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Dudh Pokhari Lake GLOF Risk Evaluation: A Comprehensive AHP Approach to Ice Avalanche

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Abstract

Exact cause of Glacial Lake Outburst Floods (GLOFs) is unpredictable prior to their occurrence, posing significant risks to vulnerable regions. This study focuses on Dudh Pokhari Lake surroundings, identified as susceptible to ice avalanches by earlier study. To assess its vulnerability, an Analytic Hierarchy Process (AHP) method, integrated with ArcGIS tool was employed. A comprehensive questionnaire survey was conducted to assign weightage to critical factors, including slope, aspect, curvature and relative relief. Findings reveal that approximately 41.915% of the surrounding area exhibits a moderate susceptibility with an additional 20.563% classified as having a moderate to high susceptibility to ice avalanches. Utilizing this susceptibility map, a high risk zone was identified, offering an opportunity for targeted mitigation efforts. This research emphasizes the precise selection of factors, striving for authenticity and precision. Further exploration aims to predict the extent of avalanches for potential GLOF occurrence. Moreover, the findings have significant implications for the design and development of downstream infrastructure, ensuring it is resilient in the face of this probable threat.

Keywords

Glacial Lake Outburst Flood,Ice Avalanche,Susceptibility, Analytic Hierarchy Process, Makalu Barun National Park

1. Introduction

The capacity of snow and glaciers to store water is undergoing modifications due to global warming, while the patterns of rainfall in terms of frequency, intensity, and timing are also experiencing changes [2]. Regions with glaciers are particularly vulnerable to rising impacts caused by climate change [6]. Since ages, it has been clear that glacial lakes pose a danger to both individuals and property situated downstream. Throughout recorded history, high-altitude regions have been documented to undergo glacial lake outburst floods (GLOFs), which are rapid and massive releases of water and sediment downstream from a glacier-associated lake [5]. GLOFs can result from two sets of factors: dynamic causes, including slope movements, earthquakes, heavy precipitation, and snowmelt, and long-term factors like buried ice melting, hydrostatic pressure changes, and gradual degradation processes [8].

Dudh Pokhari is situated northeast of the Kothe village in the Hinku Valley, with an elevation of 4765 meters, and it is drained by the Sanu Khola. The likelihood of landslides and ice avalanches exists both from the headwater and from the valley's true right side [1]. Certain lodge owners in Kothe have recently expressed worries about this lake, particularly concerning the potential occurrence of an outburst flood and the associated risk it poses to their lodges and investments [2]. Despite not being in potentially dangerous glacial lakes (PDGLs), an ice avalanches triggered a GLOF releasing huge volume of water in the downstream approximately 17.66*106 m3 [4].The main research goal is pinpointing vulnerable zones for potential avalanches triggered by human actions or seismic events.There are no past records of ice avalanches in the vicinity of Dudh Pokhari Lake, making it challenging to validate the results. The study relies on a similar scenario observed at the nearby Tam Pokhari Lake. Across Hindu kush Himalaya regions, snow avalanches frequently occurs [7] with available past data, however snow and ice has different definition in terms of hydrology and both must of studied with depth understanding. The flowing of both items shows similar patterns but factor effecting it may vary. Research is often conducted post-GLOF events, with transboundary effects examined after seismological instruments detected a surge of high-flowing water [3].

Within this study, the focus is on uncovering how static terrain factors contribute to avalanche susceptibility and the identification of vulnerable zones. The research delves into how available data and the current situation align with simulated outcomes derived from an analysis based on these static terrain factors. By investigating these relationships, the aim is to gain a clearer understanding of how these factors interact, thus improving the accuracy of assessing avalanche risk in the studied areas.

The goal is effective mitigation planning, particularly for highly vulnerable areas, to enhance understanding of avalanche risks and reduce the probability of minor GLOF due to overtopping wave generated after avalanche occurrence.

2. Study Area

The study area is situated in Nepal's Solukhumbu District, specifically within the Dudh Koshi river basin downstream from Dudh Pokhari Lake, positioned at approximately

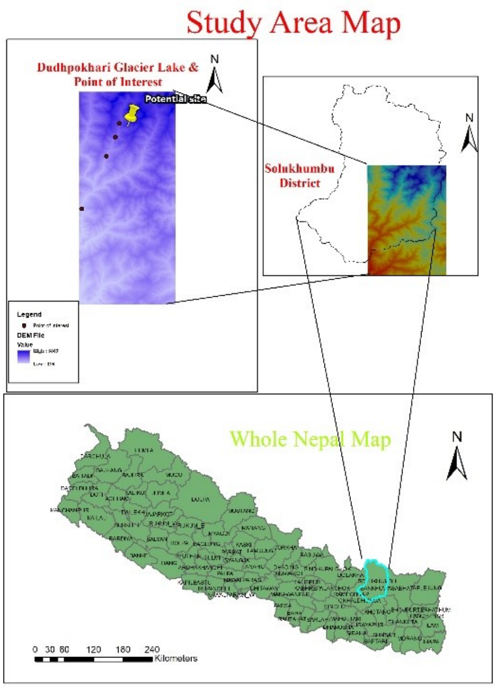

Figure 1: Study Area

86°51'1.20" E longitude and 27°41'23.14"N latitude. Covering roughly 2 square kilometers, it represents the potential avalanche-prone zone. This region is characterized by challenging mountainous terrain, featuring the Mt. Mera peak to the north. The climate is severe, with temperatures often falling below freezing, especially during extended periods. Ecologically, the area is relatively barren, lacking significant environmental features, without any human population or demographic information due to its remote nature.The map of study area is shown below as Figure 1 The significance of this study area orginates from a 2020 report by ICIMOD, identifying the risk of ice avalanches and the subsequent potential for a Glacial Lake Outburst Flood (GLOF) event. Key data sources for this research encompass ALOS PALSAR digital elevation models (DEMs), Google Earth imagery, and temperature monitoring stations located above the study area. The settlement of Kothe, situated approximately 1.7 kilometers below the study area, includes lodges that could be directly affected by a GLOF event. Furthermore, multiple hydropower intake stations are planned for the downstream region, emphasizing the critical importance of assessing and mitigating the associated risks. This research aims to comprehensively address these vulnerabilities while considering ethical, environmental, and climatic factors to enhance the overall understanding and preparedness for potential GLOF events in this remote and challenging landscape.

3. Data and Methods

ALOS PALSAR Dem of spatial resolution 12.5 *12.5 m was utilized to generate four static terrain factors based on availability of data and its importance in study. It includes slope, aspect, curvature and relative relief as displayed in Table 1.

Table 1: Various data layers and avalanche occurrence factors used in the study

S.N.	Layer	GIS data type	Scale
1	Slope	GRID	12.5 m * 12.5 m
2	Aspect	GRID	12.5 m * 12.5 m
3	Curvature	GRID	12.5 m * 12.5 m
4	Relative Relief	GRID	12.5 m * 12.5 m

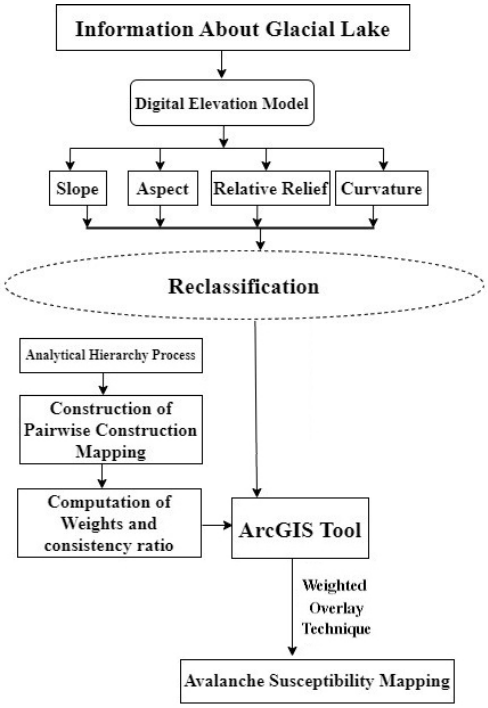

Figure 2: Methodological Framework

3.1 Generation of Thematic Layers

Understanding ice avalanches is crucial for mitigating their risks. Ice avalanches involve the sudden movement of ice masses down slopes, and assessing them is challenging due to two types of factors: static terrain factors and dynamic meteorological factors [7]. Different meteorological conditions can lead to varying ice thicknesses, influencing avalanche behavior. Ice avalanches primarily occur due to additional stresses within the ice caused by natural phenomena like temperature changes between ice layers and external triggers such as earthquakes or human activities. However, factors like slope, aspect, curvature, and relative relief are static in nature. Given the limited availability of climatic and meteorological data for the study area, this study relies on terrain parameters to investigate ice avalanche susceptibility and behavior.

3.1.1 Slope

The ALOS PALSAR DEM data played a crucial role in generating the slope map for our study area as shown in Figure 3. This slope map was then classified into five distinct classes, aligning with previous literature classifications [7].to establish individual ratings for further analysis. In the context of assessing avalanche danger in snow and ice-covered mountain regions, slope is considered an essential static terrain factor. Interestingly, ice avalanches are relatively rare

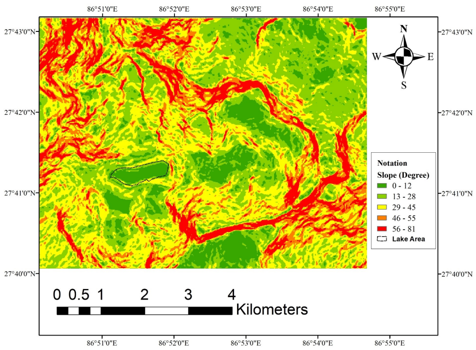

Figure 3: GIS Layer of Slope prepared for avalanche susceptibility Mapping

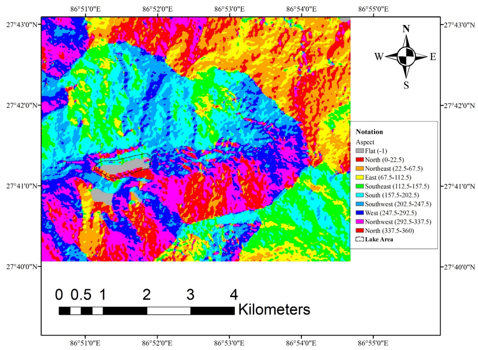

Figure 4: GIS layer of aspect prepared for avalanche susceptibility mapping

on mountain slopes with inclinations below 25°. The majority of reported avalanches occur on ice-covered mountains with slopes greater than 30° but less than 45°. Steeper slopes, ranging from 45° to 55° and above , do not support snow and ice accumulations for extended periods, resulting in frequent, albeit smaller, avalanches on such steep terrain as shown in Table 2.

Table 2: Slope classes considered for avalanche susceptibility mapping; Source ([7])

Class	Explanation
Less than 12°	Practically no avalanche observed
12°-28°	Considerable numbers of hazardous avalanches occurs in this zone
28°-45°	Majority of dangerous avalanches
45°-55°	Small avalanches
Greater than 55°	slope is very steep and the avalanche frequency is very high, due to the steepness of the slope snow keeps on sliding under the influence of gravity and hence the snow masses available for avalanche is very less

3.1.2 Aspect

The alignment of snow and ice-covered slopes concerning the sun has a direct impact on the stability of the snowpack. Shaded slopes tend to maintain their instability for more extended periods, whereas slopes exposed to the sun stabilize relatively quickly when compared to their shaded counterparts. Wind patterns play a crucial role by continually redistributing snow from slopes facing the wind and accumulating it on the sheltered, leeward slopes, making the latter more perilous than those facing the wind. To examine this aspect, we utilized ALOS PALSAR DEM data to create an aspect map for the study area as shown in Figure 4. Subsequently, this aspect map was categorized into nine classes. Notably, the North-East and North aspect classes emerged as particularly prone to avalanche occurrences, highlighting their significance in evaluating avalanche risk.

3.1.3 Curvature

Curvature plays a pivotal role in assessing avalanche susceptibility. Concave slopes have the capacity to retain substantial snow, thus contributing to snowpack stability, whereas snow cover on convex slopes tends to be less stable.

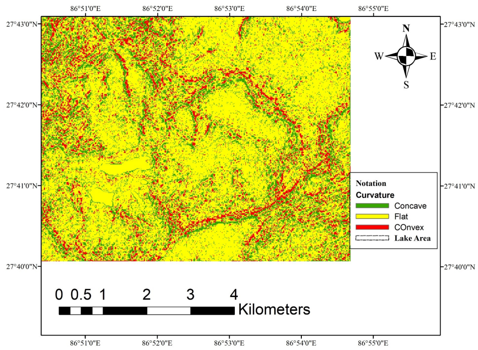

Figure 5: Gis layer of curvature prepared for avalanche susceptibility mapping

We utilized ALOS PALSAR DEM data to generate a curvature map, categorizing it into three distinct classes: concave, flat, and convex as shown in Figure 5. Among these, the convex curvature class is more susceptible to avalanche initiation than the concave class. Consequently, greater importance was assigned to the convex curvature class, while the concave class held a lower weighting, with the flat curvature class falling in between.

3.1.4 Relative Relief

Relative relief quantifies the vertical separation between two locations without considering the surrounding terrain's overall height. It is an important concept in geography and geology because it helps describe the changes in elevation within a region, which can have significant implications for various natural processes, such as an erosion, sedimentation and the formation of land-forms. A region with high relative relief might have steep mountains and deep valleys, while a region with low relative relief might be relatively flat or gently sloping as shown in Figure 6. The concept of relative relief assumes a pivotal role in our avalanche susceptibility map. It serves as a key factor for assessing the terrain's vulnerability to avalanches. To ensure consistency with existing literature, we have classified relative relief into five distinct classes, and our ratings are in harmony with established conventions in this field of research.

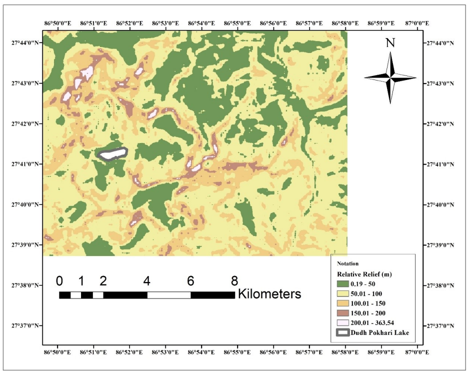

Figure 6: Gis layer of relative relief prepared for avalanche susceptibility mapping

3.2 Estimation of Weights to Avalanche Susceptibility Layers

The Analytic Hierarchy Process (AHP) stands as a mathematical decision-making tool employed across various fields to address complex decision problems with multiple criteria. It was originally introduced by Satty in 1970. AHP operates qualitatively, utilizing a hierarchical structure for decision parameters, and notably, it doesn't rely on data for model training. Instead, it operates on expert knowledge and judgments. The primary objective of this study was to define avalanche susceptibility zones around Dudh Pokhari Lake, a goal achieved through the consideration of fundamental evaluation factors such as slope, aspect, curvature, and relative relief. These factors were assigned internal weights following a comprehensive review of literature addressing similar phenomena in the HKH region. Weight assignment for each of the five factors follows the importance scale established by Satty in 1980. The process involves comparing potential pairs within a matrix to determine appropriate weightings and consistency ratios for each review.

3.3 Computation of Susceptibility Index

The Weighted Overlay Technique is a commonly employed spatial analysis approach within Geographic Information Systems (GIS). It serves the purpose of integrating and examining numerous geographic information layers, proving especially beneficial in decision-making scenarios like site selection and suitability analysis, where the simultaneous consideration of multiple factors is essential.

4. Results and Discussion

4.1 Computation of Weights

From a 10 number experts review, the geometric mean of each response is utilized and weight for each factors was calculated using AHP technique as shown in Table 3.

Individual consistency ratio was already less than 10% for each review and after taking geometric mean it comes out to be 1.2% which is acceptable. Here, from expert review slope plays a crucial role in passing avalanche to lower zones and the chances of avalanche occurrence in 28°-45° slope will be more as steep slope could not accumulate ice for a larger time period

Table 3: Pairwise comparison matrix and weight values in each layer using AHP

Layer	Slope	Aspect	Curvature	Relative relief	Weights
Slope	1.00	4.98	3.73	4.93	0.59
Aspect	0.20	1.00	1.30	1.60	0.16
Curvature	0.27	0.77	1.00	1.28	0.14
Relative relief	0.20	0.63	0.78	1.00	0.11

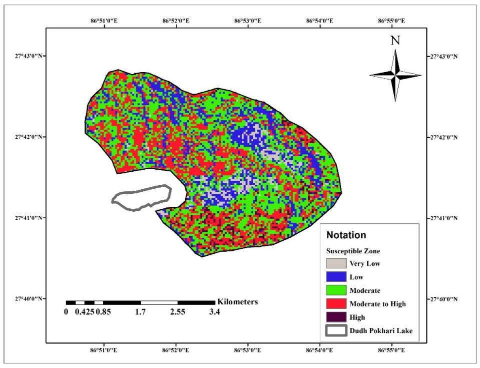

Figure 7: Avalanche susceptibility map using AHP model

or a frequent minor avalanche would occur frequently.

4.2 Generation of Susceptible Zones

Using the available information from table and map generated above an ice avalanche susceptibility map was generated in scale of 1 in 5 as shown in Figure 7.

The study categorized susceptibility levels into five groups. A very low susceptibility zone covers a small area, representing only 4.34% of the total. Low susceptibility, the largest category, encompasses 20.56% of the region. The most extensive zone, covering 41.91% of the area, exhibits moderate susceptibility. Additionally, there is a moderate-to-high susceptibility zone, covering 29.37%, and a high susceptibility zone, albeit very small at 3.805% as displayed in Table 4. Our key findings reveal a most of low susceptibility zone in the east face comprises of small valleys. The north features varying susceptibility levels, but a depressed land area acts as a barrier against avalanches. Surprisingly, the north-facing, sun-exposed zone still sees limited avalanches, while the south-facing, shadowed area has a higher susceptibility, likely due to climate change trends.

Table 4: Zone wise Distribution of Avalanche Susceptibility Map

Avalanche Susceptibility	Area (Km^2)	Percentage (%)
Very Low	0.054	4.343
Low	0.257	20.563
Moderate	0.523	41.915
Moderate-to-high	0.367	29.375
High	0.048	3.805

4.3 Comparative Analysis with Available Data

Layer of Ice thickness in surrounding of Dudh Pokhari Lake was obtained from Institute of Environmental Geoscience website. It was accumulated using remote sensing technique.

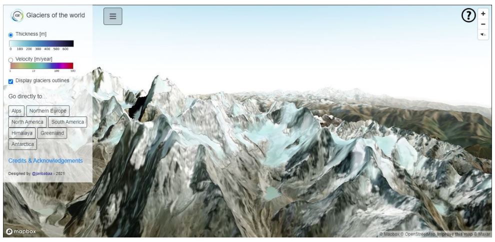

Figure 8: Glacier layer of study area (Source: Institute of Environmental Geo Sciences)

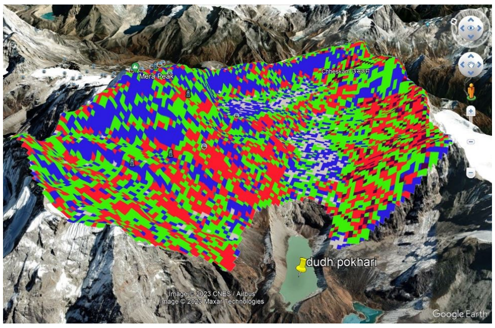

Figure 9: Overlay of avalanche susceptibility map in google earth image

A screenshot of which is presented in Figure 8.

Following the creation of the ice avalanche susceptibility map, it was superimposed onto Google Earth for a comparative analysis alongside existing ice data. The resulting overlaid map is presented as Figure 9 for visual examination and comparison.

On the southern side, there's a prevalence of Moderate to High and High Susceptibility Zones; however, due to limited ice accumulation in the current conditions and the presence of steep slopes, only small, frequent avalanches are feasible. Conversely, the northern side showcases more moderate and moderate to High Susceptibility Zones. Here, despite thinner ice and a depressed zone between the mountain and lateral moraine, the likelihood of avalanches reaching a lake is minimal. Conversely, the "Low and Very Low Susceptibility Zone" on the east side holds substantial ice and snow, coupled with gentler slopes, making avalanches highly improbable in these areas.

5. Conclusion

The research strongly underscores the crucial role of steep slopes in triggering avalanches, a viewpoint strongly supported by experts. It delineates various zones with differing levels of susceptibility, revealing that, despite receiving less direct sunlight, south-facing slopes pose a higher avalanche risk due to their steepness and lack of protective features. Seeking to understand the causes behind Glacial Lake Outburst Floods (GLOFs), the study found that minor avalanches are more frequent on steep slopes unable to retain ice for extended periods. The susceptibility map created here emerges as a valuable tool for identifying at-risk areas, guiding targeted safety measures. However, it's essential to note limitations in replicating real scenarios and the reliance solely on certain factors. Comparing ice thickness data with the susceptibility map holds promise for future avalanche prediction. Looking ahead, exploring the dynamic relationship between weather patterns and avalanches could offer deeper insights. These findings stress the need for thoughtful urban planning and protective measures, especially for areas vulnerable to potential GLOFs. In conclusion, continuous examination of avalanche triggers and preparedness is crucial for averting disasters and safeguarding valuable resources.

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References

[1] Samjwal Ratna Bajracharya, SB Maharjan, Finu Shrestha, TC Sherpa, N Wagle, and AB Shrestha. Inventory of glacial lakes and identification of potentially dangerous glacial lakes in the koshi, gandaki, and karnali river basins of nepal, the tibet autonomous region of china. *International Centre for Integrated Mountain Development GPO Box*, 3226, 2020.

[2] Alton C Byers, Daene C McKinney, Marcelo Somos-Valenzuela, Teiji Watanabe, and Damodar Lamsal. Glacial lakes of the hinku and hongu valleys, makalu barun national park and buffer zone, nepal. *Natural Hazards*, 69:115–139, 2013.

[3] Kristen L Cook, Christoff Andermann, Florent Gimbert, Basanta Raj Adhikari, and Niels Hovius. Glacial lake outburst floods as drivers of fluvial erosion in the himalaya. *Science*, 362(6410):53–57, 2018.

[4] Shree Kamal Dwivedi. The tam pokhari glacier lake outbursk flood of 3 september 1998. *J. Nepal Geol. Soc.*, 22:539–546, 2000.

[5] Narendra Raj Khanal, Pradeep Kumar Mool, Arun Bhakta Shrestha, Golam Rasul, Pawan Kumar Ghimire, Rajendra Bahadur Shrestha, and Sharad Prasad Joshi. A comprehensive approach and methods for glacial lake outburst flood risk assessment, with examples from nepal and the transboundary area. *International Journal of Water Resources Development*, 31(2):219–237, 2015.

[6] Sunwi Maskey, Rijan Bhakta Kayastha, and Rakesh Kayastha. Glacial lakes outburst floods (glofs) modelling of thulagi and lower barun glacial lakes of nepalese himalaya. *Progress in Disaster Science*, 7:100106, 2020.

[7] Rajinder Parshad, PK Srivastva, Ganguly Snehmani, and Snehmani Snehmani. Snow avalanche susceptibility mapping using remote sensing and gis in nubra-shyok basin, himalaya, india. *Indian J Sci Technol*, 10(31):1–12, 2017.

[8] Liye Yang, Zhong Lu, Chaoying Zhao, Jinwoo Kim, Chengsheng Yang, Baohang Wang, Xiaojie Liu, and Zhe Wang. Analyzing the triggering factors of glacial lake outburst floods with sar and optical images: a case study in jinweng co, tibet, china. *Landslides*, 19(4):855–864, 2022.