Journal of Engineering Issues and Solutions

Avalanche Susceptibility Mapping of Sagarmatha National Park in Nepal Using GIS-based MCDA–AHP

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Received: May 12, 2026; Revised: 13 June, 2026; Accepted: July 11, 2026

Abstract

The high mountain region of Nepal is vulnerable to avalanches and related hazards. Every year, numerous incidents of avalanche-related casualties are the new normal. However, studies about avalanches are limited. This study explores this gap and maps the avalanche susceptibility of one of the most iconic regions of Nepal: Sagarmatha National Park. This study applies the Multi-Criteria Decision Analysis-Analytical Hierarchical Process (MCDA-AHP) method to map the avalanche susceptibility of the area. The Aster GDEM and snow cover data from the High Mountain Asia (HMA) are utilized to create the susceptibility map, which is then validated using previous recorded avalanche incidents in the region. The outcomes of the results show that 40% of the park's area lies in the high and very high avalanche-susceptible region. Susceptibility is not limited to the regions that have a snowcap throughout the year, but low-lying areas with seasonal snowfall are also susceptible to avalanches. The validation has shown that 80% of recorded incidents lie in the high and very high susceptible regions.

Keywords: *AHP, Avalanche Susceptibility, MCDA, Sagarmatha National Park*

1. Introduction

Sagarmatha National Park is a prime location for hikers and mountaineers, attracting visitors with its stunning attractions such as Mount Everest and various challenging high-mountain trekking routes, including the Everest Base Camp Trek and the Gokyo Lake Trek (Mayhew, 2016). Despite its popularity, it's important to acknowledge that this great destination also comes with some risks, as every year, many trekkers and climbers lose their lives or suffer injuries due to natural disasters such as avalanches (Beaumont, 2015), which are a result of the park's high altitude, steep slopes and rough terrain.

Previously, because of poor accessibility and insufficient monitoring in such remote area of Nepal, the majority of avalanche occurrences went unnoticed, and only disasters related to mountain climbing were extensively recorded. With the recent influx of tourists eager to explore the hinterland, the likelihood of avalanche related incidents in the region has increased (Rai, 2017; Thakuri et al., 2020). Taking this into consideration, the goal of this study is to create an avalanche susceptibility map for the region, to reduce avalanche related fatalities and ensuring the safety of the many visitors to the area.

There are various methods available for mapping avalanche susceptibility one of them is empirical method, in which mapping is done by statistical analysis of past avalanche incidents and their causes. This method is suitable where there are extensive records of past avalanches in the region and applied in most of the machine learning algorithms (Akay, 2021; Bian et al., 2022; Cetinkaya & Kocaman, 2022). Another method is the geomorphic method, which involves analyzing the terrain and landforms of the region to identify potential avalanche start zones, runout zones, and other features that can contribute to avalanche activity (Šilhán & Tichavský, 2017). Similarly, the physical or numerical modeling methods can be used for susceptibility analysis. In these methods, scaled terrain models are developed to simulate potential avalanches in the region (Christen et al., 2010; Zugliani & Rosatti, 2021). Additionally, remote sensing techniques such as satellite imagery, aerial photography, and LiDAR are employed to gather data about the region's terrain and snow cover, and this data is interpolated to produce a susceptibility map (Brožová et al., 2020; Deems et al., 2015; Eckerstorfer et al., 2022). Moreover, various GIS-based techniques have been employed to analyze the susceptibility of avalanches. These methods include the utilization of frequency ratio, fuzzy logic, analytical hierarchical method, and others. These approaches provide several benefits, such as the ability to integrate multiple criteria, incorporate expert knowledge, and generate maps that are easy to interpret (Kumar et al., 2017; Varol, 2022).

This study applied the MCDA-AHP method to map the avalanche susceptibility of the area. The Aster GDEM and snow cover data from the High Mountain Asia (HMA) were utilized to create the susceptibility map, which was then validated using previously recorded avalanche incidents in the region.

2. Materials and Methods

2.1 Study Area

The Sagarmatha National Park lies in the Solukhumbu district of the northeastern part of Nepal. It was established in 1976 and has been designated as a natural World Heritage site by UNESCO. Covering an area of 1148 square kilometers in a high mountain region with elevations varying from 2845 meters to 8849 meters, the park is home to many mountains, including Mount Everest, Mount Lhotse, Mount Pumori, and Mount Ama Dablam. The region is a very popular tourist destination for climbers and trekkers, with some of the most sought-after trekking routes in the region including the Everest Base Camp Trek, the Gokyo Lake Trek, and the Ama Dablam Base Camp Trek (Daconto & Sherpa, 2010).

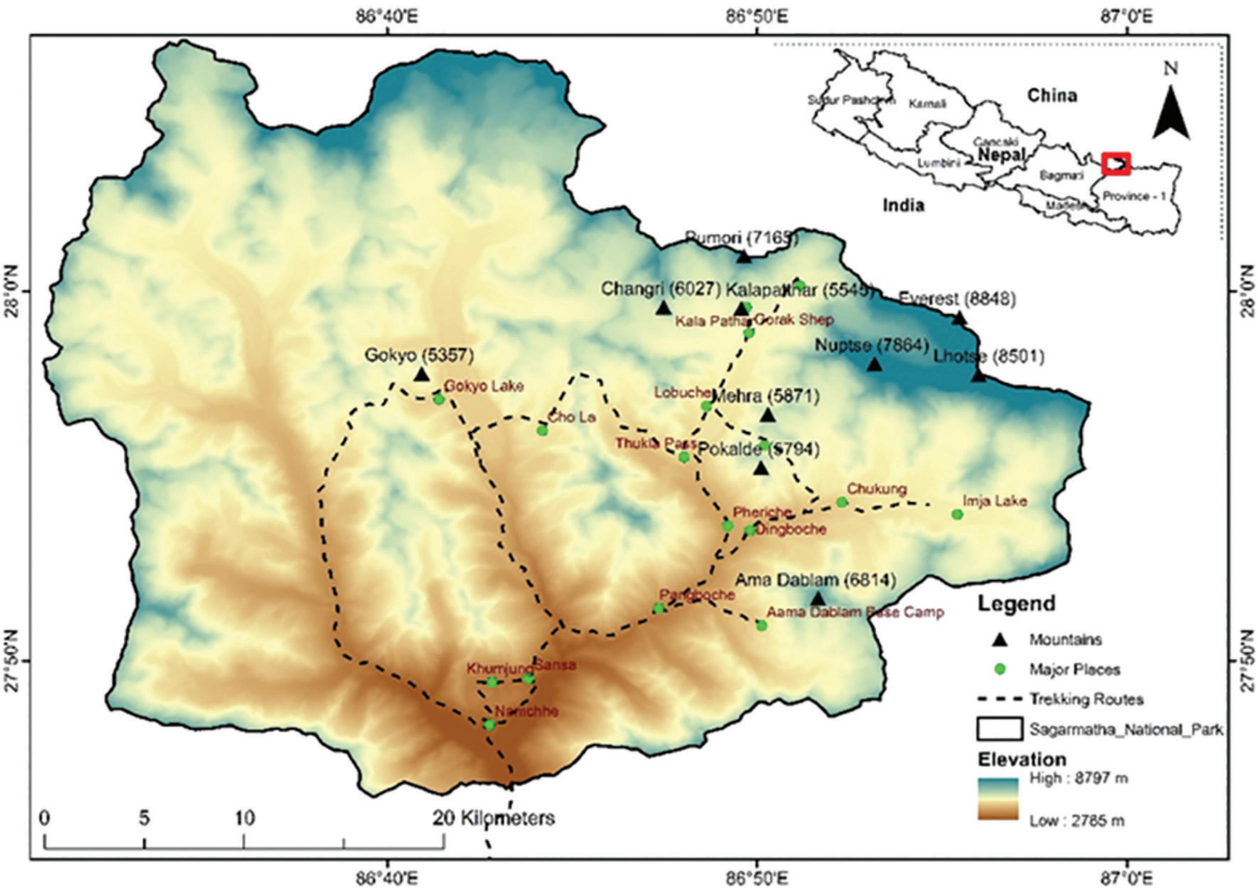

Figure 1: Study area map: Sagarmatha National Park

1.2 Data Preparation and Classification

For the analysis, the digital elevation model was acquired from ASTER GDEM, while the snow map from High Mountain Asia was utilized as the primary source. Several GIS tools were employed to generate maps of slope, aspect, curvature, and terrain roughness based on the DEM data shown in Figure 2.

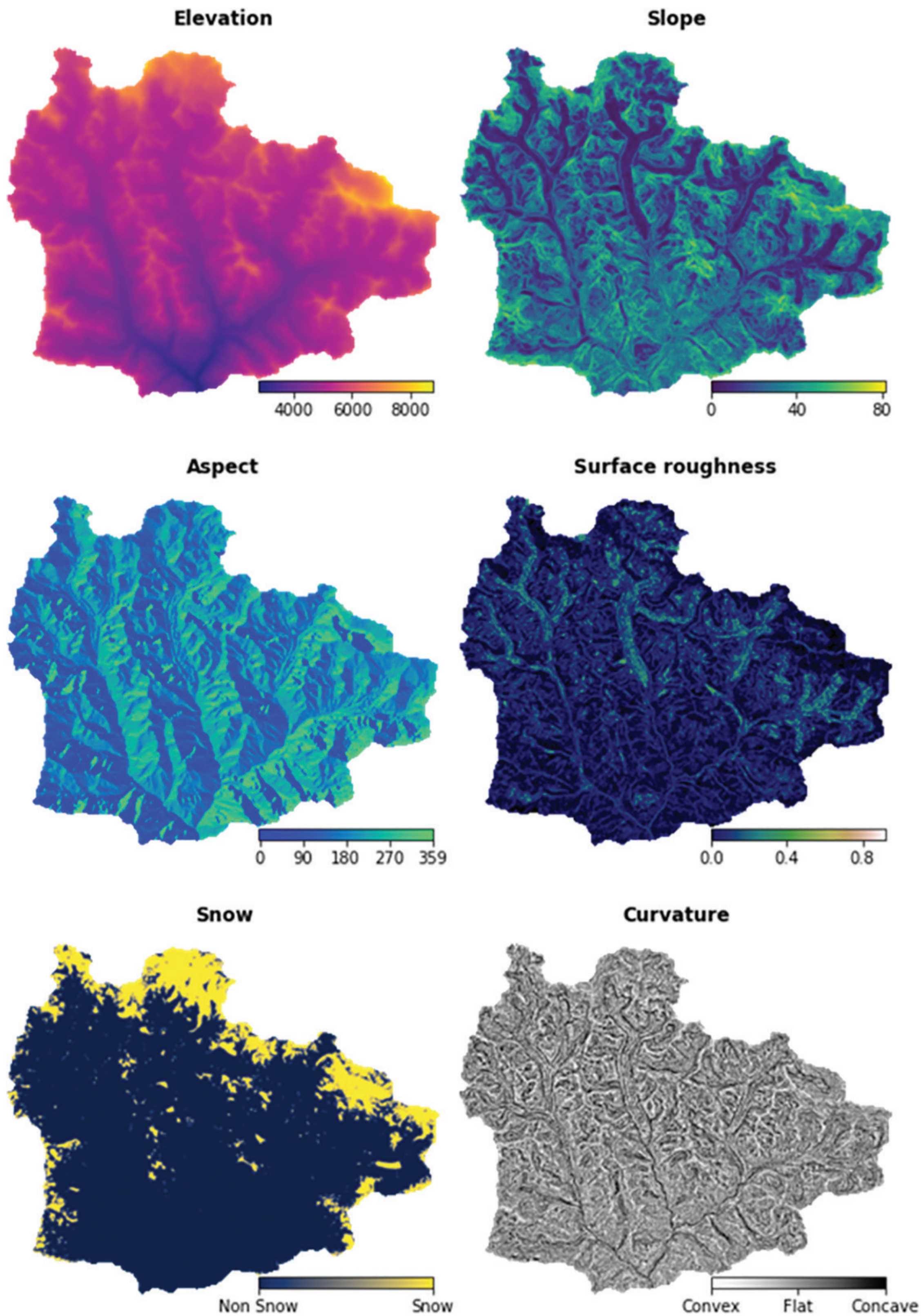

Figure 2: Input Parameters for the study

For MCDA-AHP method, various parameters that may contribute to the avalanche susceptibility. Among them the terrain slope is a critical factor that affects the occurrence of avalanches. Generally, gentle slopes are less prone to avalanches due to the low gravitational force on the snow. Previous studies have found that slopes greater than 30° are more favorable terrain for the occurrence of avalanches (Schweizer et al., 2003). Previous studies suggested that, most of the avalanche incident occurs in slope angle of 30°to 50° (Schweizer & Jamieson, 2000). For the study, a slope map of the region was generated using a DEM. The slopes were reclassified into different groups, and a rating was assigned to each category.

Similarly, Aspect can also have significant effect on avalanche susceptibility as it influences the distribution of snow. The likelihood of formation of avalanche with slopes facing north and east being more susceptible than those facing south and west as they are characterized by large temperature gradient (Schweizer et al., 2003; Schweizer & Jamieson, 2000). Also, the occurrence of avalanches is influenced by the curvature of the surface, with convex surface profiles being more susceptible to avalanches. On the other hand, concave profiles facilitate flow accumulation and promote stability (Cano, 2004). Additionally, surface roughness also plays vital role in avalanche occurrence, for instance, rough surfaces like boulder debris tend to provide better stabilization for fallen snow sheets, while smooth surfaces such as high mountain pastures are more susceptible to experiencing slides (Cano, 2004).

In order to establish the weight value for each class of map in Analytic Hierarchy Process (AHP), a pairwise construction matrix must be constructed. This involves assigning the significance of each factor in relation to another factor. To facilitate this assignment, the fundamental scale proposed by Saaty (1980) is employed. Expert input is crucial for this process, drawing from their knowledge of past avalanche events and the study of avalanches in the region. However, the available research on avalanches in the Himalayan region is limited, despite numerous avalanche incidents. Most of the existing literature predominantly focuses on avalanches in Europe or North America. To address the aforementioned challenges, this study relied on relevant previous literature by Cano (2004), Kumar et al. (2017), and Yilmaz (2010)as a point of reference for assigning importance to each category. Furthermore, a consistency index was computed to verify the consistency of the assigned values. By incorporating these measures, the study aimed to mitigate the identified issues and ensure a reliable assessment of importance within the categories.

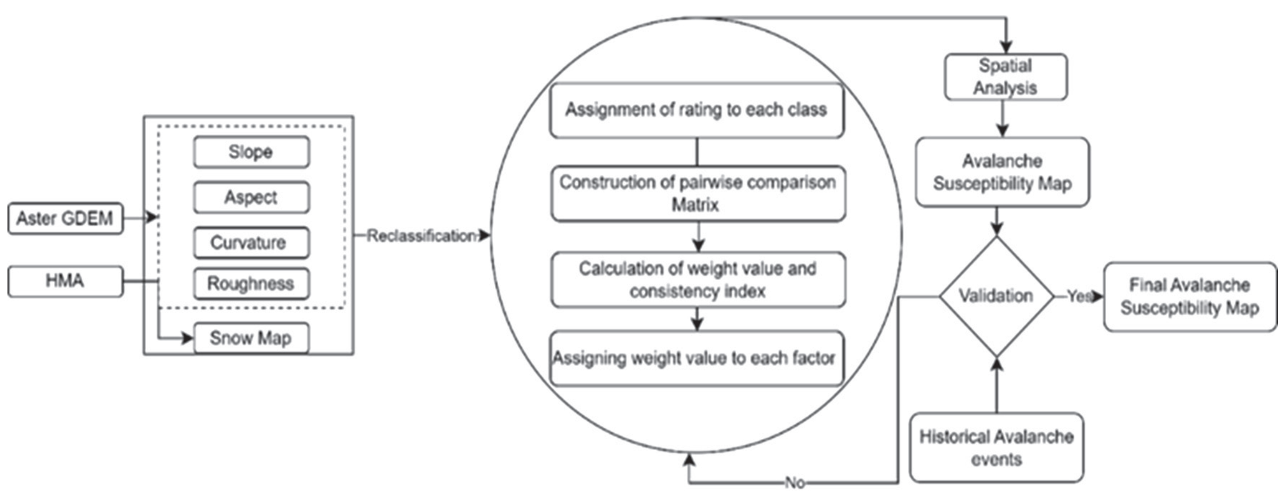

Figure 3: Methodological diagram for avalanche (Mayhew, 2016)

2.3 Avalanche susceptibility mapping using MCDA-AHP method

MCDA-AHP method is a widely used method within the field of Multi-criteria Decision Analysis (MCDA). It was developed by Saaty (1980) and provides a structured approach for decision-making involving multiple criteria (Gupta & Dixit, 2022; Kazemi & Akinci, 2018; Ouma et al., 2014). Figure 3 illustrates the methodological diagram of the study. This method is an effective approach for solving problems in a hierarchical structural. This method uses different criteria that may contribute to the overall objective.

This method used theoretical foundation of the AHP model presented in Nefeslioglu et al. (2013) and procedures from Saaty (1988). The first step is to define the unstructured problem and determine the necessary information. This involves understanding the objective and breaking it down into a decision hierarchy that includes the highest-level to lowest level of the criteria. The next step is to construct a pairwise comparison matrix for the set of criteria. Saaty's importance or preference value scale is used to assign relative weights to each criterion. The eigenvalues and eigenvectors are then calculated to estimate the weight values of the criteria. Saaty (1988)provides a specific equation for constructing the pairwise comparison matrix. By following these steps, decision-makers can systematically analyze decision criteria and alternatives, providing a structured framework for making well-informed decisions. The AHP model helps in understanding the relative importance of criteria and assists in prioritizing alternatives based on their overall contributions to the objective.

Table 1: Fundamental scale of AHP by Saaty (1980)

Intensity of importance on an absolute scale	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgement strongly favor one activity over another
5	Essential or strong importance	Experience and judgement strongly favor one activity over another
7	Very strong importance	An activity is strongly favored and its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between the two adjacent judgements	When compromise is needed

3. Results and Discussion

3.1 Weight Computation from Pairwise Matrix

The weights for each category on the map were computed from a pairwise computation matrix constructed using the fundamental scale of the AHP. The weight for each class of map is shown in Table 2. The consistency of the pairwise matrix was assessed using a consistency ratio. Since the computed consistency ratio for these pairwise matrix was 0.05, which is less than 0.1, it demonstrates that the weight of the matrix was consistent and can therefore be used for avalanche susceptibility mapping.

Table 2: Weights computation for each class from pairwise comparison matrix and consistency index.

	Elevation	**Slope**	**Aspect**	**Surface Roughness**	**Snow**	**Curvature**	**Weights**
Elevation	1	1/7	1/3	1/2	2	1/3	0.06
Slope	7	1	6	4	9	4	0.47
Aspect	3	1/6	1	2	5	1/3	0.13
Surface Roughness	2	1/4	1/2	1	3	1/4	0.09
Snow	½	1/9	1/5	1/3	1	1/7	0.03
Curvature	3	1/4	3	4	7	1	0.22
CR=0.05							

3.2 Avalanche susceptibility mapping

Using weight computed from the pairwise comparison matrix, the avalanche susceptible mapping was carried out by weighted sum procedures in the GIS. The outcomes were then reclassified into five classes of susceptibility using the natural break tool. The outcome of the study is shown in Figure 4. It displays the avalanche susceptibility map of Sagarmatha National Park. The study findings indicate the region is prone to avalanches, with around 40% of the area falling into the high and very high susceptibility categories, which can be seen in Table 3. Notably, not only the higher peaks but also areas with seasonal snowfall are highly susceptible to avalanche events. The avalanche susceptibility map also shows that the relatively flat, glacierized regions in the area have a low susceptibility to avalanches because of their level terrain.

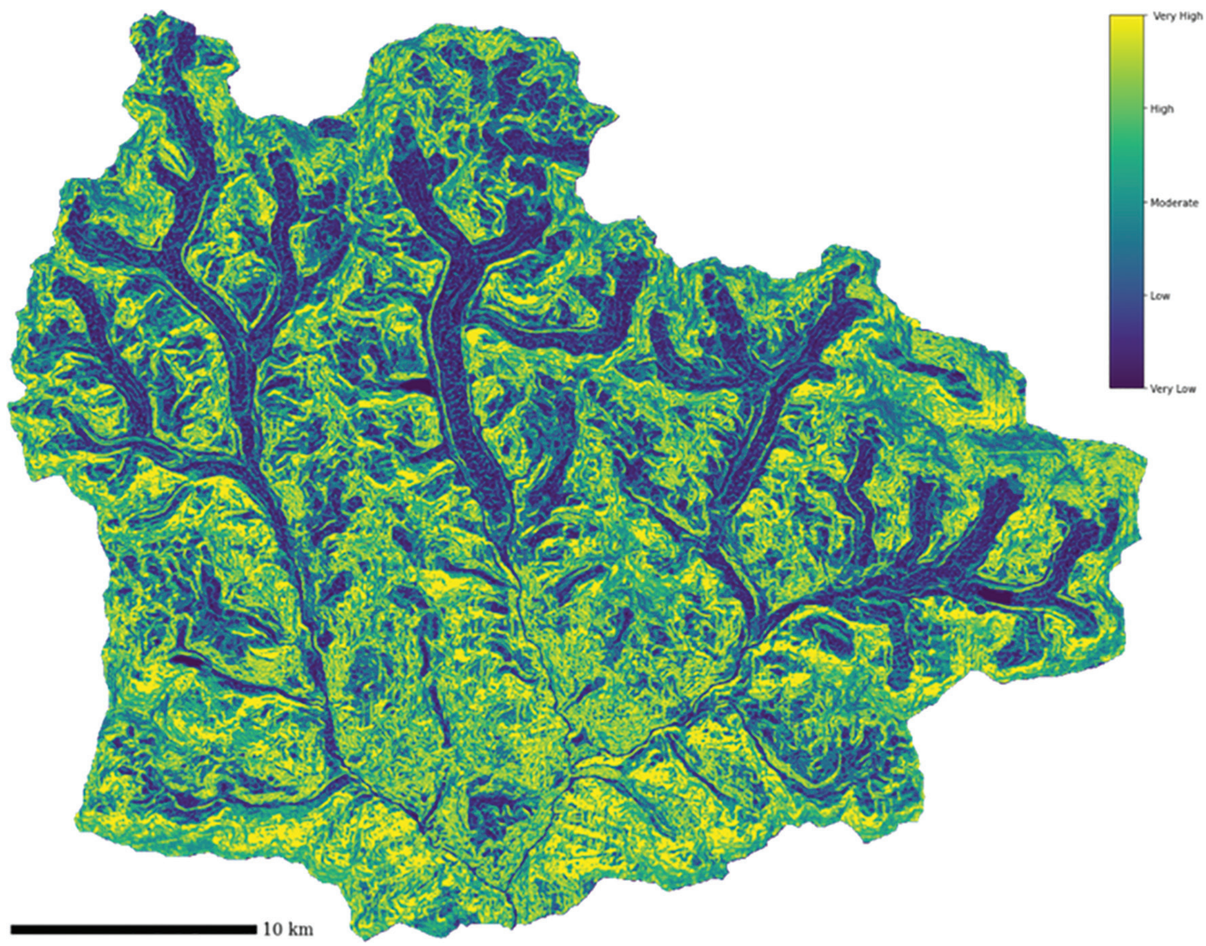

Figure 4: Avalanche susceptibility map of the region

Table 3: Susceptible region by Area in the study area.

SN	Avalanche Susceptibility	Area(Km²)	Percentage
1	Very Low	96.5	8.51
2	Low	279.16	24.63
3	Moderate	297.36	26.24
4	High	213.58	18.84
5	Very High	246.84	21.78

3.3 Validation of avalanche susceptibility mapping

The region lacks extensive monitoring and observation of avalanche evens due to remote topography and lack of monitoring infrastructures. Despite this, the susceptibility map thus prepared was validated from few recorded avalanche incidents in the region. The location of these events is shown in Table 4 and their distribution can be seen in Figure 5.

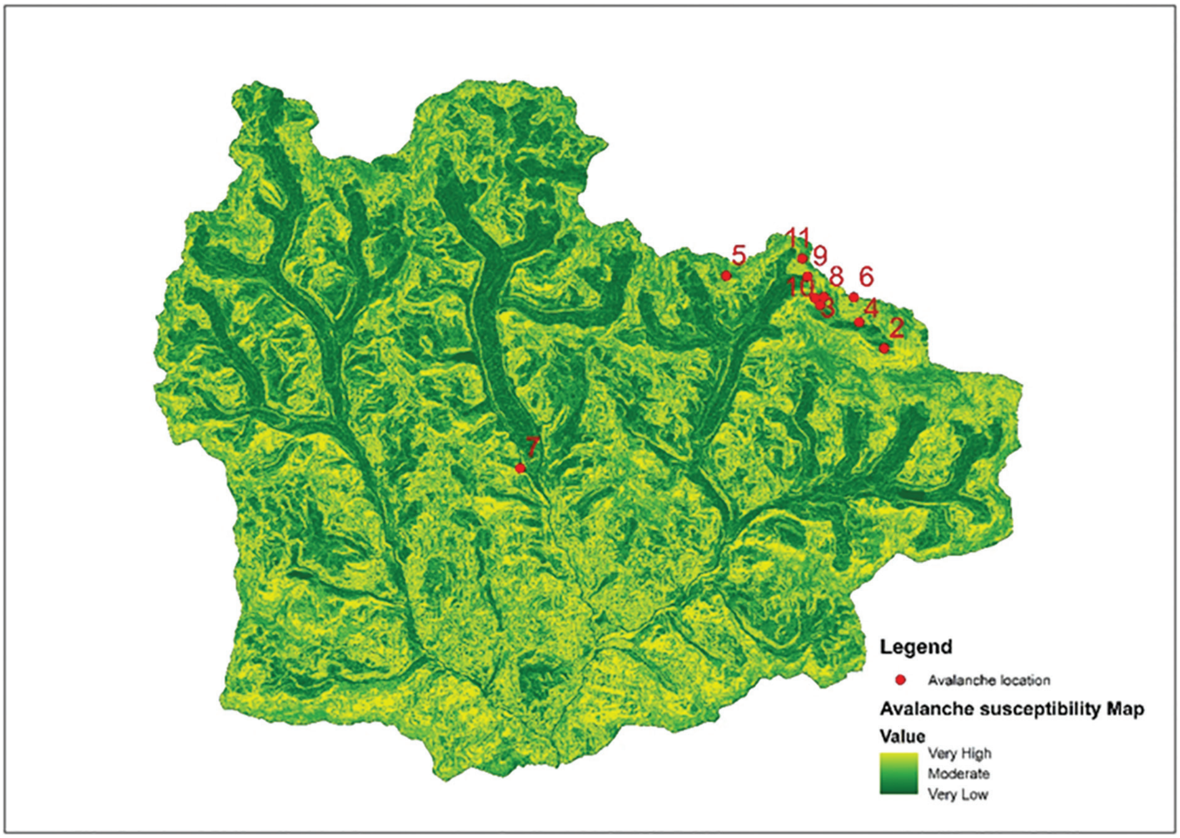

Figure 5: Avalanche locations used for validation of the outcomes of the analysis.

Table 4: Events used for validation

SN	Year	Avalanche Event	Lat	Lon
1	1982	During Swiss expedition in Lhotse face	27.9702	86.9083
2	1970	Ice-fall avalanche in the Khumbu Icefall between Base Camp and Camp I	27.9960	86.8729
3	1981	West CWM	27.9820	86.8958
4	1989	West ridge	28.0085	86.8255
5	1989	Pumori's exposed slope	27.9958	86.8941
6	1995	Khumbu region	27.9208	86.7094
7	2006	Massive serac Collapsing at the Khumbu icefall	27.9965	86.8774
8	2007	Everest region	28.0066	86.8694
9	2014	Western spur	27.9922	86.8755
10	2015	Due to shaking from an earthquake	28.0155	86.8705

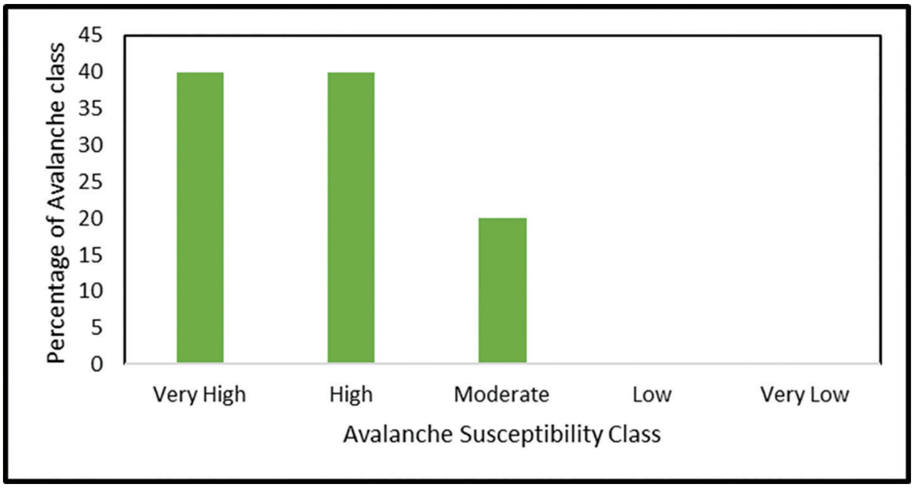

Figure 6: The distribution % of the training data in each susceptibility classes.

The study's results were validated by examining 10 previous avalanche events. Among these events, 40% data lies in the very highly susceptible region, similarly, 40% events are in the highly susceptible region, and the remaining events can be traced in the moderately susceptible region. Based on the validation, the prepared susceptibility map demonstrated a high level of accuracy.

4. Conclusions

This study developed an avalanche susceptibility map for Sagarmatha National Park using an integrated GIS-based Multi-Criteria Decision Analysis (MCDA) and Analytic Hierarchy Process (AHP) framework. The resulting map identified areas with varying levels of avalanche susceptibility and demonstrated satisfactory agreement with documented historical avalanche events, indicating the reliability of the proposed approach for regional-scale hazard assessment. The susceptibility map provides a valuable decision-support tool for disaster risk reduction, land-use planning, and the management of tourism and mountaineering activities in the Himalayan region. Future studies should integrate the susceptibility map with trekking and climbing routes, settlements, and critical infrastructure to evaluate avalanche vulnerability and support comprehensive risk management. Although the model produced reliable results, its validation was constrained by the limited availability of historical avalanche records. Establishing a systematic avalanche monitoring network and a comprehensive geospatial database would improve model validation, enhance predictive accuracy, and strengthen future avalanche hazard assessments in the Nepal Himalaya.

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