Snow avalanche risk management in Shemshak region: a modelling, mapping and evaluation of factors affecting the occurrence of snow avalanches

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In the last two decades, 40 persons have been killed by avalanches in the Shemshak region, Tehran, Iran. The area has also suffered a lot of damage. Here, we have studied 18 variables affecting the occurrence of avalanches in Shemshak region. They are related to the geomorphological, topographic, climatic and snow conditions as well as human activities. The modelling and mapping were performed using various environmental factors and statistics as well as data-driven methods (e.g. hierarchical analysis method, maximum entropy) followed by field visits. Finally the conceptual model of avalanche risk assessment was prepared using spatial mapping and HEV approaches. The results showed that avalanche hazard maps differ from the risk maps. Many areas that were considered as low- or medium-hazard areas in avalanche hazard maps are considered as the high-risk and most important areas in the avalanche risk map. Also, some high-risk areas in the avalanche hazard maps are considered as low-risk areas in the avalanche risk map. Based on the obtained results, it can be concluded that due to the complexity of the risk mapping process, it is difficult to use a worldwide benchmark and indicators system to assess hazards and prepare risk maps. Therefore, more research is needed to elucidate the applied risk maps for avalanche hazard management.

Keywords: Hazard and risk maps, mapping and modelling, risk management, snow avalanche.

TODAY, snow avalanches are considered as one of the most hazardous natural disasters. The damage they cause could be more severe than that caused by floods, earthquakes, etc. Keylock[1] reported that avalanches are regarded as a crisis in mountainous areas for people, houses, buildings, facilities and roads, and have a significant impact on human activity in these areas. With the advancement of science and technology, there are different methods for identifying avalanche-prone areas, the factors affecting the occurrence of snow avalanches, controlling snow avalanches, and various modelling techniques. According to Baggi *et al.*[2], avalanche risk activities are actually carried out through hierarchy and regular planning. At first, avalanche-prone and high risk regions in mountainous areas are identified and the causes of avalanches are examined. Next stage, management is done in this field so that appropriate planning is done for travelling, construction of facilities, and so on. When we analyse an area in terms of snow avalanche, we can actually predict what happens during an avalanche, as well as the amount of damage and its type before an avalanche occurs. A comprehensive and complete plan is needed to manage snow avalanches.

A heavy snow avalanche occurred on Chowkibal–Tangdhar road in Kupwara district, Jammu and Kashmir (J&K), India about 6 km from Chowkibal village. Ten persons lost their lives in this accident[3]. Gusain *et al.*[3] studied the cause of the avalanche accident and simulated the snow avalanche flow using rapid mass movements model. The avalanche had triggered snowfall due to overburden pressure of fresh snow on the snow layers already existing in the formation zone of the avalanche. The study also showed that improper site selection for parking of vehicles was the main cause of the avalanche accident in the area[3]. Ganju *et al.*[4] observed that ignorance regarding avalanche slopes has been the main factor for avalanche occurrence in the western Himalayan region. Gusain *et al.*[3] discussed the development of avalanche information system using remote sensing and GIS technology in the Indian Karakoram Himalaya. Several lives have been lost due to snow avalanche in this area.

Remotely acquired satellite images play a vital role in retrieving information regarding snow-bund regions[5]. Eckerstorfer *et al.*[6] presented a review on avalanche occurrence using the instrumentation data analysis and automatization techniques while detecting snow avalanches using ground, air and space-borne remote sensing data. Delparte *et al.*[7] used GIS for run-out modelling of snow

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avalanches in Canada. They have prepared snow avalanche run-out extent map using the statistical alpha–beta model in GIS environment for skiers, snowboarders, ice-climbers and snowmobilers in the Rogers Pass area. Kumar *et al.*[8] used analytic hierarchy process (AHP) modelling for avalanche susceptibility mapping of Nubra valley region. Singh *et al.*[9] used the AHP method based on multi-source geospatial data for the Chow Kibal–Tangdhar (C–T) road axis in Jammu and Kashmir. The prediction rate was observed to be 93.2%.

Furthermore, 20% of the study area was estimated to have no hazard, 55% as low hazard, 12% as moderate hazard and 13% as high hazard on 13 April 2015. Singh *et al.*[10] studied avalanche hazard mitigation in the East Karakoram mountains. They reported that some regions require special attention, and that standard guidelines and techniques may not be applicable in reducing the risk in the region. Besides, natural factors such as heavy snowfall and formation of non-persistent weak snow layers in the snow pack, human induced factors including increasing winter sports activities, tourism development, civil and military settlements and associated movements, etc. in the mountainous areas may contribute to the harmful consequences of an avalanche. Negi *et al.*[11] studied the potential of space-borne hyperspectral imaging data for estimation of selected snow-cover characteristics in the Himalayan region. Shemshak region is one of the recreational and sports areas, especially skiing and mountaineering. This region has witnessed devastating avalanches over the past decades, leaving about 40 people dead. The statistics was presented by the Shemshak District Municipality and the officials of the ski and mountaineering track. However, no effective scientific and practical actions have been taken so far in this region to prevent/control possible avalanches. In this study, facilities and places that are at risk due to avalanches in the Shemshak region are identified. Also, the economic value of places, facilities and equipment located in the avalanche danger zone is estimated. Through this study, a complete, correct, and proper planning can be done out to identify avalanche-prone areas and provide solutions for their control to reduce various types of damage. The results of this study, would benefit different sports groups such as climbers, skiers, tourists, etc. and they could avoid going to high-risk areas. Also, many organizations and protection teams will make the necessary assessments to prevent dangerous accidents and damage in these areas. In the high-risk areas, they could also implement appropriate strategies to prevent the mistakes that have occurred in the past.

Previous works have indicated that south slopes by 30–40° gradient are more sensible to avalanche generation. Direction of a slope has an effect on the occurrence of avalanches. In addition, other parameters were used with the assumptions existing in previous scientific and documentary studies on avalanche zoning. In this study, we show that the avalanche risk map is from the avalanche hazard map. Using 18 effective and important parameters on the occurrence of snow avalanches, as well as using the two models of AHP and genetic algorithm; we prepared two snow avalanche hazard maps. Next, we prepared a qualitative map of avalanche danger using field visits, and statistics and documents related to past snow avalanches. Two avalanche hazard maps obtained from AHP and the genetic algorithm were compared with the qualitative map of avalanche hazard, and finally the map that showed more accuracy was selected. Then, using the HEV model and applying the element and sensitivity parameters, we prepared an avalanche risk map. The results showed that the avalanche hazard map is different from the avalanche risk map. Areas that are considered as low hazard in the avalanche hazard map are located in the high risk and important areas in the avalanche risk map. The results of this study indicated the importance of the difference between hazard and risk areas.

Study area

Shemshak was selected as the study area. This is in Rudbar Qasran district, Shemiranat city located in Tehran Province, Iran. Its geographical position is 51°30′E (long.) and 36°1′N (lat.) and it is located 57 km north of Tehran (Figure 1). The Germans started Skiing activity in this area in 1948. In 1958, a ski lift of length 250 m was installed which had three bases. This was recognized as an international track by the World Ski Federation in 1996 (Figure 2). The average altitude of this region is 1600 m, the average annual temperature is 12.9°C and the average annual rainfall is 435.8 mm.

Occurrence of numerous avalanches in the Shemshak region has always been a threat to human lives, especially skiers and residents in the region. In addition, occurrence of snow avalanches has threatened the lives of road travellers to this city, who often come for snow sports activities. Thus in many cases, to prevent possible dangers, the roads have to be closed. Figure 3 shows the roads at risk of avalanches, as well as local crossings and access roads that have experienced avalanches in recent years.

Database

To conduct this study, the various types of data, information and parameters necessary were obtained using various methods: (i) Using the existing documents related to avalanches that had occurred in the previous years, and were available in the municipality of Shemshak. (ii) Using inquiries from local and indigenous people, and obtaining information about high-risk avalanche areas and recording their observations. (iii) Field visits and using various points identified using GPS.

We then marked the obtained points in the Google earth, and reviewed and interpreted the areas using suitable

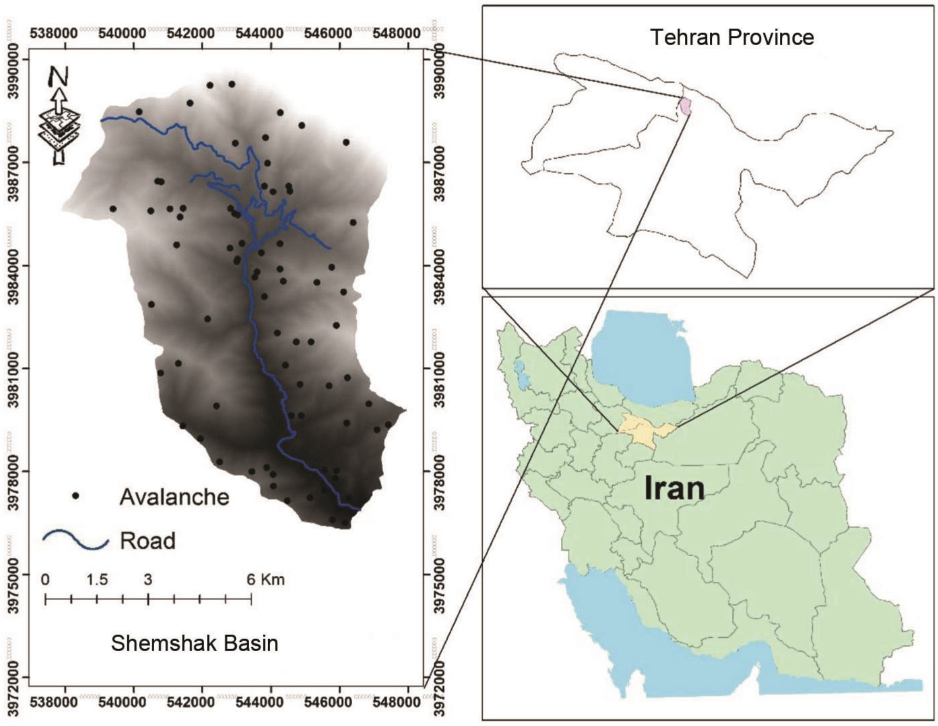

Figure 1. Location of the study area.

Figure 2. Overview of Shemshak International Ski Resort, Tehran, Iran.

Figure 3. Road-crossing in the Shemshak region.

software and ultimately prepared the avalanche hazard maps. We also implemented some indicators that have been used in reliable scientific sources and other studies associated with avalanche phenomenon in different parts of the world.

Initially, a quality avalanche hazard map was prepared using field visits, GPS and documents such as avalanche reports of previous years. We could not consider all the effective factors to prepare the avalanche danger map, because they were numerous and complex. Also, they were not of the same type. For example, among the terrestrial factors, slope is in percentage or degree, height is in metres and direction of the slope is in terms of geographical directions of north, south, east and west.

The digital elevation model (DEM) of the region was downloaded from the Vertex website having a precision of 12.5 m. The highest altitude in the region is 2500–3000 m. Also, using this map and digitizing the existing topographic maps, a geological map was obtained. DEM is a digital lattice of the Earth whose value of each pixel corresponds to the height of the data[12].

In addition to using the DEM maps of the National Cartographic Center (NCC) of Iran, field studies also helped us in preparing this map. We also used the fault and lithological maps provided by NCC. Using the DEM map and GIS software, the data corresponding to elevation, slope, slope direction, longitudinal curvature, transverse curvature, tangential curvature, road distance, waterway distance, fault distance and total performance index (TPI) maps were obtained. The vector ruggedness measure (VRM) index, which includes slope and direction criteria, was also obtained by measuring the scatter of vectors in three dimensions. This index gives a better picture of ground surface inconsistencies, as it includes both slope and direction.

The TPI model is a new method to quantify landforms, but it is directly dependent on the resolution and radius of neighbouring pixels[13]. In the present study, according to the existing resolution of the study area, a realistic test was performed for classification. The required data, including altitudes, steep slopes, flat areas, valleys, etc. in the Shemshak area were obtained quickly using the topographic position index from the DEM map.

Most of the data related to weather conditions, including precipitation, average temperature and snowfall were sorted and normalized, and their maps were prepared using GIS. Also, the data related to wind speed were arranged in Excel and the corresponding map was drawn using WRPLOT. Data on the probability of snowfall for several years were also sorted by Excel and using them, various probabilities were obtained in EasyFit. Next, the final map was prepared in GIS. Land-use map was obtained by Landsat 8 Earth Observation satellite and processing of satellite images was done using ENVI. This map helped identify different areas and determine the risk of their vulnerability during an avalanche. In general, the land use of the region was differentiated from other aspects in terms of its use[14].

Methods

In this study, the assessment process, avalanche risk management planning and collection of avalanche information in Shemshak region were accomplished. For this, we used terrestrial, climatic, cover and topographic parameters as well as field visits and various models. Parameter maps were prepared and the accuracy of the avalanche risk assessment map at different areas was assessed by performing local studies. Initially, the area was demarcated with the help of satellite images. Next, the areas and facilities at risk of avalanches in the Shemshak region were identified. The values of these facilities/places were examined and evaluated. This was based on the average population and economic value. For example, schools or hospitals which may contain many people and whose lives may be endangered during an avalanche were given priority. Next, the economic parameter was considered. For example, the destruction of an electricity tower or telecommunication in tower may cause great economic damage. The hazard element vulnerability (HEV) model then identified which areas and facilities might suffer the most damage.

NDVI is one of the most commonly used vegetation indices in ecological studies[15]. It is calculated based on near-infrared (NIR) and red (RED) light reflectance assessments as follows: NDVI = (NIR – RED)/(NIR + RED), where NIR and RED are the amounts of light reflected by the growing vegetation, as determined by the satellite sensor[16]. Green vegetation has a high visible light absorption and high near-infrared reflectance, which results in high positive NDVI values. Senescing or dry vegetation, snow, water, clouds and soil absorbance considerably increase NIR, leading to reduced NDVI values[16]. The size and spatio-temporal distribution of biomass sampling plots require moderate to high spatial resolution, high temporal resolution and high-quality NDVI data. These requirements are met using MODIS (MODerate-resolution Imaging Spectroradiometer)[17].

In this study, the satellite images of Shemshak vegetation were prepared using Landsat 8.OLI/Tires G1 level-1 sensor. Then, using the satellite images of the USGS Center, the Earth Explorer section and the aforementioned sensor, images of the Shemshak region were selected for the months where there was no snow cover. Also, those days were selected when the cloud cover was as low as possible to have more accurate images of the region. Next, these images were used in Envi.5.3, and atmospheric and radiometric corrections were performed on these images. Then NDVI index was applied on these images and the data were processed using Envi.5.3. Finally, using the output of Envi.5.3, the vegetation map of the Shemshak region was prepared using ArcGis 10.4.1.

Effective parameter

Altitude: The altitude changes indirectly and plays an important role in the formation of an avalanche[18]. Thus avalanches occur at certain altitudes depending on the geographical latitude of the study area. Altitude is an important factor, because the temperature decreases uniformly with increasing altitude. Therefore, it has significant effect on the created and deepened snow masses and their long-time maintenance before they start melting. Thus, as higher altitudes receive more snowfall, they are more likely to experience avalanches. In high peaks located at altitudes of 2500 m amsl, the steep slope is about

55–77%. Also due to the harsh climatic conditions, pedogenesis does not occur and there is no vegetation. Studies on medium altitudes (1700–2500 m amsl with slopes of 25–45%) show that the number of avalanches decreases while moving from higher to lower altitudes. In the area with altitude less than 1700 m, the probability of an avalanche is the lowest value[18]. The altitude map of the area was prepared in GIS using DEM layer. The highest altitude in the region is 2500–3000 m.

Slope: Among the topographic factors, the hillside slope plays an important role in snow accumulation and avalanche occurrence[19]. Most avalanches occur on slopes of 30–45° (ref. 20). At steeper slopes, the gravity force will be more effective. The snow is constantly rolling or detaching, preventing the snowpack from accumulation and deepening. Schweizer *et al.*[21] reported that slopes of 25–50° as starting zone, while the large and rare avalanches are starting in 30–40 gradient. The slope map of the area was prepared in GIS using DEM layer with a precision of 12.5 m. The maximum slope of the area falls in the range 20–40°.

Aspect: In terms of aspect, it can be stated that the southern slopes melt faster by receiving more solar thermal energy and the probability of avalanche increases. Considering the eastern or northern slopes that receive less light, the risk of avalanche is often lower. Jamieson *et al.*[21] conducted a study on the curvature of a hillside in the aspect and stated that the hillsides that are convex in the aspect are easily triggered by the skiers. The aspect of the area was prepared in the GIS environment using the DEM with the cell size of 12.5 m. The dominant aspects of the region are along the southern and eastern directions.

Curvature (plan, profile, tangential and total): One of the parameters studied in the event of an avalanche is the shape of hillside. The curvature can be used in relation to the shape of hillside, so that the positive values of the curvature indicate the convex hillside, and the negative values of the curvature indicate the concave hillside. Also the zero and close to zero values indicate the smooth hillside. Regarding the profile curvature of hillside, Gleason[22], stated that the hillsides with a concave profile facilitate the formation of avalanche. Jamieson and Geldsetzer[23], conducted a study on the hillside curvature in the aspect, and stated that hillsides that are convex in aspect are easily triggered by skiers. In this study, four types of curvature were considered: plan, profile, tangential and total curvature based on the Jenness[24] procedure in GIS. In general, on convex slopes, the total downhill movement of snow increases.

Lithology: This plays a key role in the formation of reliefs, shape of ground or topography of the area. In the facies of rocky outcrops and cliffs, snow cover is not thick. This is due to the fact that the dark rocks melt the snow by absorbing heat. This paves the ground for the formation of slab avalanches. Another effect of the outcrops is that they are crushed due to the freezing and formation of debris. The rocky outcrops protruding from the ground in the form of the band, if completely covered by snow, prevent movements that may occur at the top, while the movements usually continue at the bottom. This induces tensile forces at the upper layers of snow that have not been cut-off by the outcrop. These forces cause fracture to be concentrated along the rock band buried under the snow[19]. In terms of geology, in the basin under study, the mixed detrital–chemical deposits in the Barut, Mila, Jirood, Doroud, Shemshak and Karaj formations are also seen with the lithologies of sandstone, shale, siltstone, lime and dolomite. The red quartzite–arkose sandstones of Lalun and Doroud formations are highly stiff due to the silica cement and are more visible in the region. The lithological and geological map of the region was prepared through the field visits and the geological image of the region was prepared in Arc-GIS 10.2 on 1 : 250,000 scale. The geological map of the region from NCC was obtained 1 : 250,000. The fault map was prepared from the geological map.

Distance from fault: Faults are among the factors that can exacerbate an avalanche. The fault of the area was digitized from a geological map on 1 : 250,000 scale and then mapping was done in GIS. Also, the distance from the fault was prepared in five classes for the area.

Facies: This indicates the conditions of the ground feature. The facies and roads of the study area were prepared during field visits and using Google Earth, and then mapped in GIS. The facies indicates that most of the area experiences stream-rill erosion, followed by the surface-rill erosion, which accounts for about 50% of the total area.

Distance from road: In the mountainous areas, the construction of roads provide the instability causes. Roads also cause fracture of slopes. The shorter the distance from the road, greater is the instability, and vice versa. The avalanche-prone hillsides that are close to the roads or mountain passes are more dangerous. In the study area, a road file was first prepared using Google Earth and then, the distance from the road map was prepared in three classes in GIS. Through field visits, it was found that the greatest impact of the avalanche was seen in the range of 200–300 m.

Relief index: This index indicates the reliefs of the region[25]. At higher altitudes, the probability of occurrence of avalanches is more probable than the areas in lower altitudes. The relief index was calculated using DEM of the area in GIS environment.

Topographic position index: Weiss[26] officially presented a method for calculating TPI. In fact, the TPI is used for the exact and non-descriptive determination of landform boundaries such as steep slopes, flat areas, valleys, etc. TPI can take positive, negative and zero values. The positive values represent the areas that are higher than the surrounding points, such as hills, and the negative values represent areas that are lower than the surroundings, such as valleys. Also, the zero and close to zero values represent flat areas (where the slope is close to zero), or the areas with a steady slope[27]. TPI was calculated using the DEM of the area in GIS environment. The highest TPI corresponds to valleys and peaks, namely places where the avalanche starts from the peaks and flows down along the valleys.

Land use: The land-use parameter affects the occurrence of avalanches, so that the thickness of the snow cover is less in the rocky outcrops and cliffs, which form the slab avalanche. The effects of short plant cover is more significant for shallow snow pack, however the risk of avalanche increase as the depth of snow increase. In the case of forests, if the height of the forest trees is greater than the maximum snow height, the trunks hold the snow well on the hillside.

The land use of the study area include rangeland areas, rocky outcrops with high risk of avalanche, rainfed irrigated lands, and trees planted around the villages. These increase the risk of avalanche to some extent. Except for the areas of moderate risk of avalanches, the urban areas are categorized as low risk with regard to avalanche occurrence. Most of the study region are covered with bare soil and poor vegetation, which account for about 75% of the area.

Vegetation: Land cover has an important effect on avalanches[28]. Plants could sustain avalanches until they are completely covered, but when fully covered by snow, they create weak spots in the snow cover. In the case of plants and trees, if they are higher than the maximum snow height, they hold the snow well at the hillside[29]. Given that about 60% of the area is uncovered, the highest vegetative form belongs to the cover of forbs and plant and bush species, while grass cover has the lowest coverage in the region. Hence, vegetation has a controlling role, especially in areas where various types of plant species are seen. This will have an exacerbating effect on the limited area covered with grass. In relation to vegetation of the area, 65% was bare soil or uncovered area.

To generate land use and vegetation maps of the area, Landsat 8 images were obtained in spring by visiting the USGS website and preparing them using Envi5.3.

Distance from stream: Nosrati *et al.*[30] modelled the environmental parameters affecting the avalanches on the Meygoon–Shwemshak way using multivariate statistical techniques.

They reported that the curvature coefficient parameter with a significance of 0.01 was affected by both parts of the valleys with permanent and instantaneous avalanches. The map of distance from stream was first prepared using GIS environment and then completed in Google Earth.

Snowfall in winter with a 25-year return period: Snowfall height is directly related to altitude. In fact, at higher altitudes, the occurrence of avalanche is less likely. On the other hand, the fall of new snow on wet snows forms a more powerful avalanche and its pressure on the lower layers causes the formation of slab avalanches, which are also called fast or immediate avalanches. In general, snow and rainfall are the factors that cause immediate and instantaneous avalanches[31]. The meteorological information related to the amount of snowfall, rainfall and wind was obtained from the Iranian Meteorological Organization. Also, the 25-year snowfall amount in the snowfall months was obtained using Smada and the zoning map was prepared in Arc-GIS 10.2 environment. The highest amount of snow at altitudes of 1900–2500 m was 1.261 m, while at higher altitudes, it was 1.13 m.

Wind: During snowfall, hillsides may be situated along the direction of the prevailing wind, or vice versa, and as such, snow hardness on the hillsides will vary. Along the windward direction, the snow pieces are hard but less thick. The most dangerous part is the wall or slope facing the cornice, where snow accumulates. Here the accumulated layers are located over the layers that may not be well established. This makes the snow mass completely unstable. Over the windward slopes, snow thickness is less and the snow melts quickly. As a result, it is suitable for the growth of plants that are tolerant to frost and water shortage, but they need a long growing season. In contrast, the leeward slopes have thicker layers of snow, carried by the wind to this area. This prevents the frost and provides enough water for the plants, but shortens their growing season. In general, the presence of cornices and slope fractures is dangerous with regard to avalanches[31]. Data on wind frequency distribution class, wind speed, and prevailing wind direction were prepared using WRplot and wind effect was determined using Saga-GIS. Figure 4 is a flow chart of the research methodoglogy.

Preparing a snow avalanche hazard map

Avalanche zones were identified using terrestrial, climatic, cover and topographic parameters, as well as field visits and different models and methods. The accuracy of the avalanche hazard map was assessed during field visits and local enquiries. The areas and facilities at risk of avalanches were identified. Using HEV, AHP and Magenta models, factors affecting the occurrence of avalanches were identified and compared using more detailed classes. Then

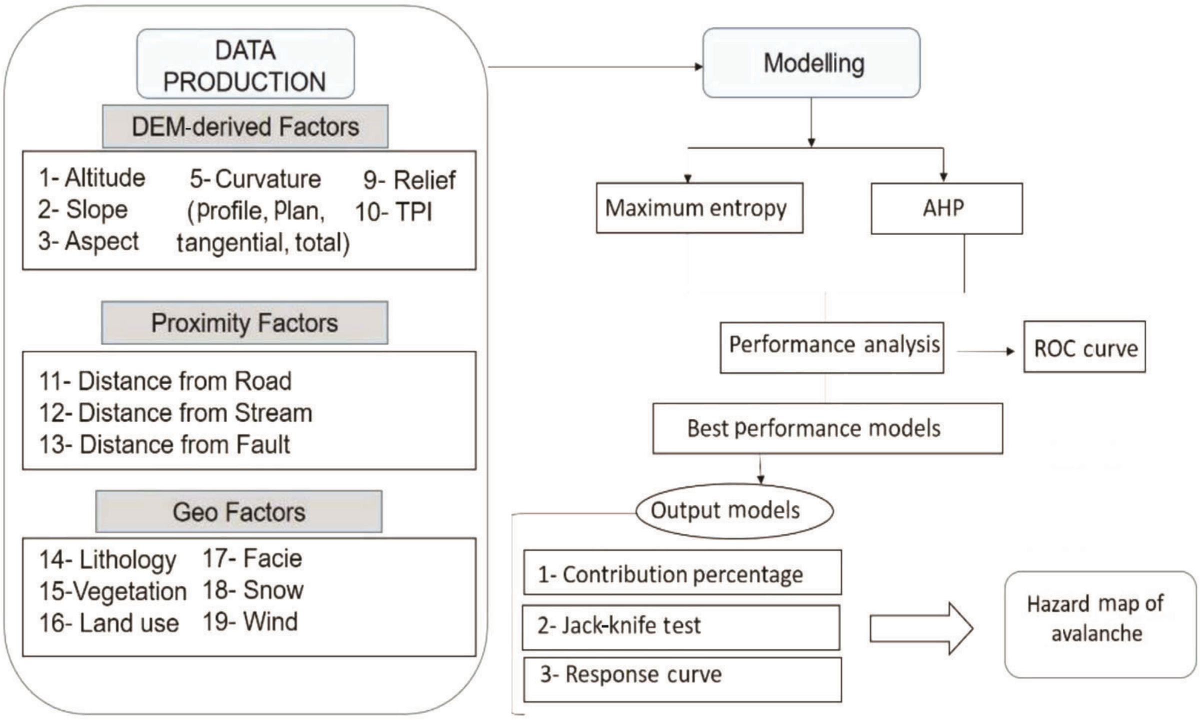

Figure 4. Flow chart of the research methodology.

the evaluated maps were prepared. Finally, the avalanche hazard map was prepared using ArcGis 10.4.1 as well as the available models and by overlapping different maps. We divided the prepared map into four – no avalanche, low-risk avalanche, medium-risk avalanche and dangerous avalanche zones.

Preparation of a snow avalanche risk map

Two maps were used to prepare the avalanche risk map. One was the avalanche hazard map which helped identify avalanche-prone areas. The other was the land-use map which showed which areas with what uses are located in the avalanche-prone areas. Each region was evaluated using two indicators – one was used to evaluate the population of a place and the other was to determine the value of each structure, place, equipment, etc. In addition, the number of avalanches in each region was determined. It should be noted that for determining this parameter, vulnerability of the elements is the most difficult part of calculating snow avalanche damage and requires detailed information. The required data include body resistance of agents, operating materials at risk, angle of slip to the agent, and impact time (in terms of resistance change and the possibility of presence or absence of the agent in the area). Equation (1) was used to assess the vulnerability of the agents[32]. The data and indicators were processed using the HEV model and the final avalanche risk map was obtained.

$$V = \text{LM} \times \text{PM}, \tag{1}$$

where V is the vulnerability of the factors, LM is the usage coefficient and PM is the demographic coefficient.

HEV conceptual model

Hazard analysis is the basis for planning avalanche defence measures. This includes assessment of the avalanche areas, factors contributing to the development of avalanches, triggering mechanism, and avalanche processes as well as potential effects of avalanche events[33]. Mathematical modelling is an important tool for solving engineering problems related to the protection of people and structures in mountainous areas against snow avalanches. The HEV conceptual model was used to detect the degree of risk and vulnerability of structures and facilities[33].

The HEV model can be described as follows.

H: In fact, the avalanche hazard map is the result of two models – AHP and genetic algorithm. The map that is more consistent with the facts is selected, which shows the avalanche hazard areas with low, medium and high degrees. Also this is a part of the used HEV model.

E: This part of the model actually identifies the elements that are at risk of avalanches and compares their importance with respect to each other. For example, different elements such as residential areas, roads, hospitals, schools, agricultural lands, telecommunication towers, electricity, etc. which may be endangered, could have different impacts and reactions. When an avalanche occurs, it could cause different risks. For example, a school with several hundred students has a much higher risk when faced with a snow avalanche than a garden.

V: This part of the model shows the sensitivity and vulnerability of the elements when faced with an avalanche. It compares them to determine their impact on risk exposure in snow avalanches. For example, a strong building will exhibit higher durability than an old rural house. So when faced with a snow avalanche, the strong building has a lower degree of risk than the old rural house.

AHP model

The hierarchical analysis process is a multi-criteria decision-making technique. It is based on the expert knowledge and was developed by Thomas Saati in 1980. In the hierarchical analysis, it is possible to formulate the problem and consider different quantitative and qualitative criteria. In this model, it is possible to analyse the sensitivity of different parameters. The AHP method is based principally on pairwise imprison matrix and consistency test[34]. Also, one of the great advantages of this method is the calculation of inconsistency rates, which allows the judgments to be revised. The first step in AHP analysis is to build a hierarchy for the decision, and then derive weights for the criteria. We are first required to derive by pairwise comparison the relative priority of each criterion with respect to others using a numerical scale developed by Saaty[9] (Table 1).

To perform the pairwise comparison, we need a comparison matrix of the involved criteria in the decision. The diagonal elements of the matrix are always 1; the importance of a criterion compared to itself is always 1. All these judgments are entered in the pairwise comparison matrix, as shown in eq. (2).

$$A=\begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ a_{31} & a_{32} & \cdots & a_{3n} \\ \vdots & \vdots & & \vdots \\ a_{n1} & a_{n2} & & a_{nn} \end{bmatrix} = \begin{bmatrix} 1 & w_1/w_2 & \cdots & w_1/w_n \\ w_2/w_1 & 1 & \cdots & w_2/w_n \\ w_3/w_1 & w_3/w_2 & \cdots & w_3/w_n \\ \vdots & \vdots & & \vdots \\ w_n/w_1 & w_n/w_2 & & 1 \end{bmatrix}. \quad (2)$$

To fill the lower triangular matrix, we use the reciprocal values of the upper diagonal. If a_{ij} is the element of row i and column j of the matrix, then the lower diagonal is filled by eq. (3) which completes the comparison matrix.

$$a_{ji}=\frac{1}{a_{ij}}. \quad (3)$$

To determine the weight of each criterion, the eigenvectors and eigenvalues should be calculated. The weights are calculated using eq (4).

$$\mathrm{AW}=\lambda_{\max}W, \quad (4)$$

where A represents the pairwise comparison matrix and $\lambda_{\max}$ is the largest eigenvalue of A. Also W is the normalized eigenvector corresponding to $\lambda_{\max}$. We divide each element of the matrix by the sum of its column; thus we normalize the relative weight.

The sum of each column is 1. The normalized principal eigenvector can be obtained by averaging across the rows[34].

To check the consistency of result we need to calculate: The principal eigenvalue ($\lambda_{\max}$), the consistency index (CI) and the consistency ratio (CR).

CI is calculated using Equation (5) as follows

$$\mathrm{CI}=\frac{\lambda_{\max}-N}{N-1}. \quad (5)$$

CR is calculated using eq. (6)

$$\mathrm{CR}=\frac{\mathrm{CI}}{\mathrm{RI}}, \quad (6)$$

where $\lambda_{\max}$ is estimated from the pairwise comparison matrix, N the number of compared elements and RI is the consistency index of a randomly generated comparison matrix (Table 2).

Finally, the avalanche hazard map (AHI) is estimated using eq. (7)

$$\mathrm{AHI}=\sum_{i=1}^{n} R_i * W_i, \quad (7)$$

where R_i denotes the rating assigned to each factor/criterion of parameters, W_i the weight of the parameters and n is the total number of factors[9]. We used this index for preparing the avalanche hazard map in ArcGis.

At the first stage, a map of the factors affecting the occurrence of snow avalanches was prepared using this model and the parameters were rated using the AHP method. Then, in GIS, the evaluated maps were overlapped and a snow avalanche hazard zoning map was prepared. Finally, using the effective parameters on occurrence of snow avalanches as well as data and maps obtained from the processes performed, the avalanche hazard zoning map of Shemshak region was derived.

Maximum entropy model

MaxEnt is one of the most commonly used machine-learning algorithms, which is based on maximum entropy

Table 1. Importance value scale[9]

Importance	Definition	Explanation
1	Equal importance	Contribution to objective is equal
3	Moderate importance	Attribute is slightly favoured over another
5	Strong importance	Attribute is strongly favoured over another
7	Very strong importance	Attribute is strongly favoured over another
9	Extreme importance	Evidence favouring one attribute is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values	When compromise is needed

Table 2. Random consistency index (RI)

Order of the matrix (n)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.53	1.56	1.57	1.59

or closeness to reality. Since the data used in MaxEnt are in point form, all avalanche occurrence points without shape and dimensions were entered in the software and each avalanche was identified with a point. Each time the software selects 75% of the data for modelling and the remaining 25% for model testing. This operation is repeated 50–100 times so that the model could predict well the spatial pattern of avalanches. The final map was classified based on the turning points of the cumulative frequency curve of the pixels. Then, the relative performance detection curve (ROC) was calculated in MaxEnt to evaluate model performance. This has been presented as a plot in which sensitivity (correct detection of avalanche occurrence points by the model) is located on the vertical axis and specificity (correct detection of absence points of avalanche occurrence) is located on the horizontal axis.

In general, maps of avalanche-prone areas and those maps corresponding to the factors affecting the occurrence of snow avalanches were prepared. Data were then entered into MaxEnt without processing, rating and valuation. Next, the AUC value was evaluated as an indicator of model accuracy. Also using the jackknife method, the important factors influencing the occurrence of snow avalanches were determined. Finally, the sensitivity map of different areas of occurrence of snow avalanches was derived and classified.

Results

In this section, we present results of models, surveys as well as maps prepared and evaluated using the effective parameters on the occurrence of avalanches. In addition, the avalanche hazard quality map resulting from field visits, the avalanche hazard map obtained from the overlap of parameter maps effective for the occurrence of avalanches, the element map, determining the sensitivity of areas are presented. Finally the avalanche risk map resulting from the overlap of avalanche hazard maps corresponding to this study is presented.

Map of effective parameters for the occurrence of snow avalanches using the evaluation results

Using the evaluation of 18 effective parameters for the occurrence of snow avalanches in the Shemshak region using Expert Choice software, based on pairwise comparisons (Table 3, Figures 5 and 6), the necessary information for this study was obtained.

Understanding the scenarios and possible consequences of changing conditions on snow avalanche behaviour is important for planning and managing mountains[35]. It was observed that among the effective parameters for the occurrence of snow avalanches, slope and land use were important. The results obtained from wind and land-use parameters and their corresponding quality maps are described separately to show the work steps as an example.

Land-use map: This map was prepared through the processes mentioned in the previous section. Table 4 shows the results. The map was incorporated by the Shemshak Municipality and relevant organizations to manage avalanche risk (Figure 7). Also, we used this map for preparing the element map and determining the sensitivity associated with each element. All the uses were specified in the map. This will be one of the most appropriate maps in the area for various purposes. In general, quantitative risk assessment has been recognized as a suitable basis for land-use planning in avalanche-prone areas[36]. Therefore, by preparing and reviewing the land-use map and avalanche risk, a positive step will be taken towards studies on snow avalanches in the Shemshak region.

The results presented in Table 4 are based on the AHP model. Processing of the results was done through weighting the effective parameters on the occurrence of snow avalanches using the AHP model.

The Shemshak land-use map was prepared by the Shemshak Municipality Office with the help of consulting companies that studied this area in 2015. We first used this map to prepare an avalanche hazard map in the models used in this study. First, we compared and weighed

Table 3. Evaluation results of effective parameters in the occurrence of snow avalanches

Parameter	Average value of class	Value of parameter	Average final value
General curvature	0.2538	0.022387	0.005681
Transverse curvature	0.2500	0.026755	0.006688
Longitudinal curvature	0.1650	0.024747	0.004083
Tangential curvature	0.1668	0.024722	0.003123
Average snow depth	0.2427	0.007531	0.001827
Lithology	0.3333	0.063	0.020997
Direction of slope	0.2500	0.105248	0.026312
Quantity of slope	0.3333	0.228074	0.076017
Distance from the fault	0.2500	0.007608	0.001902
Distance from the waterway	0.2776	0.052055	0.014450
Distance from the road	0.2695	0.009968	0.002686
Geomorphological facies	0.1866	0.057228	0.010678
TPI index	0.3333	0.021988	0.007328
Vegetation	0.2500	0.081695	0.020423
Wind	0.3333	0.023036	0.007678
Height	0.3333	0.020328	0.067753
VRM	0.3333	0.020328	0.067753
Land use	0.2500	0.112242	0.028060

Table 4. Land-use valuation results in the occurrence of avalanches

Type of land use	Average value of class	Value of parameter	Average final value
Bare soil	0.591	0.112242	0.066335
Agriculture	0.274	0.112242	0.030754
Garden	0.083	0.112242	0.009316
Residential, commercial educational centre, cultural centres, school, health centre, parking, office centre, hospital, workshop area facilities and river	0.052	0.112242	0.005837

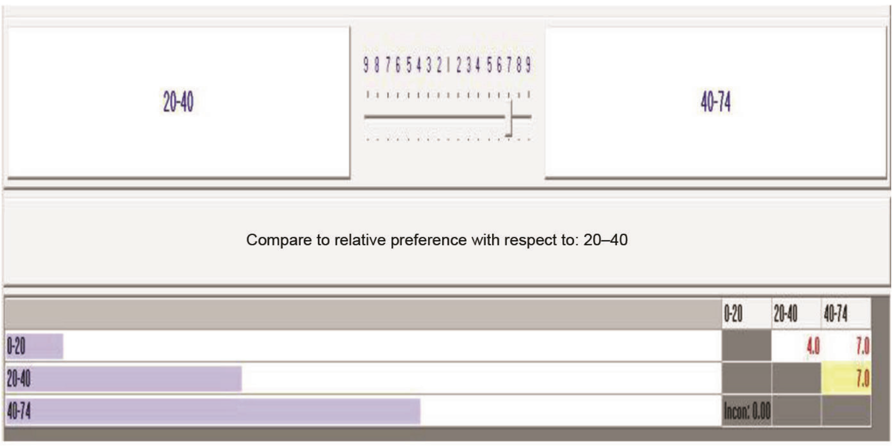

Figure 5. Expert Choice software for the AHP method.

the parameters of this map using the AHP method. Considering that parameters such as hospitals, schools, etc. do not play an effective role in the occurrence of avalanches, we considered the weight of all these items to be the same. However, other parameters such as garden, etc. were weighed using the AHP model. We also utilized the land-use map to prepare the vulnerability map, where we weighed the various parameters of the map Tables 5 and 6 presented in the previous sections. In this map, parameters such as hospitals, schools, etc. were weighed according to their sensitivity to vulnerability and population (Table 7).

Effect of wind on the occurrence of snow avalanches: Wind is one of the important factors that we studied, as it can play an important role in moving the humid air masses and thus causing rainfall, lowering the temperature,

Figure 6. Calculating inconsistency for each parameter using Expert Choice.

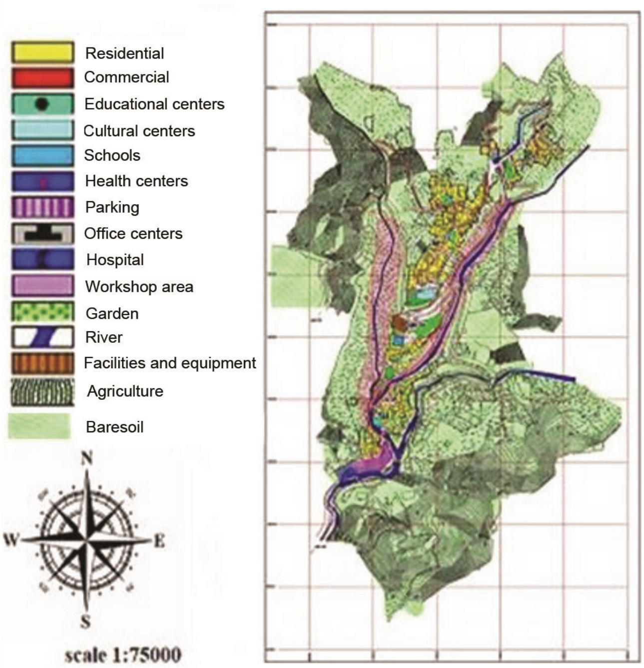

Figure 7. Qualitative map of land-use valuation in the Shemshak region.

Table 5. Land-use multipliers

Land use	Land-use multiplier
Built-up	1
Grasslands	0.95
Agriculture	0.9
Miscellaneous	0.85
Forest	0.8

Table 6. Population multipliers[32]

Population per building	Multiplier
0–1000	0.75
1000–2000	0.8
2000–3000	0.85
3000–4000	0.9
4000–5000	0.95
> 5000	1

Table 7. Vulnerability parameter calculated using the HEV model

Type of land use	Land use multipliers	Population multipliers	Vulnerability
Residential	1	0.75	0.75
Commercial	1	0.75	0.75
Educational centre	1	0.75	0.75
Cultural centres	1	0.8	0.8
Health centre	1	0.8	0.8
Parking	1	0.75	0.75
Office centre	1	0.75	0.75
Hospital	1	0.8	0.8
Factilities	1	0.75	0.75
Workshop area	1	0.85	0.85
Schools	1	0.75	0.75
Agriculture	0.9	0.75	0.675
Garden	0.8	0.75	0.600
Bare soil	0.7	0.75	0.525
River	0.85	0.75	0.638

Table 8. Evaluation results of wind impact on snow avalanche occurrence

Parameter colour	Average value of class	Value of parameter	Average final value
Red	0.691	0.023036	0.015934
Yellow	0.218	0.023036	0.005027
Green	0.091	0.023036	0.002098

increasing evaporation and snow melting. In contrast, wind is known as a destructive factor as well as an energetic factor. In the study area, it was observed that the slopes of the shelter were exposed to snow and the accumulated snow led to the formation of avalanches. Using the data in Table 4, a map of wind impact on the occurrence of avalanches was obtained (Figure 8). In addition, considering the threshold speed of 5 m/s and the wind index, the most important wind class at Lavasan station was measured at 5–7 m/s with a frequency of 11 and with a southeast wind direction (Figure 9 *a*). Also, the most important wind class at Shemiran station was 5–7 m/sec with a frequency of 1.4 and with northeast wind direction (Figure 9 *b*).

The results presented in Table 8 are based on the AHP model.

Importance of variables in the occurrence of snow avalanches

In general, if area under the curve (AUC) is between 0.7 and 0.8, then it indicates a good model. When the value is between 0.8 and 0.9, it indicates an excellent model and AUC above 0.9 indicates that the model has excellent forecasting capability[37]. In this study, AUC in the MaxEnt model was used to evaluate the overall quality of the model, which was 0.72. This indicates that the model is good for avalanche forecasting (Figure 10).

In the jackknife procedure, first the important variables are determined. Then each variable is excluded from calculation, and the model is developed with the remaining variables. At first the model is developed using all the variables and then it is executed for individual variables. Then the important variables with high importance would appear.

Map of elements

A persistent and fundamental problem in the study of snow avalanches is that it is not sufficient to consider the main elements alone. All effective elements in the problem of snow avalanches must be examined from all aspects. In this study, the element map was prepared using the land-use map which shows the most important areas that may be dangerous and result in loss of life and property during an avalanche (Figure 11).

Qualitative hazard map of snow avalanches from field visits

In many parts of the world, avalanche hazard maps are being developed for a variety of applications[38]. Information for drawing avalanche danger maps was collected through field visits, local enquiries and by accompanying mountaineering team leaders. The opinions of skiers and Shemshak Municipality experts was also considered as well as holding meetings with some of the victims and survivors of snow avalanches in the region and finally using the GPS point-picking. The dangerous locations were entered and studied in Google Earth to identify dangerous zones and starting points of avalanches. This map shows where dangerous avalanches may occur, depending on the environmental and terrestrial factors. For example, it was observed that at downstream of relatively flat areas and

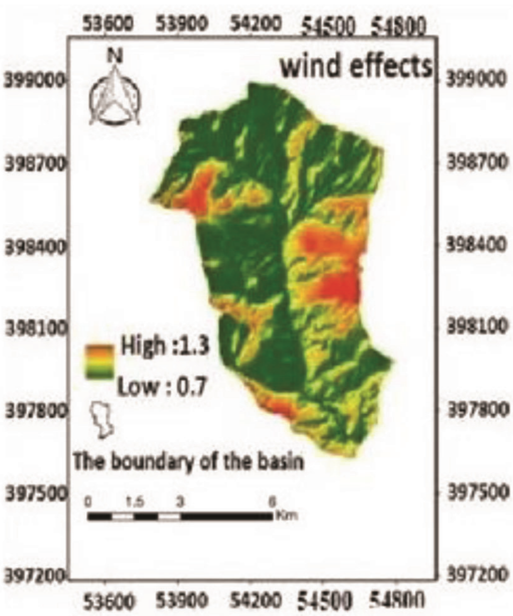

Figure 8. Qualitative map of wind impact assessment in the Shemshak region.

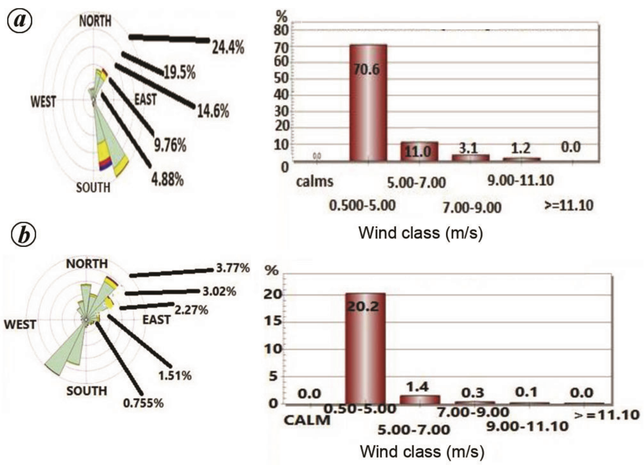

Figure 9. Direction and wind class diagrams at (***a***) Lavasan station and (***b***) at the Shemiran station.

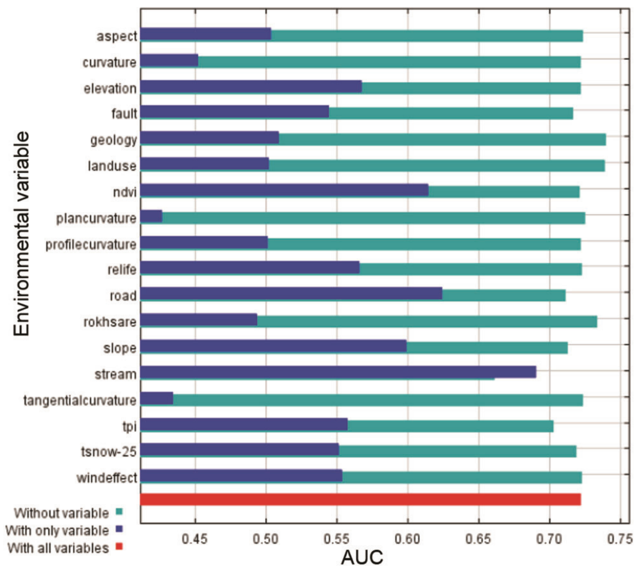

Figure 10. Jackknife test using the maximum entropy model to evaluate the importance of variables.

plains of the Shemshak region, no avalanches may occur. In contrast, in the high-risk areas upstream of this region, dangerous avalanches may occur due to environmental conditions. As mapping of avalanche hazards is time-consuming[39], this map was drawn with greater details to facilitate and expedite planning for snow avalanches in the Shemshak region and to provide complete information.

During field visits, it was observed that some of the most dangerous avalanche-prone areas were directly overlooking traffic roads. Also, one of the dangerous areas where avalanches occurred was overlooking a car park located on the ski slope. Despite the fact that these areas have witnessed dangerous avalanches in the past, no practical action or measure has been taken to prevent or control them in these areas. Also due to heavy vehicular traffic, accidents may occur because of avalanches in these areas.

In one case, local residents tried to prevent avalanches by constructing earthen ridges in the highlands, but these measures were not useful. None of this is based on scientific studies and is only based on the experiences of local residents. In addition, due to the existence of an international ski slope in the Shemshak region, field visits were made to the highlands of Shemshak, along with local people and sports team leaders using cable cars. According to the skiers and sports persons, areas of the ski slope had large and dangerous avalanches, and attempts have been made to prevent them from moving down by constructing a ditch and building a dam. These areas are marked with red polygons in the avalanche hazard quality map in the higher elevation areas at the margins of the map and near the basin boundary (Figure 12).

Since Shemshak is a tourist area, many tourists and sports enthusiasts, especially skiers, enter the city and may not be familiar with the high-risk areas. Only one no-pass sign has been installed in the whole area at one of the high-risk crossings and one avalanche warning sign has been installed at the beginning of the entrance road. No other warning signs are installed or other solutions have been adopted in these high-risk areas.

The yellow polygons in the avalanche hazard quality map are areas where snow avalanches have occurred in recent years (Figure 12). However, these avalanches were not huge in volume and mainly occurred over the valleys. No casualties were reported. The green polygons in the avalanche hazard quality map are areas that usually show small avalanches that have not caused damage, but their occurrence has been observed by residents (Figure 12). These green polygons include areas that are at very high altitude with no structures or facilities around them. In addition, due to the great distance and presence of the surrounding mountains, avalanches do not have the opportunity to reach sensitive areas. They are located downstream where the volume of the occurred avalanches was small and they have not posed significant danger so far. However, they have witnessed snow avalanches. We have provided qualitative information in order to check the accuracy and precision of the models used in preparing the avalanche hazard map. We also used this information to choose the best model.

Qualitative avalanche risk hazard map using AHP model

Avalanche risk map using the AHP model was obtained by overlapping the maps of important and effective

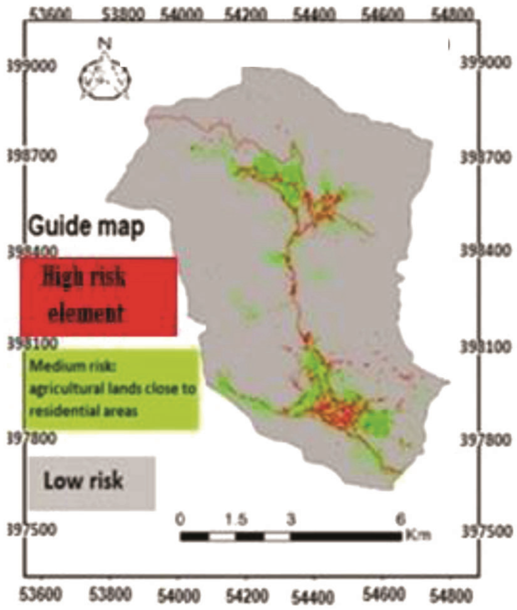

Figure 11. Qualitative map of the evaluated elements that may affect snow avalanches in the Shemshak region.

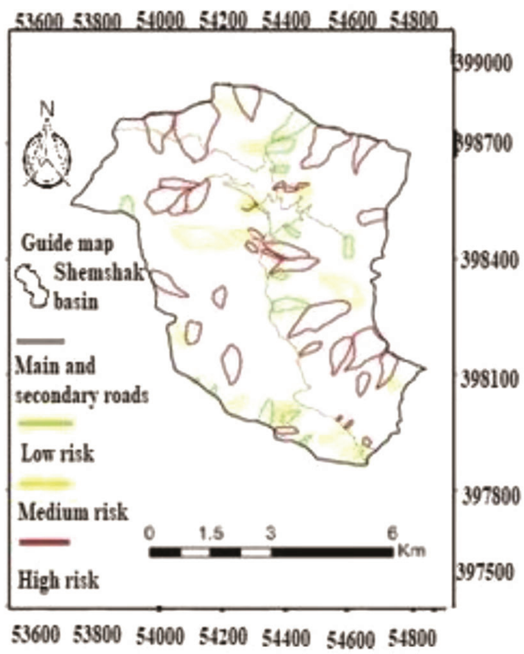

Figure 12. Qualitative map of avalanche danger in the Shemshak region.

parameters in avalanche occurrence. Weighting and the comparisons were performed based on the expert opinion and according to important study sources in the Expert Choice software with a high accuracy (Figure 13). This map was relatively more consistent with the quality avalanche hazard map obtained from field visits, compared to the two avalanche hazard maps obtained from other models.

Qualitative map of avalanche risk using maximum entropy model

The avalanche hazard map using the maximum entropy model was different from the other two maps (Figure 14). In this map, the safe areas are shown in green, covering most of the study area. In contrast, the high-risk areas are shown in red, indicating smaller areas.

Final avalanche risk map

Significant advances in automated mapping have made it possible to assess snow avalanche risk over large areas. This has been done by extracting topographic parameters from DEMs that greatly facilitate risk management[40–42]. In this study, the final map of snow avalanche risk assessment was obtained by overlapping the avalanche hazard map obtained from field visits, element map and AHP model map (Figure 15). According to the validation results, the AHP model was more accurate than the other two models. So the risk assessment map corresponding to this model was used to prepare the final risk management map. The final avalanche risk assessment map for the Shemshak region was prepared using the HEV model. Due to the size of the area, some of the important centres in the avalanche risk map could not be displayed and therefore are marked by points.

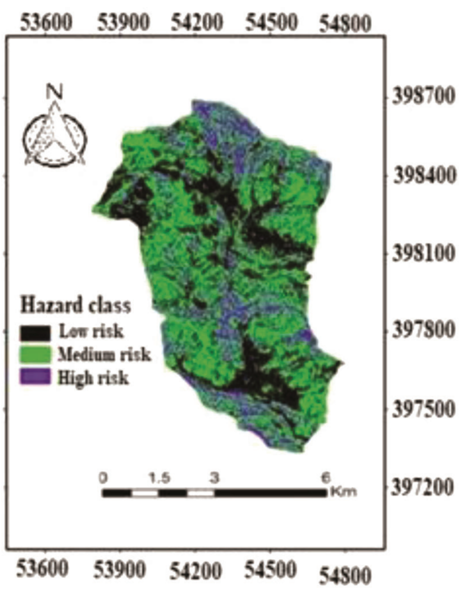

Figure 13. Avalanche hazard quality map using AHP model.

Discussion

Risk assessment using qualitative hazard map from field visits

Avalanche risk is a function of the probability of occurrence and the destructive size of avalanches. This indicates the potential to affect people, facilities or valuables, but does not include vulnerabilities or avalanche exposure[43]. Assessing

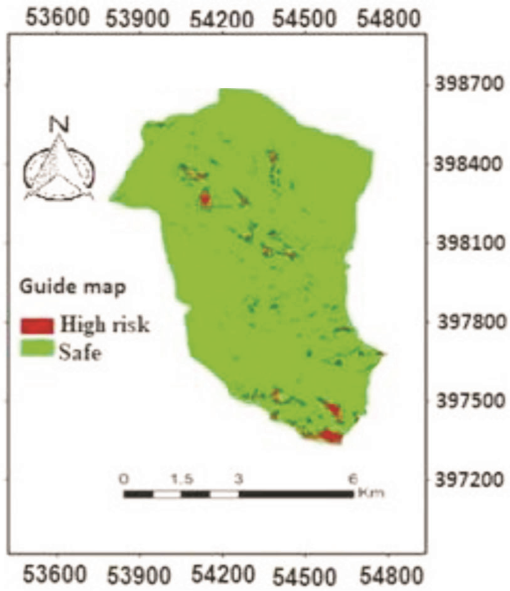

Figure 14. Avalanche hazard qualitative map using maximum entropy model.

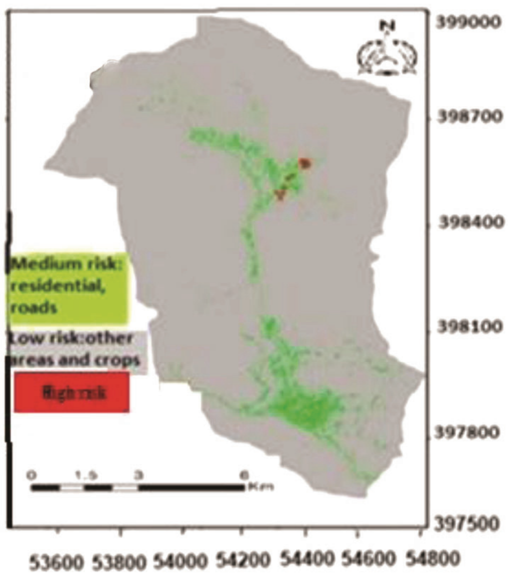

Figure 15. Final avalanche risk quality map in the Shemshak region.

the avalanche hazard quality map, we can identify three basic and important locations that have resulted in life-threatening risks in recent years.

- Areas of the entrance road to the Shemshak city have experienced heavy avalanches in recent years, causing casualties and financial losses. These areas are marked with red polygons in Figure 12 covering the southern part of the map and the road.
- Locations that are close to residential areas cover almost the central parts of the map. In the past years, these areas have experienced avalanches that even had reached the second floor windows of houses and caused damage. Also, some gardens located on the path of avalanches were destroyed.
- Areas close to the border of the basin which are located in the highlands. These areas also experienced heavy avalanches in recent years. The avalanches had even continued to the centre of the city and the main thoroughfare. These areas are located in the northern, northwestern, southeastern parts.

Risk assessment using AHP model

In the map obtained using the AHP model, low-risk areas are shown in black (Figure 13). These areas are mostly characterized with gentle slopes in comparison to other regions and are close to urban and downstream areas. Medium-risk areas are shown in blue. They exhibit higher compliance with the avalanche hazard quality map obtained from field visits. In this map, these areas had a gentler slope with lower height with respect to the high mountains and are considered as medium-risk areas. However, in some locations in the quality map of avalanche risk obtained from field visits, they are considered as high-risk areas. The reason for this, is that the upstream areas and mountains are largely inaccessible to the public and no facilities, structures or residential areas can be found in them. Some avalanches may occur that local residents do not notice as they are at very high elevated areas and far from local settlements.

In addition this map shows that generally, moderate and low-risk areas, are located on lower heights. This could be due to the mountainous nature of the region and other conditions that have been studied in terms of effective parameters. Overall, it could be stated that the map obtained using the AHP model on the occurrence of avalanches has a relatively acceptable consistency with the events that have occurred in the region. It has a qualitative map in terms of avalanche risk.

Risk assessment using maximum entropy model

The reason for the difference between the results in the model of maximum entropy of avalanche risk and those of the other models is because the results in the former model are 0 and 1. That is, either there is an avalanche which is state 1, or there is no avalanche which is state 0. Therefore, many moderate or high-risk areas in previous maps may have been set to 0 in this map and considered as safe. Hence, one of the shortcomings of this model is the inability to identify the moderate-risk areas. In this model, moderate-risk areas are mainly considered as safe areas and some may be located in high-risk areas. In general, this model and map can be used to identify high-risk areas, but not moderate or low-risk areas and areas with medium-risk avalanches that are usually large. Therefore, in future, the use of this model to study the risk of snow avalanches is not recommended.

Risk assessment using qualitative map of elements

Due to the conditions of the Shemshak region, mountainous parts lack structures, facilities and sensitive areas. Also during field visits, it was observed that they are not important areas, except snow-capped mountains. These are considered low-risk areas in terms of the element map. Some areas may contain trees or shrubs that are likely to be broken by an avalanche. Medium-risk areas in this map are those that are mainly agricultural lands and lands close to residential houses or villas. High-risk areas on the map include roads, residential areas, relief centres, schools, and infrastructure such as power lines, etc. These areas are in the high-risk category during snowstorms. As they are both densely populated and structurally weak, they will suffer maximum financial and human losses.

Sensitivity of areas during an avalanche

Due to the fact that long-term avalanche risk assessment is of importance in mountainous areas[44], the sensitivity of different areas in terms of destruction in the event of a snow avalanche was studied. In the Shemshak region, due to the concentration of residential areas, facilities and nearby schools, and the presence of large mountains around the city, the sensitivity of the areas was measured using a map of elements. Due to the large size of the study area, not all cases could be compared one by one; for example, a residential house will be more sensitive than a holiday villa in terms of damage and destruction. Land has been identified and described using the common terms and methods that vary depending on the context and scale of assessment[45]. Therefore, after field visits and local enquiries, when it becomes clear that large and dangerous avalanches occur in a region, it is necessary to look at this issue in a more general and broader perspective and consider covering the entire area. For example, roads will be more sensitive than agricultural lands in terms of destruction, and residential areas and houses will be more sensitive than roads in terms of destruction and vulnerability in the event of a snow avalanche.

Final snow avalanche risk assessment

In general, snow avalanche risk affects recreational, transportation, economic, and resource industries in snow-capped mountains around the world[45]. According to the avalanche risk map, some high-risk areas, which are shown on a case-by-case basis, can be seen in the avalanche hazard quality map as moderate-risk areas. These areas include medical centres, schools, etc. which are more populous than other centres and also prone to more destruction. In addition, these may be considered as moderate-risk areas in terms of topography, climate, snow conditions and other parameters, but if an avalanche occurs, they are likely to suffer maximum damage.

Some of the roads and access roads that are located within the avalanche danger map in areas with intermediate danger, fall within the high-risk areas in the avalanche risk map. The reason for this is the proximity of these roads to the densely populated and busy areas.

Some mountainous areas in the highlands are also considered as dangerous in the danger maps, due to the steep slope and other issues related to the occurrence of avalanches, but they are also considered as low-risk areas. The reason for this is that in these mountainous areas, with high altitude and difficult conditions, there are no structures, facilities and crowded places.

Also, some agricultural lands and gardens are located around houses and residential areas. In some cases, these areas may be included in the low-risk and medium-risk category in the avalanche hazard map due to topographic climatic and snow conditions. These are also considered as moderate avalanche risk areas in the risk map because of the importance of agricultural and horticultural products.

Comparison of snow avalanche risk assessment models

AHP model: The AHP method was used for grading. First, the data of each place were standardized. Next, an order of the population of indicators was formed. To form this matrix, we must first assign a weight to each indicator. After this stage, the score of each index was added and the sum of all indicators was calculated. Thus, the weight of each index was obtained.

The AHP model requires both expert knowledge and data. Therefore, during the study process, a lot of time, money and human resources were spent to provide the necessary information. In this study, we used the decision-making technique based on pairwise comparison. This helped us to make decisions based on continuous or discrete space, single or multi-criteria and quantitative or qualitative criteria. However, there were problems such as lack of standard for measuring quality criteria and also lack of a unit for converting various criteria. Nevertheless, AHP model has more advantages than disadvantages, i.e. unity, complexity, interdependency, hierarchy, structure, measurement, consistency, synthesis, trade-off, judgment and consensus and repetition.

Maximum entropy model: A cornerstone of statistical inference, the maximum entropy framework is being increasingly applied to construct descriptive and predictive models of snow avalanches, from large experimental datasets. Both its broad applicability and the success it obtained in different contexts hinge upon its conceptual simplicity and mathematical soundness. The maximum entropy model provides a good way to combine a variety of background evidences to estimate the probability of a snow avalanche. For this reason, as well as observing the results obtained from the model in this study, it could be one of the best methods for managing snow avalanches along with the HEV model. However, this model is not as effective as the HEV model. The reason for this is that the maximum entropy method only states whether there are snow avalanches or not, but it is not possible to classify the snow avalanches based on their intensity in the areas of occurrence. So we cannot determine the low-risk, medium-risk and high-risk areas.

HEV model: This conceptual model identifies the key components of avalanche hazard and structures them into a systematic, consistent workflow for hazard and risk assessments. The method is applicable to all types of avalanche-forecasting operations, and the underlying principles can be applied at any scale in space or time. With the HEV model, we used judgmental decomposition to elicit the avalanche forecasting process from forecasters. Then we described it within a risk-based framework that is consistent with other natural hazards disciplines.

This model conceptually provides us with a specific outline of the Shemshak region, which includes the factors affecting the occurrence of avalanches, the role of each parameter in the order of impact on the occurrence of snow avalanches, and so on. The HEV model is more efficient in determining the risk of different regions in the occurrence of avalanches compared to the AHP and maximum entropy models. The HEV model also conceptually provides us with an overview of the region. It should be noted that this model has not been used previously in Iran, so it could be utilized for further research on the avalanches. This study would pave the way for other researchers to identify the dangers of snow avalanches in Iran and evaluate them using the HEV model. Therefore, accurate results can be obtained in the snowy and avalanche-prone areas.

Conclusion

In this study, the avalanche-prone areas as well as snow avalanche risk areas were identified. Various factors affecting the occurrence of snow avalanches in the Shemshak region were identified and their impact was measured. Using the obtained maps, it was concluded that there is always possibility of snow avalanches in the Shemshak region, i.e. the risk of snow avalanches in this area is high. Several facilities, structures and agricultural lands are located in the avalanche-risk areas. So they must be managed with proper planning to reduce the damage caused by snow avalanches. Throughout this study, it was considered that avalanche hazard quality map and avalanche risk map are different. This had a significant impact on the processes of field visits, modelling and mapping. In general, using the obtained results, useful and effective planning can be done to control snow avalanches in the study region. The risk map of snow avalanches along with the avalanche hazard map presented in this study can be used in the management of snow avalanches.

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