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An avalanche hazard model for Bitlis Province, Turkey, using GIS based multicriteria decision analysis

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Abstract: Most avalanche fatalities in Turkey have occurred in Bitlis Province. The scope of this research was to identify the avalanche hazard area of that province, using geographical information system (GIS) based multicriteria decision analysis (MCDA) and to evaluate it by means of sensitivity and accuracy analysis. The model consists of 5 GIS layers: elevation, slope, aspect, vegetation density, and land use. The hazard model is obtained by using a comparison matrix where all identified criteria of GIS layers are compared against each other. The acceptability of the model was determined using historical events. All of these events plotted over the model showed that there is a remarkable coincidence with high hazard areas. Approximately 90% of avalanche events have occurred in the high and moderately high areas. Settlement areas cover approximately 39,741 ha of study area and just 41 settlement areas (villages and towns) have ideal topographic characteristics to prevent avalanche hazard, while 82% of them are not suitable. The avalanche hazard model shows that the southeast and southwest parts of Bitlis (Center), Tatvan, and Hizan counties have the highest avalanche hazard. Therefore, site planning, construction of supporting structures, and control programs should be effectively integrated with avalanche pathways in potential areas.

Key words: Avalanche, multicriteria decision analysis (MCDA), geographic information system (GIS), analytic hierarchy process (AHP), sensitivity analysis, Bitlis, Turkey

1. Introduction

Turkey has suffered a number of huge avalanches in mountainous regions. According to the statistics for 1950–2008, a total of 1370 people have been killed by avalanches (Varol and Yavas 2006; Yavas 2008). A total of 1160 of these fatalities occurred in settlement areas where 2 or more people were killed in each disaster. Most of these disasters took place in the eastern and southeastern parts of Turkey (Gurer 1998).

Snow avalanches are a major threat causing damage and death in Bitlis Province. Many roads remain blocked in the area due to avalanches and heavy snowfalls. A typical example in recent years is provided by the 2005/2006 winter, when an avalanche killed 9 and injured 17 passengers on a coach travelling in Bitlis Province. In addition to avalanches, recreational activities (ski and mountain resorts) have shown a rapid growth in many mountainous regions of the study area. Because of the increasing population, tourists, locals, hunters, mountaineers, and skiers are at greater risk in these mountainous regions.

The ability to predict avalanches is limited due to the large number of variables affecting them, such as snowfall, precipitation intensity, wind, temperature, rain, liquid water content, and snowpack structure. The weather conditions that give rise to avalanches are far from clear cut (Schweizer *et al.* 2003). It is also difficult to prevent avalanches because researchers have a limited understanding of how avalanches flow. Building walls to either stop or divert avalanches requires knowledge of how far a potential avalanche is likely to travel, how fast it will be travelling when it reaches the barrier, and how broad it will be. These pieces of knowledge are still quite hit and miss (Ancey 2009).

While the ability to predict avalanches is very limited, avalanche hazard maps or models provide useful knowledge for the evaluation of avalanche risk and planning the future direction of city growth and avalanche protection facilities. In this regard, the use of a geographic information system (GIS) is essential within avalanche research and for the production of avalanche hazard models, because it utilizes the capability of analyzing topographic terrain information and manages the large amounts of data involved in multiple criteria decision analysis.

Multicriteria decision analysis (MCDA) provides a rich collection of techniques for complex decision problems and designing, evaluating, and prioritizing alternative

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decisions (Malczewski 2006). The use of GIS and MCDA has proven successful in natural hazard analysis (Ayalew *et al.* 2004; Gamper *et al.* 2006; Fernandes and Luts 2010) and other geo-environmental studies (Dai *et al.* 2001; Joerin *et al.* 2001; Kolat *et al.* 2006).

The scope of the present investigation was to produce an avalanche hazard model using MCDA within the GIS context. Topographic characteristics of the region, vegetation, and human factors were considered major criteria for generating a final hazard model.

2. The study area

Bitlis Province is located in eastern Turkey, which is the highest region in the country (Figure 1a). In the study area, mountainous land covers approximately 70% of the region. Bitlis Province is more mountainous towards southern and southeastern parts, with the highest mountains and hills. Mountain peaks reach over 2000 m in the region. The fact that the region is separated from the sea by mountain ranges causes the average annual temperatures to be low and the climate in mountainous areas to be harsh, with long winters and heavy snowfalls. In high altitude areas of the region, the ground is covered with snow for about half of the year. Snow depths at high altitudes reach 3 to 5 m (NDAT 2010). The climate in the province displays terrestrial characteristics. Winters in the province are cold; summers are hot and dry. Mean annual precipitation is 103.4 mm and most precipitation falls in winter (Figure 1b).

Bitlis Province includes the towns of Hizan, Mutki, Güroymak, Bitlis (Center), Tatvan, Ahlat, and Adilcevaz. Recently, the province has seen significant growth so that these towns have a joint population of 328,489 inhabitants. About 150,000 people live in high-altitude rural areas (TUIK 2009).

Most of the avalanches in Turkey have occurred in Bitlis Province. A total of 203 avalanches were reported between 1950 and 2008. The numbers of avalanches were 66, 53, and 41 in the towns of Mutki and Hizan, and the city center district of Bitlis, respectively (AFAD, 2008). During some winters, such as 1992–1993 and 2002–2003, over 20 avalanche accidents occurred in Bitlis Province (Figure 1c). The total disaster victims number 1190 and most the victims lived in settlement areas (towns, villages, or districts). Some significant avalanches in Bitlis Province are given in Table 1. In these hinterlands, avalanche disasters occur almost every year, due to heavy snowfalls.

3. Materials and methods

The procedure followed in the generation of the avalanche hazard model is presented in Figure 2. The first step of the process was to obtain information from the study area. Inventory maps, detailed digital contour maps of 1/25,000 scale, and satellite images were used as data sources. A digital counter map was used to produce a digital elevation model (DEM) of the study area. The surface fitting method applied was kriging using a cell size of 25 m (pixels). This resolution of the DEM is good enough if compared to the scale of avalanches. Digital terrain model, slope, aspect, vegetation density, and land use layers were produced from these data sources. Each of them was considered a criterion for the final avalanche hazard model. The next step was to calculate the weight values of GIS layers. The calculation of the weight values was realized by the application of the analytic hierarchy process (AHP). The AHP is a mathematical method of analyzing complex decisions problem with multiple criteria. It calculates the needed importance weighting factors associated with GIS layers by the help of a pairwise comparison matrix where all identified relevant criteria of the GIS layer are compared against each other with reproducible preference factors (Chen *et al.* 2009). In order to express individual preferences (or judgments) in the pairwise comparison matrix, the AHP uses a fundamental scale that is continuous from 1/9 (the least important) to 9 (the most important) (Saaty and Vargas 1991). Here, the preferences or judgments require information on criterion values and the decision maker's knowledge and experiences in a set of evaluation criteria.

The AHP also provides mathematical equations to determine the degree of consistency for judgments. Saaty (1980) describes a procedure to calculate the consistency ratio (CR):

$$CR = {}^{CI}\!/_{RI} \tag{1}$$

where CI is the consistency index, which measures the deviation from consistency; RI is a consistency index of randomly generated matrices and depends on the number of elements being compared.

$$\mathrm{CI} = {}^{(y_{\max}-n)}\!/_{(n-1)} \tag{2}$$

In terms of numbers, the largest eigenvalue (y_{max}) is always greater than or equal to the number of elements (n). If a pairwise comparison does not include any inconsistencies, y_{max} is equal to the number of elements (n). The more inconsistent the comparisons are, the further value of computed y_{max} is from n. In addition to inconsistencies of pairwise comparisons, a CR with a value higher than 0.10 requires re-evaluation of the judgments in the original matrix of pairwise comparisons, because the decision marker is less consistent.

4. Analysis of the factors

The assessment of avalanche hazard is difficult because there are a number of factors affecting an avalanche. Some parameters for avalanche assessment such as

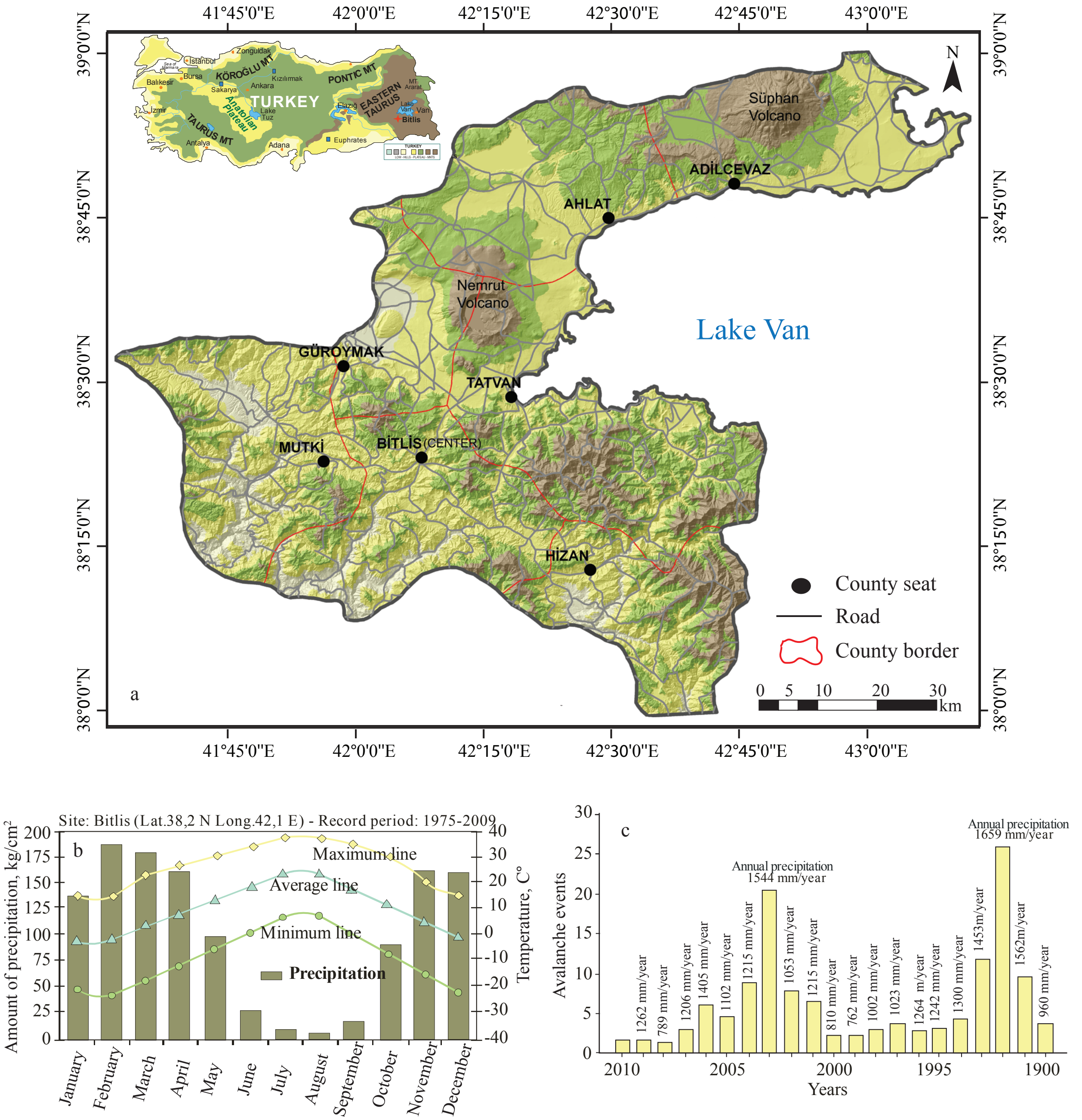


Figure 1a). Location map of the study area. b) Annual average precipitations and temperature lines of Bitlis Province. c) Avalanches between 1990 and 2010.

weather conditions, snowpack structure, topographic characteristics, natural triggers, and human activity contribute to avalanche hazard assessment. The meteorological components include snowfall, precipitation intensity, wind, and temperature. In addition to the meteorological component, snowpack structure results from successive snowfalls. The stability of the resulting layer structure depends a great deal on the bonds between layers and their cohesion (Schweizer *et al.* 2003). These layers are disrupted by natural triggers or noise and vibration from human activities. The meteorological components and snowpack structure depend on weather conditions and change continuously. However, the topography is a constant factor for avalanche assessment. It includes elevation, slope, aspect, and surface conditions.

Because of short-term validity and inadequate

Table 1. Some avalanches in Bitlis Province.

BİTLİS MUTKİ		BİTLİS TATVAN/GUROYMAK		BİTLİS (CENTER)		BİTLİS HİZAN	
Village	Year	village	Year	village	Year	village	Year
Alatoprak (a)	1992	Dibekli (a)	1988	Ağaçköprü (a)	1992	Sarıtaş (a)	2002
Alkoyun (a)	1996	Çavuslar (a)	1991	Çalıdüzü (a)	1987	Ağılözü (b)	2003
Boğazönü (a)	2003	Çağlayan (a)	1991	Ballı (a)	1986	Ortaca (a)	2002
Taşyol (a)	1992	Dönertaş (a)	1988	Ortakapı (a)	1992	Harmandöven	2002
Çatalerik (c)	2008	Pınarbaşı (a)	2001	İcmeli (a)	1992	Kepirli (b)	2002
Erler (a)	1988	Güreşli (c)	2008	Tabanözü (a)	1992	Sürücüler (a)	2002
Geyikpınar (a)	1991	Yamaç (b)	2003	Yükseliş (b)	2002	Horozdere (a)	1992
İkizler (a)	1990	Günkırı (a)	1992	Kurudere (a)	2002	Sarıkonak (a)	1992
Kayran (a)	1987	Erentepe (b)	2003	Çeltikli (a)	2002	Aksar (a)	1992
Sariçiçek (c)	2003			Yumurtatepe (a)	1992	Doğancı (a)	1992
Sekiliyazı (a)	1991			Yolcular (a)	1993	Giran (a)	1997
Taşboğaz (a)	1988			İçmeler (a)	1993	Süttaşı (b)	2002
Tolgalı (a)	1979			Ünaldı (a)	1992	Karbastı (b)	2002
Uzunyar (a)	1988			Tatlıkaynak (a)	1992	Aladana (c)	2005
Ucadim (a)	1988			Akçalı (a)	1998		
Yuvalıdam (b)	2002			Center (b)	2003		
				Gazibey (b)	2003		
				Değirmenaltı (c)	2002		

(a) NDAT (2010) (b) AFAD (2010) (c) CAGEM (2010) see Figure 4 for location of avalanches.

knowledge of the meteorological components, the present study only considers the topographic characteristics and human activities. In order to evaluate the avalanche hazard due to the topographic characteristics and human activities, the model incorporates 5 variable layers (Figure 3). These are elevation, slope, aspect, vegetation density, and human activities (land-use layer). The details of each layer are explained in the following subsections.

4.1. Elevation factor

Elevation influences avalanche initiation because snowfall, wind, and temperature vary with elevation. Generally, the wind speed at high altitudes increases with height due to the characteristics of global wind belts. The amount of wind-transported snow generally increases with height on mountains. Moreover, snow that falls on lower elevations often melts in the warmer air below and therefore changes to rain by the time it reaches the ground. The frequency of snow avalanches at low altitudes (below 1000 m) is likely to be reduced due to this change in precipitation type. In addition to elevation effects, upper slopes have different snowpack conditions, exposure to wind and sun, and ground cover than lower slopes. This produces avalanches on upper slopes when conditions on lower slopes are stable (McClung and Schaerer 2006).

The topography of Bitlis Province is quite suitable for avalanches. The region has high topography with an elevation range from 700 to 3400 m. The high altitude regions (above 1000 m) play a more important role in the deposition of snow and direction of movement. The elevation ranges of the region were divided into 4 groups. The elevation ranging from 700 to 1000 m was assigned as the most favorable group for the lowest avalanche frequency, and elevations above 2000 m were assigned as the least favorable group. The elevation ranges from 1000 to 1500 m and from 1500 to 2000 m were assigned as intermediate groups.

4.2. Slope factor

Slope is a significant terrain factor in the evaluation of potential avalanches. According to statistics, most avalanche accidents happen in an area where the slope angle is greater than 30°. On rare occasions, avalanches start on gentle slopes of less than 25° (e.g., slashflow involving wet snow with high water content), but generally the shear stress induced by gravity is not large enough to initiate an avalanche (Ancey 2009). Because the amounts of snow deposition on steep slopes are limited, avalanches are very frequent and of small dimension for inclinations in excess of 45° to 50°. The slope values of the study area were obtained from the DEM and a well-known classification was used to distinguish the slope classes. The slope values were divided into 4 classes (Figure 3) according to Albrecht *et al.* (1994):

a) Below 10°: practically no avalanches are triggered

b) 10°–28°: Avalanches are scarce

c) 28°–45°: Major danger zone for avalanche triggering

d) Above 45°: High avalanche frequency, but low snow accumulation due to steepness.

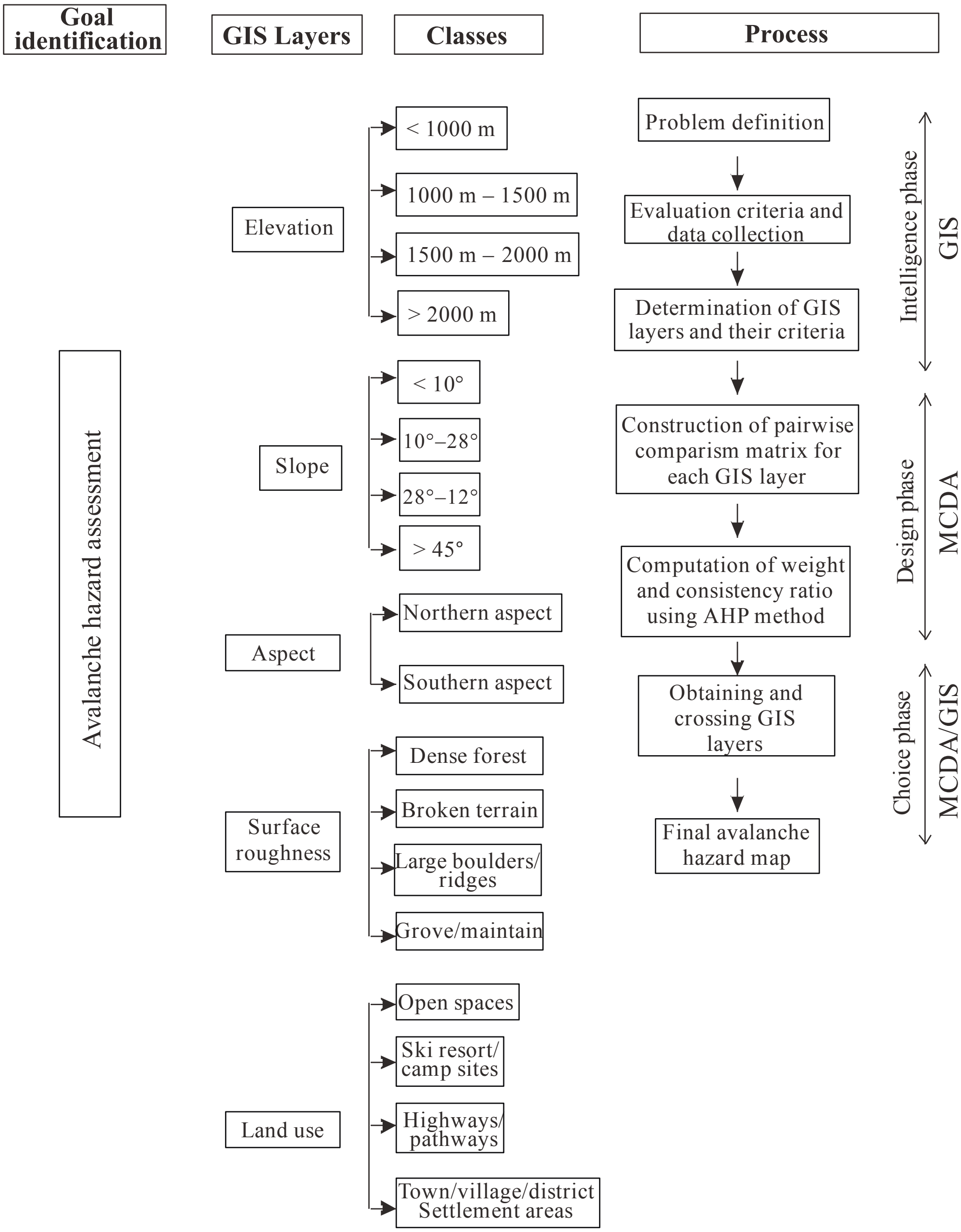


Figure 2. Flowchart of procedure for avalanche hazard assessment in Bitlis Province.

4.3. Aspect factor

Aspect is a predominant parameter in evaluating high risk areas. Although aspect has no serious impact on the risk of avalanches, it is influenced directly by the radiation heat. The orientation of slopes with respect to the sun has a significant effect on the stability of the snowpack structure. Austrian and Swiss statistics reported that 50% of all avalanches occur in the northern sector (NW–N–NE) of the aspect (Benedikt 2002). The study area was characterized as “northern aspect” and “southern aspect” in this study.

4.4. Vegetation factor

Dense vegetation coverage provides the best defense against snow avalanches (Ciolli *et al.* 1998). Vegetation coverage cannot stop them, but it generally restricts the amount of snow that can be involved in the start of an avalanche. Conversely, widely spaced forests and large and open slopes with smooth ground enable the creation of a compact and homogeneous snow layer and facilitate avalanche release.

Density and tree characteristics are key factors influencing vegetation protection ability. The forest

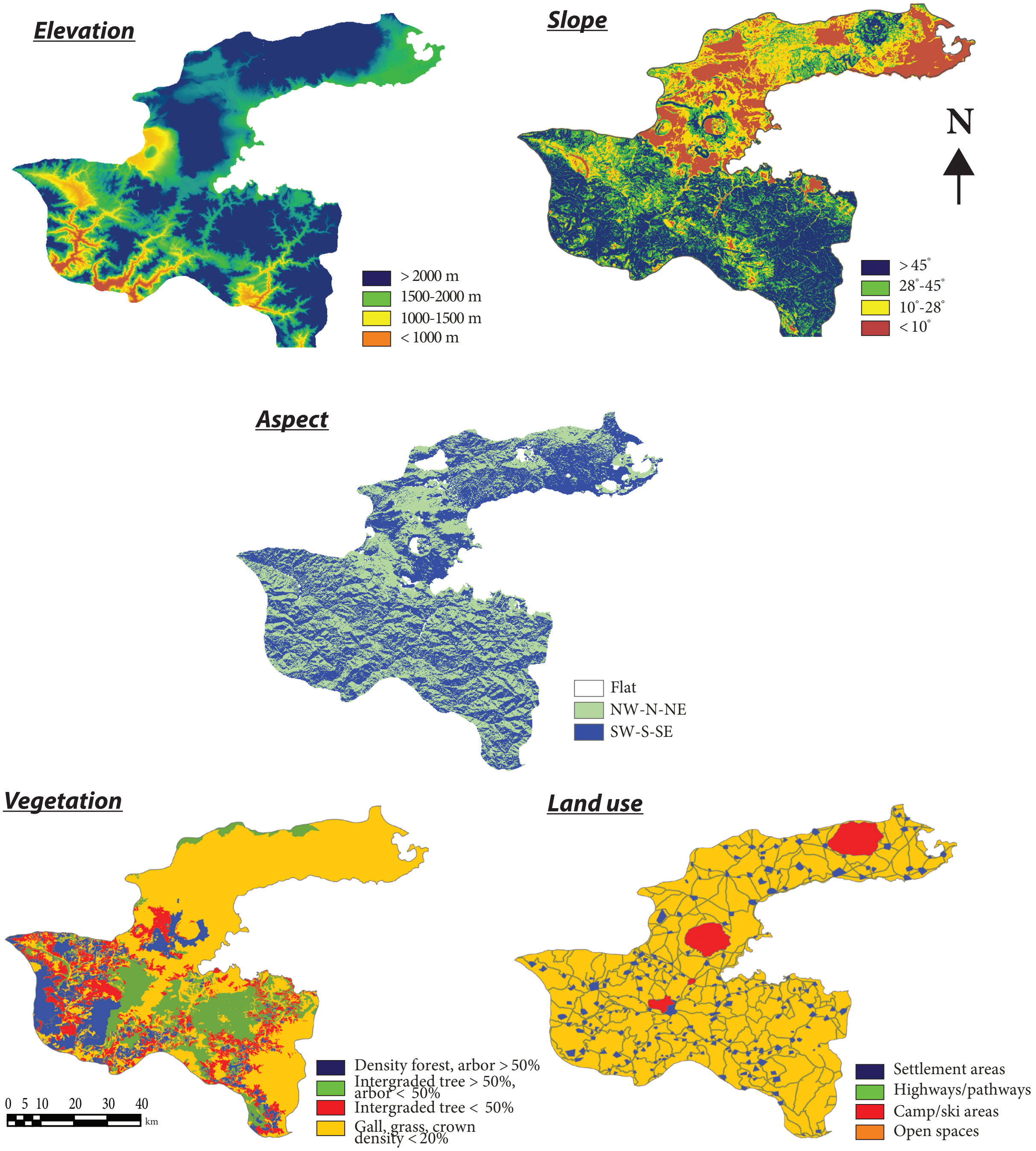


Figure 3. GIS layers and their criteria for an avalanche hazard assessment.

management plan database contains a lot of heterogeneous information about density, species distribution, and vegetation. Four forest coverage classes of the technical guidelines were adopted for the study area (Yamada *et al.* 2002):

a) Gall, grass, bush lower than 2 m, crown density smaller than 20%

b) Bush; 20%–100%, intergraded tree 20%–50%

c) Intergraded tree; more than 50%, arbor 20%–50%

d) Arbor; more than 50%.

The GIS layer of vegetation density was obtained using this classification.

4.5. Land use factor (human activities)

Avalanche disaster statistics have long shown that the majority of avalanches are triggered by human activities. While some are the result of not recognizing potential hazard, most disasters occur because the victims either underestimate the hazard or overestimate their ability to deal with it (Fredston *et al*. 1994). Therefore, the main reason for the relatively high number of fatalities is the poor knowledge of many skiers, locals, and mountaineers. In addition, local roads, camp sites, and ski areas in the free terrain are often not permanently protected against avalanches. Although the avalanche hazard in ski and mountain resorts is prevented by operating companies in particular to release avalanches by explosives or to close the specific ski runs, more and more skiers enjoy skiing off-piste and consequently the number of out-of-bounds skiers has increased (Höller 2007).

About 85% of avalanche fatalities in Turkey occur in settlement areas in free terrain (not controlled), depending on natural and human trigger avalanches. Only 15% of the victims were caught during recreational activities. Of these, 90% were killed by an avalanche that was triggered by themselves or by their party. According to these fatalities, the study area was subdivided into open spaces, highways and local roads, ski and camp sites, and settlement areas in free terrain.

4.6. Development of weights

The development of weight values for each criterion in the GIS layer is based on a pairwise comparison matrix. Before completing the matrices, the relative ranking of the criteria in each layer was evaluated by engineering geology judgments and characteristics of the layers explained above. The pairwise comparison matrices are given in Table 2. The CRs obtained from the matrices were very well within the ratio of equal to or less than 0.10 recommended by Saaty (1980).

Table 2. Pairwise comparison matrices and assigned weight values for criteria in each layer.

Layers/criteria	<1000 m	1000–1500 m	1500–2000 m	>2000 m	Weight
Elevation					
<1000 m	1	5	7	9	0.671
1000–1500 m	1/5	1	2	3	0.169
1500–2000 m	1/7	1/2	1	2	0.100
>2000 m	1/9	1/3	1/2	1	0.060
Consistency ratio (CR)	*0.038*				
	10°	*10° –28°*	*28°–45°*	*>45°*	Weight
Slope					
10°	1	3	7	9	0.592
10° –28°	1/3	1	4	6	0.272
28°–45°	1/7	1/4	1	2	0.085
>45°	1/9	1/6	1/2	1	0.051
Consistency ratio (CR)	*0.058*				
	southern sector	northern sector			Weight
Aspect					
southern aspect	*1*	2			0.667
northern aspect	*1/2*	1			0.333
consistency ratio (CR)	*0*				
	Dense forest, arbor > 50%	Intergraded tree > 50%	Intergraded tree < 50%	Gall, grass, crown density < 20%	Weight
Vegetation					
Dense forest, arbor > 50%	1	2	5	7	0.526
Intergraded tree > 50%, arbor <50%	1/2	1	3	5	0.301
Intergraded tree < 50%	1/5	1/3	1	2	0.110
Gall, grass, crown density < 20%	1/7	1/5	1/2	1	0.063
Consistency ratio (CR)	*0.011*				
	Open spaces	Highways/ pathways	Camp/ski areas	Settlement areas in backcountry	Weight
Human activities					
Open spaces	1	3	7	9	0.592
Highways/pathways	1/3	1	4	6	0.272
Camp/ski areas	1/7	1/4	1	2	0.085
Settlement areas in the backcountry	1/9	1/6	1/2	1	0.051
Consistency ratio (CR)	*0.058*				

The suitability weight values for each GIS layer were also determined by pairwise comparisons in the context of the AHP. Weight values of criteria were completely based upon real data; however, the assignment of weights for each layer was very subjective because it was dependent on the judgments of the author. In order to avoid this subjectivity, the suitability of weight values for each layer was evaluated by engineering judgments of some experts as shown in Table 3, which indicates that the most important layers were elevation and slope, because of the high weight given to them. It is thought that the level of significance for both elevation and slope layers is equal in the avalanche hazard evaluation, while experts give a high score to the slope or elevation layer. Mean weight values reveal that their importance in avalanche hazard evaluation is higher than that of the aspect, vegetation, and land use layers. They are considered next to elevation and slope layers, in terms of layer importance.

With the simple weighted combination, 18 criteria for 5 GIS layers were combined by applying their weight in the following summation:

$$H_i = \Sigma w_i x_i$$

where H_i is the pixel value of the final map, w_i is the weight value of a criterion in the GIS layer, and x_i is the GIS layer value of criterion i. The assigned weight and layer values are given Tables 2 and 3, respectively. The CRs of the expert group were found to be consistent (CR < 0.1) and satisfactory for avalanche hazard evaluation.

5. Results

A GIS-based MCDA technique was employed as a new approach to produce an avalanche hazard model. AHP was chosen over a wide variety of MCDA techniques to produce the avalanche hazard model of the area. This process has become one of the most widely used methods for practical solution of MCDA problems and has gained wide application for natural hazards, because of its capacity to integrate a large amount of heterogeneous data and the ease in obtaining the weights of enormous numbers of criteria.

The final hazard model of the study area was subdivided into the following zones (Figure 4): (i) high hazard, (ii) moderate to high hazard, (iii) moderate hazard, and (iv) low hazard. The boundaries of the categories in the final model were determined by Jenks optimization (natural breaks). This data classification method determines the best arrangement of values into classes by iteratively comparing sums of the squared difference between observed values within each class and class means (Jenks 1967). The suitability of these limit values in hazard zones was also evaluated by the professional judgment of experts in terms of the weight distribution of each criterion in GIS layers.

The final hazard model indicates that the southeast and southwest parts of Bitlis (Center), Tatvan, and Hizan counties have the highest avalanche hazard. In this area, local authorities report many fatal or nonfatal avalanches every year, due to heavy snowfalls. In addition to the avalanches explained above, some avalanches' locations are near high and high to moderate zones or situated in runout distance of avalanches. Settlement areas cover approximately 39,741 ha of the study area and just about 41 settlement areas (villages and towns) have ideal topographic characteristics to prevent avalanche hazard, while 82% of them are not suitable. These values indicate that the settlement areas already situated in avalanche hazard zones cannot be moved to somewhere else owing to the lack of sufficient suitable space for all settlement areas. Therefore, avalanche control programs for the settlement areas in hazard zones are more important than moving to another place. These mitigation programs should be focused on prevention of avalanches (the design of supporting structures such as snowsheds and tunnels).

5.1. Sensitivity and accuracy of the hazard model

Although the GIS-based MCDA method offers great advantages regarding arrangement of spatial data, the main disadvantage of the method is that the determination

Table 3. Assigned weight values of GIS layers for avalanche hazard in Bitlis Province according to 4 experts.

GIS layers	Weights				
	A	B	C	D	Mean
Elevation	0.441	0.368	0.412	0.438	0.414
Slope	0.260	0.368	0.229	0.250	0.276
Aspect	0.162	0.143	0.229	0.149	0.170
Vegetation	0.088	0.077	0.082	0.082	0.082
Human activities	0.050	0.045	0.048	0.082	0.056
sum	1.0	1.0	1.0	1.0	1.0
Consistency ratio (CR)	*0.00011*	*0.00010*	*0.00057*	*0.00004*	*0.00021*

A = Author; B, C, and D = Experts

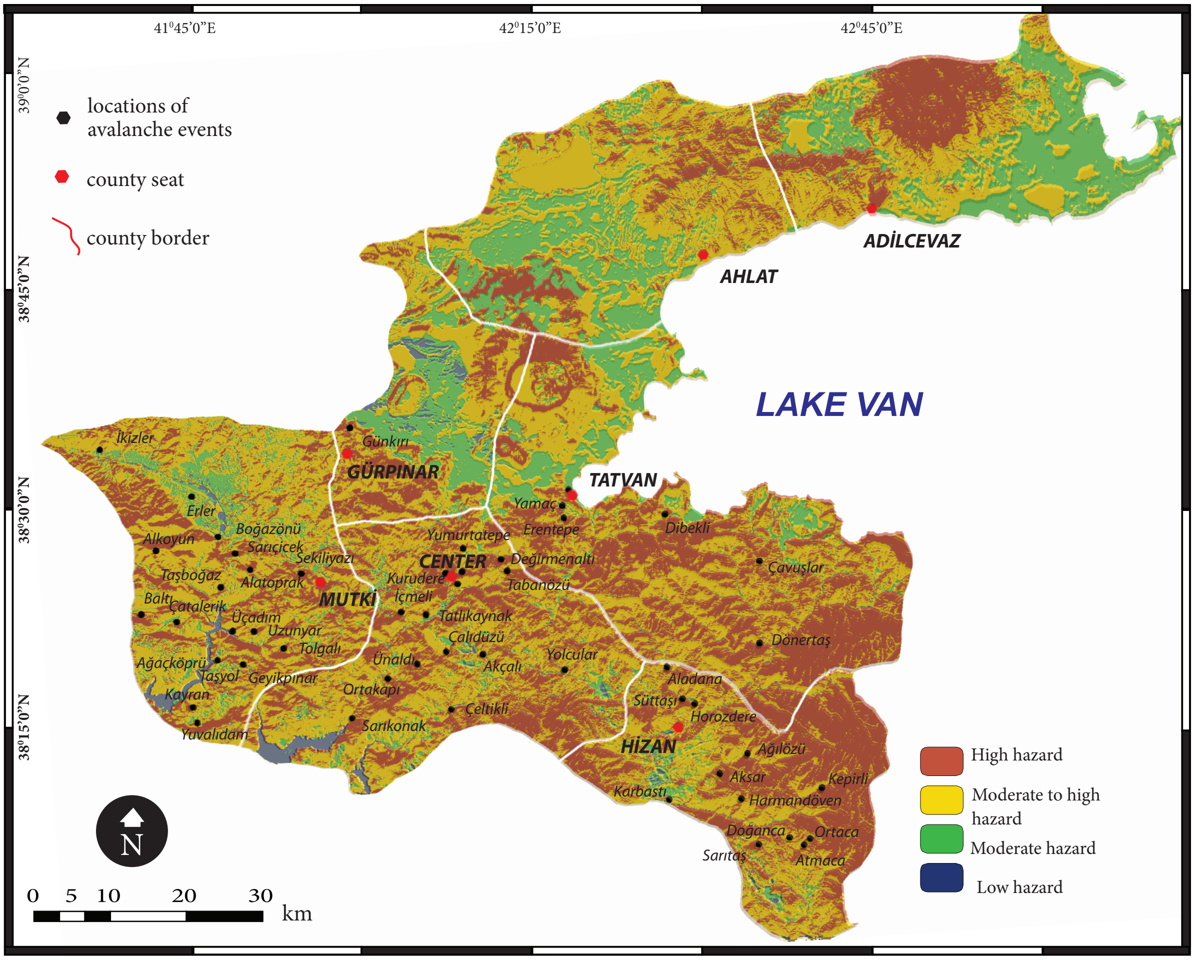


Figure 4. Final avalanche hazard model of the study area.

of the weight values of the GIS layers is dependent on the judgment of experts. In sensitivity analysis, a common approach is to change input factors (values or weights of criteria) to see what effect this produces on the output (Daniel 1958; Chen *et al.* 2009). For this reason, sensitivity analysis was done where weight values of GIS layers were changed to evaluate the differences in the final model.

To assess the sensitivity, the weight (w_i) of a layer at a certain percent change (PC) level can be calculated as follows (Chen *et al.* 2010):

$$w_i = w_{i0} \mp w_{i0} \times PC \qquad (3)$$

where w_{i0} is the weight of the main changing layer at the base run. The weights of the other layer w_j are adjusted proportionally in accordance with w_i derived in the equation (Triantaphyllou, 2000)

$$w_j = (1 - w_i) \times \frac{(w_{j0})}{(1 - w_{i0})} \qquad (4)$$

where w_j is the new weight value assigned to the j layer and w_i is the weight of i layer at a certain PC level. w_{jo} and w_{io} are weight values of i and j layers at the base run. According to Eqs. (3) and (4), when the weight value of the i-layer is increased by 20%, the new weight values of elevation (w_i) and slope layers (w_j) can be calculated as:

$$w_i = 0.414 \mp 0.414 \times 0.2 = 0.4968$$
$$w_j = (1 - 0.4968) \times \frac{(0.276)}{(1 - 0.414)} = 0.2370 \qquad (5)$$

Increments of percent change of ±1% were applied to a complete set of 5 GIS layers in this study. The sensitivity analysis (SA) simulation within the range of –20% (the 1st simulation run) to +20% (the 40th simulation run) of the initial weight value of each GIS layer consists of 200 evaluation runs where each run generates a single new hazard model and 5 tables where each one includes the results of 40 runs for each GIS layer. Table 4 is given as an example for the elevation layer. The weight values of GIS layers at any percent change and number of cells in each hazard level were calculated for the elevation layer as shown in Table 4. The sum of all layer weights at any percent change level should always equal 1.0. With the aid

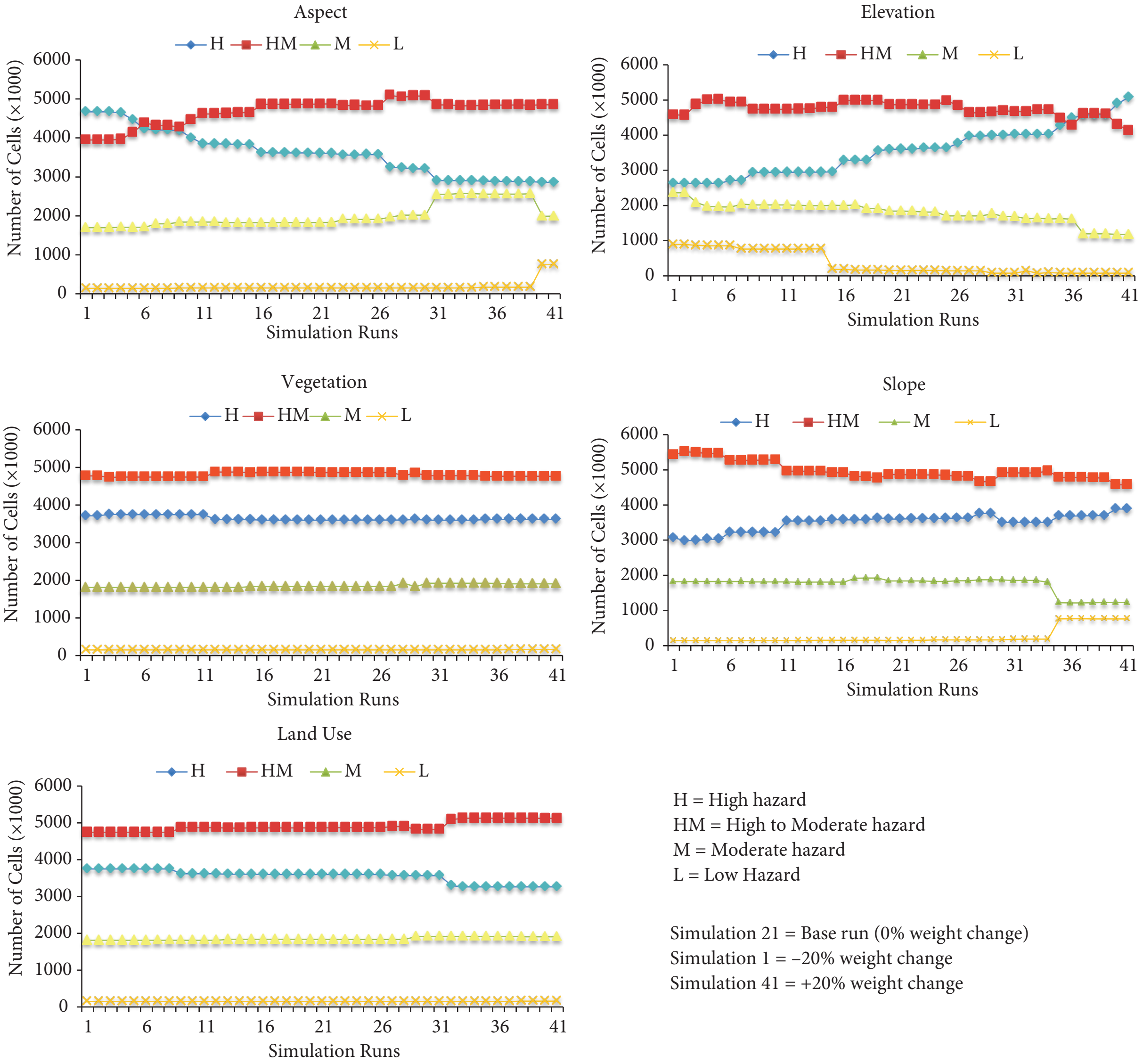
Table 4. The results of the 40 sensitivity analysis simulation runs and base run (bold) for elevation GIS-layer.

Change %	Weight values					Cells in evaluation map			
	Elevation	Slope	Aspect	Vegetation	Landuse	High	High to moderate	Moderate	Low
–20	0.3312	0.3150	0.1940	0.0936	0.0639	2631331	4573547	2360559	884160
–19	0.3353	0.3130	0.1928	0.0930	0.0635	2627975	4569081	2363001	890700
–18	0.3395	0.3111	0.1916	0.0924	0.0631	2631231	4875760	2080500	863266
–17	0.3436	0.3091	0.1904	0.0918	0.0627	2631231	4999004	1968892	851630
–16	0.3478	0.3072	0.1892	0.0913	0.0623	2631669	5010033	1957754	851301
–15	0.3519	0.3052	0.1880	0.0907	0.0619	2709724	4935932	1953994	851107
–14	0.3560	0.3033	0.1868	0.0901	0.0615	2711822	4939138	2038008	761792
–13	0.3602	0.3013	0.1856	0.0895	0.0611	2938238	4736657	2014058	761804
–12	0.3643	0.2994	0.1844	0.0890	0.0607	2938238	4736657	2013757	760921
–11	0.3685	0.2974	0.1832	0.0884	0.0604	2939317	4736771	2014098	760571
–10	0.3726	0.2955	0.1820	0.0878	0.0600	2941682	4734401	2015956	758718
–9	0.3767	0.2935	0.1808	0.0872	0.0596	2945356	4744320	2002358	758723
–8	0.3809	0.2916	0.1796	0.0866	0.0592	2945356	4746064	1994962	764375
–7	0.3850	0.2896	0.1784	0.0861	0.0588	2945356	4788452	1992516	764173
–6	0.3892	0.2877	0.1772	0.0855	0.0584	2957708	4788452	2002539	180853
–5	0.3933	0.2857	0.1760	0.0849	0.0580	3280788	4988028	2001129	180812
–4	0.3974	0.2838	0.1748	0.0843	0.0576	3284276	4988394	2016860	161227
–3	0.4016	0.2818	0.1736	0.0837	0.0572	3284276	4988394	1908553	161201
–2	0.4057	0.2799	0.1724	0.0832	0.0568	3556904	4988394	1908327	161201
–1	0.4099	0.2779	0.1712	0.0826	0.0564	3598911	4866067	1836878	148901
0	**0.4140**	**0.2760**	**0.1700**	**0.0820**	**0.0560**	**3600061**	**4865719**	**1837006**	**147971**
1	0.4181	0.2741	0.1688	0.0814	0.0556	3600061	4865719	1836462	148515
2	0.4223	0.2721	0.1676	0.0808	0.0552	3633828	4858743	1809671	148515
3	0.4264	0.2702	0.1664	0.0803	0.0548	3634022	4858743	1809920	148266
4	0.4306	0.2682	0.1652	0.0797	0.0544	3637352	4973304	1701370	138731
5	0.4347	0.2663	0.1640	0.0791	0.0540	3769562	4841554	1702371	137270
6	0.4388	0.2643	0.1628	0.0785	0.0536	3974535	4636581	1701395	138246
7	0.4430	0.2624	0.1616	0.0779	0.0532	3974535	4637363	1700613	138246
8	0.4471	0.2604	0.1604	0.0774	0.0528	3990882	4651016	1763824	75035
9	0.4513	0.2585	0.1592	0.0768	0.0524	3995676	4693514	1686082	75485
10	0.4554	0.2565	0.1580	0.0762	0.0520	4022249	4667931	1685922	74655
11	0.4595	0.2546	0.1568	0.0756	0.0516	4022249	4668283	1621958	138267
12	0.4637	0.2526	0.1556	0.0750	0.0513	4024050	4720616	1634867	71224
13	0.4678	0.2507	0.1544	0.0745	0.0509	4024050	4722081	1615249	89377
14	0.4720	0.2487	0.1532	0.0739	0.0505	4265443	4480688	1628126	76500
15	0.4761	0.2468	0.1520	0.0733	0.0501	4485729	4281068	1607436	76524
16	0.4802	0.2448	0.1508	0.0727	0.0497	4573599	4608627	1192007	76524
17	0.4844	0.2429	0.1496	0.0722	0.0493	4575728	4606498	1192363	76168
18	0.4885	0.2409	0.1484	0.0716	0.0489	4584662	4599392	1190535	76168
19	0.4927	0.2390	0.1472	0.0710	0.0485	4898831	4299966	1175786	76174
20	0.4968	0.2370	0.1460	0.0704	0.0481	5077525	4121272	1175786	76174

of results obtained from 200 simulation runs, the following conclusions can be drawn:

- Elevation and slope are main terrain features for avalanches and these 2 factors will be affected by the topography of the region in the analysis. Other factors (vegetation and land use) are secondary factors that have no effect on the occurrence of avalanches. In this respect, the elevation is a highly sensitive element to evaluate avalanche hazard. The slope layer has a similar degree of sensitivity to the elevation layer. Aspect depends on the orientation of slope; thus its sensitivity is associated with the slope layer. The vegetation and land use layers have low sensitivity among all the layers. This follows the order of average weight values associated with the judgment of the experts (Table 3).
- Elevation and slope have the highest sensitivity in all GIS layers. They cause significant change in high to moderate and high hazard areas, when their weight variations are within about ±10% (Figure 5).
- All hazard levels are relatively stable for the vegetation and land use layers despite having a certain degree of variations in their weight values. Their areas or their number of cells remained the same or slightly changed as shown in Figure 5. The fact that the perturbation of decision weights has no great impact in these hazard areas indicates that the degree of domination of hazard areas is almost independent of the variation in decision weights associated with these selected layers.

Elevation and slope have a high influence on the evaluation results; therefore, high weight values were



H = High hazard
HM = High to Moderate hazard
M = Moderate hazard
L = Low Hazard

Simulation 21 = Base run (0% weight change)
Simulation 1 = –20% weight change
Simulation 41 = +20% weight change

Figure 5. Summary results obtained from 200 simulations.

given to these layers in this investigation. Elevation is a main terrain feature along with slope and aspect. While elevation influences the amount or thickness of snow layers, slope and aspect are associated with the movement of snow layers. They have significant effects on the hazard zones. In addition to these layers explained above, the vegetation and land use layers are relatively homogeneous according to their low spatial variability in hazard zones. The small weight values assigned by the experts reveal that the proposed values are reliable to evaluate the avalanche hazard, because they have almost uniform effect on the hazard levels of the model.

Model validation was carried out by making comparisons between the avalanche hazard model and actual cases in the region. About 52 avalanches between 1980 and 2008 were evaluated as actual cases in the study area. These 52 significant avalanches directly affected settlement areas in the region. It was found that all major avalanches in the study area were compatible with the high (36.5%) and moderate to high hazard zones (53.8%) as shown in Figure 6a. In addition to these significant avalanches, many unrecorded events have been documented for the backcountries in the region (AFAD 2008), because high and moderate to high hazard zones in the final model cover approximately 530,020 ha, accounting for 34.6% and 46.7%, respectively, of the total area (Figure 6b). The fact that the settlement areas are usually situated in high and moderate to high hazard zones is the main reason for the high percentage values in Figure 6. As a result, the sensitivity and accuracy assessments demonstrate that GIS-based MCDA provides a reliable solution to determine the avalanche hazard zones produced in the investigation.

6. Conclusions

The results of this study show that the GIS-based MCDA technique is one of the most valuable tools to locate and identify avalanche hazard areas for site planning and management. The model obtained from GIS layers does not prevent avalanches, but does contribute to reducing fatal avalanches, because it involves a set of evaluation criteria represented as map layers. Local authorities and land use planners should use this model as a first step to conduct suitability analysis in support of decision making.

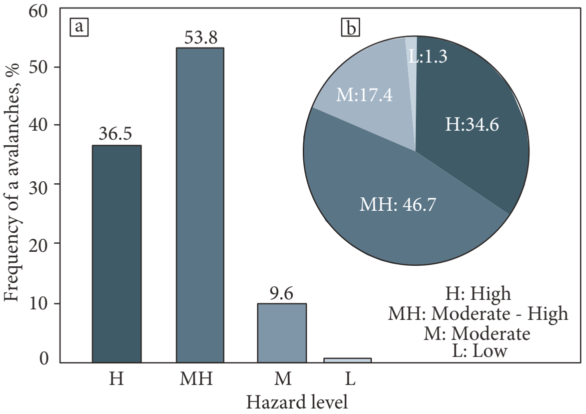


Figure 6. Comparison of actual cases with final avalanche model: a) frequency of avalanches that occurred and, b) areal percentage of hazard levels obtained from final model.

More detailed models for risk assessment will require more reliable information, such as avalanche pathways and meteorological components (e.g., snowfall, precipitation intensity, wind, and temperature).

The model definitely shows that high altitude areas with mean slopes are in danger. The highest hazard areas are those on the southeast and southwest sides of Bitlis, Hizan, and Tatvan counties. These areas are characterized by the highest mountains and hills in Turkey.

A MCDA technique within the GIS context is superior to other techniques using individual criteria in providing more reliability and accuracy. The acceptability of the model was confirmed using historical events. All of these events plotted using the model showed that there is a remarkable coincidence with high hazard areas. Avalanches in high hazard areas repeat themselves, due to heavy snowfalls. Site planning, construction of supporting structures, and control programs in these areas will be the most important methods for enhancement of avalanche safety.

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