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Snow Avalanche Risk Assessment using GIS-Based AHP for Bitlis Province

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Abstract

Bitlis province, located in the Eastern Anatolia of Turkey, is the region with the highest snowfall in the country. Due to its highland and steep structure, the region is at high avalanche risk. The assessment of snow avalanche risks is critical in modern disaster management. In this study, the avalanche risks were assessed using the analytical hierarchy process (AHP), which is an effective multiple criteria decision-making method. The avalanche risk was considered to depend on many factors, such as temperature, slope, elevation, aspect, land use, soil, lithology, precipitation, distance to the fault and population. The outputs obtained from the method were mapped in the GIS environment, and thus the avalanche risks of the region were determined. According to the results, especially the highland and steep southern parts and the two volcanic mountain foothills in the region were evaluated as high risk. The study results were validated by comparing past avalanche events and some previous research.

1. Introduction

Avalanche events are generally seen in rough, mountainous, and steeply sloping lands where there is no vegetation. Avalanches occur as a result of the snow mass accumulating in layers on the valley slopes sliding down the slope rapidly as a result of a first movement that starts with the effect of internal or external forces [1]. Physical factors such as topographic structure, earthquakes, vegetation features, gravity, the amount of snow mass, and human factors are effective in avalanche formation [2]. The main reason for avalanche formation is that the weak layer under the snow cover loses its ability to carry the load arising from the cover.

Pre-disaster risk assessments play an important role in minimizing disaster damage. For this reason, many methods have been presented in the literature for the hazard and risk assessment of natural disasters such as avalanches. Natural disaster risks depend on many factors, such as the meteorological, environmental, topographical, and human characteristics of the region. Therefore, multiple decision-making methods are often used to assess avalanche-like risks. One of these methods is the Analytical Hierarchy Process (AHP). Gret-Regamey and Straub [3] used a combined procedure of a Bayesian network with GIS for avalanche risk assessment in their study area (Davos, Switzerland), performing explicit modelling of all relevant parameters. Nefeslioglu et al. [4] used a modified analytical hierarchy process to assess avalanche hazards. They concluded that this method is a powerful tool for decision support problems, especially in complex situations. Kumar et al. [5] performed an avalanche susceptibility study for Nubra Valley using AHP with a multi-criteria decision method based GIS environment. The most important factors affecting the avalanche were considered to be slope, elevation, aspect, curvature, terrain roughness, and ground cover. Varol [6] reported that meteorological, environmental,

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topographical, and human factors should be taken into account in order to better evaluate and predict the snow avalanche, which is one of the hydrogeological disasters. Their effort is on the susceptibility maps of avalanche potential in the Uzungol in northeastern Turkey using some methods such as the Frequency Ratio (Fr), Analytical Hierarchy Process (AHP), and Fuzzy-AHP (FAHP). In the study, five criteria, namely slope, aspect, elevation, curvature, and vegetation, were applied to the model. Naseryu and Kalkan [7] performed an avalanche risk assessment using GIS based AHP for Van province, neighboring Bitlis in Turkey. In their study, they considered some basic parameters for avalanches, i.e., elevation, slope, aspect, curvature, and land cover. Elmastaş and Özcanli [8] determined the avalanche disaster areas of Bitlis using the GIS environment, and then analyzed the avalanche risk depending on only slope criterion. Göksu and Leventeli [9] obtained an avalanche sensitivity map of Bitlis province by combining elevation, gradient, aspect, curvature and land use maps with the help of GIS technique, and controlled their results by remote sensing method. However, in these last two studies, no multiple decision-making method was applied. Another study on the study area was conducted by Selçuk [10]. This study pointed out that most avalanche fatalities in Turkey have occurred in Bitlis Province, and within the scope of this study, the sensitivity and accuracy analysis for the avalanche hazard in Bitlis province was evaluated by using geographic information system (GIS) based multi-criteria decision analysis (MCDA). Five decision criteria, such as elevation, slope, aspect, vegetation density, and land use, were taken into account in the study, but some other important criteria affecting avalanche events, such as seismicity, lithology, population, precipitation/snowfall, temperature, and soil, were not considered. Flood [11], landslide [12], and rockfall [13] risk analyses were also performed for the same region using a GIS-based AHP.

As the brief literature review above indicates, multi-criteria decision making methods are a very powerful tool for assessing natural disaster risks such as avalanches when combined with GIS techniques. A few studies have been conducted on the avalanche risk assessment of the province of Bitlis, which is at high avalanche risk. In these previous studies, it was seen that either the number of criteria was not sufficient or any multiple decision-making technique was not applied. Many of these studies also failed to account for risk factors such as population. In this study, avalanche risk assessment for Bitlis province, which is the place with the highest snowfall in Turkey, was carried out using a GIS-based AHP method with a large data set.

2. Material and Method

2.1. Study Area

The region most exposed to avalanche events in Turkey is the Eastern Anatolia Region due to its barren and mountainous terrain with heavy snowfall [14]. As seen in Fig. 1, the maximum snow depth in Turkey is concentrated in the province of Bitlis, which is our study area. Also in Fig. 2, the second place where avalanches are most common in this region is Bitlis after Bingöl. The average elevation of Bitlis province, considered the application area in this study, is 1500 m above sea level, and its area is 6707 km^2. The area, which has a volcanic structure, is also located in a seismically active region. In terms of climate characteristics, Bitlis and its surroundings are a transition between the harsh continental climate of Eastern Anatolia and the Mediterranean climate. The region's location at the crossroads of hot and flat Southeastern Anatolia and cold and mountainous Eastern Anatolia provides a microclimatic feature. The humid air originating from Lake Van, which is the largest soda lake in the world at 1650 m elevation in the east, is another important factor in the heavy snowfall in the region. In the region, between 1959 and 2020, the lowest temperature in the region was -24.1 °C in January, and the highest temperature was 34.3 °C in July. The annual average temperature is given as 9.0 ^{o}C. The maximum snow depth between these years was measured as 250 cm. The total precipitation falling on the area is 1047 mm on average. The total precipitation falling on the area is 1047 mm on average [15]. About 50% of this precipitation is in the form of snowfall in winter and partly in spring and autumn. Fig. 3 depicts monthly snow covered days (a) and monthly average snow depths (b) observed at two measurement stations over many years. According to these graphs, the region is covered with snow for 6 months of the year and the snow thickness reaches 250 cm on average in January, February and March. These climatic factors are the main reasons for the frequent avalanche events in the region. In addition, the mountainous and steep topography and tectonic structure of the region are other important factors that increase the avalanche risk.

In the province of Bitlis, 265 avalanche events were reported between 1950 and 2019. Bitlis province is the region with the highest amount of snowfall in Turkey. Terzi [16] showed that Bitlis is the first in Turkey with a 50-year period ground snow load of 4.6 kN/m^2 (Fig. 4). Aydin and Isık [17] explained the reason for this as a micro-climatic feature display in which climate transitions occur in the region, and they reported 11.87 kN/m^2 the ground snow loads with the 50-year return period depending on the meteorological measurements and their statistical analyses. Based on these results, they warned that the current standards and codes do not reflect the actual snow loads. According to Elmastaş and Özcanli [8,] approximately 50% of Bitlis province is at risk of avalanche. Ekinci et al. [18] assessed the natural disaster diversity of Bitlis Province using Fine-Kinney method. They found that the settlements, especially in the rugged southern parts of the area (Hizan, Mutki and Tatvan towns together with Bitlis center) are at high risk. According to Göksu and Leventeli [9], Bitlis is the province where avalanche disasters occur the most in Turkey. The numbers of avalanche events that occurred in the study area between 1960 and 2020 are given in Fig. 5.

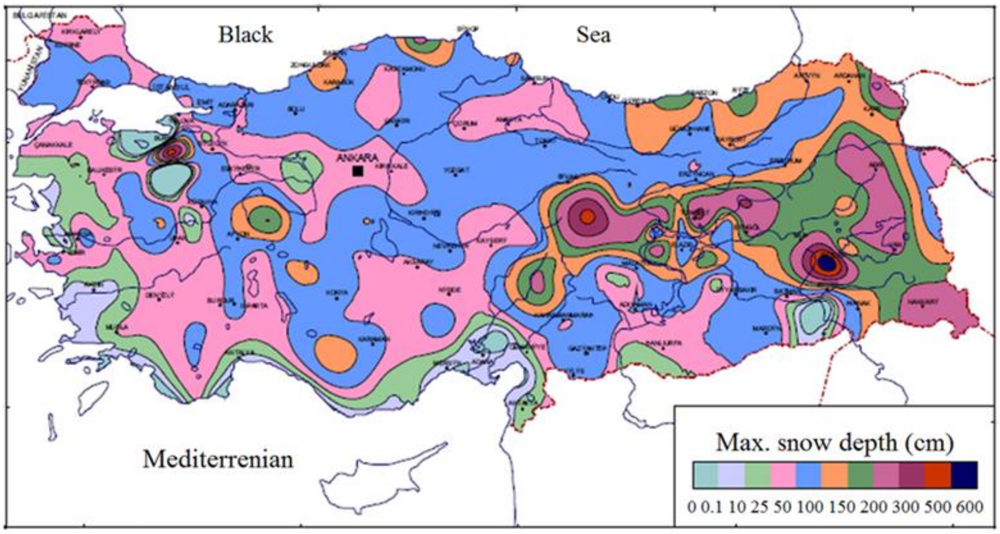

Figure 1. Map of maximum snow depth in Turkey [19]

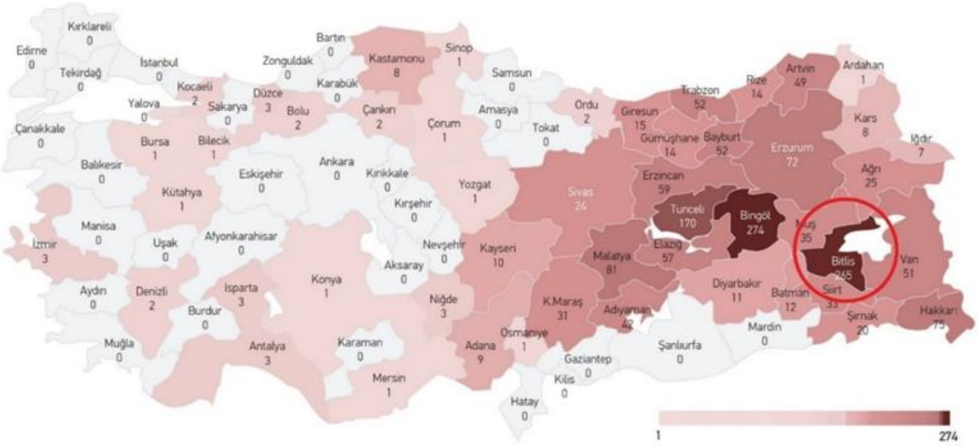

Figure 2. Location of application area and avalanche events in Turkey between 1950 and 2019 [20]

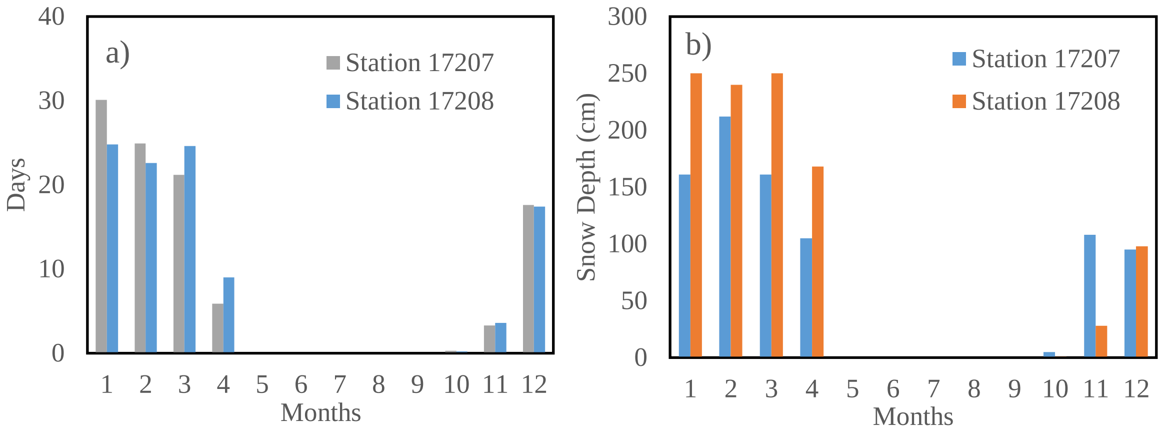

Figure 3. For long years; a) monthly number of days with snow cover, b) monthly depth of snow cover (cm)

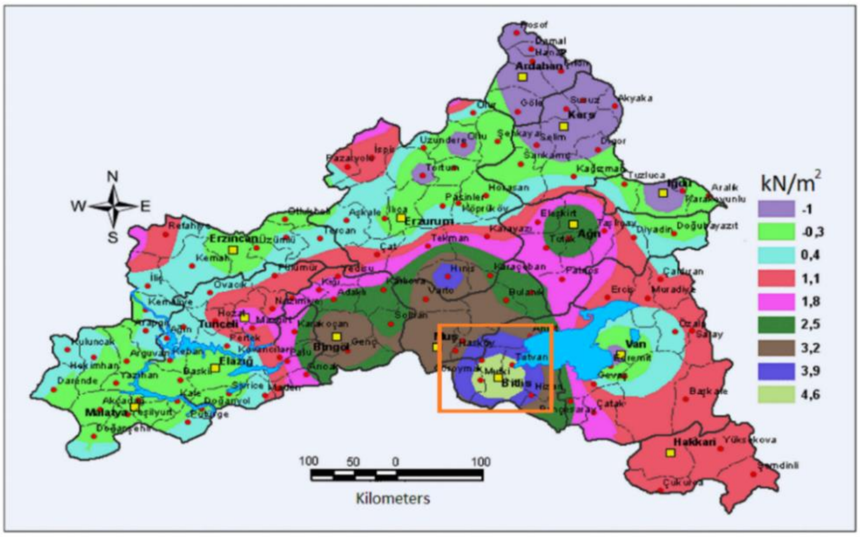

Figure 4. Normalized ground snow loads with the 50-year return period in the Eastern Anatolia region in Turkey [16]

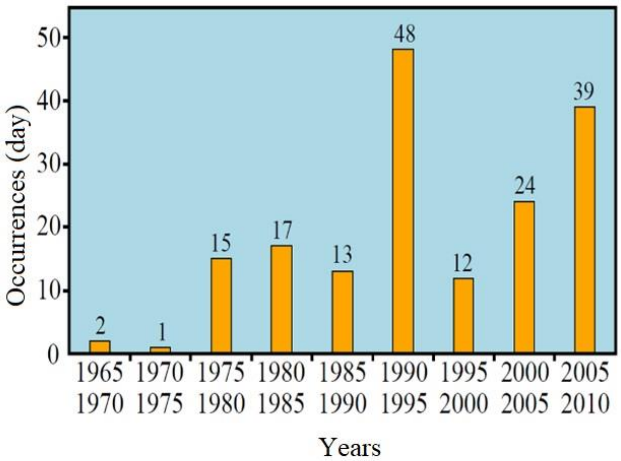

Figure 5. Annual avalanche event numbers between 1965 and 2010 [18]

2.2. Methodology

The Analytical Hierarchy Process (AHP) introduced by Saaty [21] is the most widely used method among Multi-Criteria Decision Making Methods (MCDM). In AHP, the hierarchical structure and comparison matrix are explained as the first step, and then the comparison matrix is transformed into a priority vector and the fit ratio is determined according to random index values [22]. Fig. 6 shows a schematic of the three-level hierarchical structure used for a MCDM problem, with the high-level decision goal representing the lower-level criteria and, if any, the lower-level alternatives [23]. Here, decision options are at the lowest level. AHP can be used with many criteria according to their common characteristics, so the number of criteria and the correct definition of each criterion are important for the consistency of pairwise comparison. After the hierarchical structure is established, the importance levels of the criteria are discussed with the decision makers, the importance density of the criteria is scored between 1 and 9, and the bilateral relations between the criteria are determined [23].

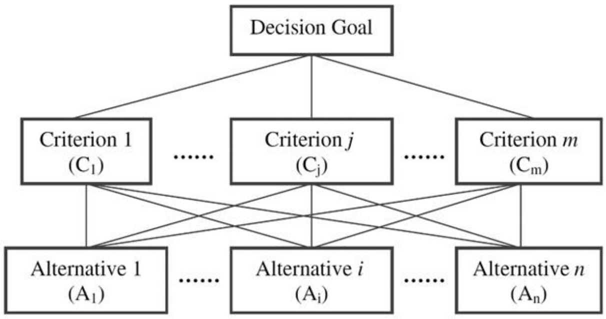

Figure 6. Network of three-level hierarchical structure for MCDM problem [23]

After the normalized matrix is obtained, the average of each row of the matrix gives the weight vector. The product of the weight vector and the comparison matrix gives the following matrix of priorities.

$$[AW_i] = [A][W_i] \tag{1}$$

The maximum eigenvalue (λ_{max}) is obtained by the following equation:

$$\lambda_{max} = \frac{1}{n}\sum_{i=1}^{n}\frac{AW_i}{W_i} \tag{2}$$

where, n is criteria number, *A* is the pairwise comparison matrix, and *W* is the weight vector. Saaty [21] called this method for determining the weight vector as the fundamental right eigenvector method (EM). It was suggested in the literature that the pairwise comparison matrix A should have an acceptable consistency controlled by the consistency ratio (CR) [23]:

$$CI = \frac{(\lambda_{max} - n)}{(n-1)} \tag{3}$$

$$CR = \frac{CI}{RI} \tag{4}$$

In which, the *CI* is the consistency index, *RI* is the random inconsistency index taken from Table 1.

Table 1. *RI* values according to numbers of criteria (n = 1 – 15) [24]

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

When $CR < 0.10$, the comparison matrix has reached acceptable consistency, otherwise, the decision-making process must be repeated until consistency is achieved. $CR = 0.00$ means that the consistency reaches the best value [24], [25].

3. Results and Discussion

3.1. Snow Avalanche Risk Assessment

Generally, risk is evaluated as the product of hazards and vulnerabilities. The factors (criteria) that may have the potential for any damage, harm, or adverse health effects on property and people are described as hazards. The vulnerability, on the other hand, is the susceptibility to damage or harm to a property or people. In other words, while the hazard refers to the factors that affect the event, the vulnerability refers to the factors that are affected by the event. In this study, precipitation, temperature, slope, elevation, aspect, soil, lithology, and fault were considered as hazard factor, while land use and population as vulnerability, as seen in the flow chart of GIS-based AHP in Fig. 7. According to the AHP results, the final risk score is calculated as follows [26], [27] and then visualized using GIS.

$$R = \sum_{i=1}^{n} w_i \times c_i \tag{5}$$

where, w_i and c_i represent the weights and the overall criteria respectively. The dataset of the criteria in Fig. 7 were obtained from open sources of the relevant institutions [15], [28]-[36].

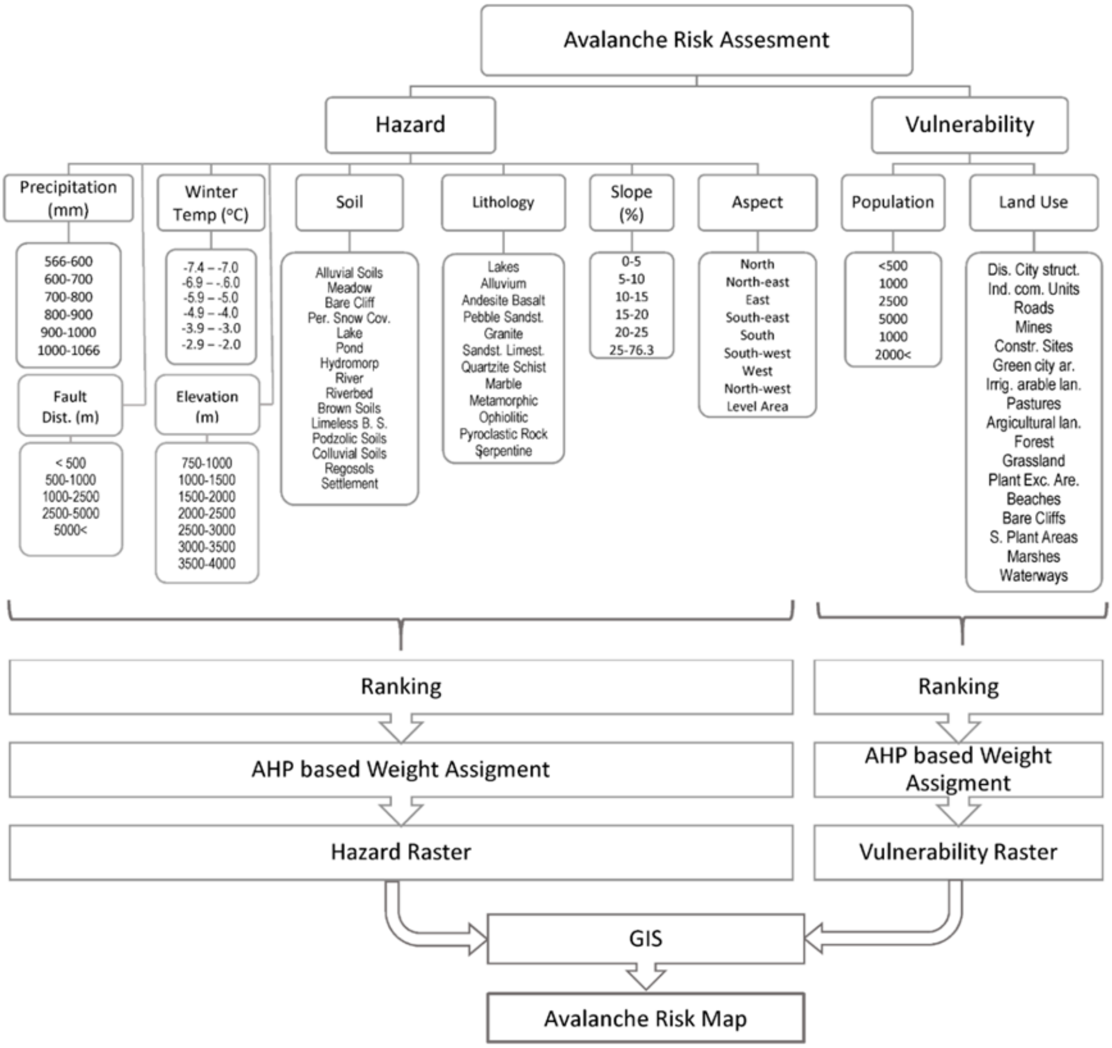

Figure 7. Flow-chart of the GIS-based AHP for risk assessment of snow avalanche

Table 2. Derivation of the weight vector based on the normalization matrix

Matrix A	Tem.	Slope	Eleva.	Aspect	L. use	Soil	Lit.	Prec.	Fault.	Pop.	W_i (%)
Temperature	0.302	0.476	0.367	0.311	0.255	0.208	0.200	0.178	0.157	0.127	25.8
Slope	0.101	0.159	0.245	0.233	0.191	0.208	0.200	0.178	0.157	0.127	18.0
Elevation	0.101	0.079	0.122	0.233	0.191	0.139	0.150	0.133	0.131	0.127	14.1
Aspect	0.076	0.053	0.041	0.078	0.191	0.139	0.150	0.133	0.131	0.109	11.0
Land use	0.076	0.053	0.041	0.026	0.064	0.139	0.100	0.133	0.131	0.109	8.7
Soil	0.101	0.053	0.061	0.039	0.032	0.069	0.100	0.089	0.105	0.109	7.6
Lithology	0.076	0.040	0.041	0.026	0.032	0.035	0.050	0.089	0.079	0.091	5.6
Precipitation	0.076	0.040	0.041	0.026	0.021	0.035	0.025	0.044	0.079	0.091	4.8
Fault distance	0.050	0.026	0.025	0.016	0.013	0.017	0.017	0.015	0.026	0.091	3.0
Population	0.043	0.023	0.018	0.013	0.011	0.012	0.010	0.009	0.005	0.018	1.6

In order to obtain the normalization matrix in Table 2, firstly, each criterion is scored and a pairwise comparison matrix is created based on expert opinion. Then, the score of each criterion is divided by the sum of its own column and the elements of the normalization matrix are calculated. The average of each row of the normalization matrix gives the weight of the relevant criterion. According to the relations given in the methodology section, the parameters of AHP were calculated as λ_{max} = 10.992, RI = 1.49 from Table 1, CI = 0.110 and CR = 0.07. The consistency ratio CR = 7% < 10% which indicates the consistency of the comparison matrix. As a result, the weights of the criteria were estimated as %25.8 of the temperature, 18% of the slope, 14.1% of the elevation, 11% of the aspect, %8.7 of the land use, %7.6 of the soil, 5.6% of the lithology, 4.8 of the precipitation, 3.0 of the fault distance, and 1.6% of the population, as seen in Table 2.

3.2. Spatial Analysis

The hazard and vulnerability maps effective for avalanches were presented in Fig. 8. The raster maps in this figure were obtained by transferring the scores of each criterion used in AHP to the GIS environment. One of the criteria that can affect the avalanche is temperature. Since snow accumulations are greater in cold areas, local cold areas in the north of the temperature map in Fig. 9 were scored high, and warm areas in the south were scored low. The volcanic Mount Süphan in the north appears to be the coldest part due to its high elevation and the colder climate of the north. However, although the southern parts are warmer, due to the mountainous and rugged nature of these parts, many snowfalls occur, and in this case, the effect of the slope comes to the fore. As can be seen on the slope map, the mountainous and rugged southern parts are more critical in terms of avalanche risk. High-altitude areas are riskier areas in terms of avalanches as both the slope and snowfall increase. Therefore, higher regions on the elevation map are scored higher. Due to the temperature differences during the day, the risk is higher on the southern faces. For this reason, the southern surfaces are rated with a higher hazard score in the aspect map. Avalanche susceptibility is high in land use, particularly on high and steep slopes prone to avalanches. Additionally, while the hazard score is low in flat alluvial lands on the soil map, rough soil structures with hard and steep structures are considered as riskier places. Although the entire region has high snowfall, the central and southern regions where precipitation is concentrated are under higher avalanche risk, as can be seen from the precipitation map. On the other hand, since active fault zones can trigger avalanches, the hazard score of the regions close to the faults is considered high in the fault map. Another factor vulnerable to avalanche risk is population. The high-population residential areas are more vulnerable to avalanche risk than other areas, as seen in the population map in Fig. 8.

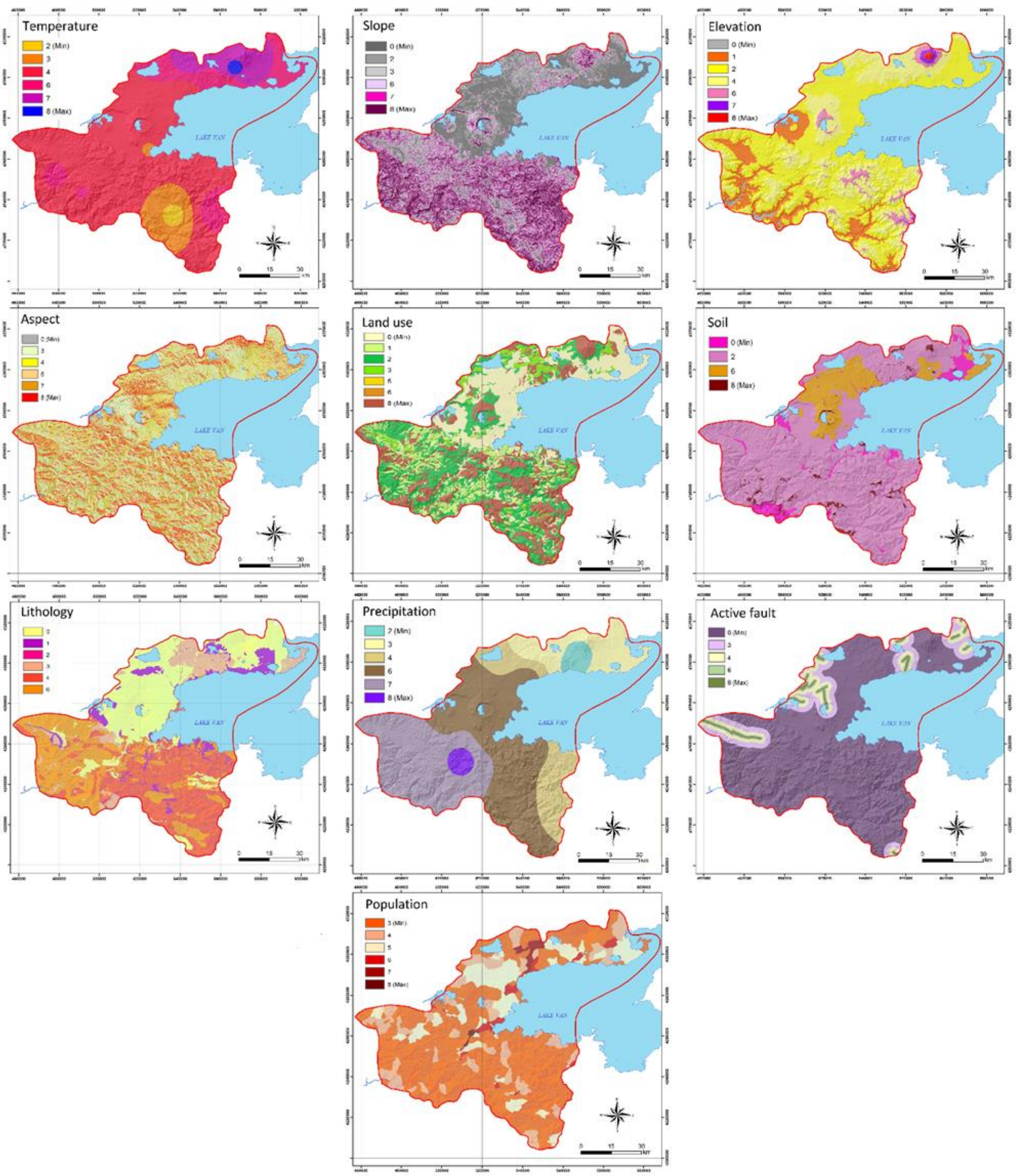

Figure 8. Raster maps of the criteria effective on avalanche risk

The maps in Fig. 8 were processed in the GIS environment in proportion to their weights gained from AHP, and the resulting risk map for snow avalanches is presented in Fig. 9. As can be seen in this risk map, especially the highland and steep southern regions were determined to be high risk, and the relatively flat middle regions were determined to be low risk. It is seen that the regions with the highest avalanche risk are the foothills of Suphan Mountain in the north and the highlands in the east of Hizan district in the south. The foothills of the Nemrut Crater Lake, which are rising in the middle flat region, are also under high avalanche risk. In order to verify the risk map, avalanche events observed in the past few years and the avalanche sensitivity map obtained by Göksu and Leventeli [9] are given in Figs. 10a and

Fig. 10b respectively. Accordingly, it was observed that the avalanche events that occurred in the past generally overlap with the medium and high-risk regions of the risk map obtained in this study. In addition, the obtained map is also compatible with the avalanche vulnerability map presented by Göksu and Leventeli [9], which was only obtained by overlaying some of the land criteria with the GIS. The study results also match significantly with the risk-hazard map of the region presented by Selçuk [10]. The results indicate the verification of the risk map in this study.

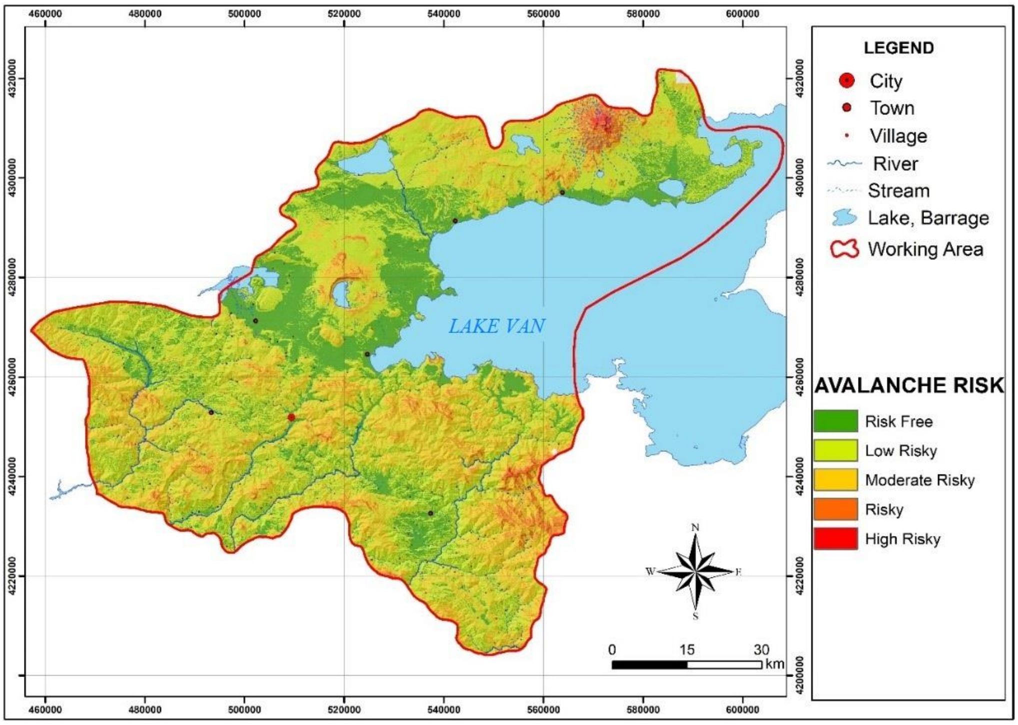

Figure 9. Final risk map of the snow avalanche

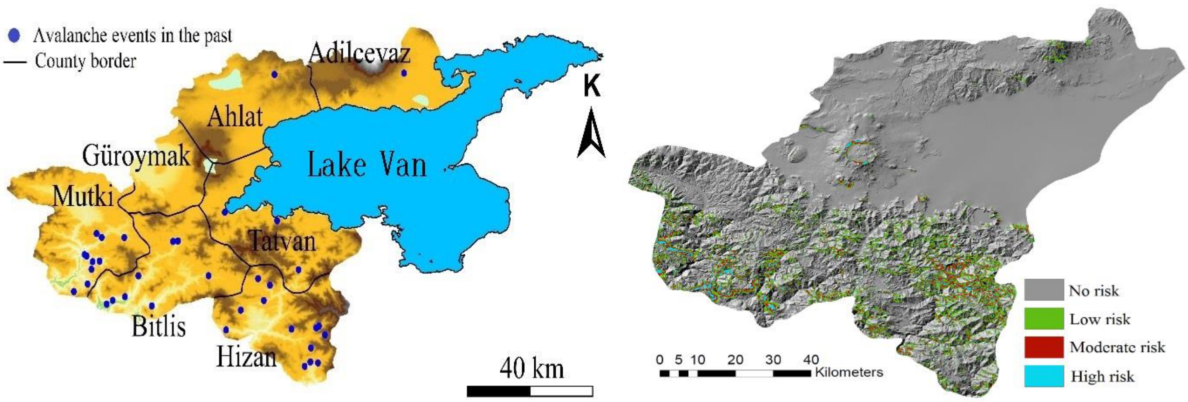

Figure 10. a) Locations of avalanche events in Bitlis between 1965 and 2010 [18], b) The avalanche sensitivity map of the Bitlis [37]

4. Conclusions

In this study, avalanche risks in the province of Bitlis, which is the region with the highest snowfall in Turkey, were assessed using a GIS-based AHP. The avalanche risk of the study area was mapped based on the weights of temperature, slope, elevation, aspect, land use, soil, lithology, precipitation, distance to a fault, and population criteria. According to the results of the study, the highland and steep southern regions of the study area were obtained as high-risk areas, and the relatively flat middle regions were determined as low-risk areas. The highest-risk regions are the foothills of Süphan Mountain in the north and the highlands in the east of Hizan district in the south. The foothills of the Nemrut Crater Lake are also under high avalanche risk. The obtained risk map is in agreement with the avalanche events of the past and with a previous avalanche susceptibility map in the literature.

The findings obtained from the study will make important contributions to effective disaster management against avalanche events in the study area. Thus, it will be possible to prevent important losses of life and property that may occur in the region. An innovative interactive risk assessment of the region can be performed by combining the risk maps obtained from this study with the risk maps obtained for other disaster types. These risk maps are expected to make significant contributions to institutions and academics operating in this field today and in the future.

Contributions of the authors

M.C.A.: Risk assessment and writing the manuscript, E.S.B.: Rastering and spatial analysis, A.E.U.: Risk assessment and editing, A.B.: Spatial analysis.

Conflict of Interest Statement

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The study is complied with research and publication ethics.

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