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Remote Sensing and GIS Based Assessment of Avalanching Glaciers in the Himalayas Due to Climate Change.

Pranav Yadav [a], Dhiraj Pradhananga [b], Khem Narayan Poudyal [c]

[a, c] *Department of Applied Science and Chemical Engineering, Pulchowk Campus, Institute of Engineering, Tribhuvan University, Nepal*
[b] *Department of Hydrometeorology, Tribhuvan University , Nepal*
[a] 078msccd007.pranav@pcampus.edu.np, [b] dhiraj@smallearth.org.np, [c] khem@ioe.edu.np

Abstract

Hanging glaciers are a significant risk factor for avalanches, which can cause major disasters. Ice-falls and avalanches from hanging glaciers pose a continuous threat to the regions beneath them. Therefore, it is imperative to invest in monitoring, analyzing, and modeling these phenomena. This will help to produce reliable forecasts, which can be used to take timely and efficient actions, such as evacuating areas. The analysis and modeling of avalanches can also help to improve our understanding of the underlying processes and influential factors. This can lead to the development of a more effective early warning system. One approach to identifying potential avalanche zones is to use the Analytical Hierarchy Process (AHP) within a Geographic Information System (GIS) platform. This method has been proven effective for mapping avalanche-prone areas in rugged mountain landscapes. Another approach is to use a numerical simulation model such as the Rapid Mass Movement Simulation (RAMMS) model. This model can be used to simulate the flow dynamics of sites with potential avalanche activity. Both approaches have demonstrated their efficacy in predicting avalanche hazards in snowy and glacial environments. The goal of this study is to comprehensively address the societal impacts of avalanches, viewing them both as hazards and as disturbances within the environment.

Keywords

Avalanche, Analytical Hierarchical Process (AHP), Hazard, Hanging glacier, Mass movement, Numerical Simulation, Climate Change

1. Introduction

After the modern industrial revolution, human has triggered the climate change effect and has caused an impact on the mountain system as well. In the mountain system, there occurs a loss of storage of water which is in the form of glacial reservoirs, change in precipitation system, and high-altitude warming has also been observed[1]. The water level in the glaciers in the high mountains is declining in an unexpected way both in the form of extent and volume causing less water availability and increasing the hazards like slope failure, Glacier Lake Outburst Flood (GLOF), etc., causing a direct impact in the mountain ecosystem[2]. Around 2 billion population downstream of the Hindu-Kush Himalaya regions directly depends upon the resources like water, food, and other services which are provided through the mountain itself. The concern is also given to about 250 million population that are Nepali, Tibetan, and Chinese residing in the same region[2, 3]. The potential risk for the people and ecosystem in the Himalayas region has significantly risen due to the rise in the environmental changes[4]. The elevation of risk/hazards is also boosted by dynamics in the climate change which includes non-physical threats like Blizzards, avalanches, and landslides[5]. The environmental aspects of the regions have threatened the stability and also have the potential to hamper the criticality of the lives of the populations residing downstream of the glacier[6]. For example, glacier dumps done by humans and GLOF can severely impact the water quality, resilience, and availability of infrastructures. Also, landslides in those regions challenge the physical safety of the residents and inbuilt infrastructures. Similarly, unclean melted water from glaciers can limit the use of water by residential populations and for agricultural use[1].

Ice and avalanches are sudden and quick movements of snow or ice after they get detached from the slopes. Snow and ice avalanches-related hazards are occurring frequently in the mountains and have a significant effect on human lives, properties, and infrastructures in the downstream[7]. Himalayas have an extremely dynamic system where numerous snow and ice avalanches are reported[8]. Snow avalanches also cause the alteration in the quantity of the glacier which ultimately results in the modification of the geometry. Thus, continuous field observation is not possible as avalanche generally occurs at high altitude and in the inaccessible region along with vulnerable slopes[9]. Generally, engineers and researchers employ a process model that helps to determine the dynamics and extent of the movement in this rugged terrain. So, the primary application is to prepare the hazard maps and these maps thus become an extremely important asset for proposing mitigation measures like dams, embankments, rock-fall protection barriers etc.[10]. Also, it can help to optimize limited financial resources by studying the nature and extent of different hazard scenarios[11].

Taking into account the model's shortcomings and the requirement for improved model parameterization as described in the previously referenced literature, the study aims to study the potential susceptible hazard especially snow avalanche-like disturbance at the high mountain landscape of the Hindukush Himalayas region triggered by the detachment of the glaciers and produce a numerical simulation that determine the dynamics of geophysical mass movement as well[12]. The scope of this research is to evaluate the snow/glacier avalanche caused by avalanching glaciers both from physio-geographical and also of environmental point of view, using terrain i.e., topographic factors and climatic variables and as well as to determine flow dynamics[13]. Thus, the primary objective is to assess the susceptibility and stability of avalanche-prone glaciers in the Himalayas. The secondary objectives are:

- To extract probable avalanche-prone glaciers in the Himalayas using remote sensing and GIS.
- To model the stability of avalanche-prone glaciers in the Himalayas and assess their potential hazards due to Climate change

2. Material and Methods

2.1 Study Area

For the study area of this project, Raunthigad-Rishiganga situated at Uttrakhand India was chosen. The study area lies in the Uttrakhand state in Chamoli district which is in the Northern portion of India and is located in the Southern part of Himalaya.

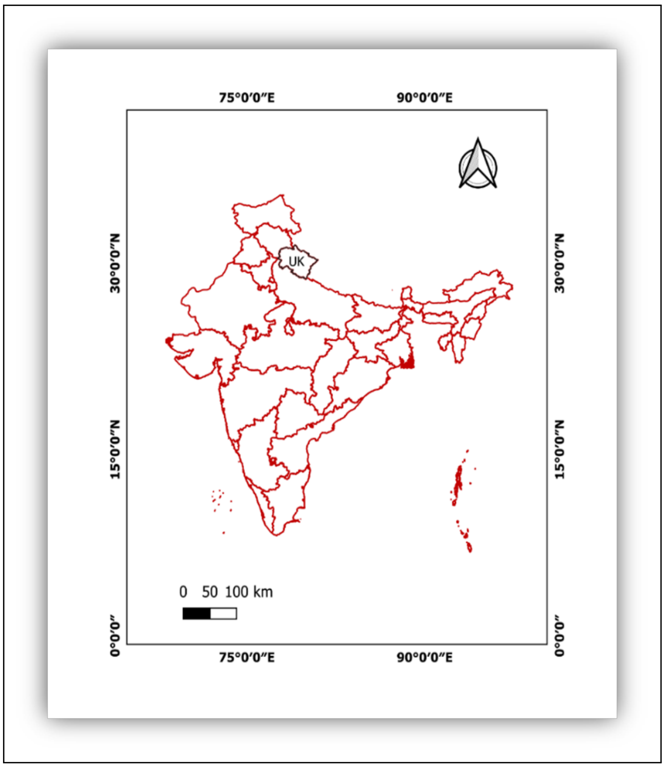

Figure 1: Raunthigad-Rishiganga located at Uttarakhand of India.

Nanda Devi glacier is the origin of the Rishi Ganga which lies at an altitude of 4132 m. This general area of Rishi Ganga origin is one of the most brittle ecosystems on the earth[14]. This region is geotechnically vulnerable with weak geological belts and also seismically nascent and tectonically active causing frequent earthquakes and is composed with geo-morphological complexity[15]. The hanging glacier is located around 5500 m at Latitude: 30°22'40.70"N and Longitude: 79°43'57.57"E. On February 7, 2021, a hanging glacier avalanche and debris flow disaster occurred at Rauthigad-Rishiganga. This was caused by the right lobe of a hanging glacier detaching, which resulted in significant property damage and fatalities[16].

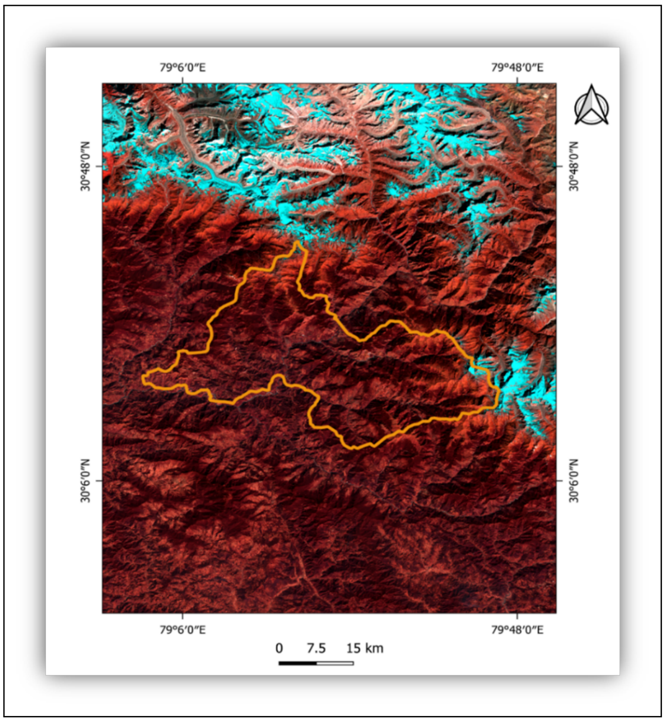

Figure 2: False Colour Composite (FCC) of the study area.

2.2 Data and Methodology

DEM with 12.5 m was downloaded from the ALOS PALSAR high-resolution DEM website. Also, Landsat-8 imagery was downloaded from the Earth Explorer website (https://earthexplorer.usgs.gov/). Together with, MODIS Land Surface Temperature (LST) data from Terra and Aqua satellites were downloaded (https://lpdaac.usgs.gov/tools/appeears/) and the batches were consolidated separately by clipping over the hanging glacier of the Rishiganga basin and average precipitation data were downloaded from the WorldClim website (https://www.worldclim.org/data/worldclim21.html) for assessing climate change studies. To identify potential avalanche zones in the designated study region, the Analytical Hierarchy Process (AHP) was employed alongside remote sensing data within a Geographic Information System (GIS) framework. AHP serves as a Multi-Criteria Evaluation (MCE) technique, involving the expertise of both specialists and decision-makers in a process of comparing various criteria. Furthermore, an additional step involved conducting a numerical simulation for one of the potential avalanche-prone areas. This simulation employed the Rapid Mass Movement Simulation (RAMMS) model, a tool utilized to ascertain the dynamic behavior of avalanches at these specific locations[17]. The methodology was divided basically into two groups: first is to calculate the weightage of different terrain parameters and employing AHP to generate avalanche site map; the second is to conduct the numerical simulation of the potential site. The terrain parameters (slope, elevation, aspect, curvature) which were generated from DEM, and the land cover which was retrieved from the Landsat-8 were resampled to a common spatial resolution. The terrain parameters were reclassified in GIS. The terrain parameters were assigned with a rating in a scale of 1 being the lowest to 5 as the highest. Slope in the range of 25^{o}-55^{o} is more prone for avalanche to occur thus assigned with the highest value. Similarly, elevation range between 5000-7000 msl, north and northeast orientation and convex curvature were allotted with maximum rating[18]. As in landcover, the area covered with snow was allotted with higher rating and low in case of vegetation. We have taken the climatic variables (precipitation and temperature) into consideration. Thus, avalanche susceptibility map was prepared and was further divided into five zones i.e., very low, low, moderate, high and very high.

2.3 Research Framework

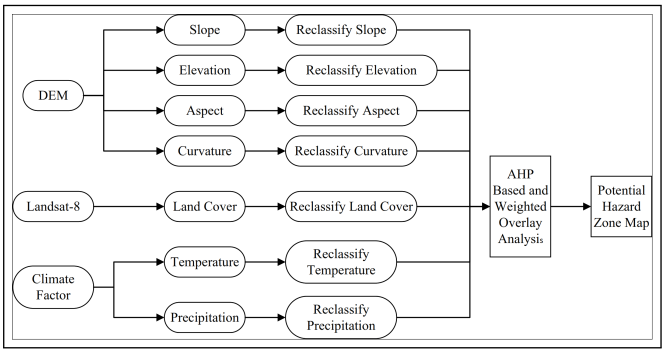

Figure 3: Methodology for Avalanche Hazard Mapping.

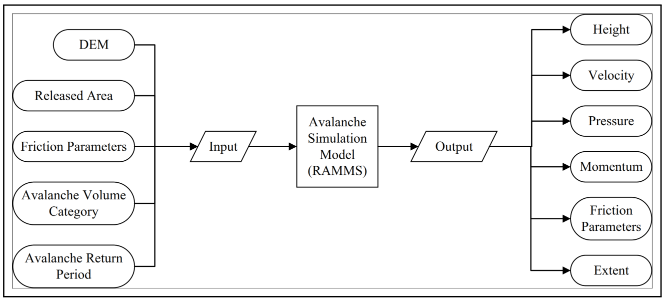

Figure 4: Methodology for Modelling through RAMMS Simulation.

The Rapid Mass Movement Simulation (RAMMS) model was used to generate the flow dynamics of the demarcated avalanche sites. Many researchers have employed RAMMS in the various part of the Himalayas to conduct simulation of avalanches hazards[19]. The DEM, release area and domain, snow density, friction parameters were used as input parameters for calculating the avalanche flow dynamics. The area of hanging glacier is digitized that is in fact used as release area. Moreover, the Voellmy-fluid friction model used by RAMMS is derived from the Voellmy-Salm methodology. The frictional resistance is split into two sections in the RAMMS physical model. The flow behaviour is determined by the friction coefficients; μ dominates when the flow is almost stopping, and ξ dominates when it is moving quickly. Return period and avalanche volume are the global parameters having a strong influence on the friction values. The values ranging from 1000 to 3000 m/s^2 were employed for turbulent friction, and values ranging from 0.1 to 0.6 for dry friction[20]. The friction parameters were chosen taking into account the nature of terrain, avalanche occurrence period, altitude, and volume of the release area.

3. Results and Discussion

The terrain parameters were resampled to a common resolution. The elevation was reclassified into 3 categories and the highest rating of 5 is allotted to the elevation for more than 5000 m to which the avalanche is more prone to occur. Similarly, slope is also reclassified for which the rating of 5 is allotted to the range of 25^{o} – 55^{o}. The same procedure is adopted for aspect and curvature where rating of 5 is allotted for north and north east orientation and for convex curvature. For land cover, the reclassified land cover consists of the vegetation cover to which least rating of 1 is allotted as vegetation causes hinderances in the avalanche flow. A higher value is allotted to barren land and urban area as this area are in a high-risk zone and finally snow cover is allotted rating of 5. The temperature and rainfall data of 20 years were also analyzed and plotted (Figure 5 ,Figure 6, Figure 7).

The temperature during July, August, September, and October shows an increasing trend, September being among the higher side (Figure 6). The past 10 years data of September have shown an increasing trend in the temperature. However, the average, maximum and minimum temperature showed the decreasing trend over the past 20 years. Hence, the decrease in temperature was observed (Figure 7). The precipitation is sparse in that region however, its effect has been taken into consideration. Figure 8 shows the increasing trend in the precipitation over the last 20 years.

Then after, pairwise comparison of different DEM parameters along with land cover and climate variables were performed. The weights of different variables were calculated along with their ranks. The weights so obtained from AHP will be used in the generation of an avalanche susceptibility map. Thus, weighted overlay analysis was performed in the GIS incorporating the weightages obtained. Hence, an Avalanche susceptibility map is prepared.

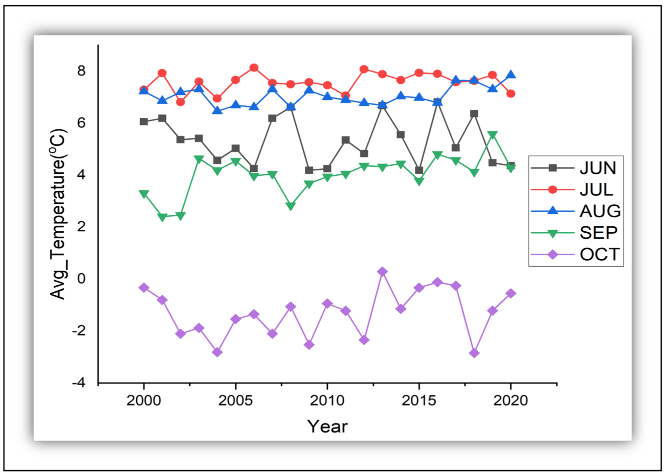

Figure 5: Average Temperature of different months of the Raunthigad-Rishiganga Area.

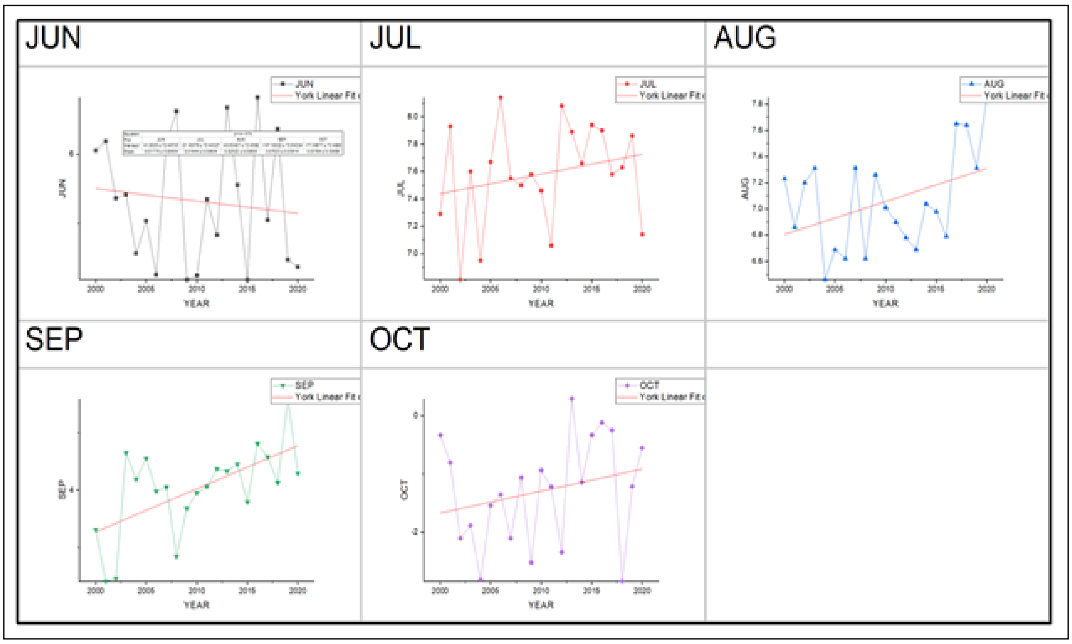

Figure 6: Trend of average temperature of different month of Raunthigad-Rishiganga Area.

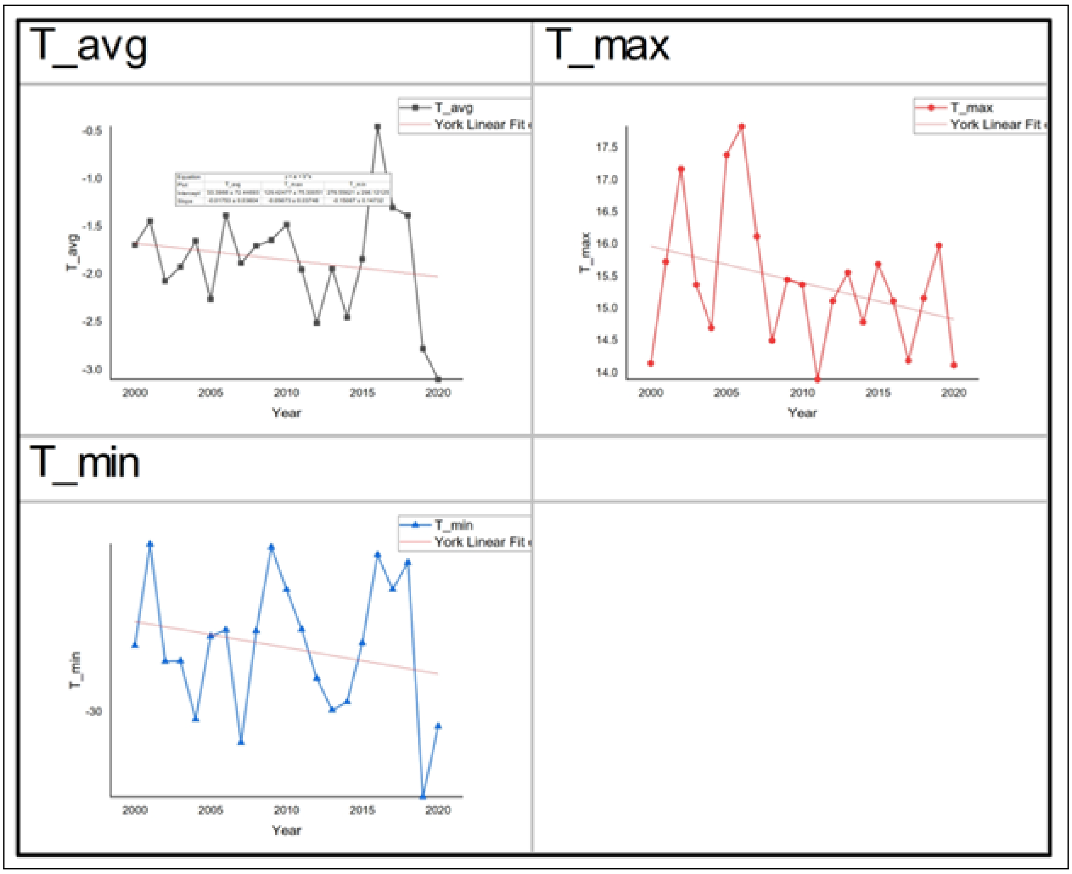

Figure 7: Trend of average temperature over the period of 20 years.

Here, in the obtained avalanche hazard susceptibility map (Figure 9) of the study site i.e., Rauthigad-Rishiganga Area, the chunk of hanging glacier that happen to fall in the map matches the real disaster site area i.e., vulnerable zone. Similarly, the color symbology labels depict the avalanche susceptibility zone as for instance, varied red color level region shows the area likely to have high prone area vulnerable to avalanche hazard and green to the lower prone susceptible area as per shown in the map (Figure 9). The glacier was digitized from google map as shape file and then overlaid on to the final susceptibility map for subjecting the validation process. This model finally validates the susceptibility of the area and henceforth the methodology can be used to extract the result for the other study area as well in the Hindu Kush Himalayan region.

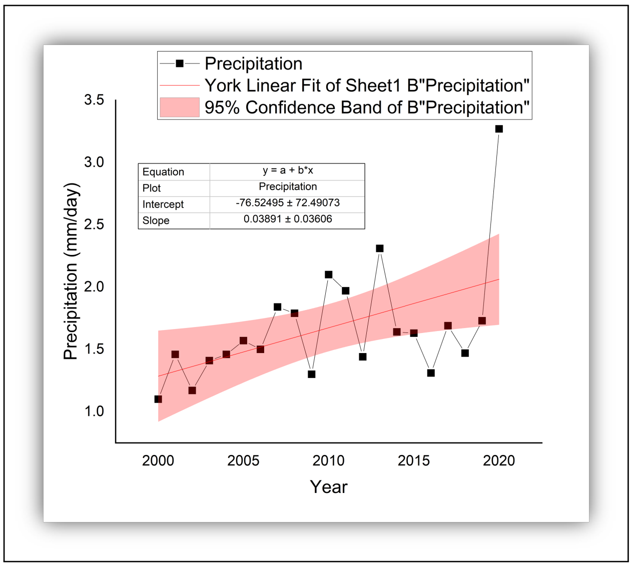

Figure 8: Trend of average precipitation over the period of 20 years.

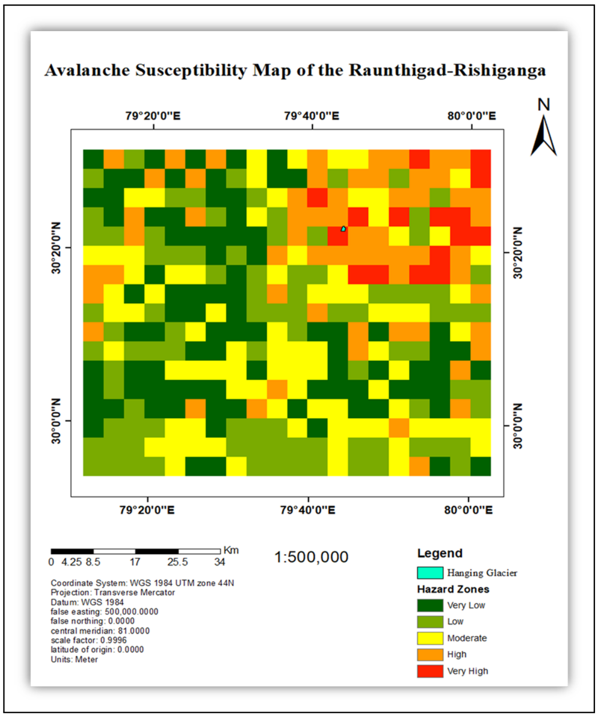

Figure 9: Avalanche Susceptibility Map of the Study Area.

Table 1: Avalanche Zone in various categories of the Study Area

Hazard Zone	Area (Km^2)	Area (%)
Very Low	1509.11	26.39%
Low	1539.18	26.92%
Moderate	1386.65	24.25%
High	1019.78	17.84%
Very High	263.02	4.60%
Grand Total	5717.76	100%

So, using the AHP and weighted overlay analysis in GIS, the potential avalanche zones of the Raunthigad-Rishiganga area was identified which is shown in (Figure 9). It is noteworthy that the moderate, high, and very high categories accounted for roughly 47% of the entire area. The very low-risk category covered about 26% of the area, while the low-risk category covered 27%. Flow simulation was thus carried out by digitizing the ice avalanche block following possible avalanche mapping. Four output parameters (velocity, height, pressure, and momentum) are obtained through modeling. The longitudinal profile for that location is also generated by the model. The information about the aerial extent of the avalanche flow is provided by the avalanche run-out distance, height, and flow velocity. The avalanche flow in the simulation branches out until it reaches the base, with a four-kilometer run-out length (Figure 13). Besides, the simulation shows a maximum velocity of 51.6 m/s which is shown in red color in Figure 10, and the velocity shows apparently zero where it meets the stream but it actually is not zero since the stream has its own flow velocity.

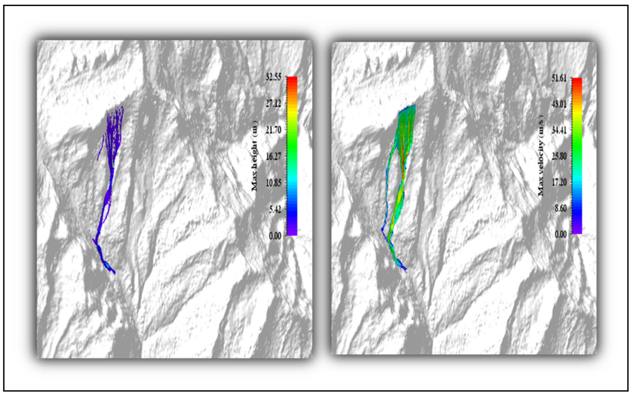

Figure 10: 3D view of simulated flow: Height and Velocity of the Study Area.

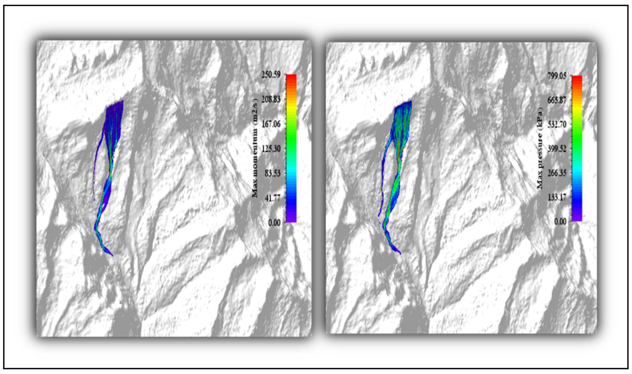

Figure 11: 3D view of simulated flow: Momentum and Pressure respectively of the Study Area.

The maximum momentum gained is 250.59 m^2/s but most of the time during the flow of avalanche, the momentum seems to be in the lower side i.e., between 0-42 m^2/s (Figure 11). Similarly, the maximum pressure obtained is 799.05 kPa but the avalanche flow represents the pressure of between 0-532 kPa mostly during the runout (Figure 11).

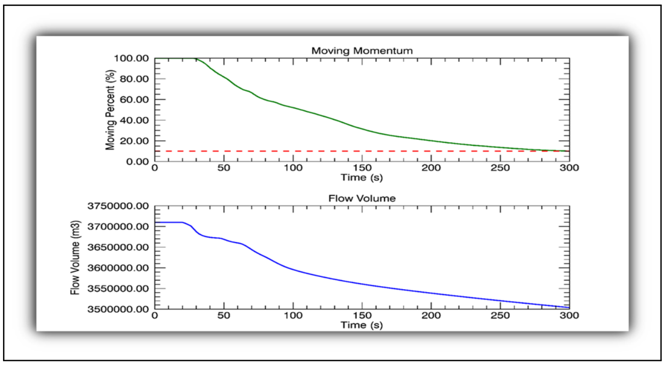

Figure 12: Moving Momentum and Flow Volume Profile of the Study Area.

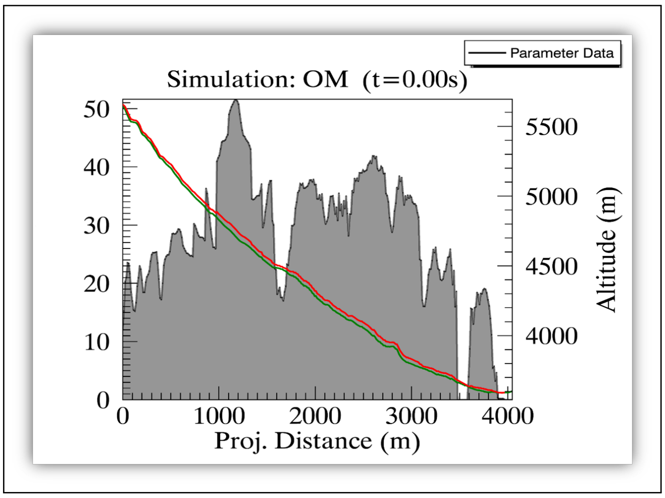

Figure 13: Plot of maximum velocity vs altitude vs run-out distance.

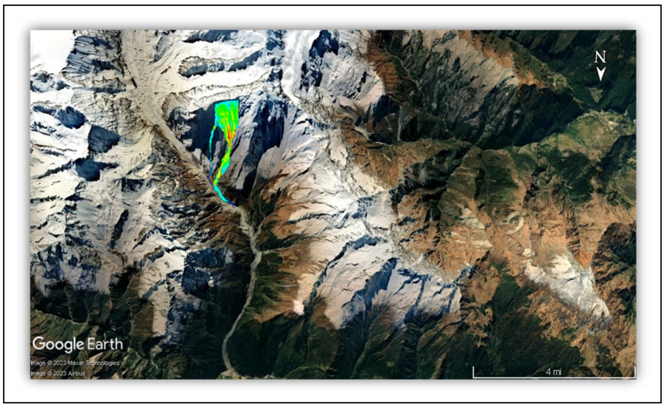

Figure 14: Simulated result of the Study Area on Google Earth.

The initial flow volume was 3,710,000 m^3. The flow volume seems to be gradually decreasing as shown in Figure 12. The simulated result is also projected to the google earth (Figure 14). The simulation projected clearly shows that the runout of the avalanche meets the stream flow and continues its flow along that stream. The avalanche along the stream flow causes huge mass of flow causing inundation and flooding in the downstream side. Hence, the amount of flow volume from the avalanche became a crucial factor as it adds more mass to the stream.

4. Validation and Predictability

In the Avalanche hazard susceptibility map generated for the research area, specifically the Rauthigad-Rishiganga area, the segment of the hanging glacier that corresponds to the actual disaster site aligns with the designated vulnerable zone on the map. The glacier's representation was extracted from Google Maps and transformed into a shapefile, which was then superimposed onto the completed susceptibility map to undergo the validation process. This model effectively confirms the area's susceptibility, establishing the methodology's applicability to derive results for additional study areas within the Hindu Kush Himalayan region.

5. Conclusion and Recommendation

Hanging glaciers often trigger icefall avalanches, which are recognized as vulnerable events capable of jeopardizing the areas beneath them. Such incidents pose threats to human life, the environment, infrastructure, and property integrity. These hazards are particularly prevalent in mountainous regions due to various factors like topography, slope, elevation, aspect, and curvature as well as ground cover and climatic elements like precipitation and temperature. The central aim of this research was to anticipate the susceptibility of snow avalanche hazards in mountainous territories. This study serves to address the broader societal implications of avalanches, encompassing their roles both as hazards and as disturbances to the natural equilibrium. The AHP-centered approach has proven to be highly effective in efficiently mapping avalanche-vulnerable regions within complex landscapes, particularly in the Himalayas. Simultaneously, RAMMS demonstrates efficiency in constructing an advanced early warning mechanism for modeling avalanches and debris flows in mountainous settings. The combined insights extracted from these methodologies aid in forecasting the potential reaction of glaciers to climate shifts, given that glacier melting and precipitation patterns are significantly influenced by diverse topographical and climatic variables. Further, glacier/snow avalanche is the collective and usual phenomena which are unimaginable to be controlled. However, reduction in their cause can be achieved from the application of following measures:

- Judicious construction of the infrastructural projects at high-altitude areas and enhancing the renewable natural resources like minimizing the numbers of construction of hydropower projects.
- Mapping the river valleys area which are vulnerable and highly susceptible.
- Resettlement planning of the residential area in the potential risk zone like river bank and below the glacier zone.
- Properly studying and re-evaluating the proposed

hydropower projects in the context of Environmental Impact Assessment and Social Impact Analysis.

- Downstream communities must be kept alert at all times along with regular and continuous supervision and plotting of glacier maps.
- Limiting the renewable energy source mainly: hydropower project construction beside the area of human residence.
- New technology to be used for the setup of an early warning system for glacier/snow avalanches.

Prominently, there should be a coordinated collaboration among the stakeholders participating in the disaster mitigation theater which includes: the local residential people, the state, climate scientists, geologists, and geographers. Together with this, community-level awareness programs regarding nature-based solutions such as large-scale afforestation programs should be launched.

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