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Risk Assessment of Rockfall using GIS-Based Analytical Hierarchy Process: A Case Study of Bitlis Province

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ABSTRACT

Rockfall is one of the important natural disasters that can result in death, although it does not occur very often. Bitlis province in Turkey is frequently exposed to serious rockfall events due to its rugged-mountainous structure and harsh climatic conditions. Rockfall risk rely on many hazard factors such as slope, lithology, soil, elevation, precipitation, vulnerability factors i.e., land use and population. The Analytical Hierarchy process (AHP) is a highly skilled approach for risk assessment studies involving multiple decision-making criteria. In this study, the rockfall risk assessment of the province of Bitlis, which was chosen as the study area, was performed using AHP, and discussed. Geographic Information System (GIS) were used to visualize the results maps. The study concluded that the rockfall risks were mostly concentrated in the mountainous and rugged southwest and partially southeast areas, including the city and district centers. Except for the foothills of the volcanic mountains, the northern parts of the study area were generally considered as risk-free. The risk zones obtained from the study are relatively consistent with the results of a previous limited study.

1. Introduction

Rockfall is an important natural disaster that occurs in sensitive and steep rocky areas on earth and can result in death. While the rockfall mechanism is generally studied with theoretical deterministic approaches, the risk assessment is performed with spatial and statistical methods. One of the most effective methods of multi-parameter decision-making processes is Analytical Hierarchy Process (AHP). Combining AHP with GIS techniques capable of spatial analysis offers a powerful hybrid approach to risk assessment. Some remarkable studies in the literature on rockfalls are summarized as follows.

In the literature many different methods were used for assessments of the landslide and rockfall hazard. Deparis et al. (2007) performed a case study to assess the rock fall using ground radar measurements, because the stability of a potentially unstable rock mass is highly sensitive to the continuity of the joints cutting it. Guzzetti et al. (2002) developed a three-dimensional simulation program that generates simple maps useful to assess rockfall hazard, using GIS technology to manipulate existing thematic information available in digital format. The raster maps obtained from the program have some features such as the number of rockfall trajectories calculated in each grid cell, maximum velocity and maximum height. Marzorati et al. (2002) presented a statistical approach to analyze landslides and rockfalls induced by the 1997 earthquake in the Umbria and Marche region of Italy. All the data collected in the study were digitized and located with the aid of Geographic Information System. After that they performed a multiple regression analysis to determine the

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relationships between seismic factors and rock fall data. Ali et al. (2021) focused on the Besham-Chilas region of Pakistan, where rockfalls and debris flow frequently triggered by heavy rains. They used remote sensing-based techniques to identify potential hazardous sites and rated potential rockfall by using modified Pierson's rockfall hazard rating system (RHRS). One of the areas at risk of rockfalls is busy highways. Steep cutting slopes in natural ground created during road construction are the main cause of rockfall hazard. In the lawsuit filed over the fatal rockfall incident on the British Columbia highway in 1982, the Supreme Court of Canada decided that the authorities could easily foresee the risks that may occur and the accident could be prevented. This event demonstrated the importance of risk assessment on highways (Bunce et al. 1997). In another study, Budetta et al. (2016) applied a quantitative risk analysis to a busy road in southern Italy using the rockfall risk management method. Giani et al. (2004) proposed a methodology for the evaluation of the features of the motion of blocks detaching from a steep rock wall and traveling down the slope below, using real scale rockfall tests with two slopes having different morphology and lithology. The effect of the evaluated parameters on the prediction of the rockfall trajectory was investigated using dimensional numerical models. Katz et al. (2011) assessed the rockfall hazard along a rail corridor in Israel, using an inventory of historical information on past rockfall events, field surveys supported by interpretation of aerial photographs, and digital rockfall modeling. Li and Lan (2015) presented a short review on the probabilistic approaches widely used for modeling of rockfall trajectories. Based on a probabilistic approach, Canal and Akın (2016) investigated slope stability of high and steep sedimentary rock cut slope along highway in Adicevaz-Bitlis (Turkey) where possible rockfall events occur. Avtia (2016) carried out a rockfall assessment using the GIS-based AHP, taking into account some physical characteristics of the rock criteria. The author integrated the GIS hazard maps and AHP to categorize the rockfall risk. Shirzadi et al. (2017) analyzed the rockfall susceptibility of a region in Iran using three different methods together with the AHP. Some criteria affecting on the rock falls including slope angle, aspect, curvature, elevation, distance to road, distance to fault, lithology and land use were considered in their study.

The literature review presents many reasons and approaches to investigate the rockfall hazard assessment. Many criteria are considered to be sensitive to rockfall hazard in multivariate decision-making processes such as earthquake, precipitation, slope, lithology, land use. In this study, rockfall risk assessment was carried out within the borders of Bitlis province in Turkey using GIS-based AHP.

2. Study Area

The concept of landslide is defined as the downward movement of rock, rubble and soil materials or their mixtures with the effect of gravity (AFAD, 2020). Considering the landslide/rockfall data in Turkey, it is seen that most of them are rockfalls, slides and flows. Black Sea, Eastern Anatolia and Central Anatolia regions are the areas where landslides are frequently seen in Turkey due to the mountainous/rough and eroded surface of the earth. Bitlis province, which has a rugged and mountainous structure, is located in the Eastern Anatolia Region of Turkey. As seen on the map in Fig. 1, 412 landslide/rockfall events were reported in the study area (Bitlis) between 1950 and 2019. This rate is above the national average. Approximately 90% of the study area is mountainous, while the remaining 10% consists of plateaus and plains. The height of the important mountain, known as Nemrut Mountain, which is also a volcano in Bitlis, exceeds 3,000 m. There were 2956 rockfall events in Turkey in 2008, corresponding to 10% of the disasters that occurred in the country. Rockfalls account for 7% of the total number of people affected by disasters (Gökçe et al. 2008). Bitlis is one of the riskiest provinces in Turkey in terms of rockfalls. There were 67 rockfall events in Bitlis province between 1965 and 2010 (Ekinci et al. 2020). Bitlis province is exposed to significant rockfall events due to its unfavorable geological and morphological features. The mountainous and steeply sloping nature of the study area increases the hazard and risk of rockfall. In addition, especially in mountainous areas such as the Bitlis-Diyarbakır highway along the Bitlis stream, the cut slopes for highways are another important cause of rockfall events. Another important factor in rockfall is seismic movements. According to Isik et al. (2012), the study area is in an active seismic region and earthquake risks for this region continue. Excessive precipitation and freeze-thaw events in the cold winter months are also factors that trigger rockfalls. The region is an area with microclimatic features that receives the most snowfall in Turkey (Aydin et al. 2015).

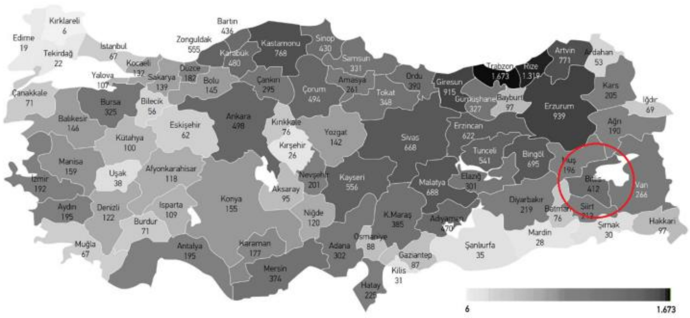

Fig. 1. Location of study area and rockfall/landslide events in Turkey between 1950 and 2019 (AFAD, 2019)

3. Results and Discussion

3.1. Rockfall Risk Assessment

The Analytical Hierarchy Process (AHP) used in this study is the most widely used and tested method among the Multi-Criteria Decision-Making Methods (MCDM). Saaty (1980), inspired by Myers and Alpert (1968), developed this method. AHP is a flexible mathematical model that considers the priorities of events and evaluates both quantitative and qualitative criteria in decision-making problems (Dağdeviren et al. 2004). The method consists of decision stages where values are assigned and alternative values are determined according to the criteria chosen to manage the decision-making process. As the first step in AHP, hierarchical structure and comparison matrix are described. After that, the comparison matrix is converted into a priorities vector and the compliance rate is determined based on the random index values (Can, 2019). In Fig. 2, Wang et al. (2008) shows the schema of the three-level hierarchical structure for a MCDM problem. In this schema, while the top level represents the decision goal, the lower level the criteria, and the lower levels, if any, represent the lower alternatives. The lowest level contains decision options. For the consistency of pairwise comparison, the number of criteria and each criterion should be defined correctly. AHP can be used with many criteria according to their common characteristics. Once the hierarchical structure is established, the importance levels of the criteria are determined mutually. In the pairwise comparison between the criteria, the importance intensity of the criteria is scored between 1 and 9 in consultation with the decision makers, as in Table 1 (Wang et al. 2008).

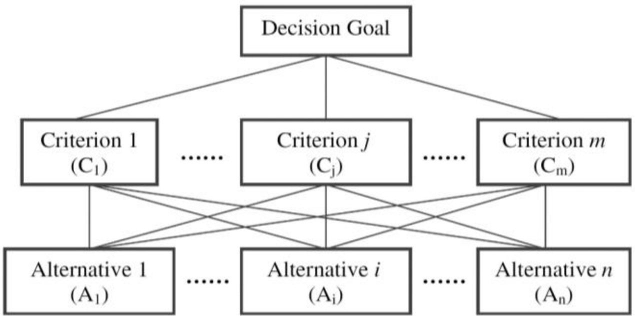

Fig. 2. Schema of three-level hierarchical structure for a MCDM problem (Wang et al. 2008)

Table 1. Importance intensities for pairwise comparison in AHP (Wang et al. 2008; Saaty, 1990)

Importance intensity (Scores)	**Definition**
1	Equal importance
3	Moderate importance of one over another
5	Strong importance of one over another
7	Very strong importance of one over another
9	Extreme importance of one over another
2, 4, 6, 8	Intermediate values
Reciprocals	Reciprocals for inverse comparison

The normalized matrix is obtained by dividing each element of the comparison matrix by the sum of the columns. The average of each row of the normalized matrix yields the weight vector. The product of the comparison matrix and the weight vector gives the following priorities matrix.

$$[AW_i] = [A][W_i] \quad (1)$$

The maximum eigenvalue (λmax) is obtained by the following equation:

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

where, n is criteria number, A is the pairwise comparison matrix, W is the weight vector. This method for determining the weight vector is called the principal right eigenvector method (EM) (Saaty, 1980). It is recommended that the pairwise comparison matrix A have an acceptable consistency that can be checked by the following consistency ratio (CR) (Wang et al. 2008):

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

$$CR = \frac{CI}{RI} \quad (4)$$

In which, the CI is the consistency index, RI is the random inconsistency index taken from Table 2.

Table 2. RI values according to numbers of criteria (n = 1 – 10) (Saaty, 1990)

n	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

For CR<0.10, the comparison matrix has acceptable consistency; otherwise, the decision-making process is repeated until consistency is achieved. CR = 0.00 means the best value for consistency (Saaty, 1990; Subramanian and Ramanathan, 2012).

Based on the expert's opinion according to the scaling in Table 1, the pairwise comparison matrix in Table 3 was obtained. After obtaining the normalization matrix in Table 4 by dividing the scores in Table 3 by the sum of the related column, the weights vector of the criteria were determined by taking the average of the rows. The parameters of AHP were calculated as λmax = 9.702, RI = 1.45 from Table 2, CI = 0.088 and CR = 0.06. The consistency ratio CR = 6% < 10% which indicates consistency of the comparison matrix. As a result, the weights were determined as 29% slope, 22% lithology, 16% the soil, %10 precipitation, 5% distance to stream, 6% elevation, 7% aspect, 3% land use and 2% population.

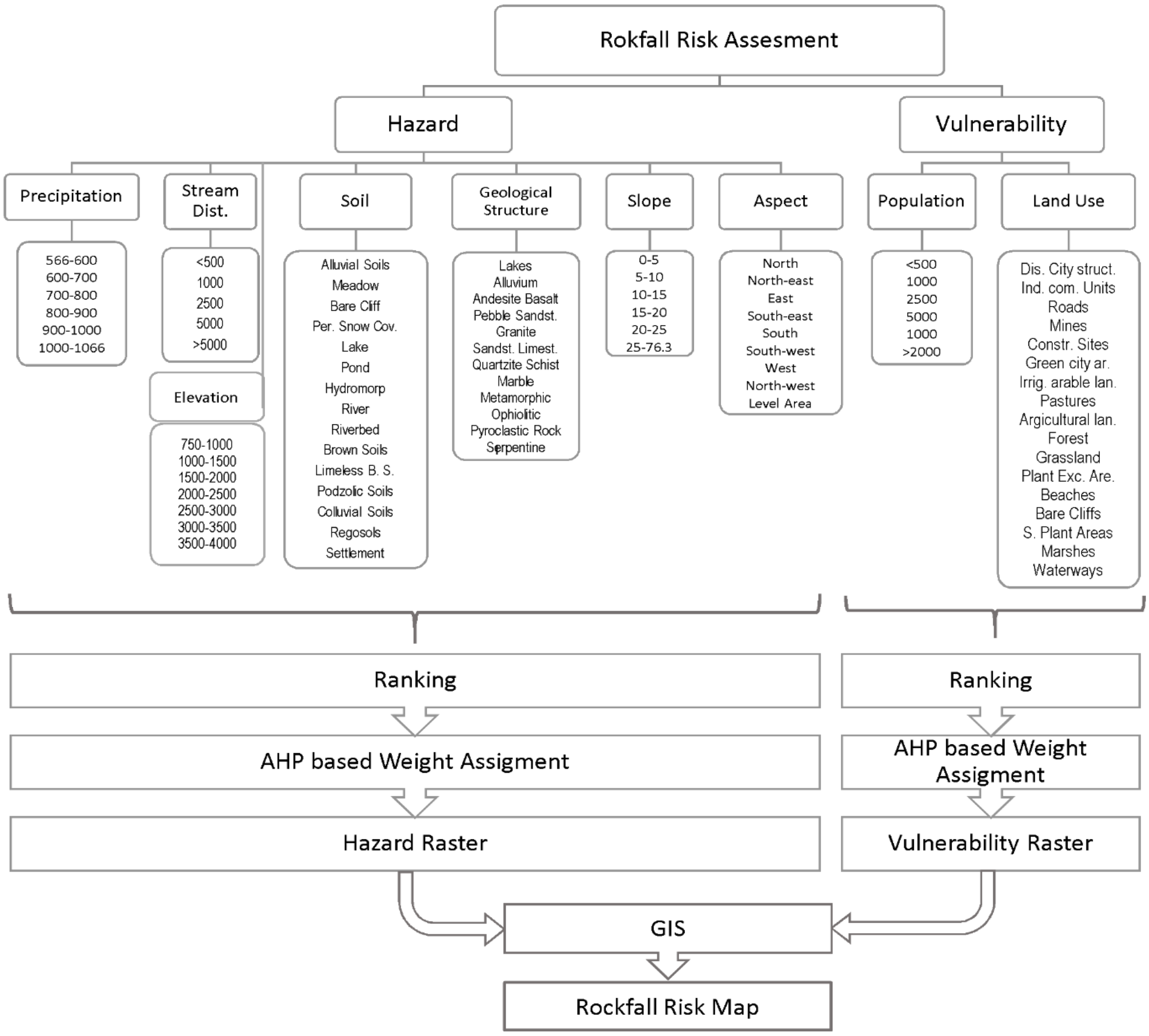

Fig. 3. Flow-chart of the GIS-based AHP for rockfall risk assessment

Table 3. The pairwise comparison matrix for flood risk of the region

Matrix A	Slope	Lithology	Soil	Precipitation	Dist. to stream	Elevation	Aspect	Land use	Population
Slope	1	2	3	3	4	5	7	7	9
Lithology	1/2	1	3	3	4	5	3	7	9
Soil	1/3	1/3	1	4	5	3	3	4	8
Precipitation	1/3	1/3	1/4	1	5	2	2	3	5
Distance to stream	1/4	1/4	1/5	1/5	1	1/2	1/3	2	5
Elevation	1/5	1/5	1/3	1/2	2	1	1/2	3	3
Aspect	1/7	1/3	1/3	1/2	3	2	1	3	2
Land use	1/7	1/7	1/4	1/3	1/2	1/3	1/3	1	2
Population	1/9	1/9	1/8	1/5	1/5	1/3	1/2	1/2	1
TOTAL	3.01	4.70	8.49	12.73	24.70	19.17	17.67	30.50	44.00

Table 4. Determination of weight vector from the normalization matrix

Matrix A	Slope	Lith.	Soil	Precip.	Distance to stream	Elevation	Aspect	Land use	Popul.	**Wi**
Slope	0.332	0.425	0.353	0.236	0.162	0.261	0.396	0.230	0.205	**0.289**
Lithology	0.166	0.213	0.353	0.236	0.162	0.261	0.170	0.230	0.205	**0.222**
Soil	0.111	0.071	0.118	0.314	0.202	0.157	0.170	0.131	0.182	**0.162**
Precipitation	0.111	0.071	0.029	0.079	0.202	0.104	0.113	0.098	0.114	**0.102**
Distance to stream	0.083	0.053	0.024	0.016	0.040	0.026	0.019	0.066	0.114	**0.049**
Elevation	0.066	0.043	0.039	0.039	0.081	0.052	0.028	0.098	0.068	**0.057**
Aspect	0.047	0.071	0.039	0.039	0.121	0.104	0.057	0.098	0.045	**0.069**
Land use	0.047	0.030	0.029	0.026	0.020	0.017	0.019	0.033	0.045	**0.030**
Population	0.037	0.024	0.015	0.016	0.008	0.017	0.028	0.016	0.023	**0.020**

3.2. Spatial Analysis

Using the obtained scoring and weights, raster maps of each criterion were obtained with the ArcGIS program as in Fig. 4. The projection system of all criteria was transformed into a common projection system through Arctoolbox - Projections and Transformations - Raster Protect. After, the raster data was reclassified by means of Arctoolbox -3D Analst Tools - Raster – Reclass, the data was converted into vector data via Conversion Tools – From Raster – Raster to Polygon. Then, vector data was integrated with Data Management Tools – Generalization – Dissolve. Scoring inputs was defined in the attribute table of each criterion through Data Management Tools- Fields - Add Field toll.

In Fig. 4, scoring maps of nine criterion in Fig. 3 are given by taking the expert opinions or decision makers. In the lithology map in Fig. 3, the geological structures sensitive to the rockfall were scored low, while loose structures sensitive to rockfall such as alluvial, conglomerate, sandstone, serpentine were scored high. On the slope map, higher slopes are more susceptible to rockfall and lower slopes are scored low. In the elevation map, considering that rockfall will not pose a hazard in high elevation sections and rocks falling from high areas will pose a hazard at lower elevations; high areas were scored low, and low-elevation sections were scored high. Since the effect of slope versus elevation is dominant in the pairwise comparison matrix, the risk of rockfall is reduced on low plains. The sections exposed to more freeze-thaw events in the aspect map were considered more sensitive to rockfall events than the south facades. On the soil map, loose soil structures that can be susceptible to rockfalls, especially in rough terrain, were highly scored on the map. Since the steep slopes close to the rivers are always risky areas in terms of rockfalls due to the erosion effect of the river, the regions close to the stream are rated with high scores on the distance to stream map. Areas with high precipitation were selected as more dangerous in terms of rockfall due to the erosive and freeze-thaw effect of precipitation, as seen precipitation map. Also, land use and population maps were scored according to their vulnerability to rockfall.

Based on the raster maps in Fig. 4 and the criteria of weights obtained from the AHP, the final map for the rockfall presented in Fig. 5 was obtained using the GIS technique. According to this map, especially the steep slopes of the rugged southwest regions are high risk for rockfall. The effect of steeply sloping river valleys in the region is clearly seen in the risk assessment. It can be said that another reason for the high risk in these areas is the concentration of precipitation in these areas. In addition, the southeast region is partially under the influence of medium-high risk. Except for the foothills of Mount Nemrut and Suphan, the northern parts of the study area are generally considered as risk-free. Göksu and Leventeli (2008) also investigated potential rockfall hazard of the Bitlis province using remote sensing. For this, first digital elevation model of the area was created by using GIS, then potential rockfall risks was mapped considering only the slope and digital elevation model (DEM) as in Fig. 6. The high-risk regions in Figs. 5 and 6 match each other; however, the risk map in this study (Fig. 5) provides much more detail thanks to AHP with multiple decision criteria.

In the southern part of Bitlis, which is located on the thrust zone, the rocks lose their primitive position and contain many discontinuities as seen in Fig. 7. The rockfalls hazard is high due to the cracks especially in formations dominated by limestones with a large amount of discontinuity at high slopes and by the deformation and disintegration of the schist, calcite and volcano-sedimentary rocks below. In addition, filled discontinuities in ophiolite and serpentinite masses in this region can trigger rockfalls (Göksu and Leventeli, 2008). Filling of the discontinuities and cracks in rock masses with precipitation waters and freeze-thaw events are other important factors inducing rockfalls. Dissolution of basalt columns and prismatic ignimbrites that form steep slopes in the study area also poses significant risks in terms of rockfalls (see right photos in Fig. 7a-d).

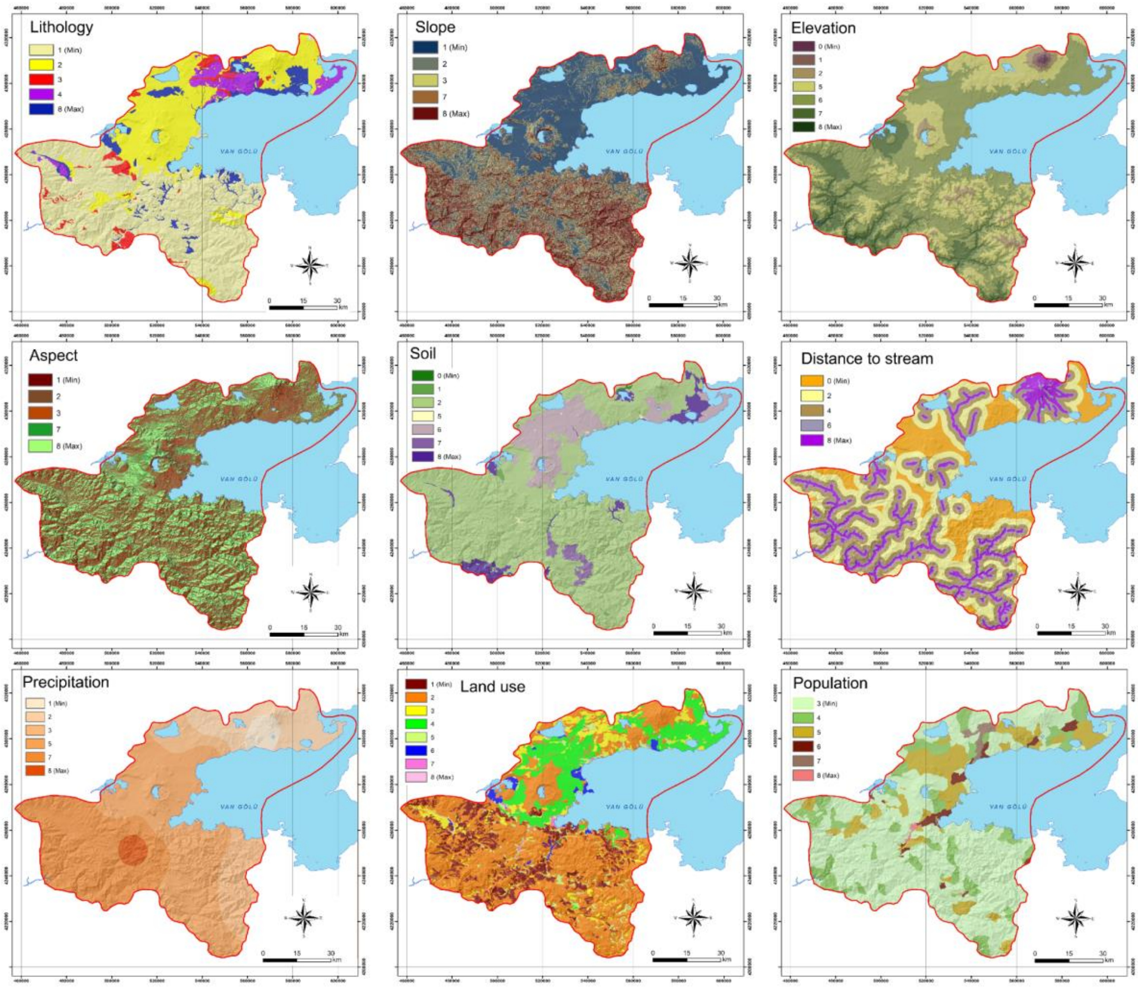

Fig. 4. Raster maps of the criteria

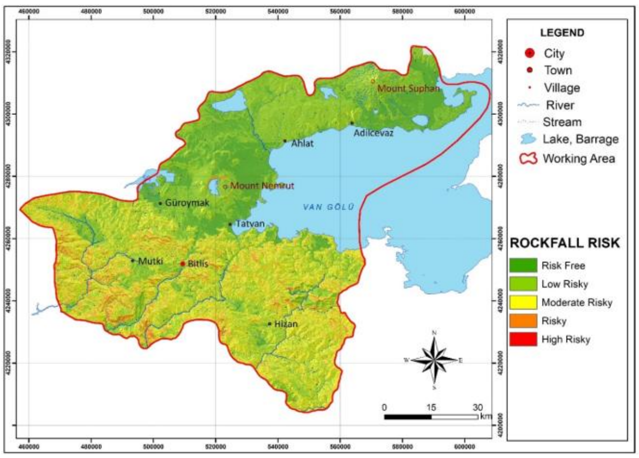

Fig. 5. Rockfall risk map of the study area in this study based on AHP

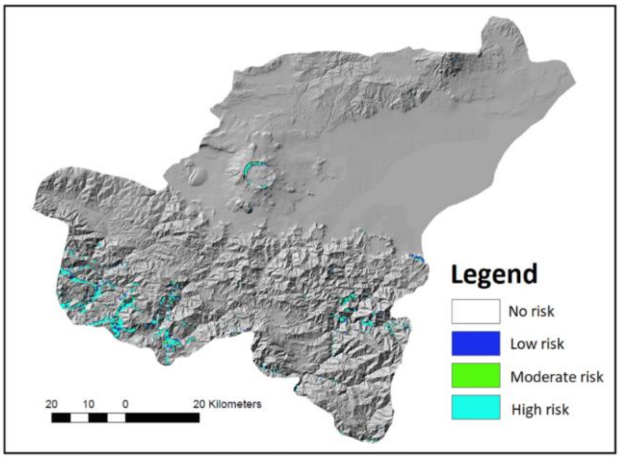

Fig. 6. Rockfall sensitivity map based on slopes and DEM (Goksu, 2017)

Fig. 7. Some photos of different lithological structures at risk of rockfall in the study area (a) and (b) cracked and decomposed ignimbrites, (c) Basalt columns, (d) prismatic ignimbrites

4. Conclusions

As a result of the rockfall risk assessment of the province of Bitlis; it was observed that the risk is high in areas with steep slopes, lithologically affected by meteorological events such as precipitation and freeze-thaw, where land use is intense or sparse and with loose soil characteristics, with high population density and with heavy precipitation is high. Rockfall risks were mostly concentrated in the mountainous and rugged southwest and partially southeast areas, including the city and district centers such as Bitlis center, Mutki and Hizan. Except for the foothills of Nemrut and Suphan mounts, the northern parts of the study area were generally considered as risk-free. The risk zones obtained from the study are relatively consistent with a limited study done before. In general, regions with mountainous steep slopes and discontinuous rock structures were considered as areas susceptible to high rockfalls. Heavy precipitation, river valleys with steep slopes are other important factors affecting rockfall. In this study, it has also been shown that GIS-based AHP is a very successful approach in risk assessments involving multiple decision variables such as rockfalls problems. The results of this study showed that a more consistent risk definition could be made with a holistic and multi-parameter assessment in a large settlement.

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