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Research Article

Earthquake Risk Assessment Using GIS-Based Analytical Hierarchy Process (AHP): The Case of Bitlis Province (Türkiye)

M. Cihan Aydin [1*], Elif Sevgi Birincioğlu [1], Aydın Büyüksaraç [2], Ercan Işık[1]

[1] Bitlis Eren University, Department of Civil Engineering, Bitlis, Türkiye
[2] Çanakkale Onsekiz Mart University, Çanakkale, Türkiye

* Corresponding author: M. Cihan Aydın
E-mail: mcaydin@mail.com

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Abstract

The risk level of natural disasters such as earthquakes depends on many factors. Some of these are direct hazards, while others are vulnerability factors that increase the risk. In this regard, risk assessment should be carried out by evaluating the hazard and vulnerability factors together. The Analytical Hierarchy Process (AHP) is a powerful tool for co-evaluating such multiple decision criteria. The spatial visualization of the results also facilitates direct risk assessment. In the present study, the seismic risk assessment of the Bitlis province in Eastern Anatolia, which has a high seismic risk, was carried out by using the GIS-based AHP method. Among many criteria, six effective criteria of earthquake risk such as seismicity, demographic and topographic criteria were considered based on expert decision makers. It is concluded that the results of the study were quite successful in terms of determining the seismic risks of the study area. Accordingly, while the risks are high in densely populated settlements with high peak ground acceleration (PGA), the risk decreases with soil and land use.

Keywords: Earthquake, Geographic Information System, Analytical Hierarchy Process (AHP), Seismic Risk, Spatial Analysis

Introduction

Disasters are the destruction of the natural environment, but they are but they are also events whose consequences must be prevented. For this reason, predetermination of the risk of natural disasters is very important for modern disaster risk management. The United Nations (UN) defines natural disasters as natural events that significantly disrupt the socio-economic and socio-cultural activities of the society, cause loss of life and property, and are beyond local capacity to cope with. The magnitude of the disaster can be measured in terms of the loss of life and property losses. For natural disasters that cannot be prevented, such as earthquakes, some precautions can be taken. The most important of these is an effective disaster management, including a detailed and comprehensive risk analysis. In this way, the harmful effects can be minimized by taking precautions against possible disasters. Disaster management planning should be comprehensive, assessing many factors such as socio-economic, cultural, geological structure, population, land use and hazard factors in a region.

A problematic aspect of physical planning for different purposes is the variety of data types evaluated for analysis and the difficulties in relating them to each other. The use of multi-criteria models in which different types of data are evaluated together, is now widespread. One of the effective multi-criteria decision-making method is the Analytical Hierarchy Process (AHP) developed by Saaty (1977). The AHP method is a flexible modelling tool for solving large-scale problems in which effective criteria pairs are scored at all levels. AHP is a very powerful method for solving problems involving subjective and objective criteria and has been successfully used in many fields, especially in recent years (Timor, 2011). In this method, mathematical decision-making is the main important advantage of the method (Saaty, 1980; Jankowski 1995; Malczewski, 2004). Spatial visualization of these model results with supporting tools such as Geographical Information Systems (GIS) provides significant benefits to users and researchers. GIS is effectively used in many processes such as data storage, analysis, querying and visualization with the development of technology. GIS, which started to develop rapidly towards the end of the 1970s, continues to be widely used for various purposes around the world, especially for spatial analysis (Taherdoost et al., 2023).

Such multi-criteria decision-making processes using GIS can be successfully applied to on the assessment and spatial visualization of disaster risks such as earthquakes. There are many studies in this area in the literature. An earthquake physical vulnerability map using the ordered weighted averaging (OWA) operator was applied by Moradi et al (2015). Erden and Karaman (2012) proposed a model for earthquake hazard map simulation by evaluating the weights of common parameters effective in earthquake formation using AHP. Peng (2015) integrated the results of different Multi-Criteria Decision-Making methods to provide a regional earthquake vulnerability assessment. Cil and Arman (2001) applied AHP to identify a new settlement in Adapazari (Turkey). The criteria used in the study are geological structure, natural wealth, forest, agricultural and irrigation areas, the status of trade centers and workplaces, the status of areas that can be opened for development in the future, transport status and cost of investment. The study aimed to determine the settlements by taking into account the possible loss of life and property due to earthquakes. Ozsahin (2014) analyzed the risk of earthquake damage in a sample of a settlements using Geographic Information System (GIS)-supported AHP. Lithology, distance to fault lines, earthquake zone classification, maximum ground acceleration coefficient, hydrogeology, landforms, slope and distance to rivers were considered as factors affecting earthquake hazard in their analysis. The results of the study indicated that the study area is under the risk of 73.8% strong earthquake damage.

In recent years, AHP supported by different methods has been used to determine the earthquake hazard and risk maps of specific regions (Yavasoglu and Ozden, 2017; Yalcin and Sabah, 2018; Demirkiran, 2019). In these studies, many different datasets such as transportation, infrastructure, building quality, number of floors, population, active fault, alluvium, epicenter points, elevation, slope, geology, GNSS and PS InSAR point velocities were used as multiple decision-making criteria. Apart from these studies, GIS-based AHP has been successfully applied by some other researchers for different risk assessments. Yalcin (2007) and Akinci et al. (2015) applied the method to landslide susceptibility considering many decision criteria such as slope, aspect, elevation, distance to streams, curvature, lithology, drainage density, precipitation distance to road, height, landslide inventory and land cover. Dandapat and Panda (2017), Ghosh and Kar (2018) and Ekmekcioglu et al. (2021) also conducted a flood risk assessment of their selected region using AHP based on demographic, socio-economic, infrastructure, hydro-meteorological and topographic criteria.

Based on these studies, it is seen that GIS-based AHP is a highly effective approach to assess the disaster risk of a particular region. In this study, the earthquake risk assessment of Bitlis Province, which is located in a high earthquake risk region and where no similar study has been conducted before, was carried out with a GIS-based AHP depending on some seismic, demographic and topographic data.

Materials and Methods

Methodology

The most preferred method, the Multi-Criteria Decision-Making (MCDM) method, is the Analytical Hierarchy Process (AHP). This method was first introduced by Myers and Alpert (1968), and then developed by Saaty (1977). AHP takes into account the priorities of the individual or group and evaluates quantitative and qualitative criteria together in decision-making problems (Dağdeviren et al. 2004). AHP can be preferred as a multi-criteria decision-making in many engineering applications such as hydrology, earthquake, and disaster risk assessment as well as in other fields. Using a flexible modelling solution tool, AHP, can evaluate multi-criteria problems by adding more criteria without enlarging the criterion matrix of the problem. Moreover, using numerical and linguistic term expressions, AHP simplifies complex problems by converting them into a tree structure, eliminating inconsistencies by determining effect weights on the criteria of decision makers. However, there are some disadvantages such as the inability to determine the results completely independently. Since it depends on the judgements of the decision makers, the inability to give precise scales, the need to reorganize the method when new criteria are added, and the in-group decision-making studies can take a lot of time (Timor, 2011). Thanks to the flexible structure of AHP in making critical decisions, many researchers have used the method by modifying it with various techniques (Yang et al. 2013; Budayan, 2019; Darko et al. 2019; Gurgun and Koc, 2020; Savun-Hekimoğlu et al., 2021).

Decision Criteria

A successful risk assessment depends on providing the necessary data for the study. In order to carry out the spatial analysis process, the criteria affecting the selection decision and the data should be correctly identified. In this study, six of the most effective decision criteria among the many used in earthquake risk assessment were considered: peak ground acceleration (PGA), the distance to active faults, the geological structure, the population density, the soil type and the land use. The relevant data for all the criteria were collected from the open access sources of the institutions (AFAD, 2021; HGM, 2021; USGS, 2020; Geofabrik, 2021; TAD, 2021; Copernicus 2021; MTA, 2021; TUIK, 2021). Peak ground acceleration (PGA) values for the highest ground motion level (DD-1) with a 2% probability of exceedance in 50 years (recurrence period of 2475 years) were obtained for 270 different geographical locations in Bitlis by using the Turkey Earthquake Hazard Maps Interactive Web Earthquake Application (TEHMIWEA). ZB was chosen as the local soil class, as specified in the Turkish Building Earthquake Code (TBDY-2018). ArcGIS software was used to map the data obtained for each criterion.

Analytical Hierarchy Process

The values assigned to the alternative criteria in the decision stage govern the AHP process. The creation of the hierarchical structure and the comparison matrix is the first step of AHP. In the next step, the generated comparison matrix is converted into a priority vector. Then, the compliance rate is calculated using a random index value (Can, 2019; Salifu et al., 2022).

As shown in Fig. 1, the hierarchical structure is determined at least three levels. There is decision goal at the top level, the criterions at a lower level, and low alternatives below if any. At the lowest level, there are decision options. The consistency of pairwise comparisons depends on the correct definition of the number of criteria and each criterion. Many criteria can be applied to AHP and these criteria should be classified according to their common characteristics. Once the hierarchical structure is established, the importance levels of the criteria are obtained by comparing the two criteria in AHP. The information from these comparisons is used to create the comparison matrix. Decision makers rank the criteria from 1 to 9 and determine which criterion is more important for the decision goals making pairwise comparisons between the decision criteria (Wang et al. 2008). The general form of a pairwise comparison matrix can be described as follows (Timor, 2011).

$$A = \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{bmatrix} = \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ 1/a_{1n} & \cdots & a_{nn} \end{bmatrix} \quad (1)$$

The relationship between the pairwise comparison scores of two reciprocal criteria can be defined as $a_{21}=1/a_{12}$. The relative importance of the criterion to each other can be calculated using the pairwise comparison scale shown in Table 1.

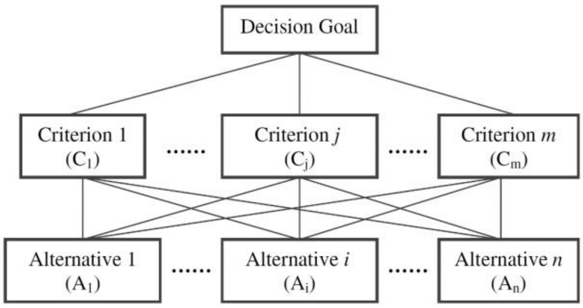


Fig. 1. Hierarchical chart of a multi-criteria decision-making (Wang et al. 2008)

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

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

Once the weights of the criteria are determined by asking experts in the scope according to Table 1, the pairwise comparison matrix are determined. The normalized matrix is obtained by dividing each element of the comparison matrix by the sum of the columns. The weight vector is determined by averaging each row of the normalized matrix. As a result, the comparison matrix and the weight vector are multiplied as follows to obtain the priorities matrix.

$$[AW_i] = [A][W_i] \quad (2)$$

The maximum eigenvalue (λ_{max}) is computed with the following equation by averaging the elements of the new vector obtained by dividing all the elements of the priorities matrix by the reciprocal elements of the weight vector.

$$\lambda_{max} = \frac{1}{n}\sum_{i=1}^{n}\frac{AW_i}{W_i} \quad (3)$$

where, n is number of the criteria or order of pairwise comparison matrix, A is the pairwise comparison matrix, W is the weight vector. The consistency of the decision maker's scores is checked by the following consistency ratio (CR) of the pairwise comparison matrix (Wang et al. 2008):

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

where, the CI = (λ_{max}-n)/(n-1) here can also be expressed as the consistency index. The random inconsistency index (RI) can be found from Table 2 depending on n number.

Table 2. Random inconsistency index against the order of pairwise comparison matrices (1 – 15) (Saaty, 1990)

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

If CR < 0.10, the consistency of comparison matrix is acceptable, otherwise the decision-making process is repeated until consistent judgments are obtained (Subramanian and Ramanathan, 2012).

Seismicity of the Study Region

The area of Bitlis, located in the Eastern Anatolia Region of Turkey, is 6,706 km^2. The region lies between 41º 33' - 43º 11' east longitudes and 37º 54' - 38º 58' north latitudes. The distance between the ends of the province is 144 km in the east-west direction and 120 km in the north-south direction. It is surrounded by Van to the east, Ağrı to the northeast, Muş to the northwest, Batman to the west and Siirt in the south. Bitlis province has six districts, namely Adilcevaz, Ahlat, Güroymak, Hizan, Mutki and Tatvan. The city center of Bitlis, located to the west of Lake Van, is located at an altitude of approximately 1550 m above sea level. The geographical boundaries of the province are approximately 71% mountainous, 19% plateaus and 10% plains (Gür et al., 2012).

The general tectonic structure of the Eastern Anatolia Region is mainly controlled by the northward motion of the Arabian and Anatolian plate which collide along the deformation zone known as the Bitlis Thrust Zone. The collision is governed by the right-lateral strike-slip North Anatolian Fault and the left-handed East Anatolian Fault, which converge at the Karlıova Triple Junction (Fig. 2). In addition, due to this collision, mostly NW-SE trending dextral faults and NE-SW trending left directional faults are the dominant elements of the region. E-W trending Muş – Van Lake and Pasinler ramp basins are other prominent tectonic elements of the Eastern Anatolia Region (Isik et al. 2012). The 2003 Bingöl (Mw = 6.4), 2011 Van (Mw = 7.2), and 2020 Elazığ (Mw = 6.8) earthquakes are some of the more destructive seismic ground motions in the region (Isik et al 2020). This region, which also has a volcanic structure, has been subject to significant earthquakes throughout its history and seismic activities continue recently. It is noted that more work is needed to take measures to eliminate the risks in earthquake-prone region (Isik 2010). The region has one of the longest active faults in Turkey. The 1939 Erzincan earthquake, the largest recorded earthquake in Turkey, also occurred in this region (Alkan et al. 2021). These similar seismicity data highlight the seismic risk of the region.

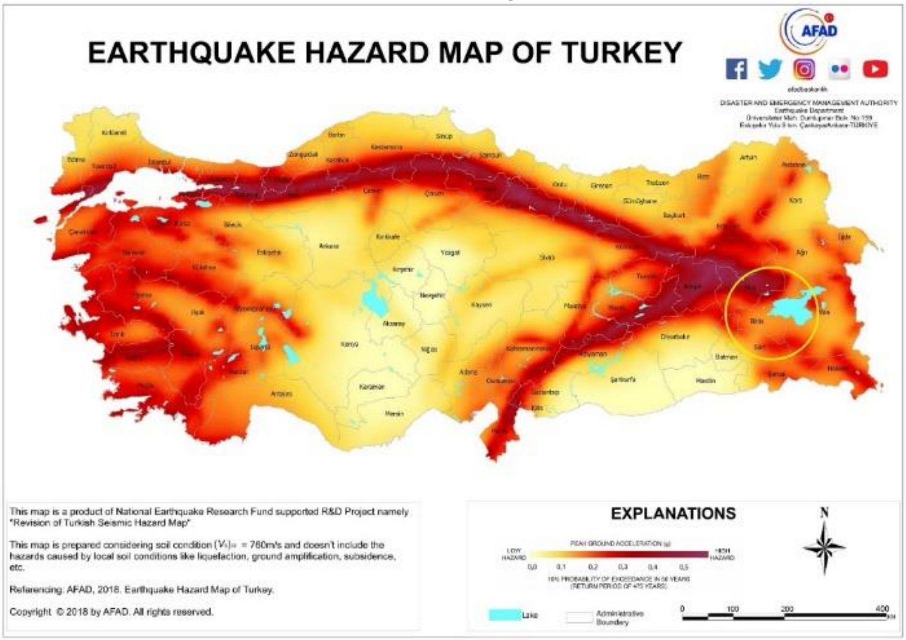


Fig. 2. Earthquake hazard map of Turkey according to distribution of PGA values (AFAD, 2018).

Results and Discussion

The earthquake risk scores were obtained by combining the hazards and vulnerability criteria. Earthquake risk was considered as a combination of both the factors that generate the earthquake hazard (ground acceleration, distance to the fault, geological structure) and the factors that increase the vulnerability to the impact of the earthquakes on loss of life and property (population, soil, land use), as detailed in Fig. 3. Accordingly, as used in most disaster risk management, risk can be generally expressed in the following relationship (Wisner et al. 2004; Masood and Takeuchi 2012; Dandapat and Panda, 2017; Chakraborty and Mukhopadhyay, 2019):

Risk (R) = Hazard (H) × Vulnerability (V) (5)

Vulnerability can be defined as the potential for damage to the environment, people and economic assets exposed to natural disasters, while hazard refers to the degree of impact of natural disasters. Unless these two factors come together, there is no risk. In this study, the flowchart and framework of the method developed based on GIS-based AHP are detailed in Fig. 3. GIS is an excellent tool for combining hazard and vulnerability maps to create the risk maps. The final risk score was estimated based on determined weights (w_i) and overall criteria (c_i) and from AHP as follows (Hajkowicz and Collins 2007; Ekmekcioglu et al., 2021).

$$R = \sum_{i=1}^{n} w_i \times c_i \quad (6)$$

Although fault lines are the primary factor contributing to the occurrence of earthquakes, the PGA factor is more decisive in terms of earthquake risk. Earthquake energy propagates in waves from the center, causing ground motion in multiple directions, but is typically modelled horizontally and vertically. In order to define the earthquake hazard, the acceleration, velocity and displacement levels that an earthquake will produce in a given area need to be defined. These levels are also an indicator of the vulnerability of a given area. Accordingly, identification is made by considering the levels at which these physical parameters, as well as the values that define the magnitude of the earthquake, are greatest (Geologic Hazards Science Center, 2011; Whole Building Design Guide, 2010). In this study, PGA, distance to fault, geological structure, soil, land use and population maps were used as input dataset in earthquake risk analysis as shown in the pairwise comparison matrix in Table 3. The pairwise comparison matrix was marked according to the scale in Table 1 by taking into account the opinions of the experts.

Table 3. The pairwise comparison matrix for earthquake risk of study area

Matrix A	PGA	Land use	Soil	Popul.	Geolog. structure	Fault dist.
PGA	1	2	1	2	1	2
Land use	1/2	1	1	2	2	2
Soil	1	1	1	1	2	3
Population	1/2	1/2	1	1	4	3
Geological structure	1	1/2	1/2	1/4	1	2
Fault distance	1/2	1/2	1/3	1/3	1/2	1
TOTAL	4.50	5.50	4.83	6.58	10.50	13.00

In the comparison matrix in Table 3, the values in each column were summed, then each value in the comparison matrix was divided by the column sum to determine the normalization matrix given in Table 4. The average of each row of the normalization matrix yields the weights vector in the last column of Table 4.

Table 4. The normalization matrix and weight vector

Matrix A	PGA	Land use	Soil	Population	Geol. Struc.	Fault dist.	W_i
PGA	0.22	0.36	0.21	0.30	0.10	0.15	0.224
L. use	0.11	0.18	0.21	0.30	0.19	0.15	0.191
Soil	0.22	0.18	0.21	0.15	0.19	0.23	0.197
Pop.	0.11	0.09	0.21	0.15	0.38	0.23	0.195
Geolo. Stru.	0.22	0.09	0.10	0.04	0.10	0.15	0.117
Fault dist.	0.11	0.09	0.07	0.05	0.05	0.08	0.074

Once determining the priorities matrix using Eq. (2), the maximum eigenvalue (λ_{max}) was calculated as 6.50 by Eq. (3). CI and RI values were obtained as 0.10 and 1.24 respectively (Table 2) then the consistency ratio (CR) was calculated as 0.08 from Eq. (4) that should be less than 0.1 for consistency of the comparison matrix. Consequently, based on the pairwise comparisons of the layers with the AHP, the weights of the considered criteria were obtained 22% of the PGA, 19% of the land use, 20% of the soil, 19% of the population, 12% of the geological structure and 8% of the fault distance.

Spatial Analysis for Seismic Risk

The weights of the criteria determined above were converted into a common projection system with the help of ArcGIS tools. The raster data were reclassified by means of Arctoolbox-3D Analyst Tools and the weight values of each criterion were entered into the scoreboard. The raster data maps generated by scoring the quality values of the criteria determined according to the seismic risk on a scale of 1-8 are presented in Fig. 4.

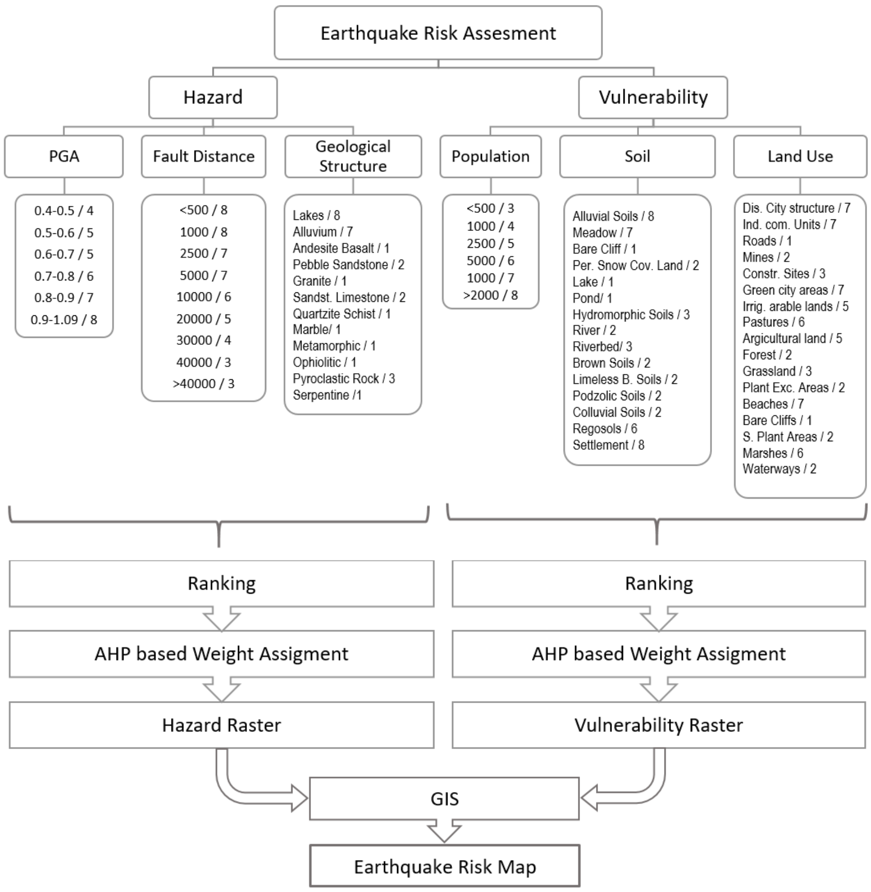
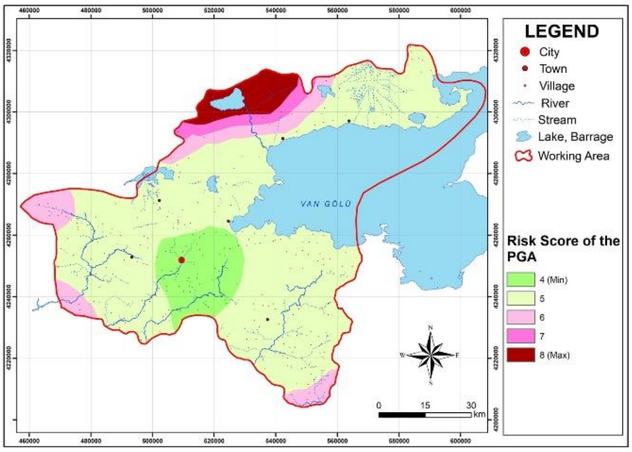


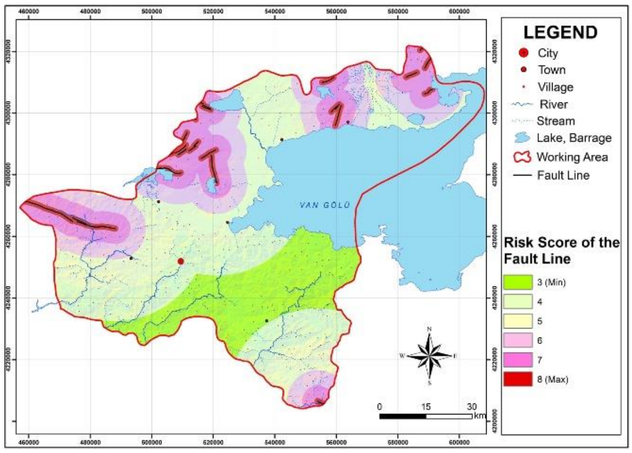
Fig. 3. Hierarchical flow chart for the earthquake risk assessment

Fig. 5 shows the earthquake risk maps obtained from AHP. Some hazard maps such as PGA and fault distances was presented in Fig. 6 to compare the risky areas with the hazard region as well. According to these risk maps, Bitlis, Tatvan, Ahlat and Adilcevaz settlements with high population density and the active fault zone in the west of the province are in high-risk areas. On the other hand, the southern regions, which are relatively flat and have a higher earthquake sensitivity, are considered to be at medium risk.

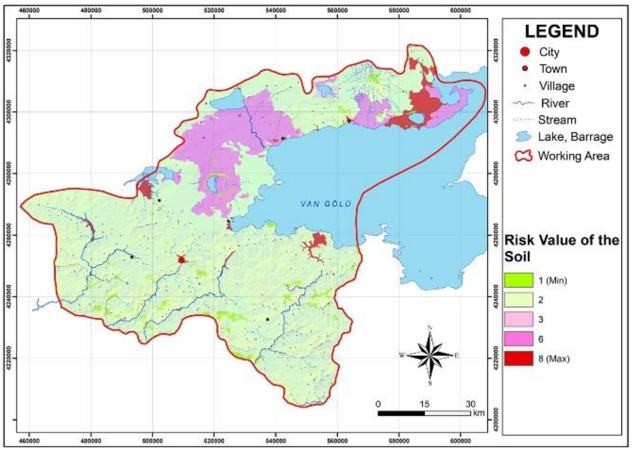
The areas that are close to the fault line, have a higher PGA, are not resistant to earthquakes in terms of geological structure, soil and land use characteristics, and have a high population density are identified as high and very high risk areas. Accordingly, it has been determined that the risk is high in the southeast of Hizan, northwest of Mutki, northwest of Ahlat and close to the center of Adilcevaz, where the active fault lines pass and the PGA value is high.



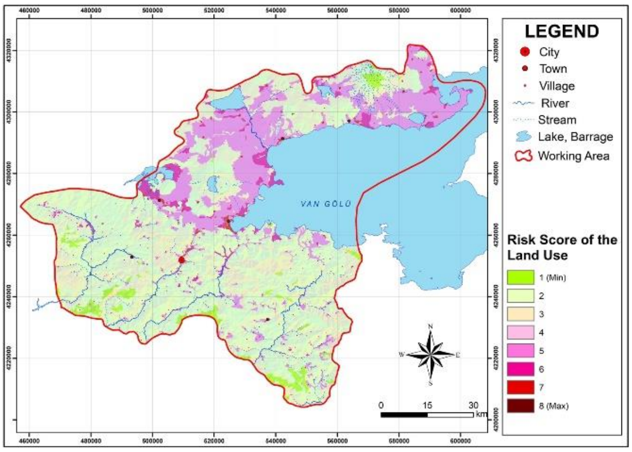
a) PGA



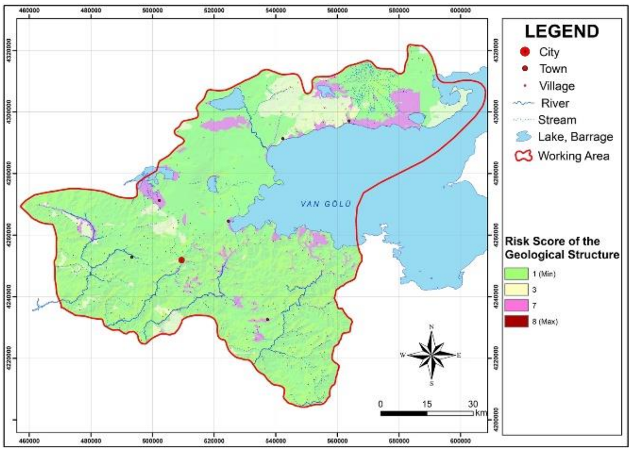
b) Fault distance



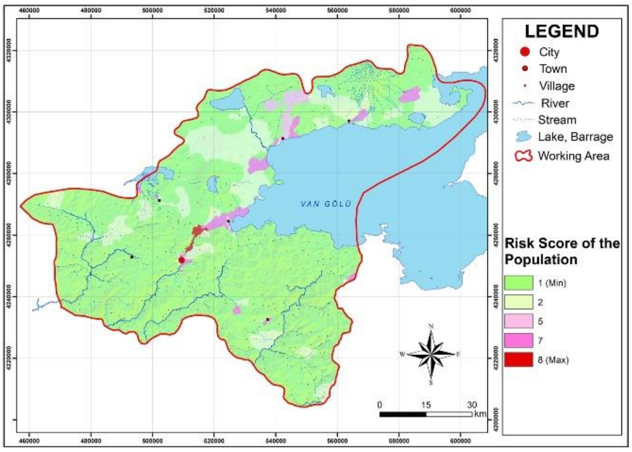
c) Soil



d) Land use



e) Geological structure



f) Population

Fig. 4. Raster maps of the selected criteria scored

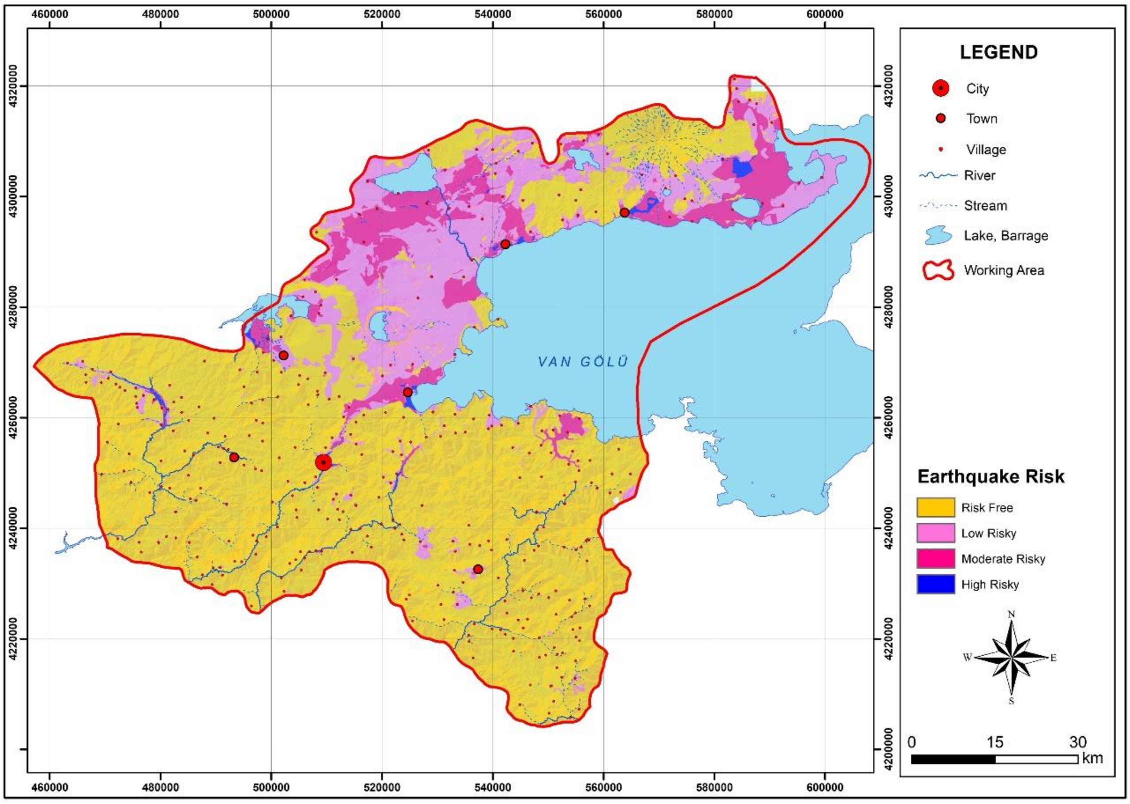


Fig. 5. Earthquake risk maps of the Bitlis

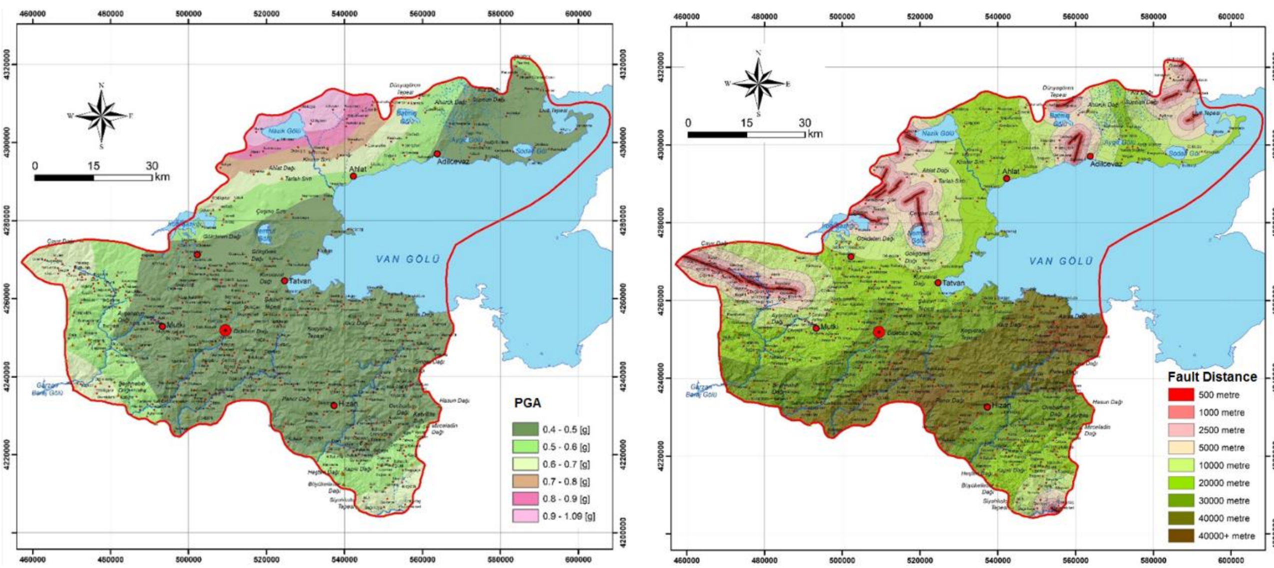


Fig. 6. Earthquake hazard maps of the Bitlis: a) PGA values, b) Distance to fault

Conclusion

Earthquakes cause the greatest loss of life and property among all natural disasters. Determining the earthquake risk to settlements cannot be treated locally like the risks in other types of disasters. Since earthquake is a regional interaction, it is possible to define the earthquake risk by considering the target area as the center and a wider region. In this context, the determination of the earthquake risk of the city of Bitlis located near to the intersection of the North Anatolian and East Anatolian Fault Zones, was carried out in line with these principles. When historical and instrumental earthquakes are examined, Bitlis province, which has been exposed to major earthquakes, is also under the influence of faults located in settlements such as Muş, Bingöl and Van, which can produce significant earthquakes. The risk potential is higher in the regions due to the presence of faults such as the Kavakbaşı Fault, Nemrut Extending Fractures, Süphan Fault, Muş Thrust, Manzikert Fault and Ahlat Segment, which are completely or partially within the borders of Bitlis province.

In this study, a holistic risk assessment was carried out by considering the vulnerability parameters such as population density, land use, geological structure, soil, as well as the effective seismic hazard parameters in determining the risks. For this purpose, GIS-based AHP was used as an excellent tool for performing multi-parameter spatial analyses. It was found that the obtained maps are quite effective in determining the earthquake risks of the study area. The criteria and parameters considered in the study were obtained for the whole study area.

As a result of the risk assessment obtained, it has been observed that the risk is very high especially in the densely populated city centers. On the other hand, especially in the northern regions, the soil and land use together with the PGA increase the risk to a generally moderate level and partially to a high level. Therefore, this study can be used as an example for risk prioritization at the pre-disaster stage, which is an important part of modern disaster management, especially in small settlements. Obtaining risk priorities more practically and scientifically by considering different parameters will facilitate the decision-making processes of decision makers. Finally, it is recommended that by adding parameters related to buildings to those considered in this study, the seismic risk analysis of settlements can be taken to further stage.

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