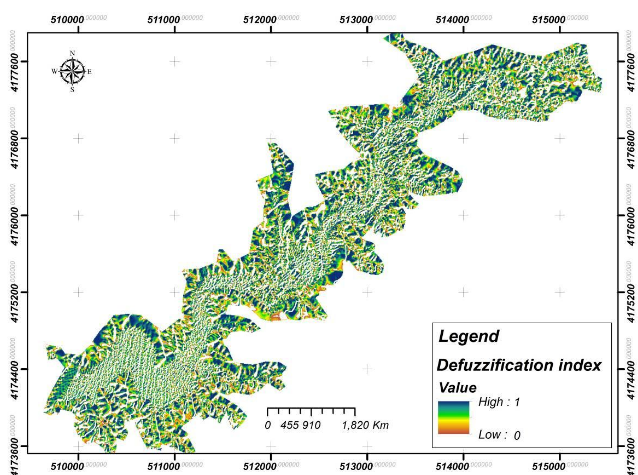

Figure 11. Defuzzified index map prepared for the study area

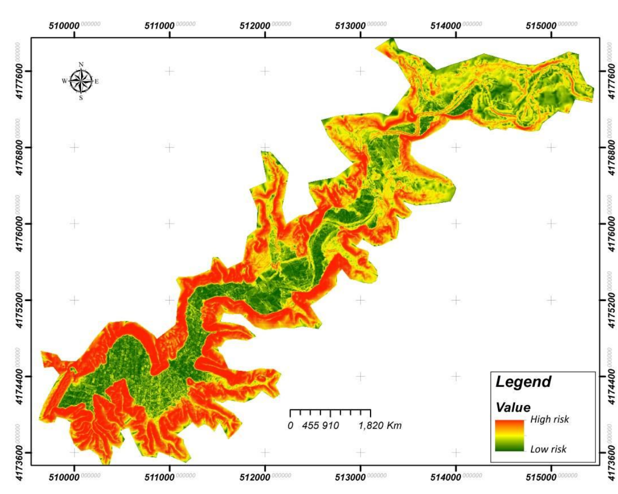

Figure 12. The landslide susceptibility map for the study area

In the present study is attempted to prepare a susceptibility analysis of landslides occurrence upstream and the reservoir of Shirin-darreh dam as one of the most important concerns in dam site. In this regard, the study tried to prepare a landslide risk map based on the identified triggering parameters. Methodologically, the FAHP approach has been used to prepare the impact coefficients of each factors and analyzed in GIS environment. This data is classified as information layers and is used in the preparation of fuzzy index maps. Fig. 10 shows the fuzzification index maps for landslide in the study area. As stated, the direct application of these maps without making logical inferences is accompanied by computational errors. Therefore, fuzzification indices are deconstructed as shown in Fig. 8. The result of this processing operation is a defuzzification map shown in Fig. 11. The defuzzification index map prepared for the area is used to prepare the hazard map and landslide susceptibility assessments as well as illustrated in Fig. 12. Based on the results of this assessment and hazard map, it can be stated that in the periphery of the southern and upstream part of Shirin-darreh dam has high slip susceptibility which can be considered as a dangerous point for dam destruction and flooding downstream of the dam.

6. Conclusion

Landslides can be introduced as one of the most common geological phenomena on the planet, which is the second largest natural hazard in the world. Based on various studies, it has been determined that landslides cause significant financial and human losses in different countries. This has led to the use of management and containment strategies to improve the situation in crisis management programs and development strategies at the national and regional levels. Looking at the nature of landslides, it can be said that these geological phenomena are always under the triggering factors that cause distortion and contribute to the occurrence of landslides in different areas. By identifying these factors, landslide risk-able areas can be identified. Identifying such susceptible areas can be very effective in applying managemental strategies. So far, various methods (quantitative, qualitative or combined) have been developed and used to analyze the susceptibility assessment of landslide risk zones, where each of methods has its advantages and disadvantages. But by development of computer technologies and utilization of computational intelligence procedures for landslide risk analysis (knowledge-based approaches); susceptibility mapping have been prepared with more accuracy.

In the present study, a computational model based on fuzzy logic and hierarchical analysis has been used to assess the risk and landslide susceptibility analysis, which has been implemented for the upstream area of Shirin-darreh dam's site. To make this assessment, three categories of studies including desk studies, remote sensing and field surveys have been conducted which have led to the preparation of an input database and identification of affecting factors for susceptibility assessment. These factors are classified into 6 main groups including morphology, geology, climate, seismicity, field and prone regions, human work parameters. The fuzzy-hierarchical model (FAHP) has been used to estimate the impact coefficients and classify the susceptibility of each of the mentioned factors. Based on the results of this assessment and hazard map, it has been determined that in the southern margin and upstream of Shirin-darreh dam is a high susceptibility which can be considered as a dangerous point for dam destruction and flooding downstream of the dam.

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