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Glacial Lake Outburst Flood Susceptibility Mapping in Sikkim: A Comparison of AHP and Fuzzy AHP Models

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Abstract: The Sikkim region of the Eastern Himalayas is highly susceptible to Glacial Lake Outburst Floods (GLOFs), a risk that has increased significantly due to rapid glacial retreat driven by climate change in recent years. This study presents a comprehensive evaluation of GLOF susceptibility in Sikkim, employing Analytic Hierarchy Process (AHP) and Fuzzy Analytic Hierarchy Process (FAHP) models. Key factors influencing GLOF vulnerability, including lake volume, seismic activity, precipitation, slope, and proximity to rivers, were quantified to develop AHP and FAHP based susceptibility maps. These maps were validated using Receiver Operating Characteristic (ROC) curves, with the AHP method achieving an Area Under the Curve (AUC) of 0.92 and the FAHP method scoring 0.88, indicating high predictive accuracy for both models. A comparison of the two approaches revealed distinct characteristics, with FAHP providing more granular insights into moderate-risk zones, while AHP offered stronger predictive capability for high-risk areas. Our results indicated that the expansion of glacial lakes, particularly over the past three decades, has heightened the potential for GLOFs, highlighting the urgent need for continuous monitoring and adaptive risk mitigation strategies in the region. This study, in addition to enhancing our understanding of GLOF risks in Sikkim, also provides a robust framework for assessing and managing these risks in other glacial regions worldwide.

Keywords: glacial lake outburst flood; glacial lake outburst susceptibility; analytic hierarchy process; fuzzy analytic hierarchy process; ROC and AUC curve

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1. Introduction

The effects of climate change on glaciers are apparent worldwide [1]. The interconnected relationship between rising temperatures, glacial retreat, and the formation of glacial lakes in high mountain regions is complex [2,3]. GLOFs are common in regions experiencing glacier retreat, which can occur rapidly, making newly formed glacial lakes particularly susceptible to outbursts [4]. A sudden outburst of a glacial lake can lead to catastrophic downstream flooding, characterized by intense erosive power and significant debris transport within a short time frame [5–9]. These events are typically triggered by dam breaches or overtopping, influenced by local lake positioning, surrounding landscape, and other natural factors. Triggers include rapid glacial meltwater, extreme rainfall, mass movements into the lake (e.g., rockfalls, landslides, and avalanches), flood waves from upstream lakes, ice calving, earthquakes, piping, and prolonged processes like dead-ice melting, hydrostatic pressure, or dam erosion [10,11]. Additionally, causes of failure can include the undercutting of slopes due to glacio-fluvial erosion and heavy monsoon rains, which lead to the saturation and erosion of frontal moraine slopes or unstable rock structures around the lakes, ultimately resulting in devastating GLOF events [12,13].

The Himalayan region is home to numerous glacial lakes, which have been expanding rapidly due to the thinning of glaciers caused by global climate change. This phenomenon, known as global warming, has led to significant shrinking of glaciers, including those in the Himalayas [14]. This retreat can be attributed to the negative mass balance between the amount of snowfall and glacial ice loss [15]. The Himalayan glaciers are projected to lose 0.4 percent of their mass annually due to the region's temperature increase of 1 to 6 degrees Celsius [16]. In the coming decades, it is anticipated that the glaciers may retreat or even disappear completely. Overall, increased global temperatures have led to the melting of alpine glaciers, resulting in a reduction in both their volume and coverage and has resulted in the creation and growth of glacial lakes, which are stored behind often unstable moraine ridges and pose a significant threat to GLOFs [17]. These glacial lakes can be found either on the surface of the glacier (supraglacial lakes or ponds) or in unconnected lakes on the glacier's periphery that receive water from the glacier's melting ice [18]. As the melting process progresses, the pressure on these natural dams increases, increasing the likelihood of an unplanned collapse [19]. They can cause catastrophic downstream floods that result in significant property damage, fatalities, and environmental consequences [20]. In addition, the frequency of glacier melt and rising temperatures contribute to an increase in the vulnerability of these lakes to explosions [21]. The significant damage caused in downstream areas due to them are primarily due to sediments and debris flows [22]. For instance, in 2013, a GLOF occurred in the Kedarnath region of the central Himalayas when the Chorabari lake overflowed due to heavy rain, causing a flash flood and landslides that resulted in the death of over six hundred people and the destruction of most of the buildings in a nearby village located just over a kilometer downstream of the lake [23].

Sikkim is relatively a small region located in the northeastern part of India, which is prone to being severely impacted by GLOFs due to its geography and climate and has the highest number of glaciers in the Eastern Himalayas, which has undergone rapid deglaciation, resulting in numerous historical GLOFs [24]. Sikkim's rate of glacier melting is notably higher than the Western, Central, and Karakoram regions of the Himalayas [25]. Studies have reported that there has been a glacial expansion on the north face of the Kangchengyao massif in Sikkim, with nine additional glacial lakes documented between 1988 and 2014 [26]. Approximately 200 sq.km of glacial area has melted in the Teesta River Basin over the past two decades (1990–2010), resulting in the formation of numerous debris-covered supraglacial and moraine-dammed lakes [27]. The Gurudongmar lakes are considered one of the most potentially dangerous lake complexes in the Teesta basin of Sikkim Himalaya, making flood susceptibility mapping crucial for identifying potential risk areas [28].

Mool et al. [24] provided the first set of data on the population of glacial lakes with 266 identified and having an total area of around 20 sq.km. An area of approximately 2 sq.km was observed, and 14 of the 96 lakes were identified as having potential risks. A similar glacial lake inventory identified 14 potentially dangerous out of 320 total lakes listed within the area [29]. Subsequently, another inventory was established with the help of Resourcesat-2 and LISS IV imageries, where the study revealed that there are a total of 472 lakes with an area of more than 0.01 sq.km; however, 21 out of the enumerated lakes were considered critical [2]. Excluding these, few other research works on the numerical modelling of a hydrodynamic moraine dam breach and the hazard identification and in situ bathymetric investigation on South Lhonak Tso of Sikkim Himalaya have been documented [30].

Sikkim's climatic conditions have a significant impact on its susceptibility to GLOFs, particularly due to the monsoonal rainfall that accelerates glacier melt and increases the volume of water in glacial formations. Additionally, temporal changes influence the rise and collapse of these natural dams, with warmer temperatures hastening glacier melt and resulting in more outburst floods [31]. The susceptibility of GLOFs in this region depends on a variety of factors, such as the rate of expansion of glacial lakes, their volume, seismicity, slope angles, avalanches, and debris flow. Climate change leads to a faster rate of glacier melting and an increase in the formation and volume of glacial lakes, which significantly raises the risk of outburst flooding [32]. This risk is further exacerbated by seismic activity in the region, as tectonic activities can cause shifts in the frozen surface beneath which glaciers form, creating conditions suitable for the formation of lakes that may be breached by the calving of glacial dams [33]. The topographic factors prevalent in the Sikkim region increase the vulnerability to GLOFs because of the steep gradient that allows water to flow downhill rapidly when natural barriers are breached [34]. Avalanche activity also poses a challenge, as large masses of snow and ice can descend and infiltrate glacial lakes, resulting in rapid displacement of water and pressure on natural barriers [35].

Debris flows, avalanches, and earthquakes exacerbate the stability challenges faced by moraine dams in glacial lakes, adding additional mass to these structures [36]. To identify the appropriate zoning for glacial lake susceptibility, it is essential to utilize complex analytical methods such as AHP and FAHP to assess the significance and weight of each contributing factor [37]. Such an approach is invaluable to comprehensively assess GLOF hazards particularly in Sikkim region, so as to assist in monitoring, mitigating, and managing associated risks to protect its vulnerable communities. In this context, the primary aim of this research is to conduct a comprehensive assessment of GLOF causing processes in the Sikkim region, with a particular focus to develop management and mitigation strategies. The study uses a multidisciplinary approach, including remote sensing analysis, geospatial modeling, and empirical volume estimation techniques. The key objectives are to delineate glacial lakes in the Sikkim region, to identify and analyze the key factors influencing GLOF susceptibility, and to develop GLOF susceptibility maps using the AHP and FAHP approaches.

2. Materials and Methods

2.1. Study Area

Sikkim is a small and one of the most beautiful states of India well known for its scenic beauty, and immensely rich biological diversity manifested by wide ranges of eco-climatic conditions [38]. It is bordered by Tibet in the north, Nepal in the west, Bhutan in the east, and West Bengal in the south (Figure 1). It covers an area of 7096 sq.km and is located between 27°05′ and 28°07′ N latitudes and 87°59′ to 88°56′ E longitudes. Nestled in the eastern Himalayas, Sikkim has multiple glaciers that are essential to the region's ecology, hydrology, and management of water resources. The majority of these glaciers are found in high-altitude areas, mostly in the state's northwest and northern districts. In its northern part, the state hosts numerous Glacial lakes of different sizes and types (supraglacial, proglacial, blocked, or erosional). These lakes are fed by important glaciers such as the East Rathong, Talung, Changme Khangpu, Lhonak, and Zemu glaciers. Tso Lhamo Lake, situated in the northeastern region of the state, is the source of Teesta, the principal river in Sikkim. Teesta's principal tributary is the river Rangeet. As per the Census of India 2011, Sikkim has a population of 610,577 which increased by +13% compared to 2001. Sikkim is a part of the inner Himalayan Mountain range and more than 43% of the state consists of steep slopes and escarpments with a rugged terrain. Sikkim is characterized by a tundra climate in its northern part and a sub-tropical climate in its southern part. The dense forests lie in the snow-covered regions and four ecological zones: subtropical, temperate, sub-alpine, and alpine. The average annual rainfall is 2739 mm. The highest annual rainfall for the individual station may exceed 5000 mm (https://sbbsikkim.nic.in/sikkim-physiography.html (accessed on 31 April 2024)). The state's rainfall distribution varies because of its geographical variations. Northern regions and other higher-elevation locations receive less rainfall than southern, lower-elevation regions. Temperature varies with the altitude and the slope. In lower altitudes, the temperature is between 4.5 °C and 18.5 °C, whereas at higher altitudes, it varies from

1.5 °C to 9.5 °C. Still higher up, the temperature can go below −30 °C. The Tista River rises northeast from a glacier near the Tibetan border and descends steeply at about 4800 m to Rangpo on the West Bengal border, where it carves a valley through the Darjeeling Ridge (2100 to 2400 m) before flowing into the Indo-Gangetic Plain. The rock structure of the mountain ranges is dominated by gneiss and schist and the combined effects of heavy rainfall, structural weaknesses, and steep slopes make them highly susceptible to denudation. Deep mountain valleys in the Sikkim Basin are formed by deep valley formations of the Teesta River and its tributaries, including the Rangit, Ronak, Tarung, and Lachung rivers. Both glacier melt and monsoon rain are responsible for the large flows into Sikkim's renowned perennial rivers. During the monsoon period, which lasts from June to September, the rivers tend to become enlarged and the risk of floods and landslides is often high and affects river runoff.

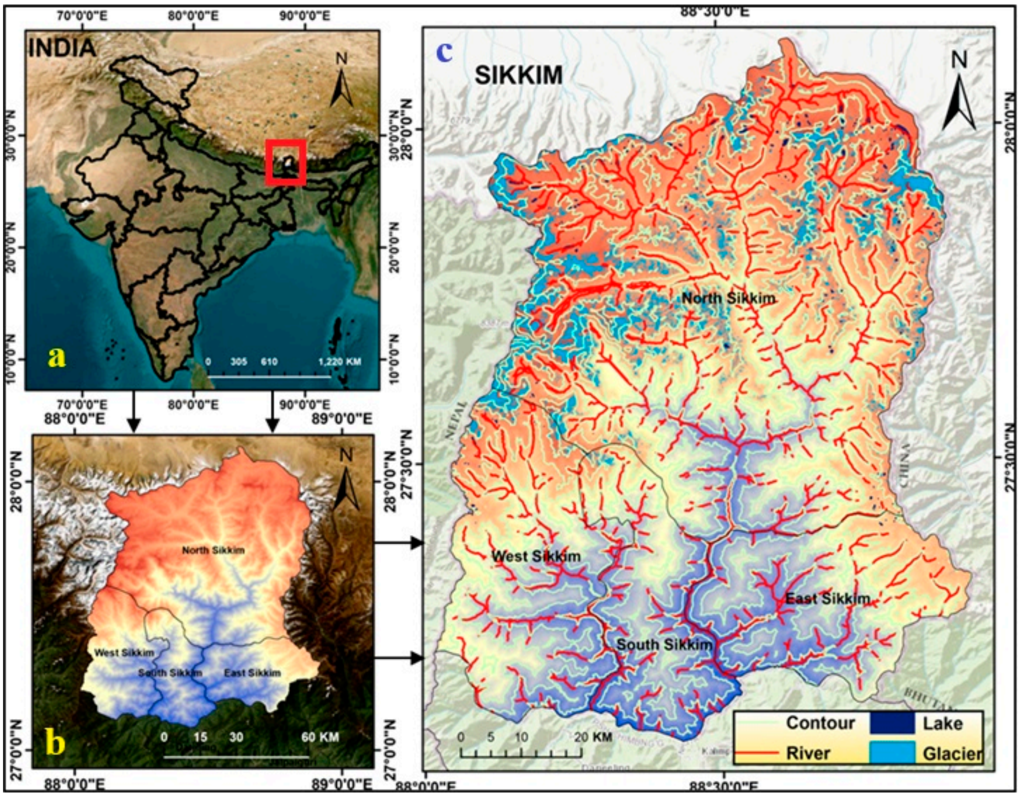


Figure 1. (**a**) An overview map of India showing the geographical location of Sikkim in the northeastern part of the country (highlighted in red). (**b**) A topographic map of Sikkim, displaying elevation variations across its four districts (North, West, South, and East Sikkim). (**c**) A detailed map of Sikkim illustrating its river systems (in red), lakes (in blue), glaciers (light blue), and contour lines indicating elevation changes. The map highlights the intricate hydrological features and topography critical to the study of Glacial Lake Outburst Flood (GLOF) susceptibility.

2.2. Data

Our assessment of GLOF susceptibility integrated various datasets such as Cartosat-1 mission, developed by ISRO (Table 1). It provides high-resolution earth observation data, which was crucial for this study. Its panchromatic resolution of approximately 2.5 m enables detailed mapping of glacial features, including lakes, glaciers, and landform morphology. This level of detail is essential for accurately identifying and analyzing the physical characteristics that influence GLOF risks, such as the size and structure of glacial lakes and surrounding topography. Additionally, we utilized data from Landsat 9, from NASA's Landsat program, launched on 27 September 2021, in collaboration with the USGS Earth Observation Satellite System. Landsat 9 continues the legacy of its predecessors by providing consistent, long-term data for monitoring the Earth's land surface and coastal regions. It is widely used in applications such as agriculture, forestry, and land use planning, but in this study, they were instrumental in capturing temporal changes in glacier and lake formations. With a resolution suitable for large-scale environmental monitoring, Landsat 9 data allowed us to track glacial lake expansion over time. Climate data was another critical dataset, as the relationship between climate change and glacial dynamics is a central focus of GLOF susceptibility studies. We used data from the Climate Hazard Group Infrared Precipitation with Station data (CHIRPS), covering the period from 2003 to 2021. This dataset provided high-resolution rainfall data, which are vital for analyzing how changing precipitation patterns contribute to GLOF risk by influencing lake levels and glacial melt rates.

Table 1. Details of data used in this study.

Data Used	Date	Resolution	Purpose	Source
Landsat 5	23-12-1990 18-12-2000 30-12-2010	30 m	Change Detection of Glacial Lake	USGS Earth Explorer
Landsat 9	26-12-2023	30 m	Glacial Lake Inventory	USGS Earth Explorer
Cartosat 1	2005–2014	2.5 m	Slope, Elevation, Distance From River, Watershed	Bhuvan Data Portal
Climate Data	2003–2021		Average Annual Rainfall	Chirps data Portal
Earthquake Data	2000–2024		Seismic Activity	USGS Earthquake Catalog

Additionally, seismic activity data, from the USGS Earthquake Catalog, was also incorporated into our study to assess how seismic events may potentially trigger GLOFs. This data is crucial, as it provides key information about the geological processes and includes the analysis of landforms, surface morphology, and geological structures, integral to understanding the physical vulnerabilities of moraine-dammed lakes and glacial landscapes.

2.3. Methods

2.3.1. Glacial Lake Inventory

In this study, glacial lakes in the Sikkim region were analyzed using geospatial techniques, with multispectral data from Landsat 9, managed by the US Geological Survey (USGS) and NASA. In our study we used NDWI (Normalized Differences Water Index) to detect the water in the study area [39]. NDWI is based on the following Equation (1):

$$NDWI = \frac{G - NIR}{G + NIR} \quad (1)$$

NDWI enhanced the detection of glacial lakes. It was subsequently followed by glacial lake mapping and classification by manual digitization method using the generated NDWI. This manual process is important in confirming the accuracy and precision of the automatic process to account for misclassifications that the NDWI component might have produced.

2.3.2. GLOF Susceptibility

GLOFs occur when natural reservoirs such as glaciers, moraines (glacial debris accumulations), or other drainage systems fail. These disasters can be triggered by multiple factors, including melting glaciers, intense rainfall, seismic activity, or internal changes within the glacier [40]. In this study, we used nine critical factors for glacial lake outburst susceptibility mapping. Among these, the volume and area of the glacial lakes were considered as the primary drivers in determining the probability of a GLOF event. It has been established that the risk of a GLOF is directly proportional to the volume of water contained within a glacial lake, larger lakes with higher water content pose a greater threat, as they would release more water during an outburst [40]. These physical attributes of glacial lakes are tangible, quantifiable, and key to assessing GLOF susceptibility using both AHP and Fuzzy AHP methods. To estimate the volume of the lakes, we applied three empirical volume formulae and finally used the average of the three in the analysis. These formulae, based on glacial lake areas, provide a method for calculating volume (V) as a function of lake area (A). The average lake volumes were computed using equations shown in Table 2.

Table 2. Empirical formulae of estimate glacial lake volume.

References	Formulae
[16]	$V = 0.104 \times A^{1.42}$
[20]	$V = 0.0578 \times A^{1.4683}$
[36]	$V = 0.0522 \times A^{1.1766}$

Sikkim is prone to earthquakes and these have the potential to trigger the release of the moraine imbedded water that leads to the formation of glaciers via landslides or directly breach the moraine barrier. The frequency and intensity of the manifested seismicity must be monitored within the highest degree of accuracy; an increase can lead to sudden and large-scale GLOFs [41]. Erosion and transitional zones between glaciated and non-glaciated areas are other factors involving avalanche and rock fall zones and play a crucial role in the instability of glacial lakes [42]. Disasters such as avalanches have abilities to significantly increase the water filling rate of a lake to reach its banks or even breach natural dams. The same could happen with rock falls on the landscape, falling directly into the lake and adding a load to the lake, or contributing to the destabilization of the lake's dam. The proximity of glacial lakes to river systems is an important factor in establishing the potential impact of a GLOF downstream [43]. Lakes that are closer to rivers will aid in the quick transmission of floodwaters, thereby posing a greater risk to the people and infrastructure at the bottom [44]. The distance of the river affects the speed and force of the floodwaters, thereby making it an important parameter in both AHP and Fuzzy AHP evaluations. Topographical factors include slope and elevation, both of which are very important in the process of glacial lakes and possible outburst floods. Steeper slopes can very likely result in greater water flow and higher erosion levels, whereas higher elevations could affect the temperature and, thus, the melting rates of the glaciers that were feeding the lakes. These two factors are interlinked and must be integrated into a comprehensive GLOF risk assessment. The overall methodology is depicted in Figure 2.

2.3.3. AHP Methods

The ability to consider several parameters simultaneously has placed the AHP, created by Saaty in 1980, among the most popular MCDM (multi-criteria decision-making) tools [37]. This approach helps researchers in providing priority comparisons of various factors in a more systematic way. AHP hierarchy is developed in the form of a decision hierarchy, where the higher level is the objective of the study, the middle level is the criteria, and the lowest level is the alternatives. The basic concept of AHP is the conversion of ratios to numerical values to facilitate their representation in a matrix format. This assists in identifying those criteria that have the greatest bearing on the achievement of the above-mentioned objective [45].

AHP utilizes a judgment matrix to comparatively assess the importance of different criteria consistently [37]. Thus, it makes comparisons possible on a scale between 1 and 9, whereby 1 indicates that the two objects are similar in importance and 9 is indicative of unequal importance. Thus, for each of the considered criteria, a geometric mean for their importance was obtained while summarizing the importance indicated by each evaluator.

These geometric means are then normalized to provide a set of weights that are relative to each other, and the weights add up to one, which reflects the relative importance of each criterion.

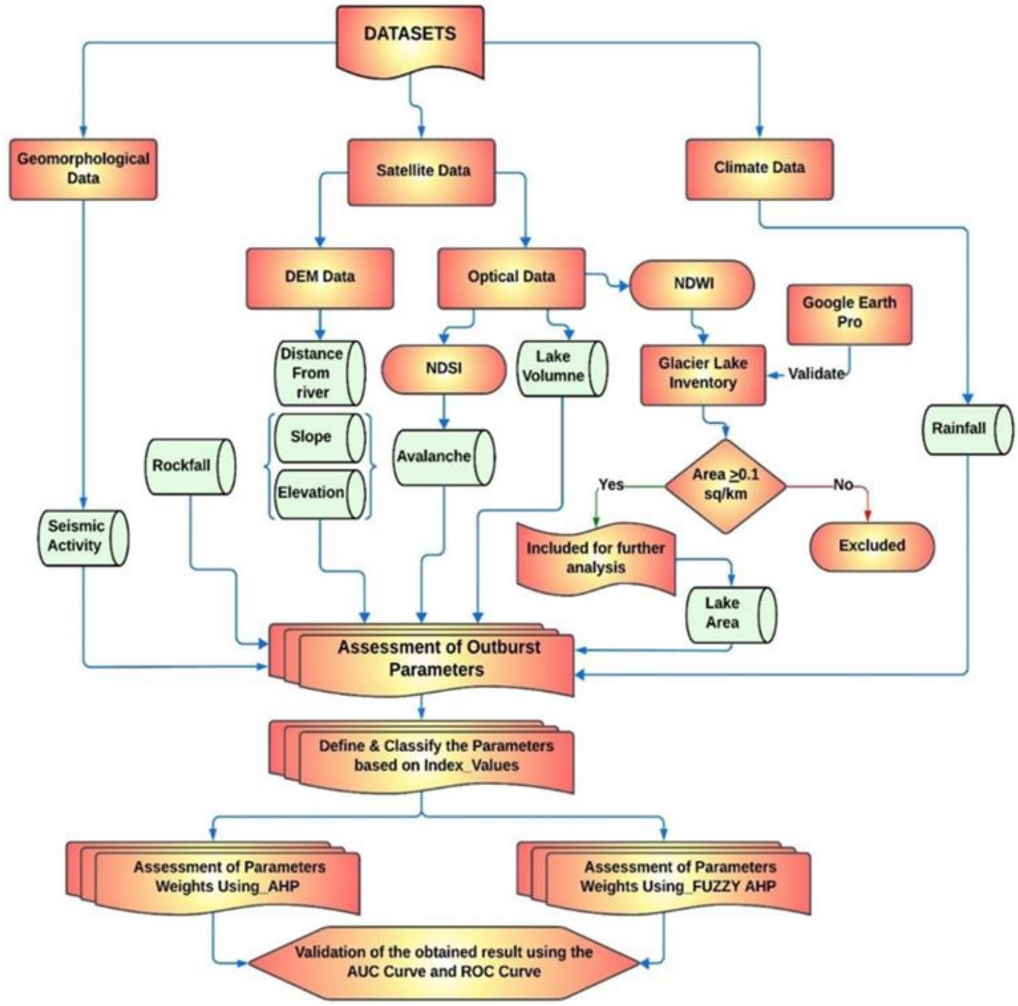


Figure 2. Overall methodology flowchart used in the study.

2.3.4. FAHP Analysis

FAHP is an expansion of the basic AHP that accounts for fuzzy logic because the original AHP is highly sensitive to variations in human judgment owing to its vagueness [46]. For relative importance in pairwise comparison, FAHP applies fuzzy numbers, specifically triangular fuzzy numbers. These fuzzy numbers are defined by three parameters: the three values are the lower bound, which is the widest from the likely value; the probable value, which is the middle value of the triangle; and the upper bound, which is the nearest to the likely value, making a triangle encompassing a given range of values rather than a single value [46]. This approach helps in preserving the differentiation of the extent and nature of uncertainty and ambiguity in the decision-making process.

These triangular fuzzy numbers are then used as the decision matrix in the FAHP, where pairwise comparisons yield the fuzzy pairwise comparison matrix. The fuzzy geometric mean was then produced for each criterion, and the results of the pairwise comparison were then aggregated. The geometric means calculated are fuzzy numbers, and the values are converted into fuzzy weights that compare the relative importance of these criteria to decision-making. After obtaining the fuzzy weights, a defuzzification process converts them into crisp values, and the selection and ranking of the alternatives are performed using the centroid method [46].

The use of fuzzy logic in AHP enhances its capability to deal with subjective assessments and uncertainty, making it an intensified tool for robust decision-making in complex situations. By embracing the principles of fuzzy sets, FAHP is more realistic and flexible, and especially conforms to the inherent imprecision of human judgment; thus, it provides powerful methodologies for systematic, quantifiable, and reliable decision-making in many fields. Therefore, AHP and FAHP are strong methodologies in various fields for systematic, quantifiable, and reliable decision-making (Table 3).

Table 3. Level of importance of AHP and Fuzzy AHP methods.

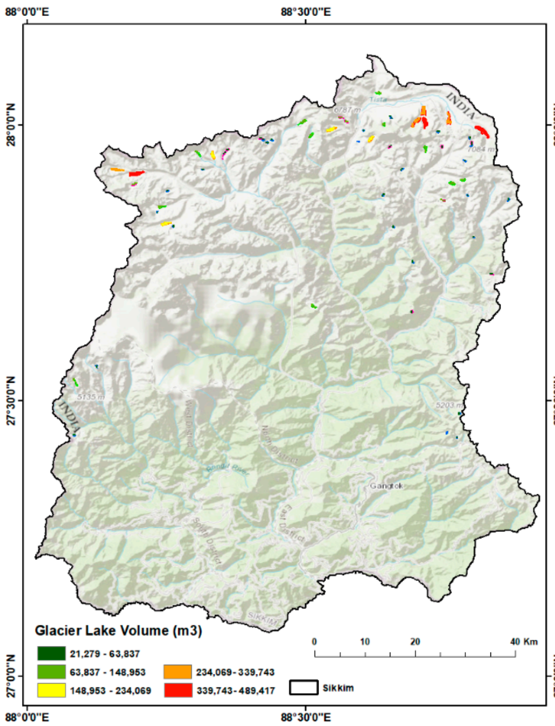
Level of Importance		Definition
AHP	**FAHP**	
1	(1,1,1)	Equally Preferred
3	(2,3,4)	Moderately Preferred
5	(4,5,6)	Strongly Preferred
7	(6,7,8)	Very Strongly Preferred
9	(9,9,9)	Absolutely Preferred
7	(6,7,8)	Very Strongly Preferred
9	(9,9,9)	Absolutely Preferred

3. Results

In this study, nine key parameters were utilized to assess GLOF susceptibility: avalanche zone maps, elevation, slope, rockfall, distance from rivers, rainfall, seismic activity, lake area, and lake volume. Each parameter was classified into five susceptibility categories ranging from extremely low to very high, based on their values. Following this classification, weights were assigned to each parameter using the AHP and FAHP. Finally, weighted overlay analysis was performed by incorporating the parameter weights derived from both methods to generate a comprehensive Glacial Lake Susceptibility Map. This map provides valuable insights into the spatial distribution of the GLOF risk across the study area.

3.1. Assessment of Significance Factors for GLOF Susceptibility

To assess the significant factors influencing GLOF susceptibility in Sikkim, nine critical parameters were quantitatively analyzed. These parameters include lake volume, lake area, seismicity, rainfall, distance from rivers, elevation, slope, rockfall, and avalanche-prone areas. The occurrence of outburst floods is influenced by the complex interactions between these factors, which collectively define the overall risk of such events. The lake volume, categorized in this study range between 21,279 and 489,417 cubic meters, correlates with flood intensity, where larger volumes increase the potential risk of an outburst (Figure 3a). Similarly, the lake area, ranging from 0.1 to 1.87 sq.km, contributes to GLOF susceptibility, as larger lakes hold more water, increasing the likelihood of severe flooding (Figure 3b). Seismic sensitivity is also a key factor, with earthquake magnitudes ranging from 4.0 to 4.6 in the study area (Figure 3g). Earthquakes can trigger rockfalls and destabilize lakes, potentially leading to outburst events. Annual average rainfall, which varies between 6170.12 and 20,488.3 mm/year (Figure 3i), significantly affects lake levels. Higher rainfall leads to lake overflow, which increases the risk of moraine breaches. The proximity of lakes to drainage channels was categorized into five distance classes: 400, 800, 1200, and 1600 m and beyond 1600 m (Figure 3h). Lakes located closer to rivers pose a greater threat, as they facilitate quicker transmission of floodwaters downstream during an outburst. Topographical factors such as elevation, ranging from 197 to 7884 m (Figure 3c), and slope, with values between 0 and 79.6 degrees (Figure 3d), also play a crucial role in GLOF susceptibility. Steeper slopes and higher elevations are associated with rapid water movement, landslides, and avalanches, which may destabilize lakes. Finally, rockfall and avalanche-prone zones were classified into five categories: very low, low, moderate, high, and very high, highlighting areas susceptible to sudden movements of rock and snow that contribute to GLOF risk (Figure 3e,f).



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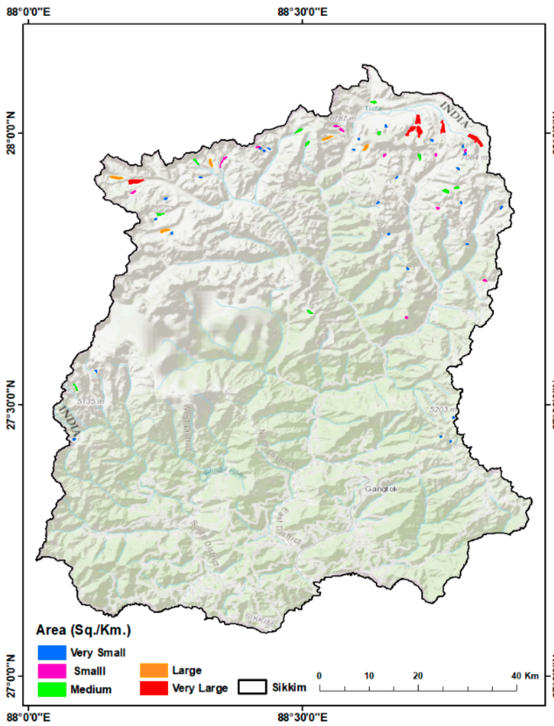

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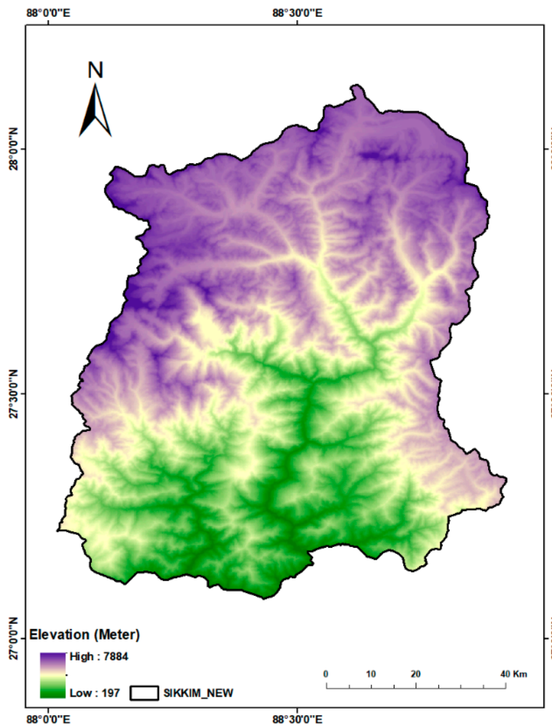

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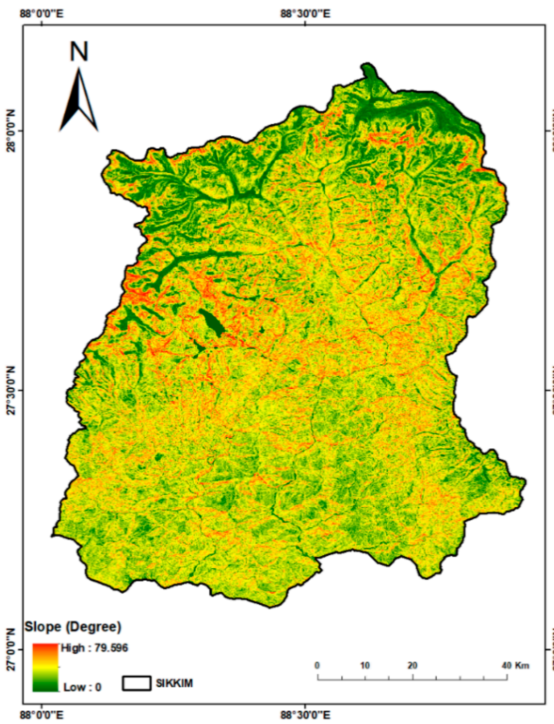

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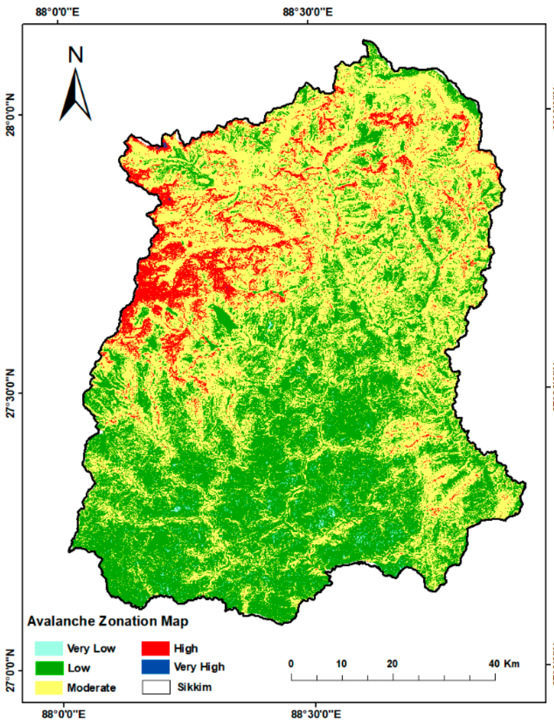

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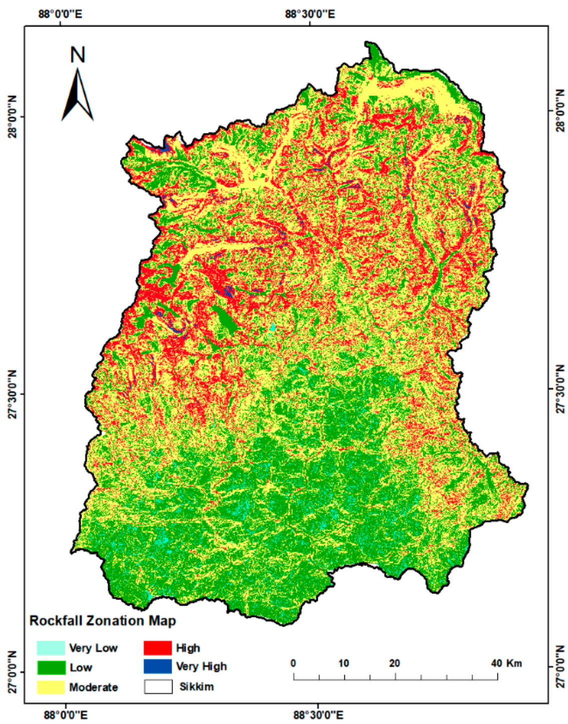

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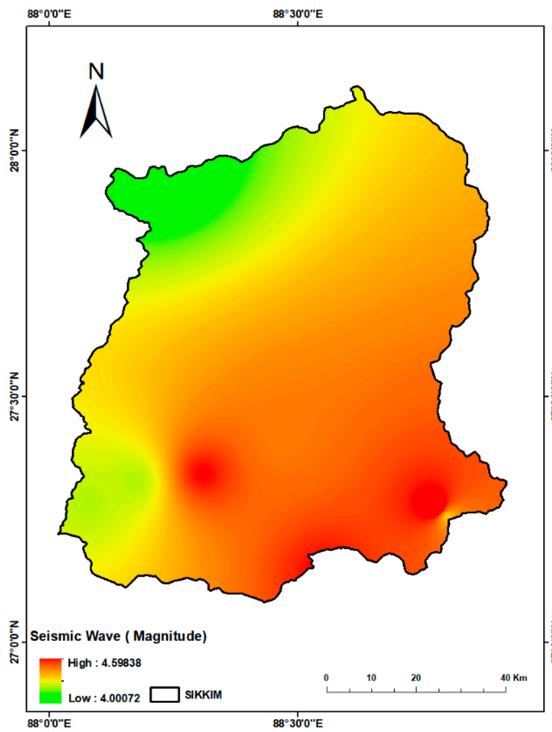

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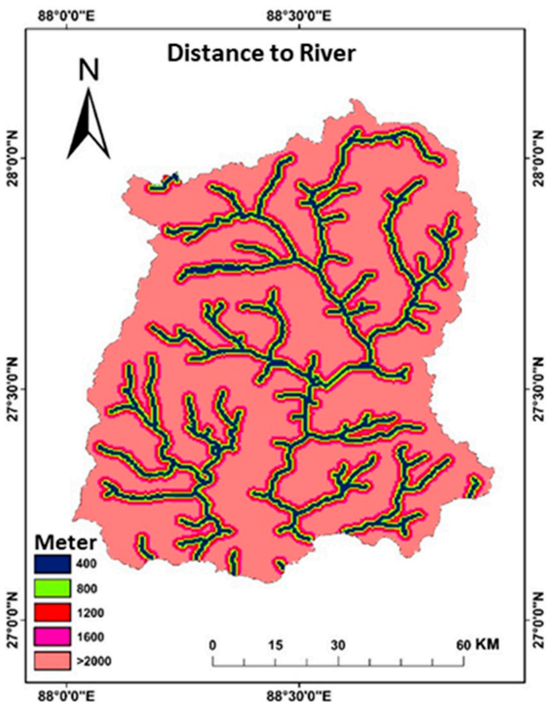

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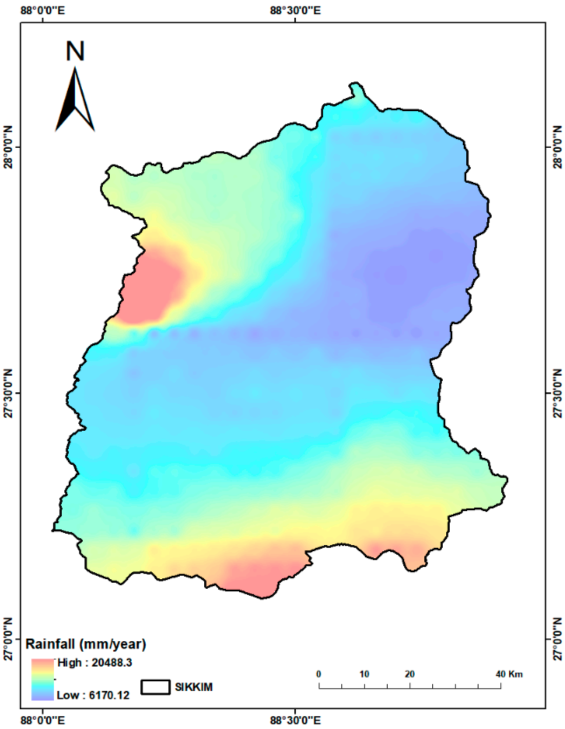


(i)

Figure 3. Illustrations of the critical parameters analyzed in this study. (**a**) Glacial Lake volume (in cubic meters). (**b**) Glacial Lake Area (in sq.km), categorizing the lakes by size, where larger areas correlate with higher flood potential due to larger water storage. (**c**) Elevation Map (in meters), highlighting the topographical variance across Sikkim, which affects water flow dynamics and flood pathways. (**d**) Slope Map (in degrees), illustrating the steepness of the terrain, a key factor in assessing water movement, erosion, and landslide potential. (**e**) Avalanche Zonation Map, identifying regions at different levels of avalanche risk. (**f**) Rockfall Zonation Map, which pinpoints areas vulnerable to rockfalls, another factor contributing to the risk of outburst floods. (**g**) Seismic Activity Map. (**h**) Distance to River (in meters), indicating proximity to drainage channels. (**i**) Rainfall Distribution Map (in mm/year), showing areas with high rainfall.

3.2. Assessment of Glacial Lake Outburst Flood Susceptibility Map Using Comparative Study Between AHP and Fuzzy AHP Method

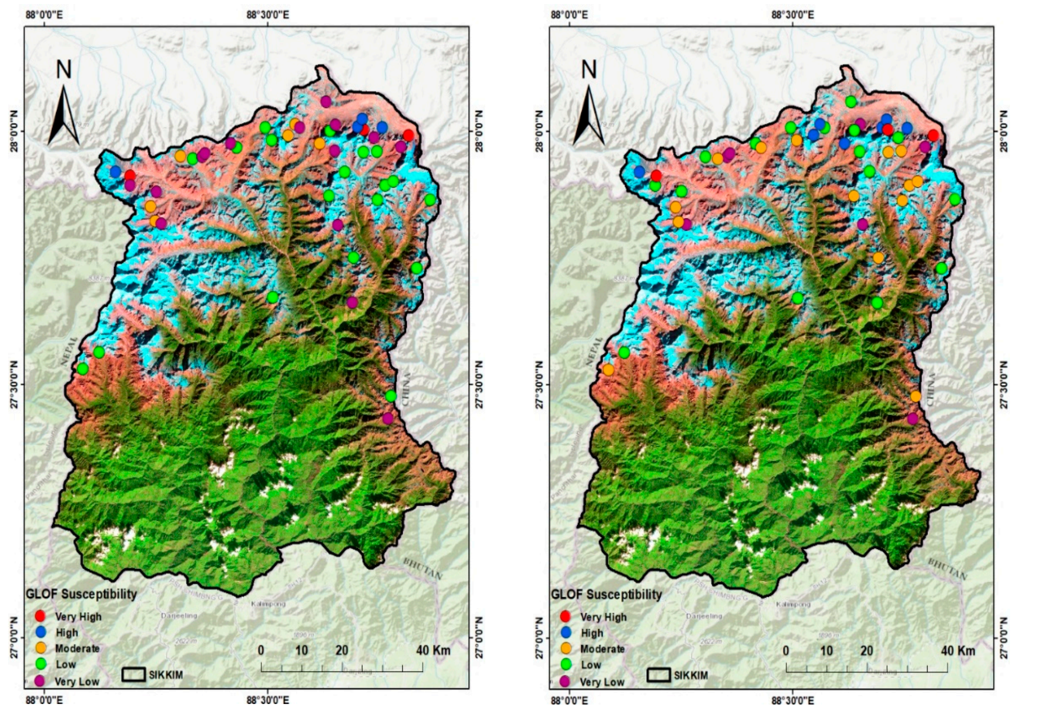
In this study, the indicators for GLOFs were identified and the degree of vulnerability was determined using AHP, and Fuzzy AHP. The factors included volume, the seismically active region, area, elevation, avalanche, rock, proximity to the river, and rainy areas. The weights for these parameters were calculated using both AHP and FAHP approaches. These parameters were then combined using weighted overlay tools to develop a glacial lake outburst susceptibility map. The degree of glacial lake susceptibility was classified into five classes: low, moderate, high, and very high, in a similar fashion after working individually on each factor and then gradual addition of the factor scores. The presented map is useful in assessing the levels of susceptibility towards different risks and allocating the needed resources for risk management and mitigation. Table 4 displays the weights of each parameter using the AHP and fuzzy AHP methods.

The glacial lakes' vulnerability is categorized as follows using the AHP method. After analysis it was observed that 15 lakes fall in the Very Low Zone, 19 in the Low Zone, 6 in the Moderate Zone, 4 in the High Zone, and 3 in the Very High Zone (Figure 4a). AHP analysis shows that the majority of glacial lakes (34 out of 47) fall in the very low to low susceptibility bands. In view of this, it could be inferred that, in terms of the AHP method, most of Sikkim's glacial lakes are in less danger of outburst floods. But there are 7 lakes still falling in the high to very high susceptibility zones, which means that there is a need for water managers to check on these lakes more and probably take precautions to avoid the outburst of floods.

The glacial lakes' vulnerability is categorized as follows using the Fuzzy AHP method. Number of Lakes in the Very Low Zone were 7, Low Zone, 16, Moderate Zone, 14, High Zone, 7, and in the Very High Zone, 3 (Figure 4b). The FAHP approach shows the ranking and distribution of glacial lakes are more distributed in the susceptibility zones compared to the AHP method. However, there is a relatively higher number of lakes (14 lakes) that fall in moderate susceptibility zones as observed from the AHP analysis alone where susceptibility has decreased to the lower zone. This demonstrated that the Fuzzy AHP model offered a subtler evaluation and acknowledged that most lakes fall under the middle risk category. The number of lakes in the very high susceptibility zone remains the same (three lakes), which supports the congruity between both methods with respect to the lakes with increased risk.

Table 4. Weight of each parameters using the AHP and Fuzzy AHP method.

Parameters	AHP Weight	Fuzzy AHP Weight	Ranking
Glacial Lake Volume	14.61	17.77	1
Seismic Activity	10.18	6.48	6
Glacial Lake Area	14.61	10.2	5
Elevation	6.69	5.77	7
Avalanche	15.1	17.22	2
Rockfall	15.1	16.81	3
Slope	13.86	16.81	4
Distance from River	4.19	4.81	9
Rainfall	5.66	4.13	8



(**a**) (**b**)

Figure 4. GLOF Susceptibility Maps of the Sikkim region, showing the variation in risk classification based on two different methodologies. (**a**) Shows the susceptibility map generated using the Analytic Hierarchy Process (AHP) method, and (**b**) shows the results derived from the Fuzzy Analytic Hierarchy Process (Fuzzy AHP). The maps classify GLOF risk into five categories: Very Low, Low, Moderate, High, and Very High, depicted by different colors, with areas in red indicating the highest risk of outburst events.

3.3. Validation with Receiver Operating Characteristic (ROC) and Area Under the Curve (AUC)

Consideration of weights for specific parameters as established by both the AHP and fuzzy AHP methods has led to the application of AUC of ROC to verify the validity of susceptibility assessment in this regard. In general, the AUC denotes the benchmark of model accuracy in the prediction of highly susceptible lakes. The AUC obtained by the AHP method is 0.92, indicating higher effectiveness in predicting glacier-lake-outburst-flood-prone lakes (Figure 5). The closer the AUC is to 1, the greater the accuracy, thus confirming the AHP model for its high productiveness. The AUC of 0.88, obtained using the fuzzy AHP method, also seems to be indicative of robust predictive capacity but is still relatively lower compared to AHP. These results endorse both methods for identifying GLOF vulnerability in Sikkim with AHP showing marginally superior performance.

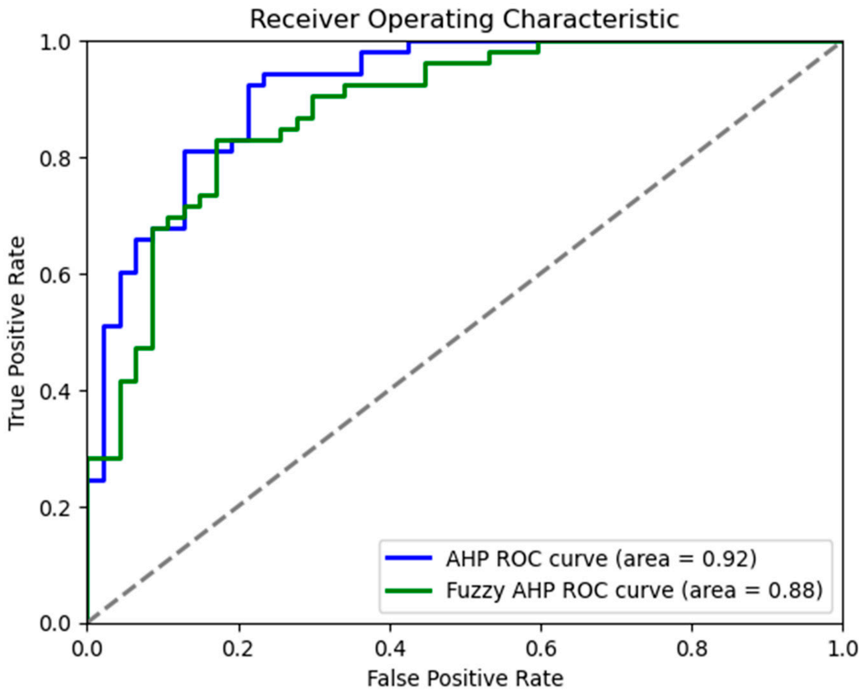


Figure 5. ROC curves illustrating the AUC values for two different methods used in the study, AHP and FAHP. The AHP method achieved an AUC value of 0.92, indicating high accuracy in GLOF susceptibility prediction, while the FAHP method had an AUC value of 0.88, demonstrating a slightly lower but still reliable predictive performance. The ROC curve plots the true positive rate (sensitivity) against the false positive rate, providing a visual assessment of the model's performance.

3.4. Change Detection of Glacial Lakes (1990–2023)

In this study, some of the lakes were classified to be high to very high-risk areas by both methodologies. This assessment highlighted the high risk associated with these lakes and the need to assess the spatio-temporal changes associated with them. It was observed that the rate of expansion of these glacial lakes from 1990 to 2023 is significant (Figure 6). The volume of the water from such lakes plays a very vital role in enhancing the intensity of outburst floods. During the analysis period, this expansion was closely related to climatic factors like rising temperatures and increased glacial melt. These findings bring to the forefront the imperative need for management and mitigation strategies of GLOF risks in Sikkim, where in fact the threat continues to pick up momentum.

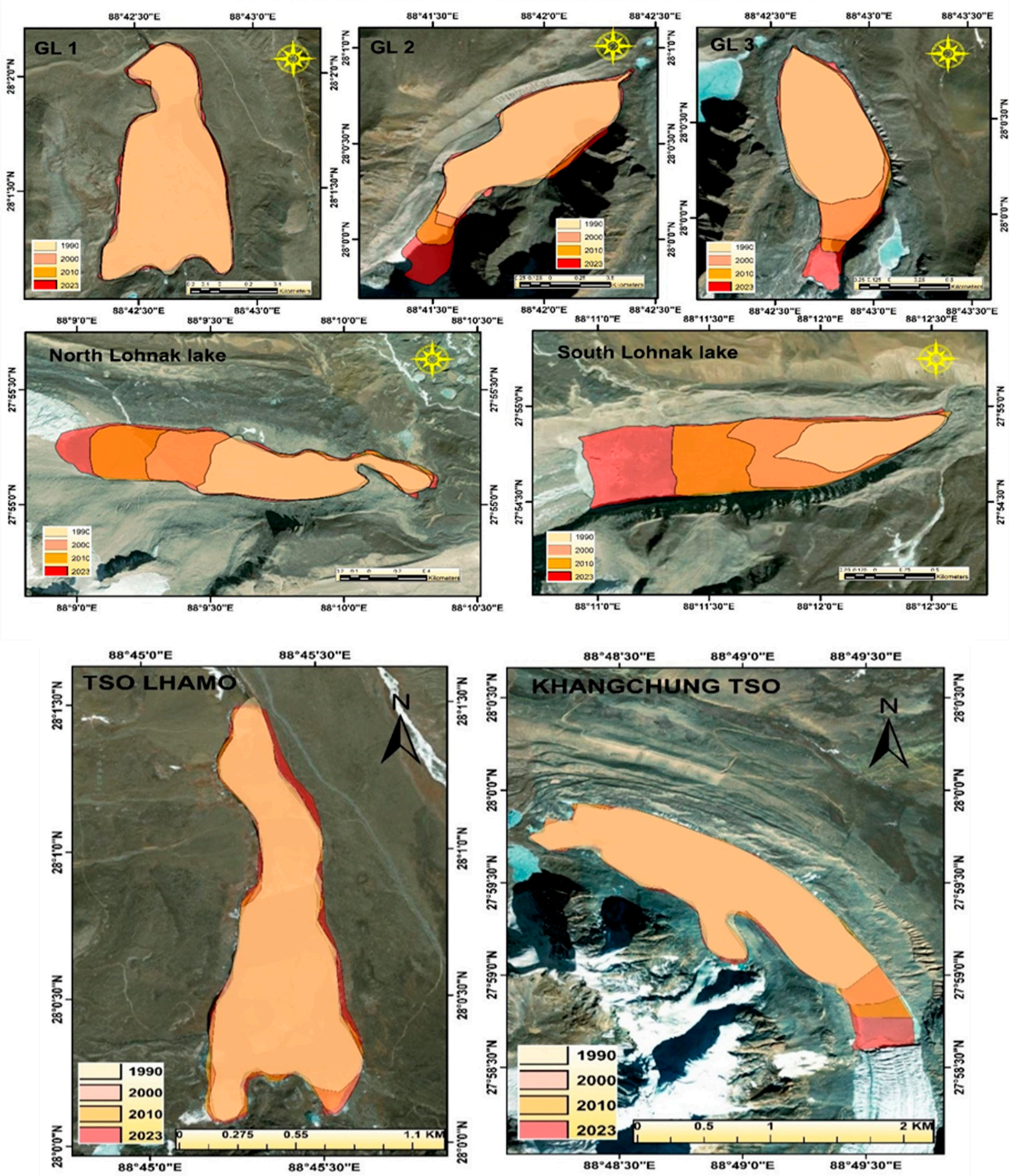


Figure 6. Change detection map showing the expansion of high to very high GLOF-susceptible lakes from 1990 to 2023, identified using both the AHP and FAHP methods. The map displays the temporal progression of selected lakes: GL 1, GL 2, GL 3, North Lohnak Lake, South Lohnak Lake, Tso Lhamo, and Khangchung Tso. Different colors represent lake extents at four specific time points, 1990, 2000, 2010, and 2023, with darker shades showing earlier lake boundaries and lighter shades indicating more recent expansions.

Every lake that has been identified was larger in size, suggesting higher levels of glacier melt over the years. Changes in a few glacial lakes of Sikkim from 1990 to 2023 show a continuous rise in lake size during the observed period. Gurudongmar 1 has increased from 1.109 sq.km in 1990 to 1.157 sq.km in 2023, portraying a gradual increase. Gurudongmar 2 has undergone more changes, from 0.823 sq.km to 1.074 sq.km. Similarly, Gurudongmar 3 expanded from 0.915 sq.km to 1.231 sq.km. Now, a highly abnormal growth was recorded at both North and South Lohnak lakes: North Lohnak from 0.412 sq.km to 0.744 sq.km, and South Lohnak from 0.391 sq.km to 1.201 sq.km. Others that showed notable expansion include the Khangchung TSO and TSO Lhamo Lake: the former from 1.518 sq.km to 1.788 sq.km, while TSO Lhamo grew from 0.97 sq.km to 1.084 sq.km (Figure 7).

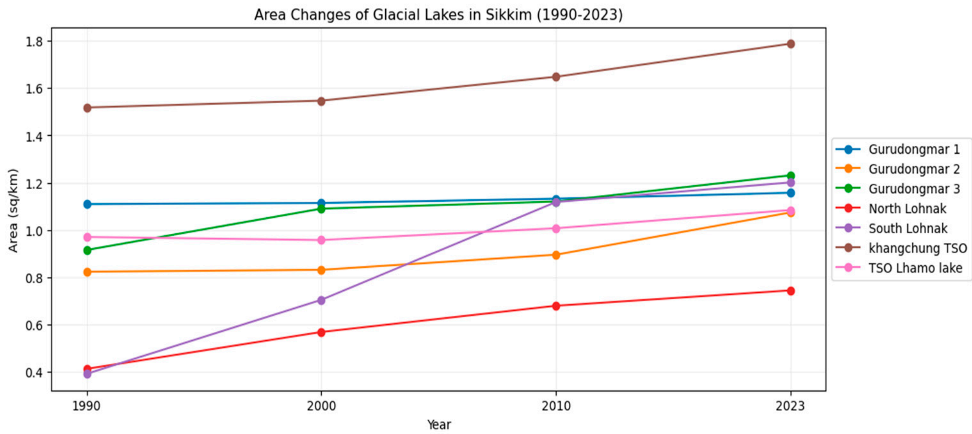


Figure 7. Line graph illustrating the changes in the area (in sq.km) of selected glacial lakes in Sikkim between 1990 and 2023. The graph tracks the expansion of Gurudongmar 1, Gurudongmar 2, Gurudongmar 3, North Lohnak, South Lohnak, Khangchung Tso, and Tso Lhamo Lake over time. The trends show a general increase in lake areas, indicating progressive glacier melt and lake expansion over the observed period, which correlates with the rising susceptibility to GLOFs.

4. Discussion

The results of this study provide a comprehensive understanding of GLOF susceptibility in Sikkim using AHP and FAHP. The findings reveal notable differences and similarities between these methods, offering valuable insights for future risk management and mitigation strategies. The AHP method identified 34 out of 47 glacial lakes within very low to low susceptibility zones, suggesting that most glacial lakes in Sikkim pose a minimal risk of outburst floods. However, it also highlighted seven lakes in the high to very high susceptibility zones, underscoring the need for close monitoring and precautionary measures. This suggests that while a majority of the lakes are currently considered safe, the high-risk lakes present potential threats that need to be addressed through effective planning and mitigation strategies to prevent future disasters. On the other hand, the FAHP method displayed a more specific distribution of susceptibility zones, with a higher number of lakes (14 in mumber) classified in the moderate susceptibility zone compared to the AHP method. This indicates that the FAHP method may offer a more detailed evaluation of GLOF susceptibility, capturing subtle variations in risk levels. Despite these differences, both methods consistently identified three lakes in the very high susceptibility zone, reinforcing the critical need for targeted risk mitigation efforts. The FAHP method's ability to detect finer gradations of risk highlights its potential utility in more precisely identifying areas of concern and developing more tailored mitigation measures.

This understanding is crucial for implementing specific interventions that address the unique characteristics of each glacial lake and its surrounding environment. The study assigned weights to nine parameters influencing GLOF susceptibility: lake volume, lake area, seismic activity, rainfall, distance from the river, elevation, slope, rockfall, and avalanche zones. These weights were calculated differently using AHP and FAHP, reflecting methodological variations. For instance, glacial lake volume received the highest weight in both methods, but the exact values differed (14.61 for AHP and 17.77 for FAHP), indicating its paramount importance in both approaches. This differentiation in weighting underscores the flexibility and adaptability of the FAHP method in accommodating the inherent uncertainties and complexities of the factors contributing to GLOF susceptibility. Moreover, the consideration of diverse parameters provides a holistic view of the multiple forces at play, enabling a more comprehensive risk assessment.

The validation of these models using the AUC of ROC curves demonstrated high predictive accuracy for both methods, with AUC values of 0.92 for AHP and 0.88 for FAHP. Although both methods exhibited robust predictive capabilities, the slightly higher AUC value for AHP suggests marginally better performance in predicting GLOF-prone lakes. This slight edge in predictive accuracy indicates that the AHP method may be more reliable in certain scenarios, although the FAHP method remains a strong contender. The high AUC values for both methods highlight their effectiveness in accurately identifying high-risk lakes, providing a solid foundation for decision-makers to develop targeted strategies aimed at reducing the potential impacts of GLOFs. The analysis of glacial lake changes from 1990 to 2023 revealed significant expansions in lake areas, particularly for lakes categorized as high to very high risk by both AHP and FAHP methods. For example, Gurudongmar lakes and North and South Lohnak lakes have shown considerable growth, likely due to climatic factors such as rising temperatures and increased glacial melt [47–50]. This alarming trend emphasizes the urgent need for adaptive management strategies to address the escalating risks associated with GLOFs. The continuous expansion of these lakes over the years signals a growing threat that requires immediate attention from both researchers and policymakers [51]. Implementing proactive measures, such as improving early warning systems and reinforcing glacial lake barriers, can help mitigate the risks and protect vulnerable communities downstream [52]. The study's findings highlight the critical importance of continuous monitoring and assessment of glacial lakes in Sikkim. The comparative analysis between AHP and FAHP methods provides a dual perspective on susceptibility mapping, enhancing the reliability of the results. These insights can guide policymakers and water managers in prioritizing resource allocation, implementing early warning systems, and developing robust mitigation plans to safeguard communities and infrastructure from the devastating impacts of GLOFs [53,54]. By leveraging the strengths of both methods, stakeholders can create a more resilient framework for managing glacial lake risks, ensuring that both immediate and long-term challenges are effectively addressed.

Although this study provides valuable insights into GLOF susceptibility in the Sikkim region using AHP and FAHP methods, it has some limitations that should be acknowledged. One of the key limitations is the reliance on Landsat 9 multispectral data, which, although effective, has spatial and temporal limitations. Higher-resolution satellite data or the integration of multiple satellite platforms can improve the precision of susceptibility assessments. Furthermore, while nine parameters were used to model GLOF susceptibility, other potential influencing factors such as glacier dynamics, permafrost conditions, and human activities were not considered. Including such parameters could yield a more comprehensive model of GLOF risk. Additionally, this study primarily focused on historical data without accounting for future climate change projections, which are crucial for understanding long-term trends in glacial lake expansion and potential risks. Incorporating climate models into future research would enhance the predictive power of GLOF risk assessments, allowing for better preparedness in the face of accelerating glacial melt due to global warming. Finally, the AHP and FAHP methods, though effective, are based on expert judgment, which introduces subjectivity in the weighting of the parameters. Future studies could explore integrating machine learning techniques or hybrid MCDA approaches to reduce subjectivity and improve model accuracy. Long-term monitoring and collaboration between scientists, local authorities, and communities will also be essential to developing adaptive strategies that effectively mitigate GLOF risks.

Future research should aim to enhance the susceptibility models by incorporating additional factors such as glacier dynamics, permafrost conditions, and human activities, which could provide a more holistic understanding of GLOF risks. Exploring advanced MCDA techniques, including machine learning and hybrid approaches, could also help reduce subjectivity and increase the precision of the assessments. Additionally, integrating climate change projections into models is essential for predicting long-term trends in glacial lake dynamics and improving the accuracy of future susceptibility assessments. Continuous monitoring of glacial lakes in combination with real-time data and advanced predictive tools will further improve the reliability of risk assessments. Collaborative efforts involving researchers, policymakers, and local communities are crucial for building adaptive and robust risk-management frameworks.

5. Conclusions

This study presents a comprehensive assessment of glacial lakes in the Sikkim region, utilizing advanced geospatial techniques alongside the latest Landsat 9 multispectral data to evaluate their conditions and susceptibility to GLOFs. By applying the Normalized Difference Water Index (NDWI), the research accurately detected and mapped these glacial lakes, highlighting the effectiveness of remote sensing in environmental monitoring. The integration of critical factors, such as lake volume, area, seismic activity, rainfall, elevation, slope, and proximity to river systems, underscores the complex relationships influencing GLOF susceptibility. Additionally, this study employs MCDA methods, specifically the AHP and FAHP, to offer vital insights into managing GLOF risks. The AHP method classifies the majority of glacial lakes as low risk but identifies specific lakes in high-risk zones, emphasizing the necessity for vigilant monitoring and proactive mitigation strategies. In contrast, the FAHP approach provides a more nuanced evaluation, placing greater emphasis on moderate risk categories and demonstrating its potential for detailed risk assessments. Both methods exhibited impressive predictive accuracy, with AHP achieving a higher AUC of 0.92 compared to FAHP's 0.88, thereby confirming their reliability in identifying high-risk lakes and guiding targeted risk reduction initiatives. The study also reveals a concerning trend, where the enlargement of high-risk lakes over the past three decades, indicating an urgent need for adaptive management strategies to address the increasing risks associated with climate change and glacial dynamics. While most glacial lakes in Sikkim are categorized within the low to moderate risk levels, a significant number still reside in high to very high susceptibility zones, underscoring the need for focused management strategies. Moreover, the growing relationship between increasing glacial lake volumes and the intensity of outburst floods necessitates proactive monitoring, especially in the context of ongoing climate change impacts. This research enhances our understanding of glacial lake dynamics in Sikkim and serves as a crucial resource for policymakers and disaster management authorities. By incorporating these findings into comprehensive risk management frameworks, policy makers can effectively mitigate potential GLOF hazards, protecting both human life and infrastructure in vulnerable regions. Continued interdisciplinary collaboration and further research will be essential for refining susceptibility models, incorporating additional parameters, and enhancing predictive accuracy. By prioritizing proactive measures, such as improved monitoring systems and infrastructure fortification, stakeholders can build resilience against future environmental challenges, ensuring the safety and sustainability of communities in Sikkim and similar regions worldwide.

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