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

By

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This is to certify that this thesis entitled "**Remote Sensing and GIS Based Assessment of Avalanching Glaciers in the Himalayas Due to Climate Change**" prepared and submitted by **Pranav Yadav (078MSCCD007),** in partial fulfillment of the requirements of the degree of **Master of Science (M.Sc.)** in **Climate Change and Development** Programme.

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ABSTRACT

Hanging glaciers are a significant risk factor for avalanches, which can cause major disasters. Icefalls 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 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, Digital Elevation Model (DEM)

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CHAPTER I

INTRODUCTION

1.1 Introduction

Worldwide, mountain systems are undergoing fast change as a result of human influence and climate change. Alpine ecosystems around the world are impacted by changes in precipitation patterns, warming at high elevations, and the loss of water stored in glacial reservoirs. Globally, the area and volume of high mountain glaciers are rapidly declining, which has important ramifications for ecosystems, socioeconomic future, and water availability as well as hazards like glacier lake outburst floods and slope failure. With the 250 million people who live in Nepal, Tibet, and China, the region's rich biodiversity, and an additional 2 billion people who depend on the mountain's abundance for food and water, among other services, climate change in the Hindu Kush Himalaya is especially concerning. Given the speed at which the environment is changing, it is imperative that we clarify any potential risks to all Himalayan inhabitants and ecosystems. Hazards exacerbate non-physical threats like avalanches, blizzards, and landslides, which are driven by the dynamics of climate change. A number of environmental services that are essential to the stability of the population below the glaciers may be impacted by this threat. For instance, the resilience and availability of water and water infrastructure can be impacted by both glacier waste and outburst flooding. The supporting infrastructure and inhabitants' physical safety are put at risk by avalanches and landslides. The amount of water available for use by the local population and in agriculture may be limited by contaminated meltwater (Miner et al., 2020).

Outside of the polar regions, the highest concentration of glaciers is found in High Mountain Asia. In one of the world's most populous regions, these glaciers play a significant role in streamflow. The glacier's contribution to rivers and sea level rise has been evaluated in the past using techniques that can only provide regionally averaged glacier mass balances (Brun et al., 2017). The Himalayas are prone to earthquakes, which increases the possibility of avalanches and mass movement that could endanger people' lives and means of subsistence. The topography relief and high-altitude mountains of the Himalayas depict the processes of erosion and crustal deformation dividing the earth's crust in this area. Due to the strength of the rock and soil, topography, vegetation, and climate, hill slopes in the Himalayas are typically steep and have high rates of erosion. The steep hillside is prone to dangerous avalanches, landslides, and erosions. The glaciers melt away from the head walls as a result of climate change and retreat, exposing steep rock faces that make the structures more susceptible to failure. Avalanches, rockslides, and river valley flooding are examples of descending hazards that can be brought about by landslides of any kind, including those caused by earthquakes and glacier recession. These geologic events have the potential to seriously impair infrastructure, agriculture, ecosystem health, and human populations, resulting in damage and fatalities. Climate change is causing ecosystems to shift, revealing hidden human impacts throughout diverse landscapes—even on the world's highest mountain. As glaciers melt at a rate never before witnessed, this frozen chemical signature of human interaction is an unfortunate side effect of innovation that gets worse with time (Miner et al., 2021). Destabilizing ice, rock, or debris slopes linked to changing glacial lakes are hallmarks of changing high-mountain environments. These arrangements could result in mass movement sequences that could be disastrous (Mergili et al., 2018).

Glacier-related avalanches and falls of ice frequently endanger the area underneath them. For instance, in 2002, a hanging glacier collapsed, causing a flash flood in Uttrakhand and 125 fatalities from boulders and ice falling from the glacier. A scientist at the Wadia Institute of Himalayan Geology made an initial assessment that suggested (Thayyen et al., 2022). Furthermore, the Langtang tragedy in Nepal has brought to light the destruction that can result from massive snow avalanches breaking free from steep glacial headwalls (Fujita et al., 2016). With the continued warming of the global climate, glaciers and seasonal snow cover are predicted to alter their capacity to store water, which will have significant effects on the water supply downstream (Kaser et al., 2010).

The aim of this research is to investigate the possible risks, particularly the snow avalanche-like disturbance in the high mountainous regions of the Hindukush Himalayas region caused by glacier detachment. Additionally, numerical simulations will be generated to determine the motion of geophysical mass movement. Using terrain, or topographic factors and climatic variables, as well as flow dynamics, this research aims to assess the snow/glacier avalanche caused by avalanching glaciers from both a physio-geographical and environmental point of view.

1.2 Statement of Problem

Ice and avalanches are sudden and quick movement of snow or ice after they get detached from the slopes. Snow and ice avalanches related hazard are occurring frequently in the mountains and have a significant effect on the human lives, properties and infrastructures in the downstream. Himalayas have an extremely dynamic system where numerous snow and ice avalanches are reported. Snow avalanches also causes 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 in high altitude and in inaccessible region along with vulnerable slopes. 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 prepared become an extremely important assets for proposing the mitigation measure like dams, embankments, rock-fall protection barriers etc. Also, it can help to optimize limited financial resources by studying the nature and extent of different hazard scenarios.

1.3 Need of the Study

Mapping areas that are vulnerable to hazards and assessing risks are the goals of avalanche hazard mapping. Such mapping makes predictions about areas that are prone to avalanches possible, which greatly improves public safety—especially in light of the rising number of avalanche-related deaths during mountain climbing expeditions. Furthermore, vulnerability mapping makes it easier to assess past, present, and future avalanche patterns, protecting important infrastructure such as hydroelectric dams and other valuable resources. This procedure helps understand what causes avalanche risks to increase, assesses changes in these characteristics, and predicts changes in these avalanche-related parameters as a result of shifting climate patterns. As a result, this study broadens our understanding of the relationship between spatial expansion and, consequently, advances public safety, protects infrastructure, and lessens the effects of avalanches in areas that are vulnerable to them. Moreover, this project advances our understanding of avalanches as disturbances across the entire landscape.

1.4 Research Question

i) What are the factors that contribute to the identification and extraction of spatial extent of avalanching glacier?

ii) What are the factors that are responsible for triggering potential glacier avalanche hazards in the Himalayas due to Climate Change?

iii) How can remote sensing and GIS be used to identify and map avalanche-prone glaciers in the Himalayas?

1.5 Research Objective

The primary objective is to assess susceptibility and stability of avalanche-prone glacier in the Himalayas. The secondary objectives are:

i) To extract probable avalanche prone glaciers in the Himalayas using remote sensing and GIS
  a. Digitize glaciers in the proposed study area
  b. Using slope and aspect data

ii) To model the stability of avalanche-prone glaciers in the Himalayas and assess their potential hazards due to Climate change:
  a. Identify the factors that affect stability of avalanche-prone glaciers.
  b. Assess the potential hazards of avalanche-prone glaciers to downslope and downstream areas.

1.6 Research Limitations

i) Time limitation: The study was limited by the amount of time available to complete it.

ii) Lack of field visit due to extreme remote area and lack of budget: The study was limited by the inability to conduct field visits to the study area. This was due to extreme remoteness of the areas and the lack of budget to cover the costs of travel and accommodation.

CHAPTER II

LITERATURE REVIEW

Along with melting glaciers, climate change will change when and how intensely precipitation occurs, increasing the variability of river runoff. Runoff will rise as a result of glacier melt at first, but it will eventually fall as the glaciers disappear. A further effect of climate change could be to upset normal patterns of snowfall and rainfall. It is anticipated that this disruption will make extreme weather events—such as avalanches, storms, floods, and droughts—more common. As a result, there may be fatalities and significant reductions in agricultural output. It's possible that knowledge and tactics that were formerly effective in addressing these inherent hazards to food security are no longer adequate. Disasters brought on by climate change have a serious negative impact on people, severely compromising the security of many people's livelihoods. Floods, landslides, and other water-related disasters are common in Nepal (Chaulagain, 1970). It has long been the practice to extrapolate local geodetic and glaciological measurements to produce global estimates of changes in glacier mass. According to these records, mass loss has increased recently (Gardner et al., 2013).

Because of their own weight and gravity, glaciers—also referred to as ice rivers—move like enormous masses of ice at a very slow pace. These enormous ice formations are the result of yearly snowfall in the same area or location. Where the rate of ice melting is lower than the rate at which ice accumulates, glaciers form. The formation of glaciers occurs when snow crystals that were previously fluffy become dense and tightly packed ice pallets due to constant ice accumulation and reduced melting. It took hundreds or thousands of years for glaciers to form. There are primarily two kinds of glaciers: Alpine glaciers are located in tropical areas with extremely high mountains, as well as in temperate and polar regions. In the Polar region, such as Antarctica and the island of Greenland, are continental glaciers, also known as ice sheets. Antarctica does not contain glaciers. Whereas alpine glaciers flow toward the valley, continental glaciers are found on a level surface and move the center points in every direction (Sharma & Deen, 2021).

The high-mountain glacial environment has been significantly impacted by recent climate changes. The creation and growth of moraine-dammed lakes as a result of the rapid melting of glaciers has raised the possibility of glacial lake outburst floods (GLOFs). The latter part of the 20th century saw the formation of the majority of lakes. The average rate of glacier retreat in the Nepalese region of Mount Everest (Sagamartha) is 10-59 ma^{-1}. Lumding and Imja glaciers receded 42 and 34 ma^{-1}, respectively, between 1976 and 2000. Between 2000 and 2007, both glaciers retreated at a rate of 74 ma^{-1}. Over the last ten years, there has been a general decrease and faster retreat of Himalayan glaciers, accompanied by an increase in the number of moraine-dammed lakes. The area covered by lakes dammed by moraine is growing, despite a decline in the number of lakes above 3500 m above sea level. An essential component of GLOF disaster management is knowing how glaciers and glacial lakes behave (Bajracharya & Mool, 2009).

The effects of climate change in the Himalayas are a hotly contested topic, primarily raising concerns about the availability of water resources for the lowland population. There are various ways that climate change can manifest itself. Bullying is widespread and could get worse as climate change becomes more unpredictable. Increased earthflows and sporadic debris flow that impact large shale/marly substrates are also anticipated, as they are associated with variations in snow cover and seasonality. In a similar vein, increased precipitation combined with quick melting could encourage the occurrence of flash floods. The current limited glaciation makes the likelihood of glacial outburst floods less likely. The steepest cliffs may eventually experience rock avalanches as a result of permafrost melting, which could also have an effect on the valley floors nearby. All of these risks will have an impact on newly constructed infrastructure, fields and irrigation systems, and the expanding communities that surround them. It is harder to forecast how much water will be available in the near future, but any variation in the type and quantity of precipitation could have an impact on groundwater reserves, which could have an impact on spring runoff and discharge and agricultural output. Eventually, the growth of small markets and the effective connectivity of these upper valleys to the major urban centers of Nepal—a nation with a very low economic and social capacity to adapt—may be jeopardized by the overall potential increase in natural hazards (Fort, 2015). It's critical to understand the effects of glacier surging, which is the recurring, swift advance of glaciers brought on by the relatively quick movement of ice mass from the upper to lower regions of the glacier. The functions of groundwater storage and permafrost are additional factors to take into account (Bolch, 2017).

Because of their sensitive response to even minute climatic changes, glaciers are regarded as important indicators of climate change. This is primarily because, in terrestrial conditions and for temperate glaciers, the ice is at pressure melting point, meaning that any excess energy melts the ice. The geometry (length and surface elevation) of glaciers is adjusted to balance with the dominant climate, which primarily regulates mass gain and loss. In this way, mass gained in accumulation is transported by glacier flow to the ablation region, where it melts. Thus, measuring changes in glacier surface elevation, flow velocity, and size/length, among other factors, is necessary to determine how the geometry of glaciers is changing in response to climate change. These parameters' variations are related to one another on different time scales (Paul et al., 2015). The major risk that affects structures, roads, and puts people in danger in mountainous areas is the glacial avalanche. When a sizable chunk of ice separates from a weak glacier, an avalanche of ice typically happens. Avalanches have damaged buildings and claimed lives in the Caucasus, Iceland, the Alps, and Canada. The regular depletion phenomenon of steep glaciers in higher elevation ranges with high relief energy is indicated by ice avalanches. Extreme catastrophes are brought on by glacial avalanches when they combine with debris (Gilany & Iqbal, 2019).

In the Himalayan region, landslides vary in size, ranging from small slope failures to the massive collapse of entire mountain ranges due to gravity tectonics (Shroder & Bishop, 1998). The potential for these slope failures to cause other natural hazards, such as flash floods, makes them extremely vulnerable in addition to their inherent uncertainty. Floods are a devastating natural disaster that occur when a significant amount of water unexpectedly overflows its bounds. Due to their quick onset, minimal warning period, and enormous water and debris load transported with tremendous energy, flash floods rank among the most destructive natural disasters in terms of the number of people affected. There are many different kinds of flash floods that can occur, including intense rainfall floods (IRF), glacial lake outburst floods (GLOF), landslide dam outburst floods (LDOF), and flash floods brought on by quickly melting snow and ice. Most reports of them are from the Himalayan region (Poudel & Hamal, 2021).

One of the most trustworthy indicators of the changing global climate since the middle of the 19th century is the astounding global retreat of mountain glaciers. Hence, mountain glaciers are thought to be important markers of climatic shifts and serve as a kind of "global thermometer." The phenomenon of GLOFs dramatically demonstrates the potential local effects of global climate change. This evidence of the anthropogenic greenhouse effect also emphasizes the various ways that developed and developing nations can respond to similar effects (Horstmann, 2004).

Due to the significant risks they pose to numerous high-mountain areas worldwide, glacial lake outburst floods, or GLOFs, have received more attention in recent years because of the catastrophic damages and fatalities they can cause. The majority of the regions that GLOFs strike are the Himalayan, Karakorum, and Hindukush (HKH) regions. The region's shifting climate is expected to have an impact on the ablation of snow masses, the growth of glacial lakes, and GLOFs. Studies on glacial lakes are also required for the resilient to disasters sustainable use of water resources. Remote sensing is the most effective technique for early detection and monitoring of glacial lakes and GLOFs in high mountainous areas (Khan et al., 2021). A lake in a cold climate that is either developing due to recent glacial morphology, or that is close to or in contact with a glacier, is known as a glacial lake. Because many glacial lakes are unstable, they can suddenly burst, causing catastrophic floods in cryosphere regions known as glacial lake outburst floods (GLOFs). This disaster-prone area lacks well-developed glacial lake inventories, assessments of GLOF risks, and studies of the physical geographic conditions (D. Li et al., 2020).

High temperatures will shorten the total snowfall season, accelerate the rate of snow and glacier melt, and increase the ratio of rain to snow. Following the conclusion of the Little Ice Age, global temperatures have been rising and most glaciers are receding (IPCC, 2001). The permanent snowline moves upward as the temperature rises. Many people who live downstream may experience severe difficulties with water availability if this results in a major reduction in the amount of water stored in the mountains. Since snow and glacier meltwater contribute significantly to the runoff of the Himalayan Rivers, they are anticipated to be particularly vulnerable to climate change. Diverse river systems may exhibit varying degrees of sensitivity. Because most rivers in Nepal experience rapid withdrawal following summer rains, the volume of snow, rate of melting, and amount of precipitation during the melt period all influence how big snowmelt floods will be. As a result of warming, rivers fed by glaciers are flowing more quickly because more water is released when snow and glaciers melt. The flow of the dry season declines as the glaciers recede and the amount of meltwater drops (Chaulagain, 2009). Since the Himalayan melting season falls during the summer monsoon season, any acceleration or intensification of the monsoon would raise summer runoff, which would raise the possibility of flooding disasters (IPCC, 2001).

Extreme weather events will occur more frequently and with greater intensity as a result of climate change's increased climatic variability. A few recent occurrences have raised awareness of the potential threat posed by glacial lake outburst floods in the area, which are widely recognized as powerful natural disasters with glacial origins (Komori et al., 2012). Worldwide glacier thinning and shrinking is caused by global warming, which could have serious repercussions for human society. Because they are so sensitive to variations in the climate, glaciers are essential for monitoring climate change. In order to understand glaciers, hydrology, and water resources, one must understand glacier mass balance (Y. J. Li et al., 2019).

A vast and varied ecosystem, as well as a population exceeding one billion, are sustained by multiple major Asian rivers that originate from the Himalaya and the nearby Tibetan Plateau. Sitting as the exit points for sediments from the orogen, large rivers like the Indus, Sutlej, Ganges, Arun, and Brahmaputra drain the southern Tibetan Plateau and the Himalaya and are vital for agriculture and energy production. Snowfall occurs in the upstream and high-elevation regions of these basins, naturally delaying the river's discharge. The fluctuations in snow cover in the Tibetan Plateau and the High Himalaya consequently affect the amount of water available downstream in Asia's major river basins, particularly in the spring when the growing season begins and in the fall following the monsoon season (Bookhagen & Burbank, 2010).

Twenty percent of humanity's well-being is expected to be impacted by climate change in the Himalayas, a biodiversity hotspot, the source of eight major rivers in Asia, and the location of many sacred landscapes. And yet, very little is known about real variations in the two most important climate variables—temperature and precipitation—despite the Himalayas' extraordinary environmental, cultural, and socioeconomic significance and their fast-growing ecological degradation. We also don't know how adjustments to these parameters might affect the phenology of vegetation and other ecosystems (Shrestha et al., 2012). In regions where snow avalanche activity is present during the snow season, snow avalanches may recur on the same path under varying snowpack and weather conditions. In a warming climate, the amount of snowfall, air temperature, and snow cover can all fluctuate significantly, changing the risk of snow avalanches (Hao et al., 2023).

More people perish from snow avalanches, which are a serious and potentially fatal hazard in mountainous environments. For slab avalanches to form in the highly stratified seasonal snowpack, weak layers are essential (Birkeland, 1998). Only a small percentage of the approximately 160,000 glaciers on Earth have known ice volumes, but these quantities are crucial for many studies on sea level and climate change that depend on estimates of water flux. A power law relationship between glacier volumes and more readily observed glacier surface areas can be observed through a scaling analysis of the mass and momentum conservation equations. Four closure options are needed for the relationship in order to account for the mass balance, side drag, slopes, and glacier width scaling behavior. Observations are consistent with the volume-area scaling exponent predicted by reasonable closures, providing a theoretical and practical foundation for ice volume estimation. Changes in average accumulation area ratios indicate substantial changes in the mass balance and ice volume scaling, but glacier volume is insensitive to changes in the mass balance scaling (Bahr et al., 1997).

Avalanching glacier instabilities are rupture phenomena caused by gravity that have the potential to cause large-scale catastrophes, particularly if they are the starting point of a chain of events. Accurately predicting such occurrences along with promptly clearing out inhabited areas in danger often amounts to the most effective course of action. Destabilization process understanding has significantly improved recently as a result of significant efforts in monitoring, analyzing, and modeling such phenomena. This has improved early warning perspectives (Faillettaz et al., 2015). The water resource benefits greatly from seasonal alpine snowfall. From the standpoint of socioeconomic sustainability in the alpine regions, it is essential for controlling the environmental feedback. While hydropower produced from snowmelt runoff is one of the main sources of renewable energy, most countries are pursuing other options. Avalanches and other natural disasters frequently affect alpine regions with snow cover, which is also a popular tourist destination. Early avalanche warning systems and snowmelt runoff depend on timely information on the spatial-temporal aspects of the snow geophysical parameters (Awasthi & Varade, 2021).

The recession of the Himalayan glaciers suggests that the topography and climate of the area have a major role in the significant variations in mass balance and terminus retreat rate observed in the various mountain range sectors. Developing a coherent picture of the impacts of climate change is challenging due to variable retreat rates of glacier termini and insufficient supporting field data (e.g., mass balance, ice thickness, velocity, etc.) in the Himalayan glaciers (Dobhal et al., 2013).

As of December 2004, the Indian Ocean tsunami, the 2013 Uttarakhand calamity is regarded as the country's worst natural disaster. When rivers from the Himalaya rushed down torrential rains, roads, bridges, houses, and buildings were washed away in the whirling waters, causing unprecedented damage to life and property. Over 1000 people are anticipated dead, over 6000 people are missing, and tens of thousands have been displaced, according to government officials. The main cause of the massive flow is a break in the snowmelt and rainfed Chorabari Lake, also known as Gandhi Sarovar Lake (3960 m amsl, about 400 m long, 200 m wide, and 15–20 m deep), which was dammed by the moraines the Chorabari glacier deposited. The loose-moraine dam burst under the weight of millions of gallons of water, causing the glacial lake outburst flow (GLOF) (Dubey et al., 2013).

It is anticipated that throughout the 21st century, permafrost, glaciers, and snow cover will all continue to decrease in practically every region. Low elevation snow depth will probably drop by 10–40% for 2031–2050 (regardless of the Representative Concentration Pathway [RCP]) and by 50–90% for RCP8.5 and RCP2.6 for 2081–2100 (respectively) compared to 1986–2005. Between 2015 and 2100, glacier mass reductions are anticipated to range from 22–44% for RCP2.6 and 37–57% for RCP8.5 (IPCC, 2022).

It is well known that the Himalayan Mountain ranges are among the most susceptible locations on Earth to landslides and flash floods. On May 5, 2012, there was a devastating flash flood in the Seti River, which demonstrated how destructive it can be not only for the loss of property and finances but also for the loss of the environment and cultural heritage sites. It was discovered that a temporary dam was built as a result of the Annapurna IV's mass failure, and the flash flood was caused by the sudden release of water that had accumulated. It is also emphasized that the relevant authorities should take action to reduce the potential impact by raising awareness, putting in place an early warning system, and improving community-based readiness (Poudel & Hamal, 2021).

A rockslide on the western cliff of Annapurna IV on May 5, 2012, caused floods that flowed down the Seti River, severely damaging nearby villages and tourist destinations. Taking into account the gravity of the catastrophe and the requirement to look into the phenomenon in order to mitigate future disasters in Nepal. An earthquake, a lot of rain, or melting snow could not have been the direct cause of the rockslide. Given that the calcareous sedimentary rock that forms the dip slope was exposed, the rockslide may have started as a large-scale landslide that happened (OI et al., 2014).

Due to global warming, a significant number of glacial lakes have emerged in many mountainous regions of the world over the past 50 years. The glacial lakes have frequently erupted, causing catastrophic floods. There have also been glacial lake outburst floods, or GLOFs, in the Himalayan mountains. For the downstream region to be protected from disasters, research into the glacial lakes is essential (Komori et al., 2008). Research on climate forcing and related Earth-System responses has been prompted by worries about greenhouse gas forcing and rising temperatures. Because complex geodynamics control feedback mechanisms that couple climatic, tectonic, and surface processes, there is a great deal of scientific debate regarding climate forcing and landscape response. The cryosphere plays a crucial role in the coupling of Earth's systems because it regulates atmospheric, hydrospheric, and lithospheric response through feedback mechanisms related to glaciers. More precisely, the mass distributions of snow and ice control some aspects of atmospheric properties (Shroder & Bishop, 2010).

These changes also have a significant impact on steep high-mountain rock walls, which are frequently characterized by hanging glaciers, ripped fields encompassing large portions of the flank, and widespread permafrost occurrence. Numerous factors impact the stability of the slope in these types of banks. On the other hand, the hydrological regime, temperature, and stress fields in rock and ice all have a significant impact (Fischer et al., 2006). The high avalanche mobility is probably caused by fluidization effects at the base of the moving ice/debris mass, where there are high pore pressures and a constant water supply from ice melting through friction (Huggel et al., 2005).

In June 2013, over 6000 people died in Uttarakhand, an Indian state in the Himalayas, as a result of flash flooding and landslides brought on by heavy rains. On June 16 and 17, a lake outburst and debris flow disaster that originated above the village of Kedarnath was directly responsible for the great majority of deaths and destruction. Here, we offer a methodical examination of the topographic predisposition and hydrometeorological triggering elements that contributed to the Kedarnath tragedy. The topography of the lake watershed above Kedarnath is contrasted with other glacial lakes in the northwest Himalayas, as well as with other notable flood and landslide disasters that have occurred in the Indian Himalayan states in the last century (Allen et al., 2016).

On February 7, 2021, a massive rockslide caused by wedge failure devastated the catchments of the Rishiganga and then Dhauliganga valleys in the Chamoli district of Uttarakhand, resulting in a catastrophic flood. Before having a significant negative impact on the Ronti Gad valley, which is 1.5 km downstream of Ronti Glacier's nose, the enormous rockslide, estimated to have a volume of 23 million cubic meters and contain base rock, deposited ice, and snow, broke away from the northern slopes of the Trishul mountain range near Ronti Glacier. The rockslide created a vertical fall of nearly 1700 meters. The enormous detached mass of rock and ice quickly moved downstream through the glaciated valley, carrying with it snow, debris, and mud. It also caused rapid mudslushization, massive waves of water or slush, and the partial or total removal of bridges and hydroelectric projects that were in its path. Considerable kinetic and thermal energy were produced in response to an estimated 0.90 Peta Joules of potential energy, sufficient to start the aforementioned processes. High-resolution satellite data analysis conducted after the event reveals flood water marks in the valley and on the rock, with outcrops on the route to Raini Village reaching heights of 80–150 meters. A dammed lake was created as a result of the mud and slush created by this process, which also momentarily stopped one of the tributaries of the Rishiganga joining from the northeast (Pandey et al., 2021).

On February 7, 2021, a brief flash flood in the Rishi and Dhauli Ganga rivers in Uttarakhand, Himalaya, destroyed two hydropower projects and left 65 people dead or missing. A combination of debris flow and avalanche, according to meteorological data and geomorphological observations, may have caused the flood. Because of the preservation of ponded sedimentary sequences (silty-clay and laminated sand), the Dhauli Ganga valley may have been subject to episodic mega foods in more recent geological times. Such disasters are expected to occur more frequently as the climate warms, given that the retreating glaciers in the higher Himalaya have left behind massive sediment deposits. So, the study suggests routinely monitoring the areas of probable structural collapses in the glaciated valleys and supra-glacial lakes, in addition to implementing the catastrophe risk assessment into the Himalayan region's developmental planning (Rana et al., 2021).

In the Himalaya, summertime calamities have become more frequent and intense. But during the winter, the region typically does not see natural calamities like flash floods. Since melting is indicated by the breakup of the hanging glacier or its separation from the main body, this phenomenon may also be connected to the effects of global warming. Climate change caused the former to melt away and expose the bedrock even before the hanging glacier was placed over it. After that, weak zones had formed along the rock's joints as a result of chemical and physical degradation. Because of an increase in anthropogenic activity, there have been more disasters in the area. Since development activities pose a harm to the environment, this tendency is probably here to stay. River flow has deviated from its normal course as a result of human development obstructing their natural flow pathways. Selecting safe land-use choices would be a difficult task to do given the inclination toward greater urbanization caused by an increase in construction activities in the region (Mehta et al., 2021).

High Mountain Asia's (HMA) cryosphere is home to possible threats in addition to supporting downstream residents' lives through water storage. About 1.9 billion people live downstream on the ten main river systems of Asia, which receive their water from these cryosphere sources. The Himalayan Mountain Area (HMA) is home to the greatest concentration of snow, glaciers, and permafrost outside of the polar regions. As a result, it is crucial for guaranteeing the supply of water for hydropower, industry, household requirements, agriculture, and ecosystem services. Nonetheless, there are a number of possible risks associated with the cryosphere in HMA. There is documented evidence of both direct and indirect glacial hazards, including snow/ice avalanches, glacial lake outburst floods following calving events or high melt, glacier detachments and surges, and breaching of moraine-dammed lakes following intense rainfall or disrupted irrigation channels linked to receding glaciers. Every year, avalanches do significant damage to infrastructure and property and have a negative impact on livelihoods and socioeconomic activity (D. Li et al., 2020).

Destabilizing ice, rock, or debris slopes linked to changing glacial lakes are hallmarks of changing high-mountain habitats. These arrangements might result in large movement sequences that could be disastrous (process chains or cascades). In order to minimize losses, computer simulations are meant to help predict potential outcomes of such occurrences (Mergili et al., 2018). In all of the world's high alpine areas, lakes have formed and grown along the edges of glaciers and moraines as a result of glacier thinning and retreat during the previous century (Worni et al., 2014). The Gorkha earthquake on April 25, 2015, caused a catastrophic rock avalanche in the central Nepalese Langtang valley that buried a tourist hamlet and killed over 350 people. This was a multiphase avalanche that originated from several source regions and consisted of a mixture of rock debris and glacier snow and ice. It happened in phases (Gnyawali et al., 2020).

Himalayan communities stand precariously in an era of phenomenological uncertainty. Climate change is merely a lens through which we may observe and begin to understand such localized modern complexities. The people of the Tarap Valley in Dolpo, Nepal have experienced an increase in avalanches, snow leopard attacks and unpredictable precipitation patterns in recent years. In upper Mustang, Nepal, people have endured the harshest winter in generations and suffered from reduced water access. Environmental, climatic, and weather-related changes in both Himalayan districts have severely impacted traditional livelihoods and led some to adopt modern means of adaptation. The scientific data points to human-caused climate change as the cause, yet traditional, astrological, and religious beliefs still dominate how the locals interpret these changes. Scientists predict that the changes in climate will only worsen, with Himalayan tribes among those most affected. Many Himalayan villages are geographically isolated, which highlights the gap between the perplexing realities of people's lived experiences of climate change and the contemporary, global academic knowledge of climate change (McChesney, 2015).

Thus far, the Bhagirathi and Alakananda basins of the upper Ganga basin (UGB) have been regarded as a single hydrological entity with similar climatic influences. Here, we display three separate "topo climatic zones" inside this basin, each with its own unique precipitation patterns, temperature, and orographic processes. Cryosphere areas exist at higher elevations primarily because of elevation-dependent cooling of the mountain side. Differential LST distribution, precipitation, and LSTLR reflecting the variations in orographic processes and climatic causes in zones (Yadav et al., 2020).

The frequency of glide avalanche and gliding snowpack damage instances has significantly increased in recent years owing to warmer snow cover. The majority of them have been full-depth, wet-snow avalanches, which surprised some of the following people: How may moist snow masses moving slowly enough to create pressure that is high enough to seriously harm heavy-duty structures? (Ancey & Bain, 2015).

Communities and infrastructure in glacierized mountains may be seriously endangered by catastrophic mass flows (CMFs), a key geomorphic event in the glacial environment. Mass movements of glacial ice, ice-rock avalanches, flows created by outbursts, and glacial debris flows are among the many glacial dangers known as CMFs. When CMFs move, they frequently experience dramatic process transformations in response to a variety of factors, including river damming, entrainment of new materials, melting of entrained ice and snow, and integration or displacement of water in the periglacial environment (Evans & Delaney, 2015).

Another calamity that is occurring more frequently in the Himalayan region is cloudburst. ((Das et al., n.d.) ; (Kumar et al., 2018) ; (Thayyen et al., 2013);(Dimri et al., 2017)). In the area, snow avalanches are likewise recognized as a serious calamity, and modeling and forecasting are routine tasks. However, glacier avalanches are not now taken into account when planning infrastructure and development projects, nor are they part of daily operations in the upper Himalayan area (Thakuri et al., 2020).

The Himalayan glacier ecosystems were significantly impacted by the twentieth-century shift in climate. Concerns about the creation of supraglacial lakes, glacial lakes trapped by moraine, and glacial lake outburst floods are significant in nations like Bhutan, China (Tibet), India, Nepal, and Pakistan. The most effective method for identifying and keeping track of the dangerous characteristics of the glacier lakes in the Indian Himalaya is remote sensing. A comprehensive inventory of glacial lakes using high-resolution satellite data and in-person field surveys is advised in order to determine the hazard potential of these bodies of water. The value of using information from remote sensing to quickly and qualitatively evaluate glacier lakes in the difficult Sikkim Himalayan region. Standardized disparity The glacial lakes were automatically distinguished from the other features using the best available technique based on the water index. The growth of lakes between 2003 and 2010 demonstrates the alterations in the environment that are relevant to the Himalayan region. The lakes' expansion suggests that the hazard scenario may worsen. A thorough inventory and field assessment should be conducted in this region of the Himalaya, and GLOF early warning systems should be built in potentially risky areas, according to the changes in the glacier lake environment. (Govindha Raj et al., 2013).

The current studies showed that a number of variables, including glacier size, topography (slope, aspect, and altitude), and debris cover, influence how glaciers evolve. The steep surface slope, small size, low altitude, south-to-east direction, and debris-free surface are factors that contribute to the basin's increased glacier loss. The evolution of glaciers is mostly influenced by climatic conditions, especially air temperature and precipitation, in addition to local considerations. (Mir et al., 2017).

In order to lessen the effects of large-scale flooding and wasting—a significant concern in the Himalaya—early warning systems are vital possibilities. Major flooding may occur in mountainous areas, such as the Himalayas, due to the outbursts of glacier lakes, landslide blocked lakes, and more complex danger cascades. With retreating glacial lakes and thawing permafrost causing mountain slopes to become unstable, they pose an increasing concern in the changing environment. Loss of life, property, and means of subsistence is a major concern posed by mountain flash floods to susceptible populations and infrastructure. Catastrophic mountain floods are naturally unpredictable due to their multiplicity, complexity, and sometimes remote origins.

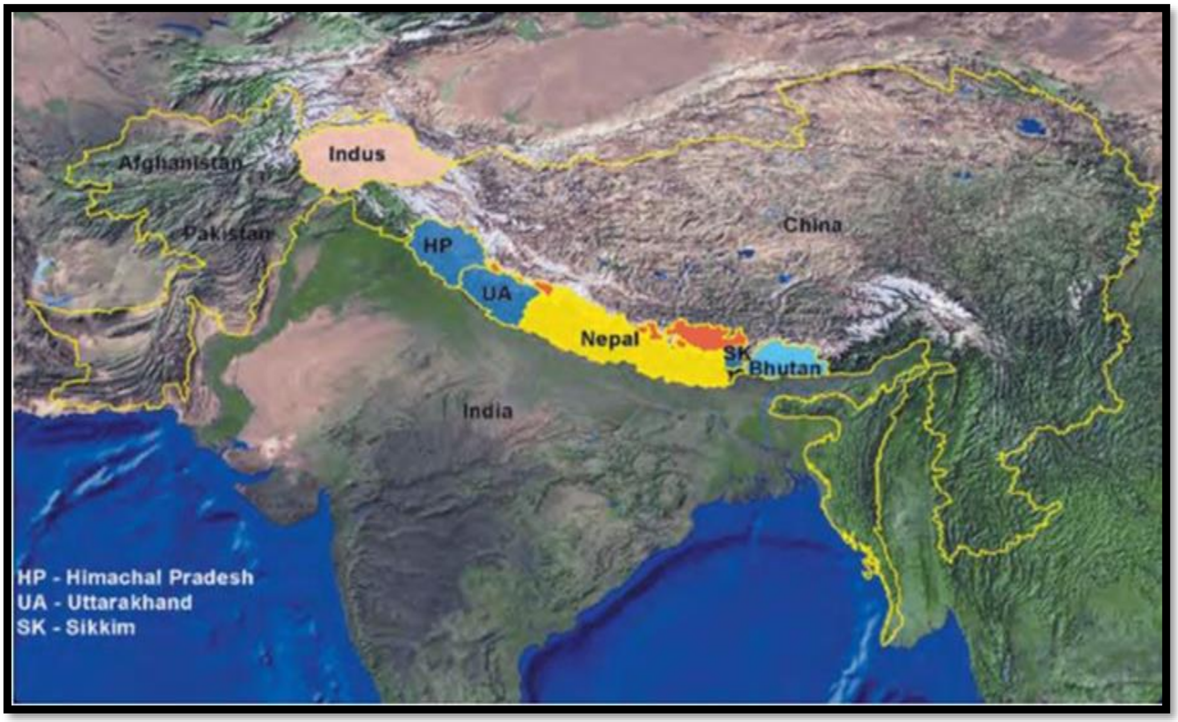


Figure 1: Hindukush Himalayan Range

(Source: ICIMOD's inventory of glaciers and glacial lakes study from 1999-2004)

It is still rather difficult to predict when an event will occur, especially in cases when probable flood sources may be located. Regional early warning becomes an essential tool to lessen the impact of events on populations downstream when there is no good flood prediction. Unlike existing warning systems that concentrate on a specific hillslope, channel, or catchment, regional seismic networks have the unique capacity to register a variety of major geomorphic events across a region without needing prior knowledge of possible event locations or triggers.

Thus, there is a great chance that early warning systems for catastrophic floods might be provided by regional seismic networks. The HKH area stretches 3,500 km from Afghanistan in the west to Myanmar in the east, covering all or a portion of eight nations. A population of over 240 million people reside in the region, depending on it for water, ecosystem services, and their means of subsistence. It is the source of eleven significant Asian river systems. It is Central Asia's magnificent mountain range. In general, it is up to 150 miles (240 km) broad and 500 miles (800 km) long. A quarter of the world's population, or 1.9 billion people, depend on the water in the basins of these rivers. In the HKH, a considerable amount of water resources is frozen as glacier ice and snow. Communities in the mountains and downstream benefit from a variety of ecological services provided by components of the cryosphere, such as permafrost and glacial lakes. During the winter, the area covered by snow cover fluctuates from 951,000 to 1,390,000 square kilometers. It varies from 388,000 to 481,000 sq km in the summer. A glacier's overall area might reach 87,340 square kilometers. Catastrophic mass flows are a necessary geomorphic process in the alpine glacier environment, but they also present a serious risk to downstream populations and infrastructure (Thayyen et al., 2022)

These occur at a period when glaciers are receding due to climate change and involve a mass movement of glacial debris flows, ice rock avalanches, and outburst produced flows (Chiarle et al., 2007). A harsh but uncommon example of a catastrophic catastrophe of this nature is the 2002 Kolka glacier detachment in the southern Russian Caucasus Mountains. (Haeberli et al., 1997)

CHAPTER III

RESEARCH METHODOLOGY

3.1 Study Area

The study area for the project is mentioned below:

3.1.1 Study Area I: Raunthigad-Rishiganga located at Uttrakhand of India

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. 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 among the most brittle ecosystem in the earth. The area is the host of some of the most fragile ecosystem in the world (Chiarle et al., 2007). This region is geotechnically vulnerable with weak geological belt and also seismically nascent and tectonically active causing frequent earthquake and is composed with geo-morphological complexity. 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 (Thayyen et al., 2022).

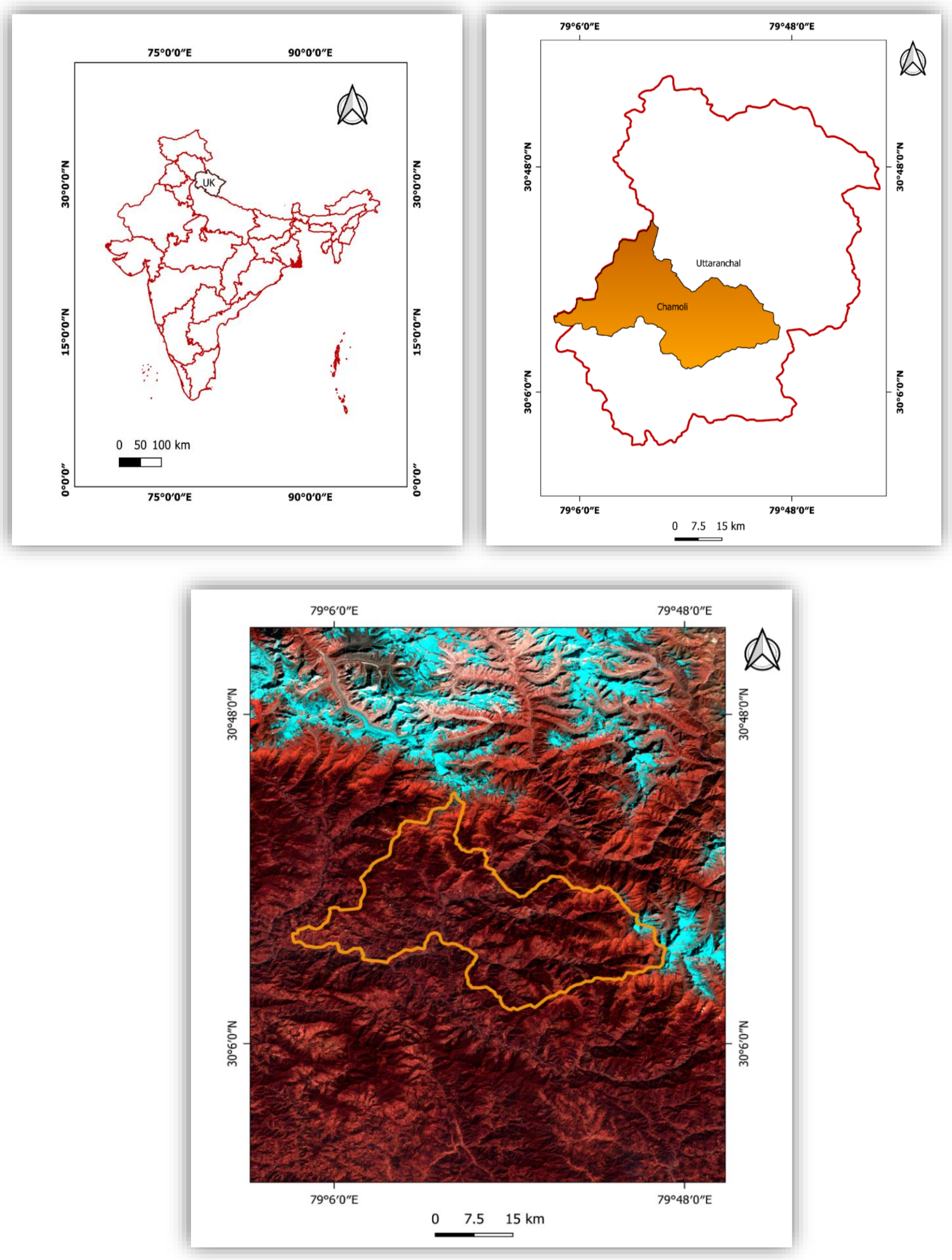


Figure 2: Raunthigad-Rishiganga located at Uttrakhanda of India

3.1.2 Study Area II: Ama Dablam Area of Nepal

Within Province No. 1 of Nepal, Ama Dablam is a notable peak in the eastern Himalayan range. Situated roughly 152 kilometers northeast of Kathmandu and 162 kilometers north of the provincial capital, Biratnagar, is where it is located. Both the lower western peak and the main summit of this mountain reach elevations of 6,812 meters. Ama Dablam, sometimes known as the "mountaineer's mountain," is well known for its difficult terrain and demanding technical features. At coordinates of 27°51'40"N latitude and 86°51'40"E longitude, there is a notable hanging glacier.

"Mother Necklace" is how the name "Ama Dablam" translates in relation to its appearance. The long ridges on either side resemble a mother holding her child in her arms. In addition, the hanging glacier is similar to a "Dablam," a customary double-pendant that Sherpa women wear and are decorated with images of gods. For trekkers making their way to the Mount Everest Base Camp, Ama Dablam's massive presence dominates the eastern skyline. This peak attracts climbers from all over the world who come to test their technical skills in the demanding high-altitude conditions of the Himalayas. According to authorized expeditions, Ama Dablam is the third most popular Himalayan summit. As a result of its towering ridges and sheer faces, it is known as the "Matterhorn of the Himalayas."

However, because of its topography and the nearby tectonic activity, this mountain is also prone to avalanches. A major incident happened in 2006 when a portion of Dablam collapsed, killing multiple people in the exposed camp three.

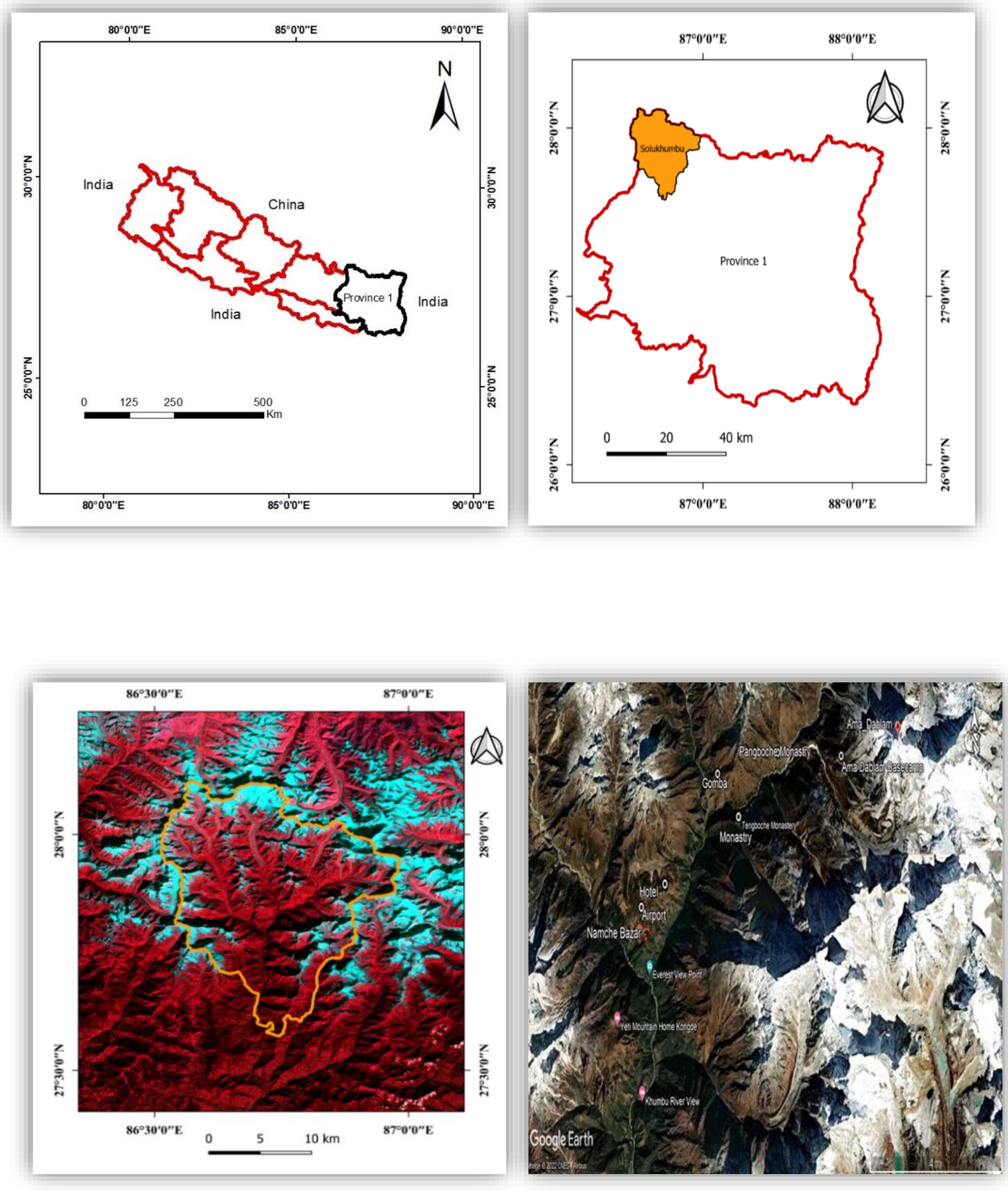


Figure 3: Ama Dablam located in Nepal

3.2 Data and Methodology

DEM with 12.5 m was downloaded from ALOS PALSAR high resolution DEM website (https://search.asf.alaska.edu/#/). Also, Landsat-8 imagery has been 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. There may be a considerable difference between the ground surface temperature (GST) data and the satellite-derived LST data. Three years of rock temperature data from 2016 to 2019 were collected in the Ladakh mountain range in order to improve the LST data. GST observation and MODIS LST were used to create monthly regression equations for this site, and the results showed a good match with observations (R^2=0.92) (Thayyen et al., 2022) . Based on that very observation we considered the LST data without validation with DHM data 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. By using pairwise comparisons carried out by experts and decision-makers, this MCE approach facilitates the evaluation of the relative strengths of various spatially related criteria. This methodical approach to research yields a comprehensive and consistent set of hazard mapping criteria, which are useful for further GIS analyses. AHP has proven to be particularly effective in mapping avalanche-prone areas in rough, highly undulating mountainous terrain.

Additionally, for one of the possible avalanche-prone areas, a numerical simulation had to be carried out. The Rapid Mass Movement Simulation (RAMMS) model, which is used to determine the dynamic behavior of avalanches at these particular locations, was employed in this simulation. Process models are becoming increasingly important in the field of natural disasters to help understand the flow of geophysical phenomena. Engineers and scientists can use these models to predict the speed and volume of dangerous movements in complex landscapes. They are especially helpful when planning ways to lessen these occurrences, like building snow shelters or avalanche barriers. Hazard mapping is an important practice, especially in countries with high elevations.The main driving force behind the development of dynamic mass movement models is the ability to accurately predict the paths taken, flow velocities, and impact forces in intricate, three-dimensional environments.

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; 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 the scale of 1 being lowest to 5 as 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 (Sethia et al., 2018). 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

3.2 Research Framework

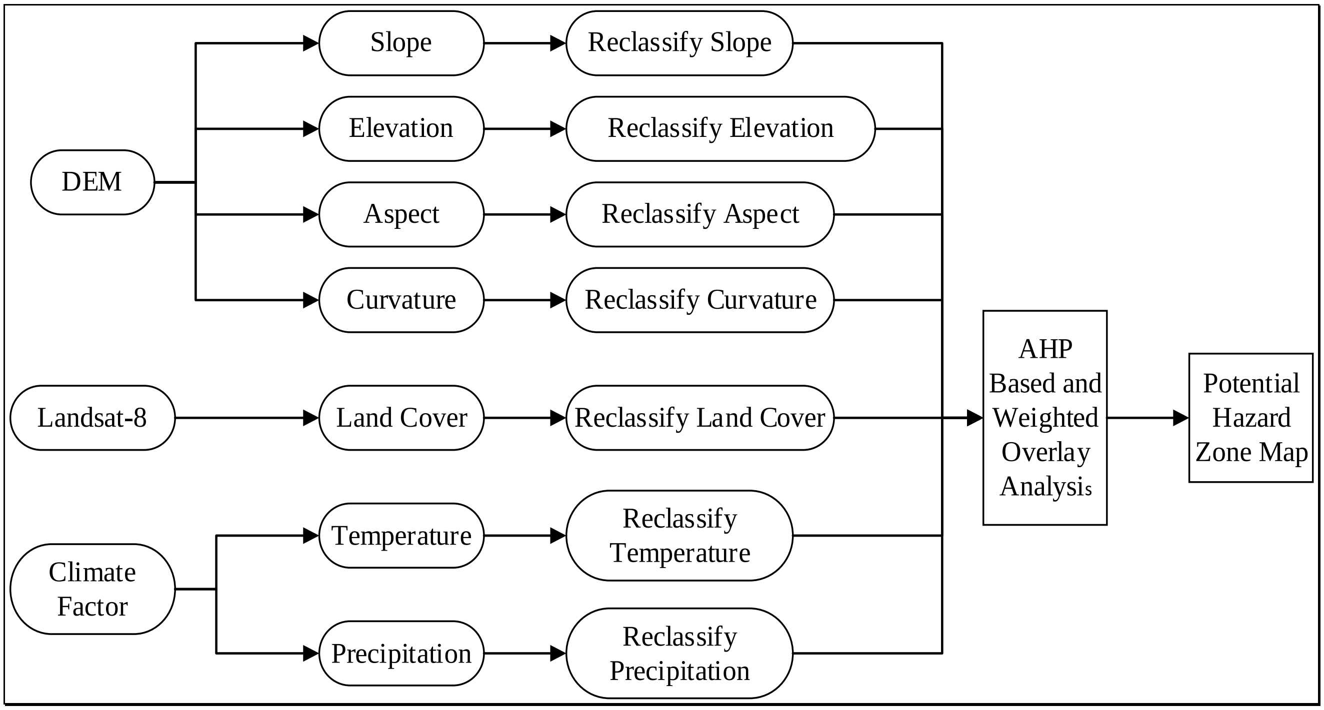


Figure 4: Methodology for Avalanche Hazard Mapping

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 (Worni et al., 2014). 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. For implementation, the DEM in the ESRI ASCII Grid format and the ASCII X,Y,Z format are needed. The release area can be specified using a polygon shape file, meaning that it can be created manually in the program or that it can be imported from any GIS program using a predefined release area shape file. The height of the release zone can be used to determine the initial volume of the area. Height and release volumes are correlated, meaning that when an area's height rises, so does its volume, and vice versa.

Additionally, RAMMS uses a Voellmy-fluid friction model, which is derived from the Voellmy-Salm methodology. Two components make up the frictional resistance in the RAMMS physical model. Viscosity-turbulent friction (coefficient) and normal stress are scaled by a dry-column type friction (coefficient μ). When ρ is the density, g is the gravitational acceleration, φ is the slope angle, H is the flow height, and U is the flow velocity, the frictional resistance S (Pa) is then equal to $\mu\rho H g \cos(\varphi) + (\rho\, g\, U^2/\xi)$. One parameter, N, can be used to represent the normal stress on the running surface, $\rho H g \cos(\varphi)$.

The resistance of the solid phase (ε, which Voellmy introduced using hydrodynamic arguments) and the turbulent or viscous fluid phase (ξ, which Voellmy introduced using the internal shear angle as its tangent) are taken into account by the Voellmy model. The flow behavior is determined by the fiction coefficients; when the flow is running quickly, ξ dominates, and when it is almost stopping, μ dominates. The simulation of mass movements, particularly snow avalanches, has made extensive use of the Voellmy friction model. RAMMS: There are two calculation modes available with Avalanche: constant and variable. Forest areas and undulating terrain are obviously not taken into account if a calculation is performed using constant friction values.

Based on the analysis of topographic data (slope angle, altitude, and curvature), forest information, and global parameters like return period and avalanche volume, an automatic RAMMS procedure classifies values (μ and ξ). Values for μ and ξ are stored as MuXi-files, which are ASCII files. The global parameters return period and avalanche volume have a significant influence on the friction values μ and ξ. We used coefficients of dry friction ranging from 0.1 to 0.6 and values of turbulent friction ranging from 1000 to 3000 m/s^2. Based on the terrain type, avalanche occurrence period, altitude, and volume of the release area, the friction parameters were chosen.

RAMMS Modeling Parameters (Avalanche, 2010)

i) Study Area Information

   a. Release zone locations: (Position of probable avalanching glacier of the respective study areas on DEM)

   b. Domain Area (Extraction of location covering the avalanche zone around the release area)

ii) DEM (Terrain Analysis)

   a. Elevation: (Altitude is extracted from the input DEM)

   b. Slope: (Slope angle is calculated from known altitude)

   c. Curvature:(Is calculated from the know altitude)

   d. Terrain classification (track type): (Channeled/Branched)

iii) Friction Parameter (Physical friction information)

   a. Dry columbo friction (coefficient μ) that scales with the normal stress: (0.235)

   b. A velocity-squared drag or viscous turbulent friction (coefficient ξ): (2000)

iv) Global Parameters

   a. Return period: (10- Year)

   b. Avalanche volume category: (Considered the large avalanche (>60000m3)

   c. Altitude limits: (above 1500 m.a.s.l.)

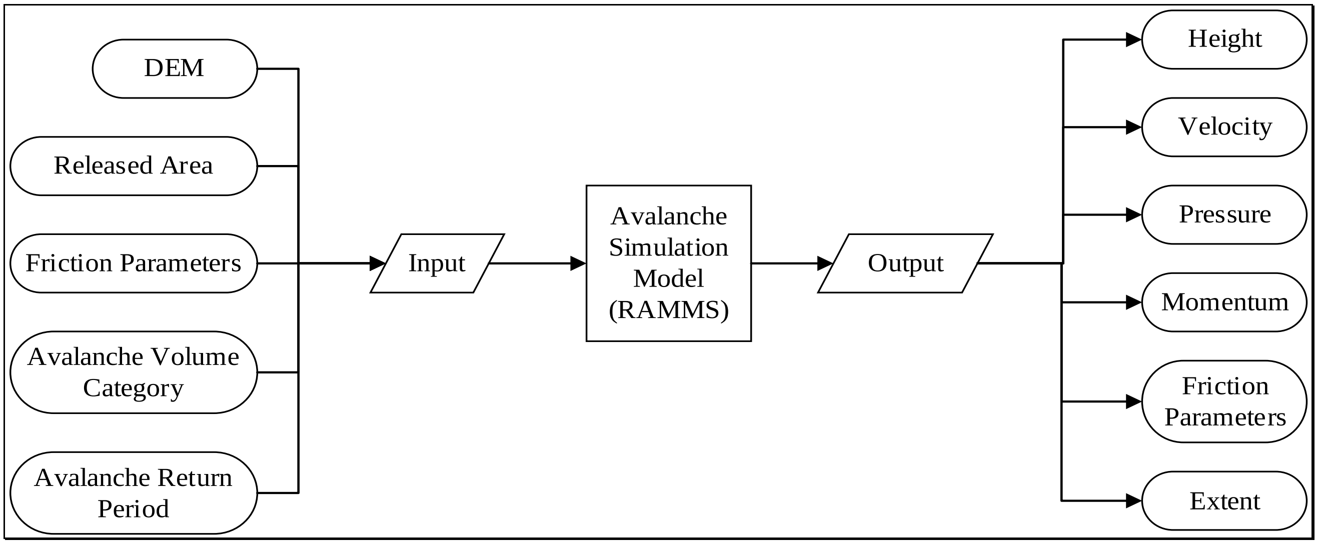


Figure 5: Methodology for Modelling through RAMMS Simulation

CHAPTER IV

RESULTS AND DISCUSSION

The terrain parameters were resampled to a common resolution. The reclassified imagery of various terrain parameters is shown in the figure below: *Figure 6* depicts the elevation and reclassified elevation of the study area- I. 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, *Figure 7* depicts the slope and reclassified slope for which the rating of 5 is allotted to the slope of 30^o – 55^o. The same procedure is adopted for aspect and curvature where rating 5 is allotted for north and north east orientation and for convex curvature as shown in *Figure 8* and *Figure 9* respectively. 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 as shown in *Figure 10.* The temperature and rainfall data of 20 years were also analyzed and plotted *(Figure 12,Figure 13,Figure 15)*. The temperature during July, August, September, and October shows an increasing trend, September being among the higher side (*Figure 14)*. 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 16*). The precipitation is sparse in that region however, its effect has been taken into consideration. *Figure 17* shows the increasing trend in the precipitation over the last 20 years.

Then after, pair wise 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 as shown in *(Table 1)*. The weights so obtained from AHP will be used in generation of avalanche susceptibility map. Thus, weighted overlay analysis was performed in the GIS incorporating the weightages obtained from *(Table 1)*. Hence, Avalanche susceptibility map is thus prepared.

Here, in the obtained avalanche hazard susceptibility map (*Figure 19*) 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 19*). 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.

So, using the AHP and weighted overlay analysis in GIS, the potential avalanche zones of Raunthigad-Rishiganga area was identified which is shown in (*Figure 19*). 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%. (*Table 3*). 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 modelling. 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. Besides, the simulation shows maximum velocity of 51.6 m/s which is shown in red color in *Figure 20*, 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. 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 21)*. 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 21*). *Figure 22* shows shear stress generated during the flow of avalanche. The maximum stress generated during the flow was 23.18kPa but most of the time the stress generated was on the lower side. The initial flow volume was 3,710,000 m^3. The flow volume seems to be gradually decreasing as shown in *Figure 24*. The simulated result is also projected to the google earth (*Figure 26*). 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.

As the model finally validates the susceptibility of the area and henceforth the above methodology is used to extract the result for the other study area i.e., study area-II (Amadablam area) as well which happens to fall in the Hindu Kush Himalayan region.

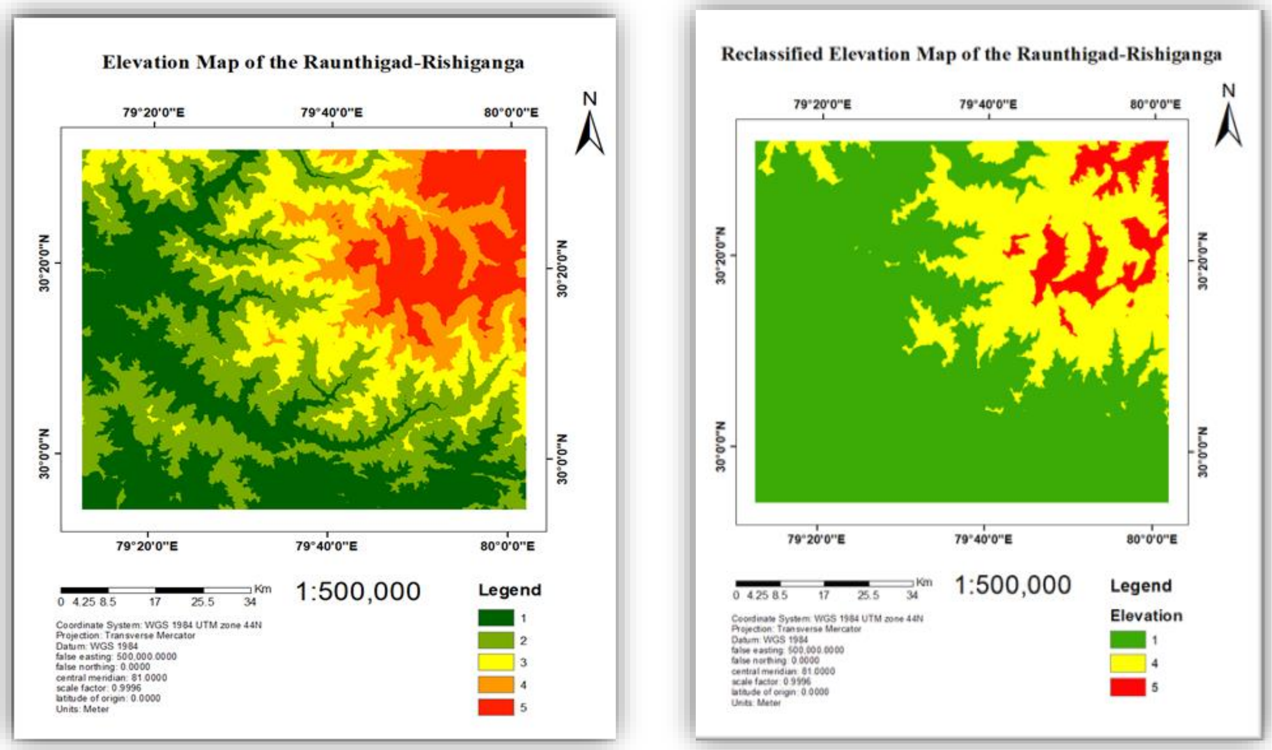
Similarly, the methodology is repeated again for the Amadablam area and the following outputs are generated which is described as below: *Figure 27* depicts the elevation and reclassified elevation of the study area- II. The elevation is reclassified into 3 categories and the highest rating of 5 is allotted to the elevation for more than 5000 m to which the avalanche is more prone to occur. Similarly, *Figure 28* depicts the slope and reclassified slope for which the rating of 5 is allotted to the slope of $30^o – 55^o$. The same procedure is adopted for aspect and curvature where rating 5 is allotted for north and north east orientation and for convex curvature as shown in (*Figure 29)* and (*Figure 30)* respectively. 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 as shown in *(Figure 31).* The precipitation and temperature data over the period of 20 years were also analyzed and plotted (*Figure 32*) and (*Figure 33)* respectively .The average temperature during the month of July seems to be among the higher side than any other month (*Figure 34)*. When the variation in the temperature over the past 20 years was plotted, the average temperature seems to have more or less the constant trend while annual maximum temperature seems to have increasing trend and minimum annual temperature showed the decreasing trend (*Figure 36*, *Figure 37*, *Figure 38*). The precipitation is sparse in that region however, its effect has been taken into consideration. *Figure 39* shows the increasing trend in the precipitation over the last 20 years.

The pair wise 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 as shown in (*Table 1).* The weights so obtained from AHP will be used in generation of avalanche susceptibility map. Thus, weighted overlay analysis was performed in the GIS incorporating the weightages obtained from (*Table 1)*. Hence, Avalanche susceptibility map is thus prepared.

Here, in the obtained avalanche hazard susceptibility map (*Figure 40*) of the study site i.e., Amadablam area, the chunk of hanging glacier happen to fall in the highly 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 shown in the map (*Figure 40*). It is noteworthy that around 75% of the overall area was covered by the moderate, high, and very high classifications (*Table 4)*. The area covered by the low and very low risk categories adds up to approximately 25%, while the high-risk category covers about 54% of the area and the very high-risk category covers 14%. The map encompasses 5,27,433 m^2 in total. The ice avalanche block has been digitally scanned in order to simulate flow following possible avalanche mapping.

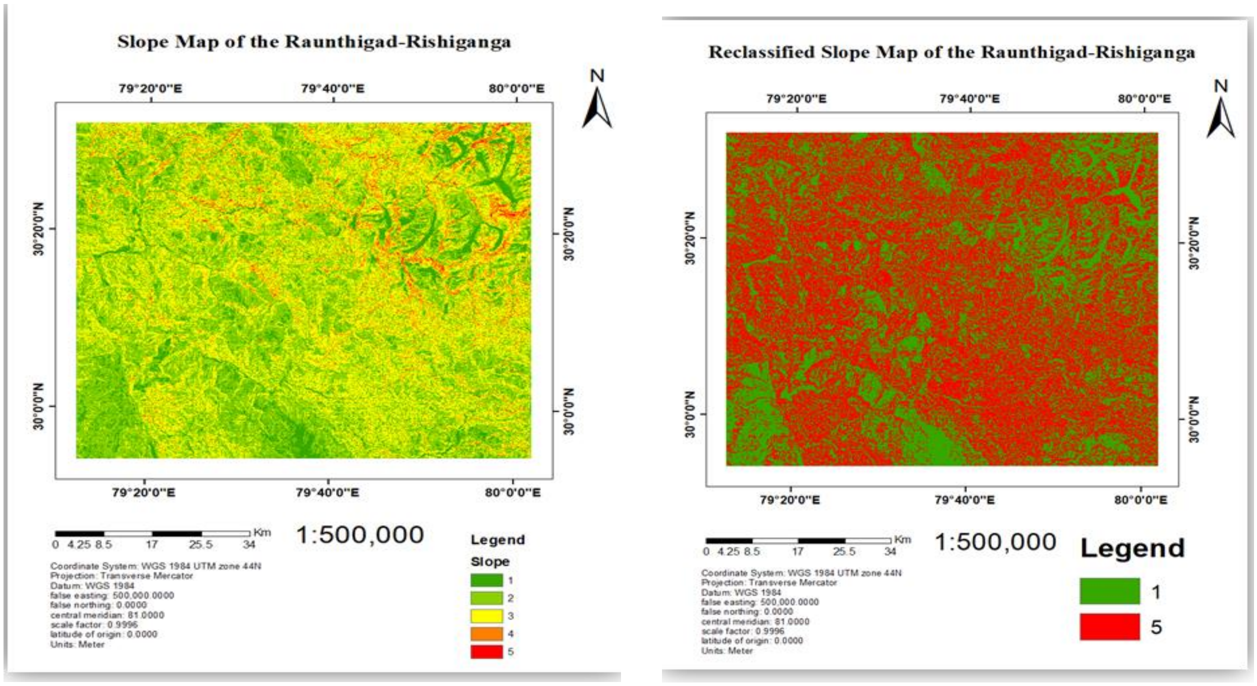
With the second study area, the two lobes of glacier are found as the most probable avalanching glacier lobes around the Amadablam area while performing simulations in RAMMS software since the average slope of the chunk of the release areas are found to be in range of 35- 55 degrees. According to RAMMS simulation modelling, Avalanche release area are normally between 30 and 55 degree and beyond these ranges of slope, it does not really move. So, the simulation shows the two chunks of hanging glaciers undergoing flow as shown in *Figure 48*. The simulation result is thus analyzed. The avalanche flow is branched till it reached base and has a runout length of (1st) 2.6 Km (2nd) 1.8 Km. *Figure 41* shows the height of the glacier fall of study area II (1st and 2nd) respectively. The maximum height observed is 11.60 m and 6.77 m for 1st and 2nd glacier respectively of the study area II. In both the cases the maximum height of fall is in the lower side. Maximum velocity observed is 37.51 m/s and 35.38 m/s for 1st and 2nd glacier respectively of the study area II. The velocity seems to be in higher side for most of the time for both the glaciers of study area II as shown in *Figure 42*. The maximum pressure exerted is 422.06 kPa and 375.55 kPa for 1st and 2nd glacier respectively as shown in *Figure 43*. The stress generated by the flow seems to be in the lower side for most of the time for both the glacier flow. The maximum shear stress generated is 12.74 kPa and 3.91 kPa for 1st and 2nd glacier respectively. The stress generated by the 2nd glacier is quite low than the 1st glacier as shown in *Figure 44.* Similarly, momentum of study area II is shown in *Figure 45.* The maximum momentum was observed in 1st glacier i.e. 23.75 m^2/s. The initial flow volume for the 1st glacier was 210,512 m^3. The mass movement started to occur at around 25 sec and about 90% of the mass movement had occurred within 150 sec as shown in *Figure 46*. Similarly, for the 2nd glacier the mass movement started at around 15 sec and about 80% of the mass movement had occurred within 50 sec which shows that the movement is quite rapid in comparison to the 1st glacier. The initial flow volume for the 2nd glacier was 65,958 m^3 as shown in *Figure 47*.

A. Outputs of the Study Area I: located at Uttarakhand of India


Elevation Map of the Raunthigad-Rishiganga

Reclassified Elevation Map of the Raunthigad-Rishiganga

Figure 6: Elevation and Reclassified Elevation of the Study Area I


Slope Map of the Raunthigad-Rishiganga

Reclassified Slope Map of the Raunthigad-Rishiganga

Figure 7: Slope and Reclassified Slope of the Study Area I

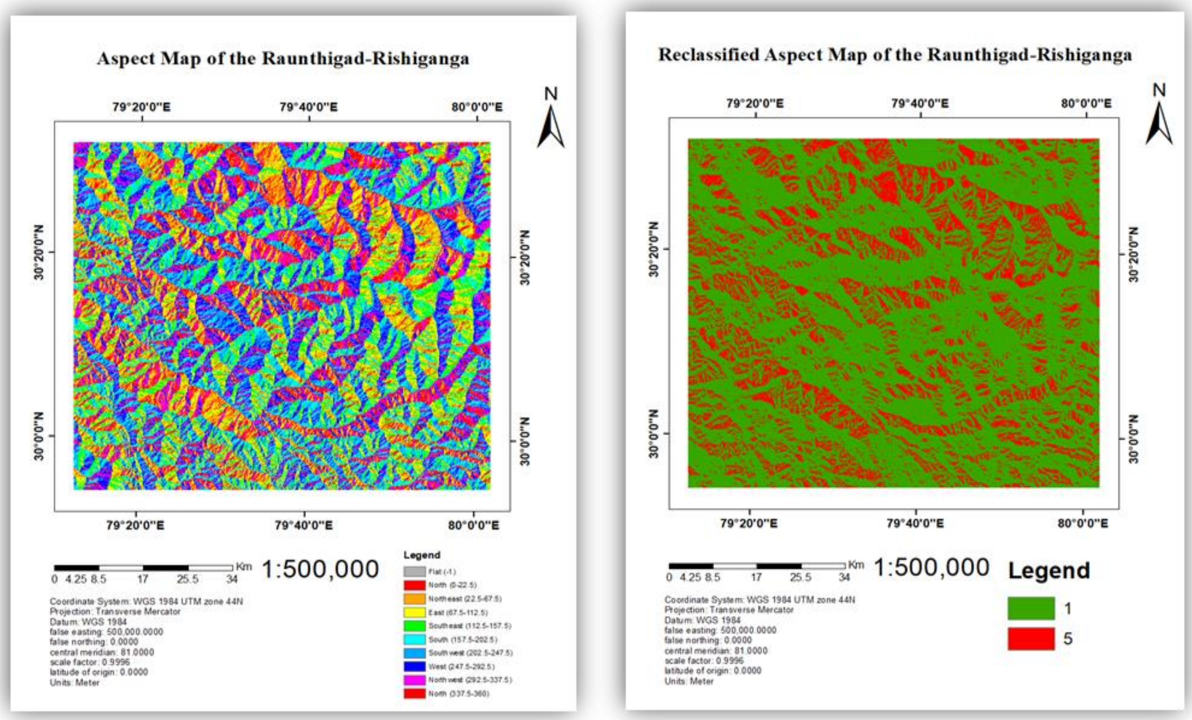


Figure 8: Aspect and Reclassified Aspect of Study Area I

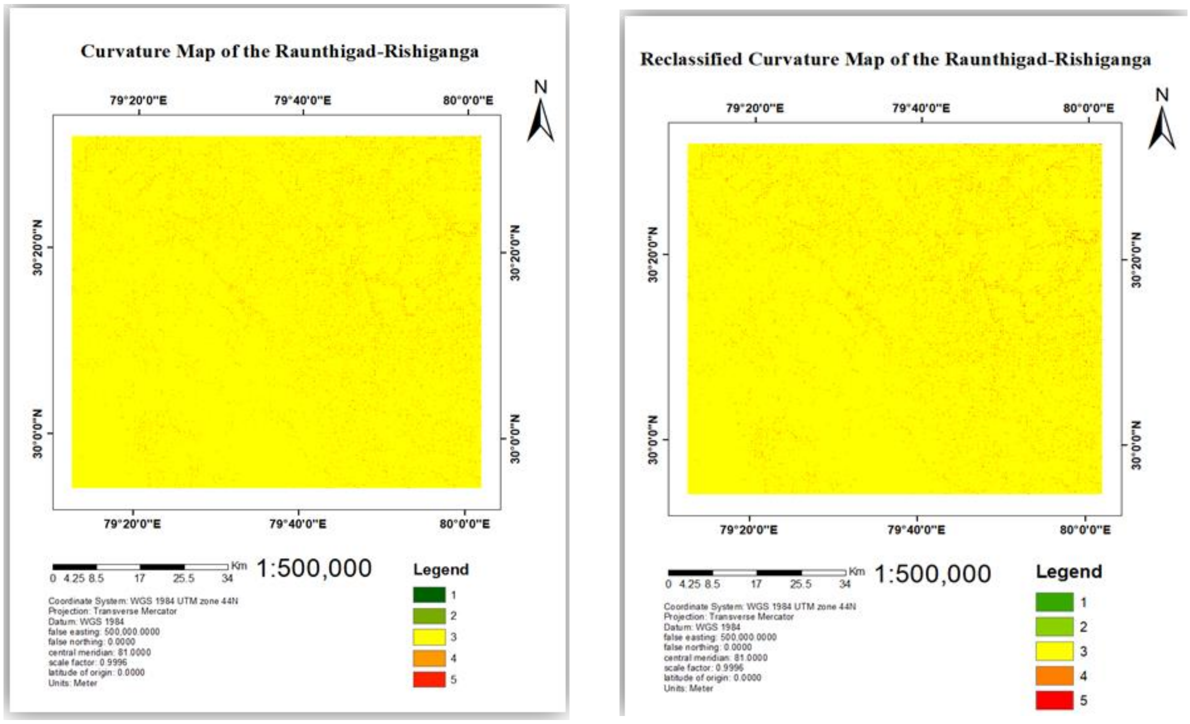
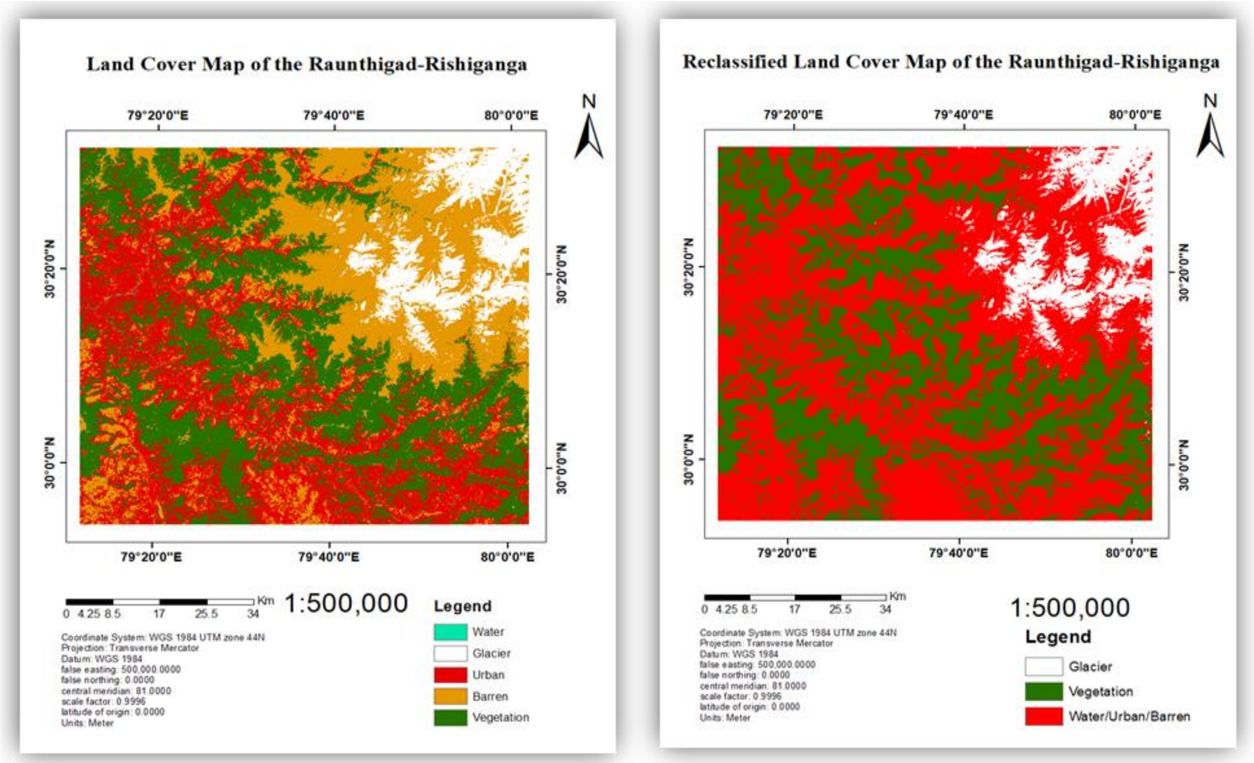
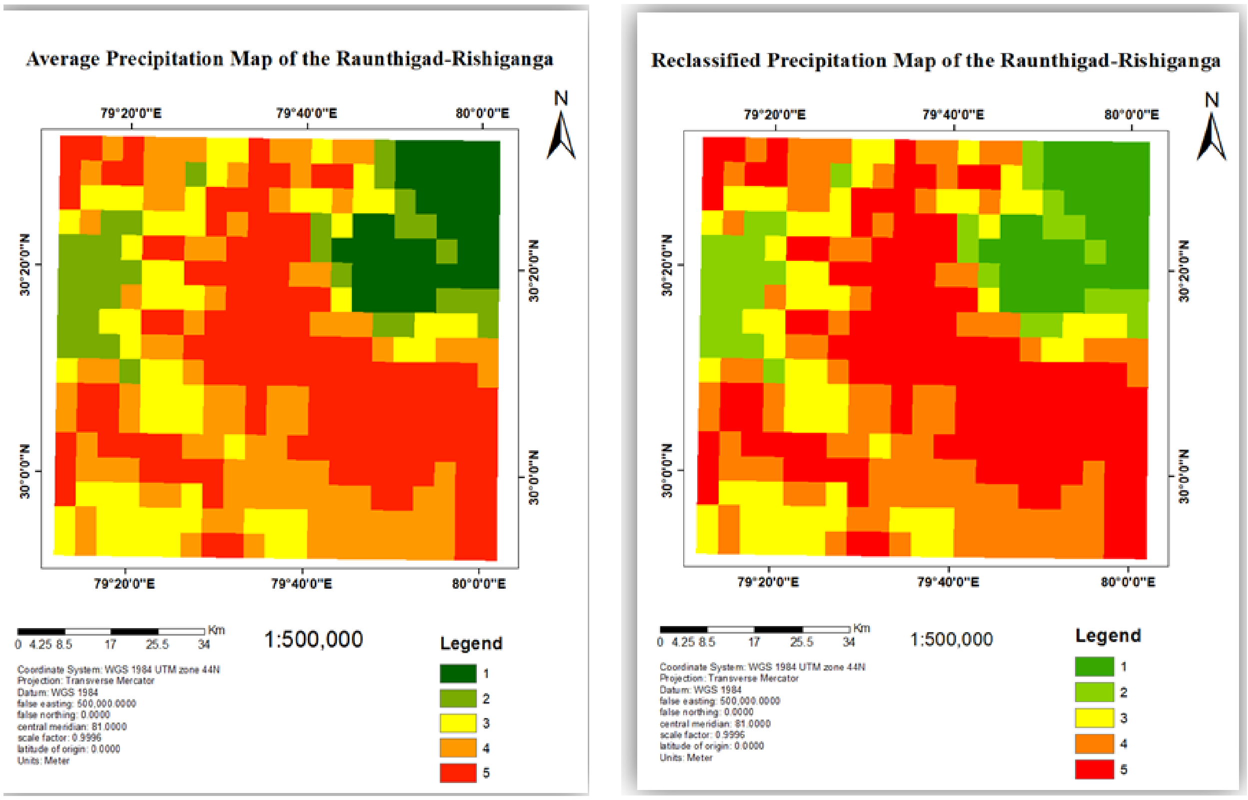


Figure 9: Curvature and Reclassified Curvature of the Study Area I


Land Cover Map of the Raunthigad-Rishiganga

Reclassified Land Cover Map of the Raunthigad-Rishiganga

Figure 10: Land Cover and Reclassified Land Cover of the Study Area I


Average Precipitation Map of the Raunthigad-Rishiganga

Reclassified Precipitation Map of the Raunthigad-Rishiganga

Figure 11: Average Precipitation and Reclassified Precipitation of the Study Area I

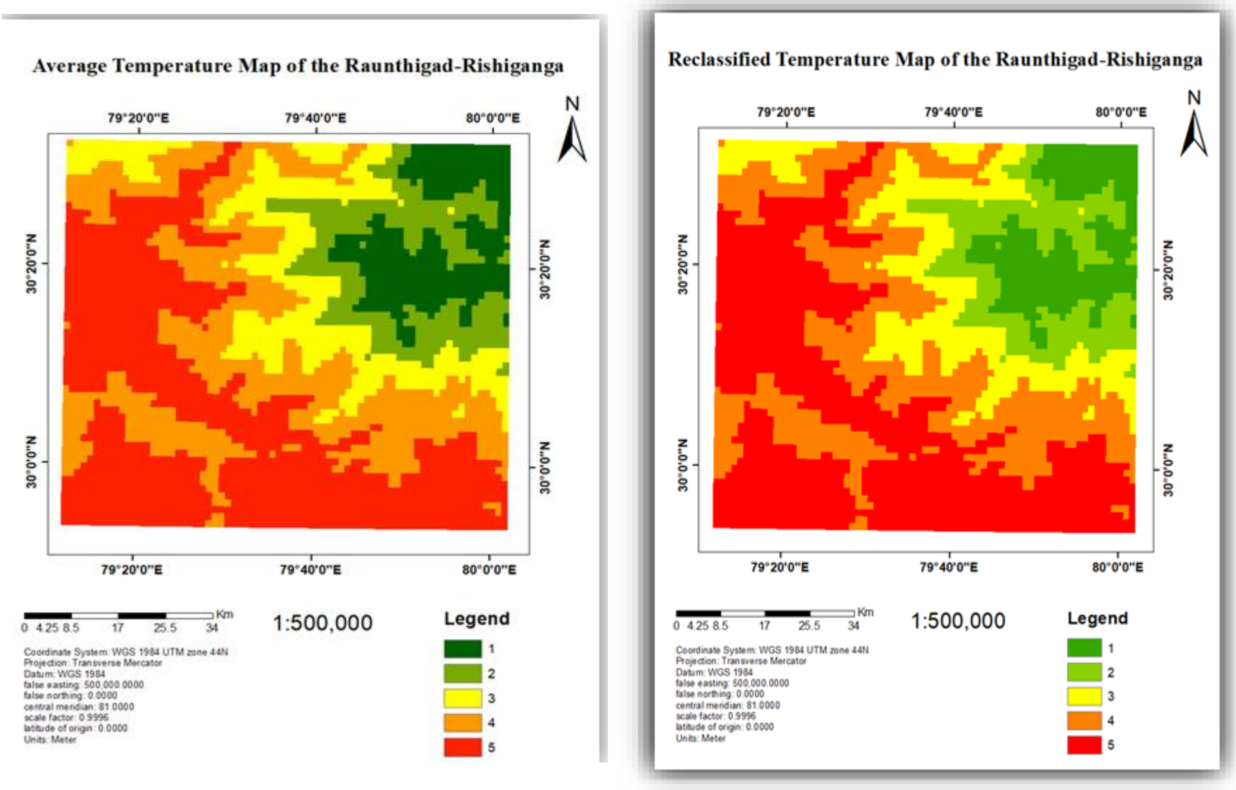


Figure 12: Average Temperature and Reclassified Temperature of the Study Area I

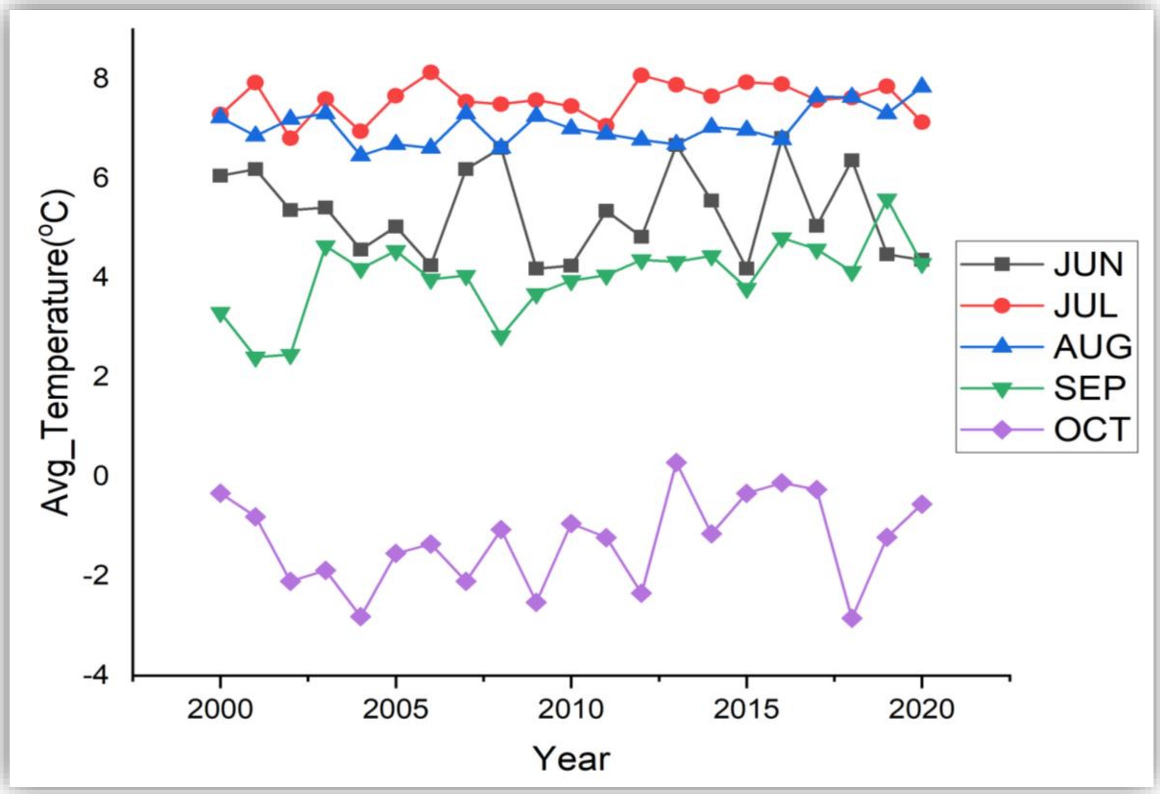


Figure 13:Average Temperature of different months of the Raunthigad-Rishiganga Area

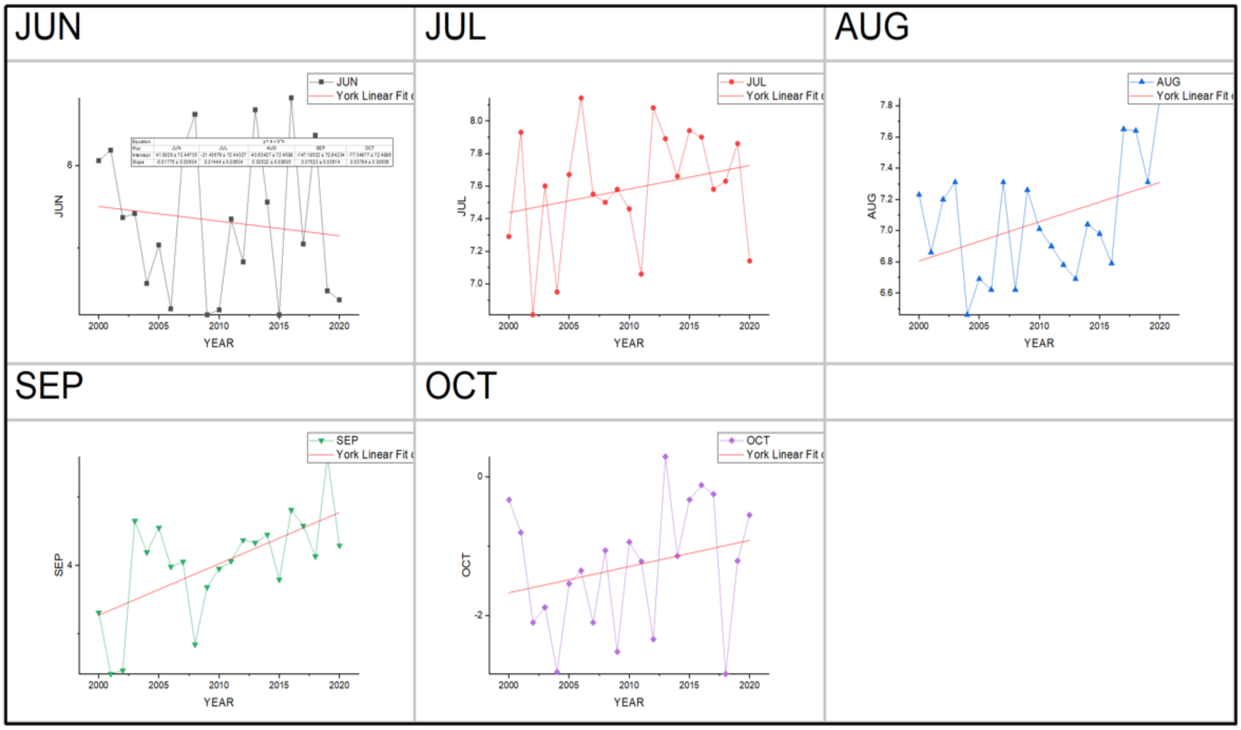


Figure 14: Trend of average temperature of different month of Raunthigad-Rishiganga Area

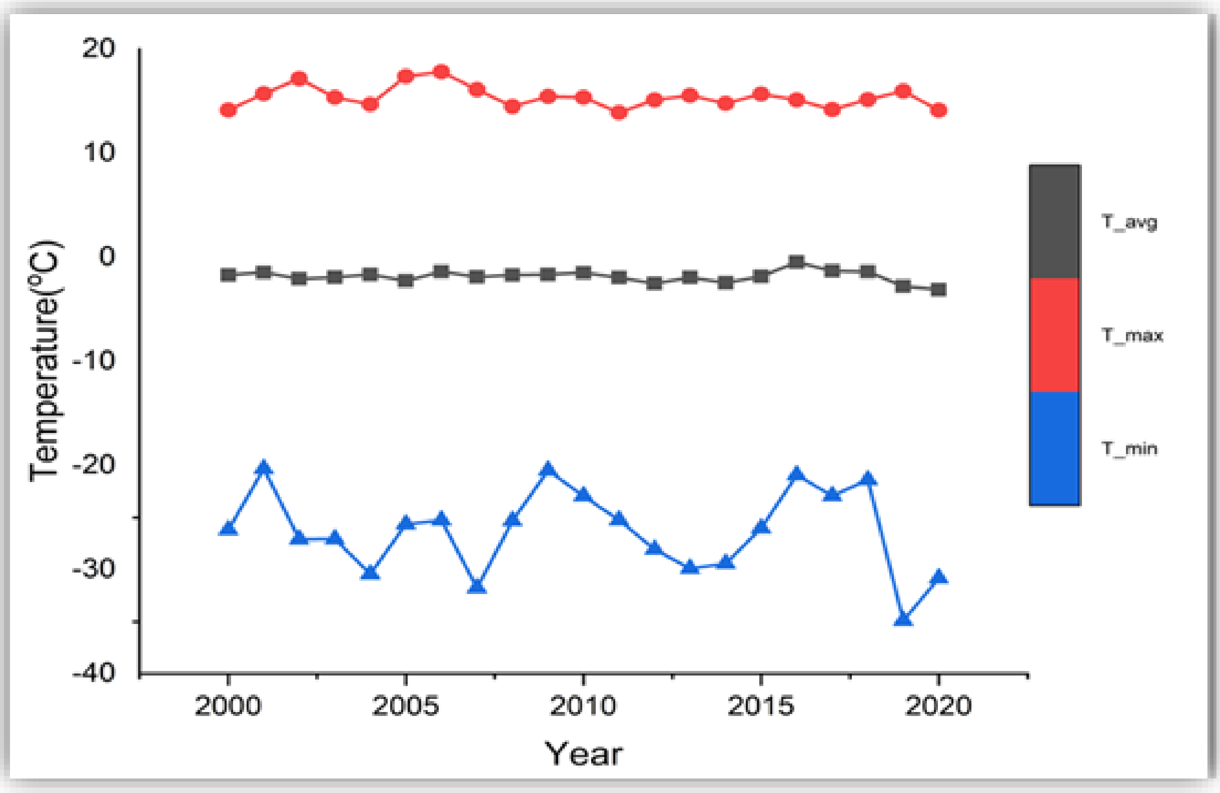


Figure 15: Variation of average temperature over the period of 20 years

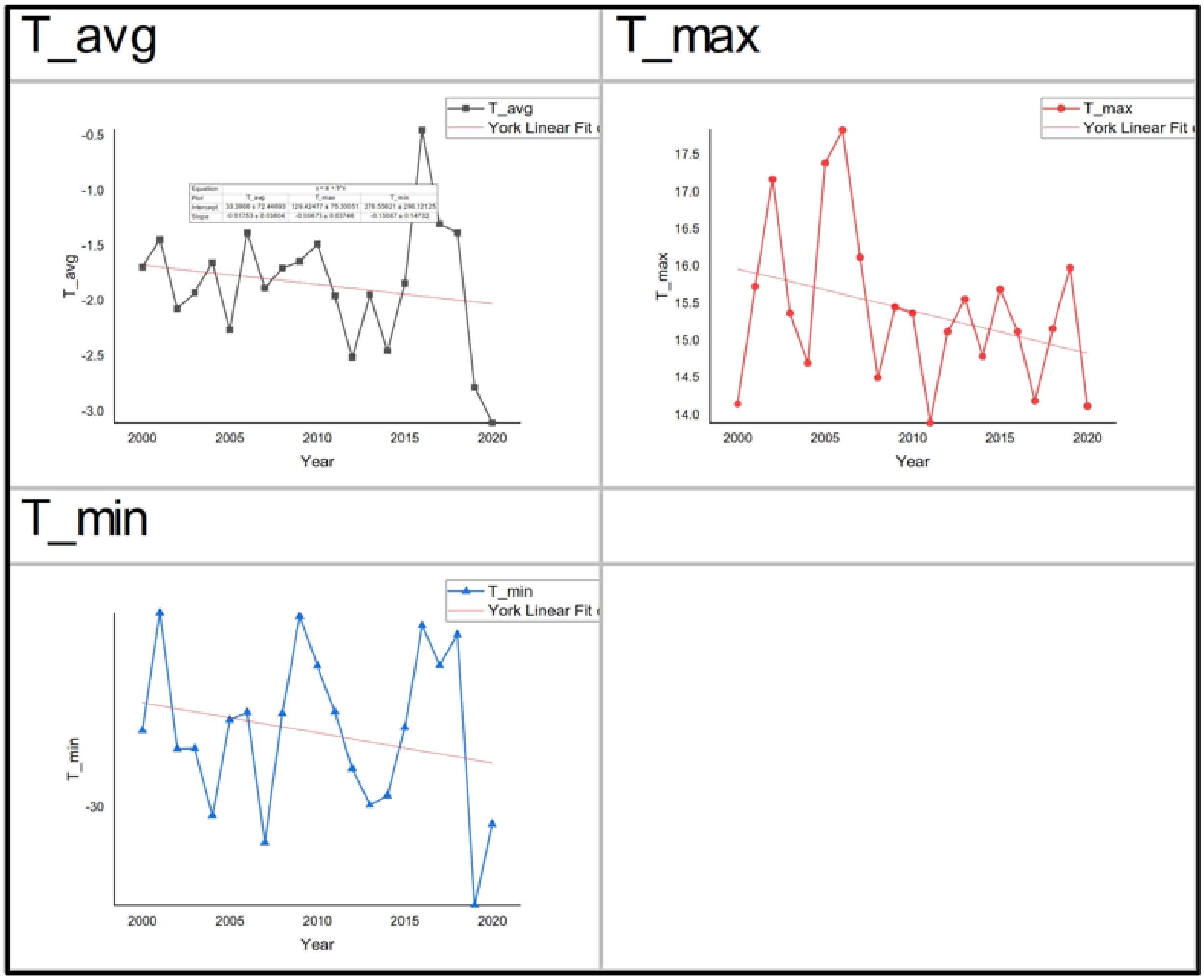


Figure 16: Trend of average temperature over the period of 20 years

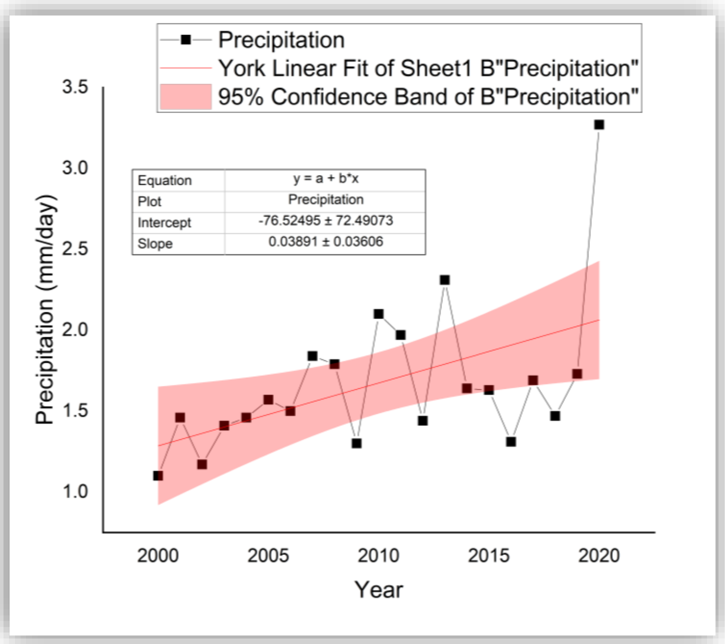


Figure 17:Trend of average precipitation over the period of 20 years

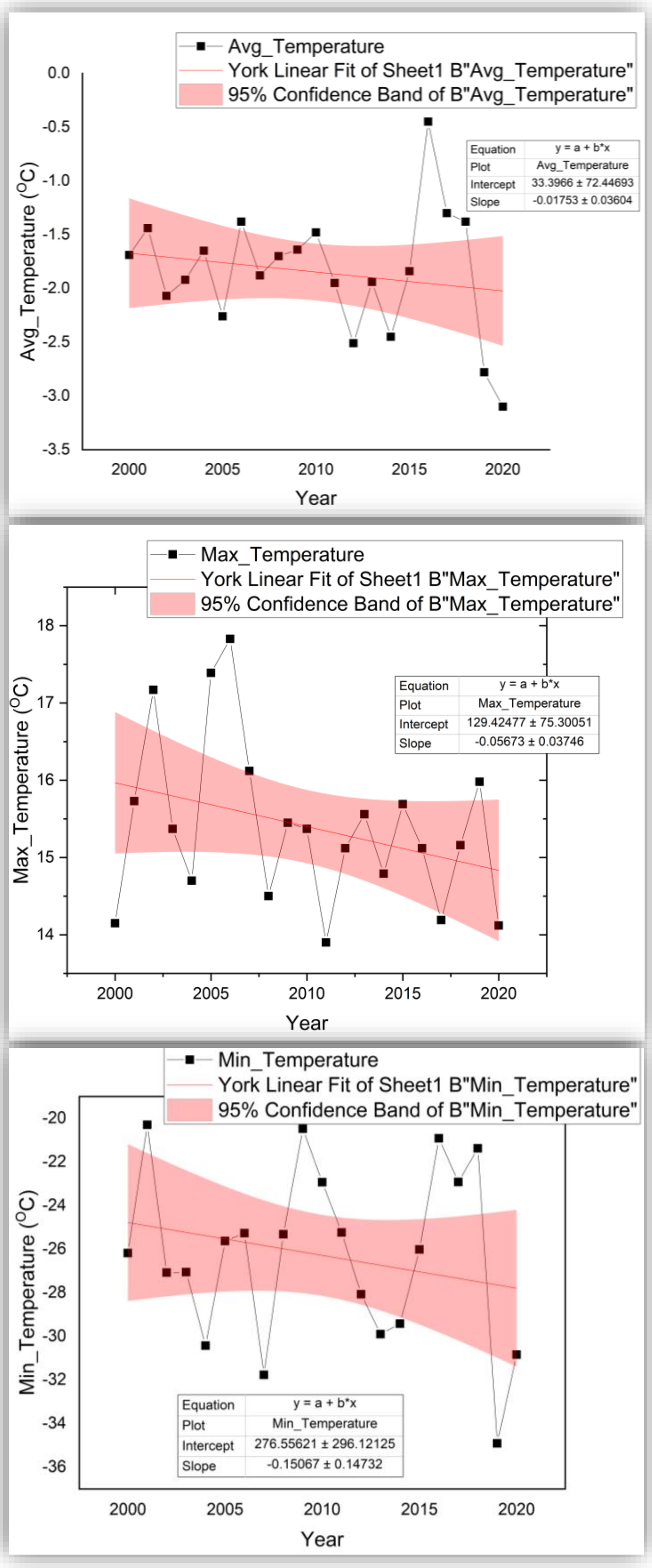
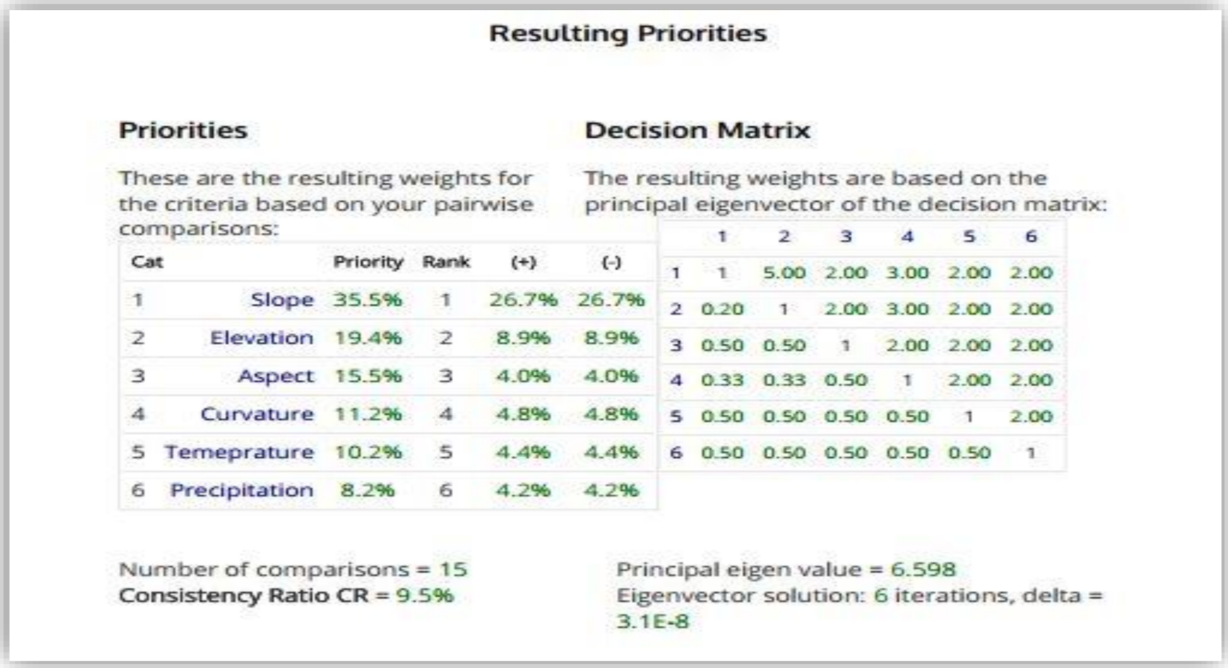


Figure 18: Average, average max, average min temperature over the period of 20 years

Table 1: AHP Weightage



Resulting Priorities

Priorities

These are the resulting weights for the criteria based on your pairwise comparisons:

Cat		Priority	Rank	(+)	(-)
1	Slope	35.5%	1	26.7%	26.7%
2	Elevation	19.4%	2	8.9%	8.9%
3	Aspect	15.5%	3	4.0%	4.0%
4	Curvature	11.2%	4	4.8%	4.8%
5	Temeprature	10.2%	5	4.4%	4.4%
6	Precipitation	8.2%	6	4.2%	4.2%

Decision Matrix

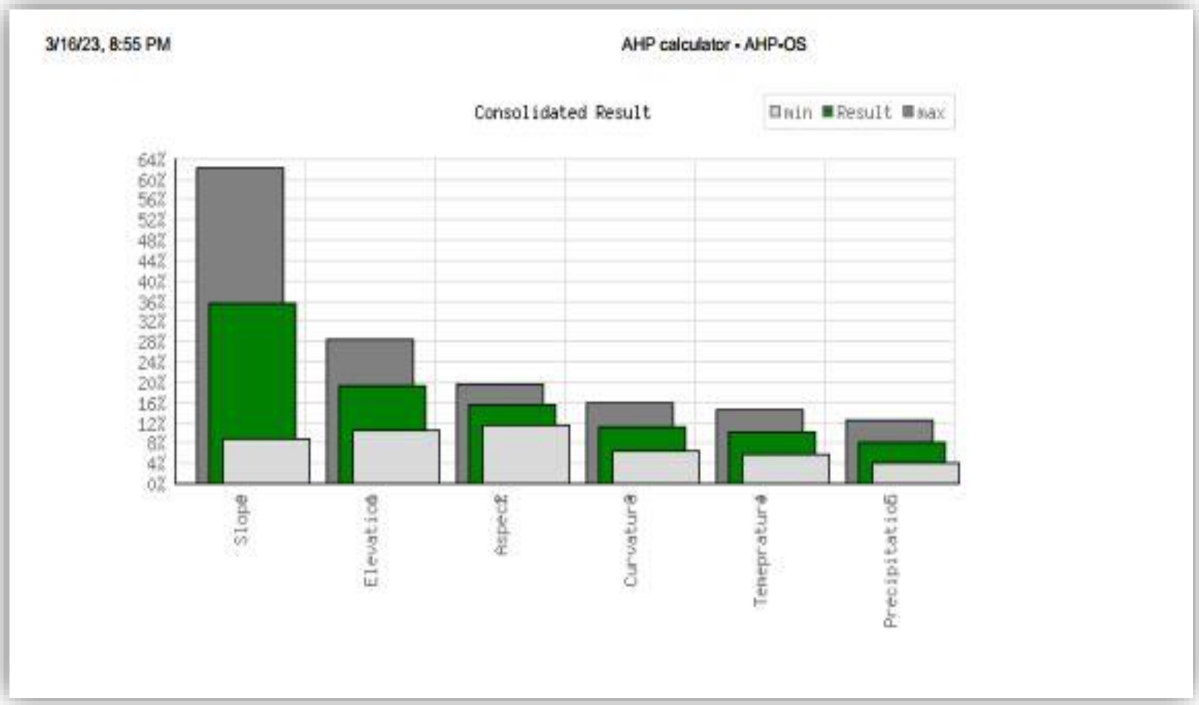
The resulting weights are based on the principal eigenvector of the decision matrix:

	1	2	3	4	5	6
1	1	5.00	2.00	3.00	2.00	2.00
2	0.20	1	2.00	3.00	2.00	2.00
3	0.50	0.50	1	2.00	2.00	2.00
4	0.33	0.33	0.50	1	2.00	2.00
5	0.50	0.50	0.50	0.50	1	2.00
6	0.50	0.50	0.50	0.50	0.50	1

Number of comparisons = 15
Consistency Ratio CR = 9.5%

Principal eigen value = 6.598
Eigenvector solution: 6 iterations, delta = 3.1E-8

Table 2: AHP Weightage Graph



3/16/23, 8:55 PM

AHP calculator - AHP-OS

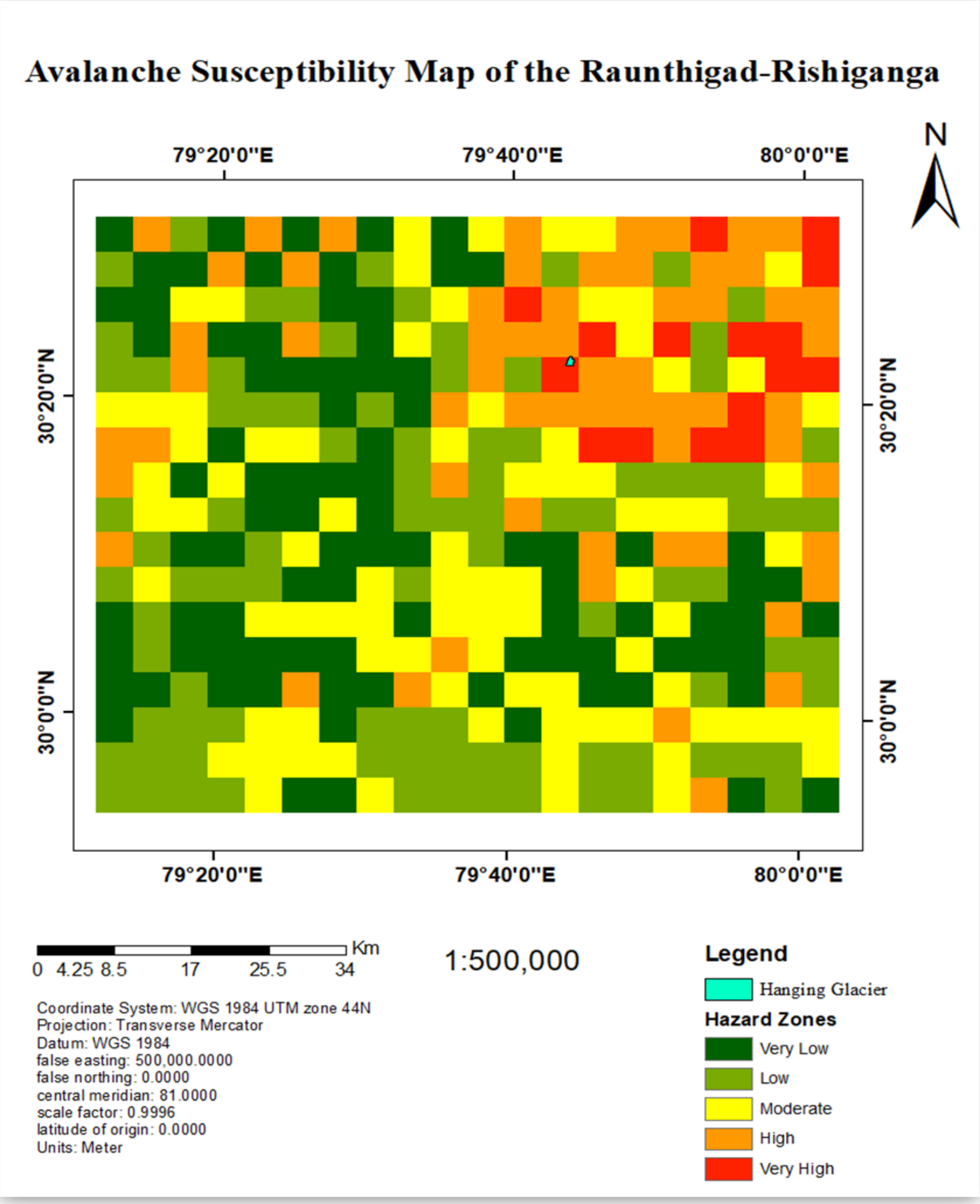


Figure 19: Avalanche Susceptibility Map of the Study Area I

Table 3: Avalanche Zone in various category of the Study Area I

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%

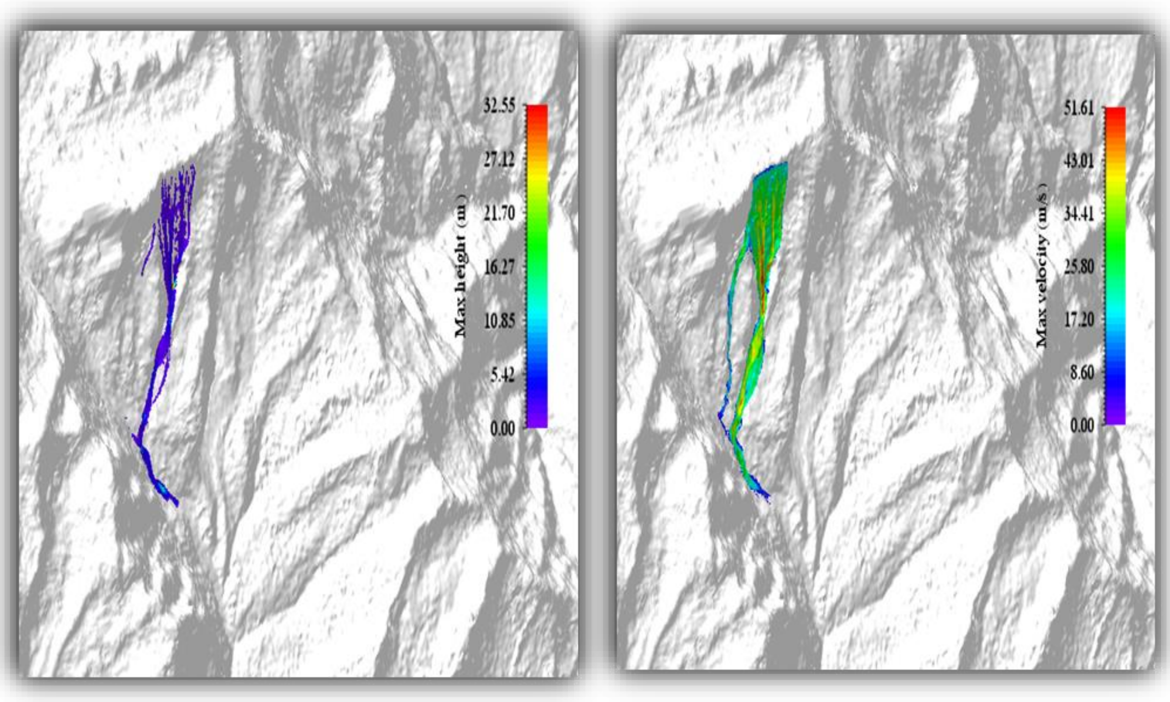


Figure 20: 3D view of simulated flow: Height and Velocity respectively of the Study Area I

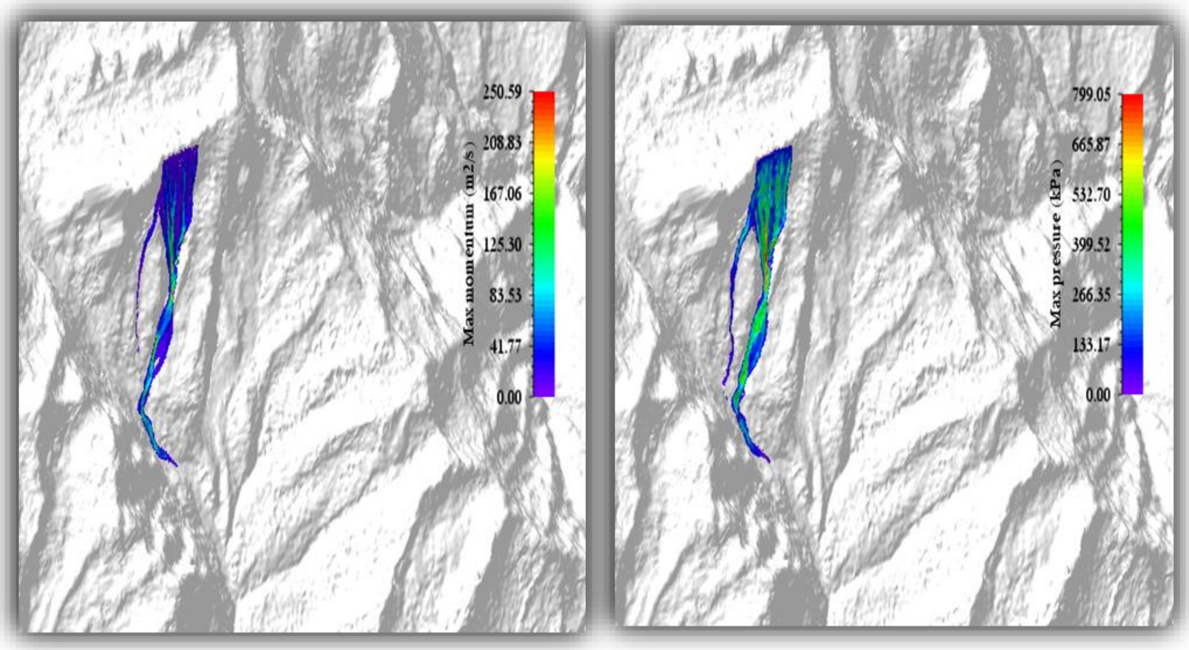


Figure 21: 3D view of simulated flow: Momentum and Pressure respectively of the Study Area I

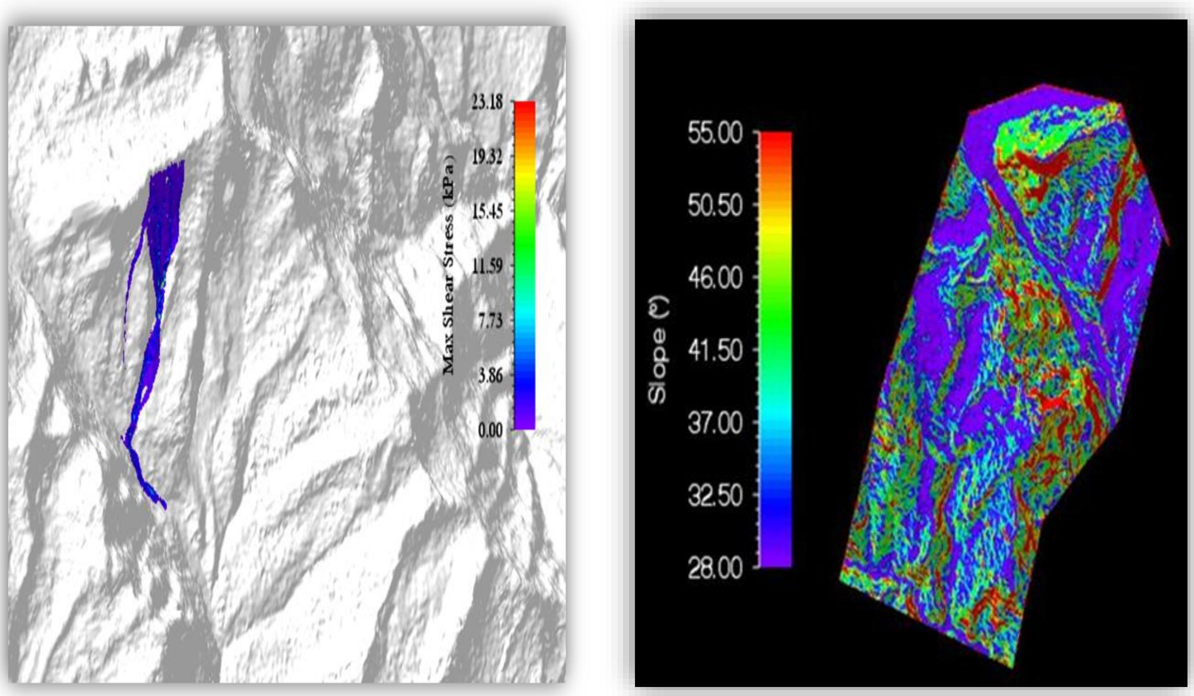


Figure 22: 3D view of simulated flow: Shear Stress And 3D view of Slope of the Study Area I

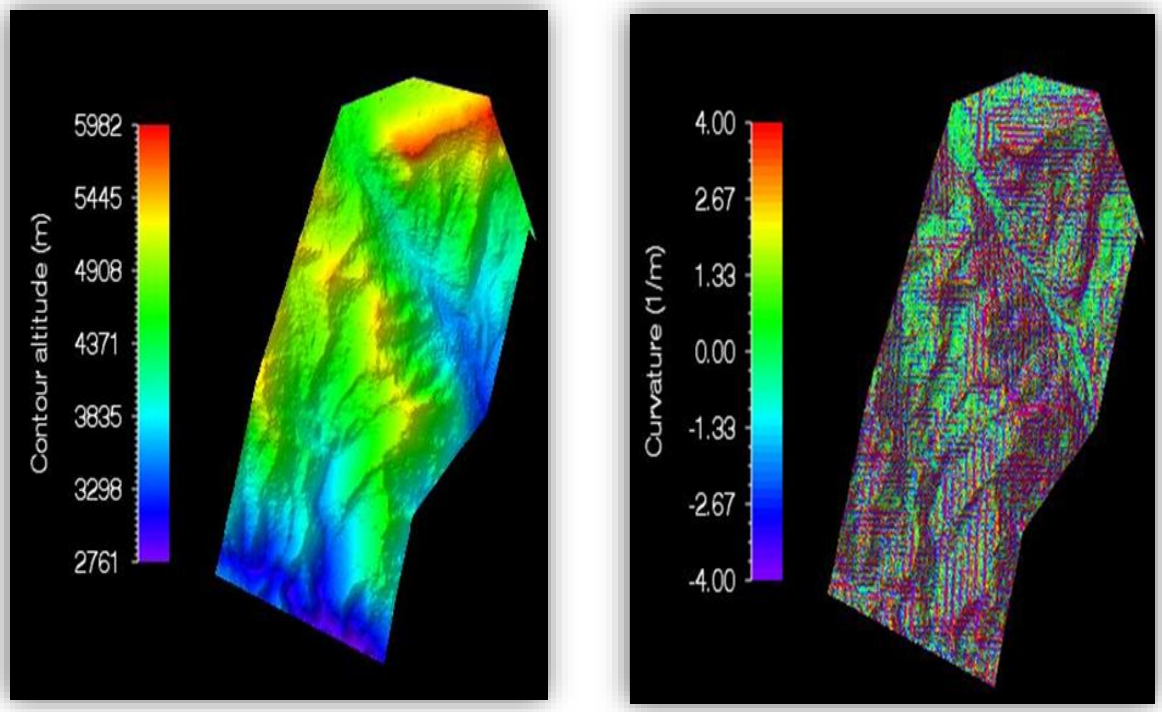


Figure 23: 3D view of Contour altitude and curvature of the Study Area I

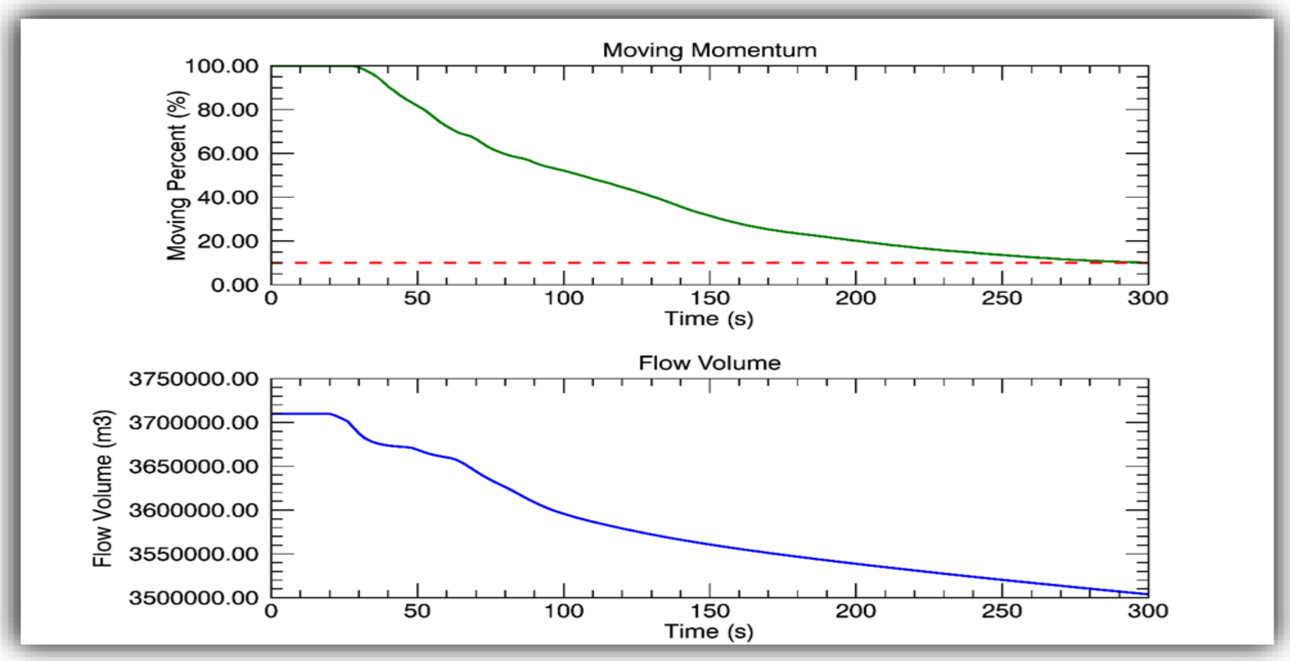


Figure 24: Moving Momentum and Flow Volume Profile of the Study Area I

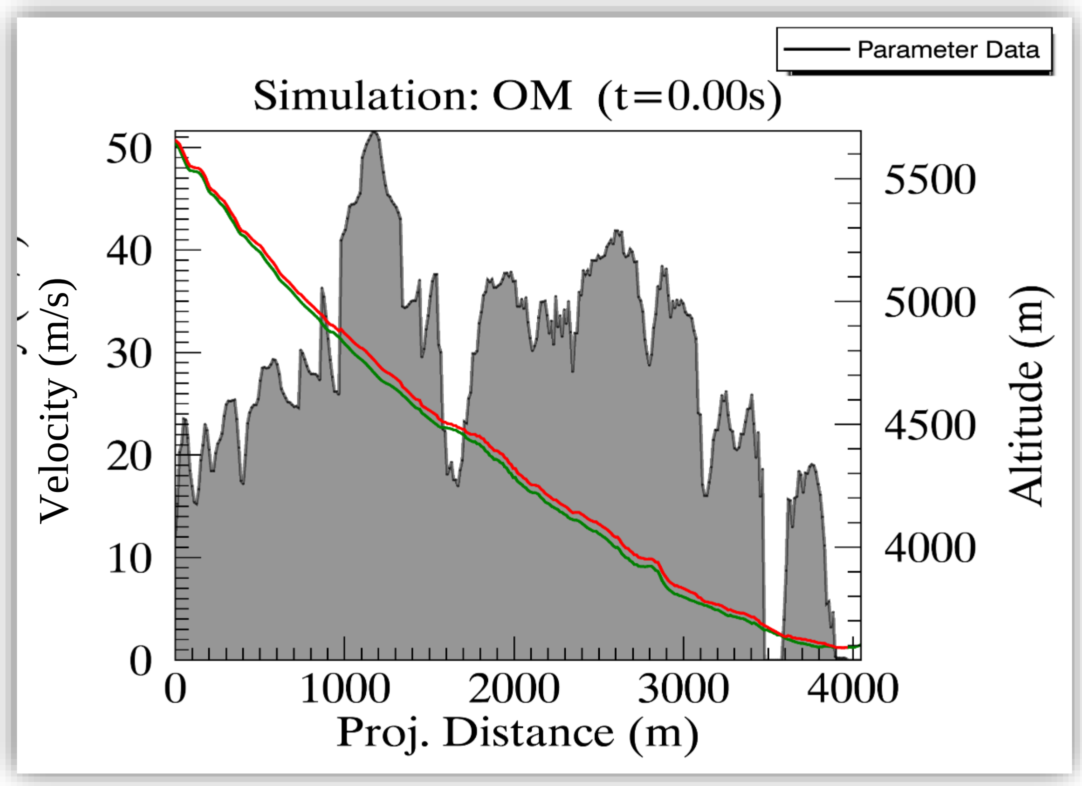


Figure 25: Plot of maximum velocity vs altitude vs run-out distance

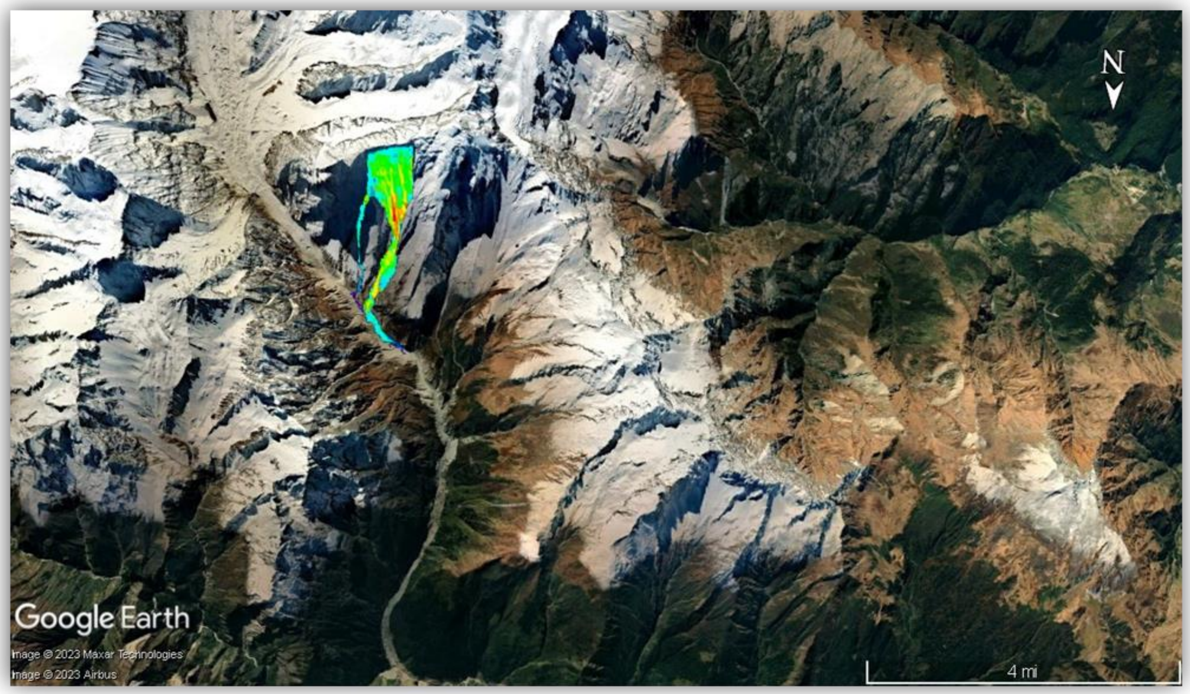


Figure 26: Simulated result of the Study Area I on Google Earth

Outputs of the Study Area II: located at Ama Dablam Area of Nepal

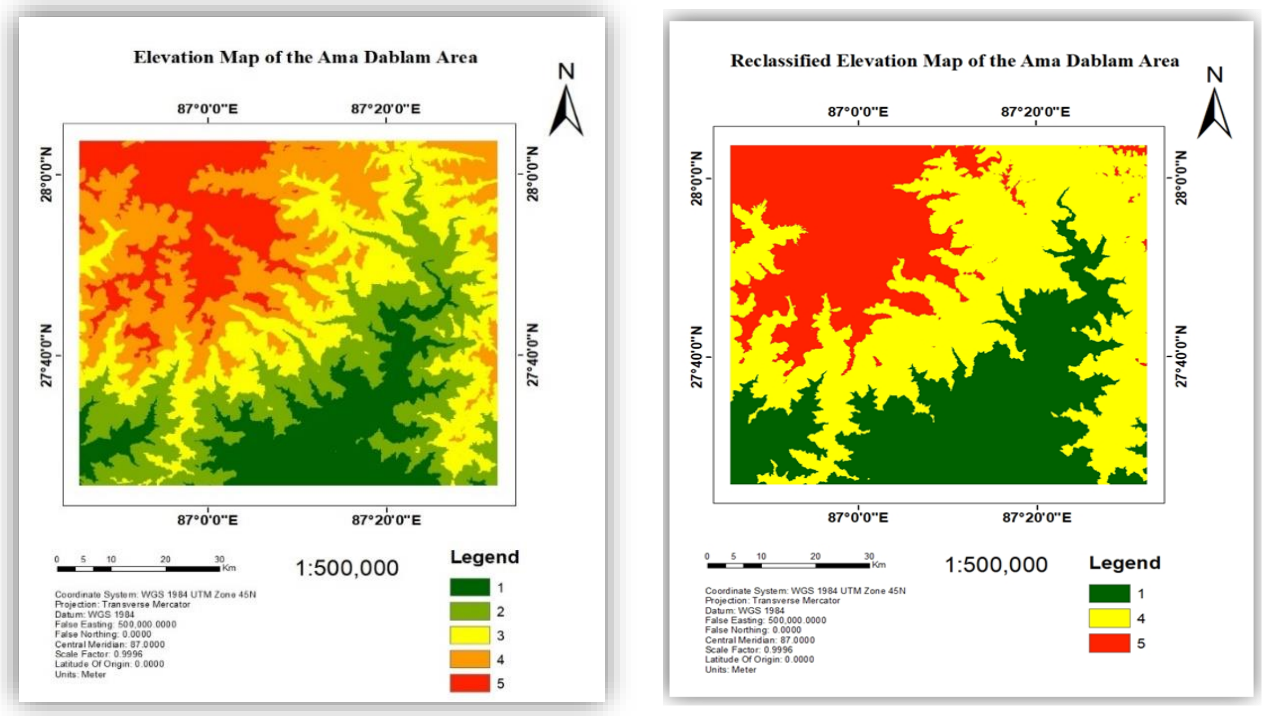


Figure 27: Elevation and Reclassified Elevation of the Study Area II

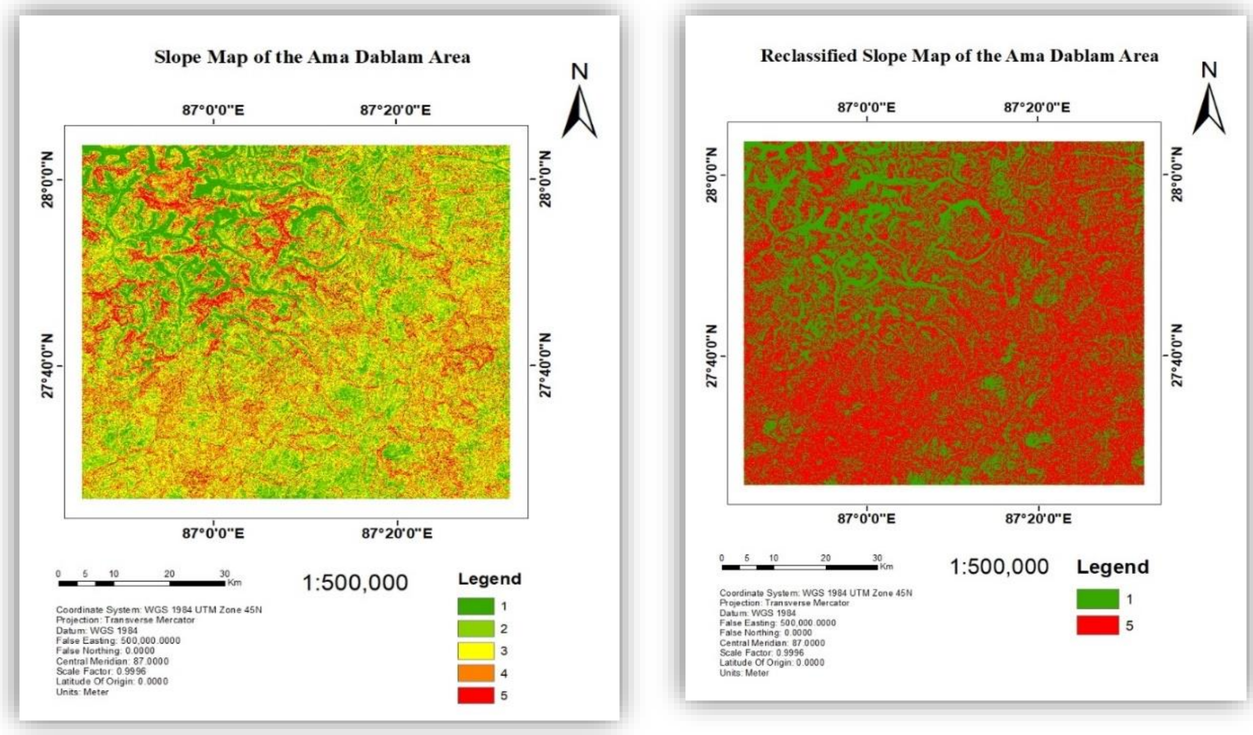


Figure 28: Slope and Reclassified Slope of the Study Area II

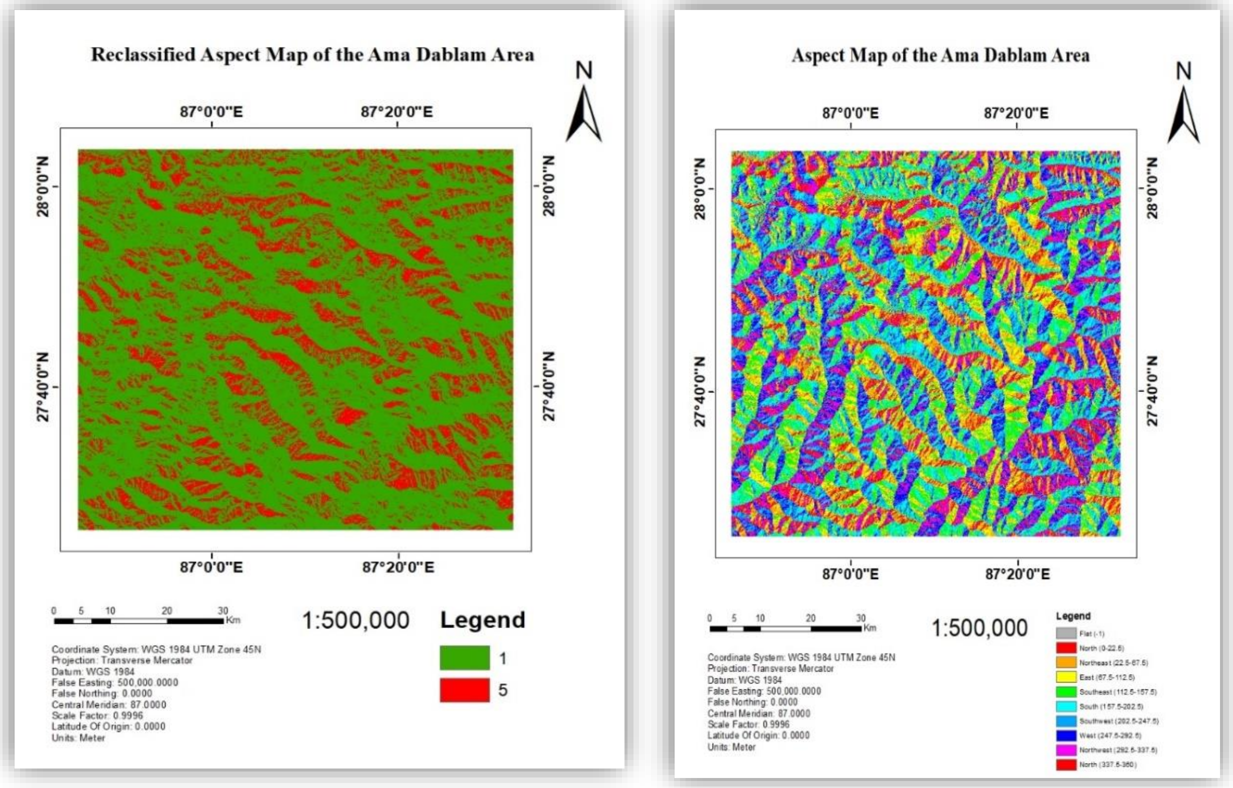


Figure 29: Aspect and Reclassified Aspect of the Study Area II

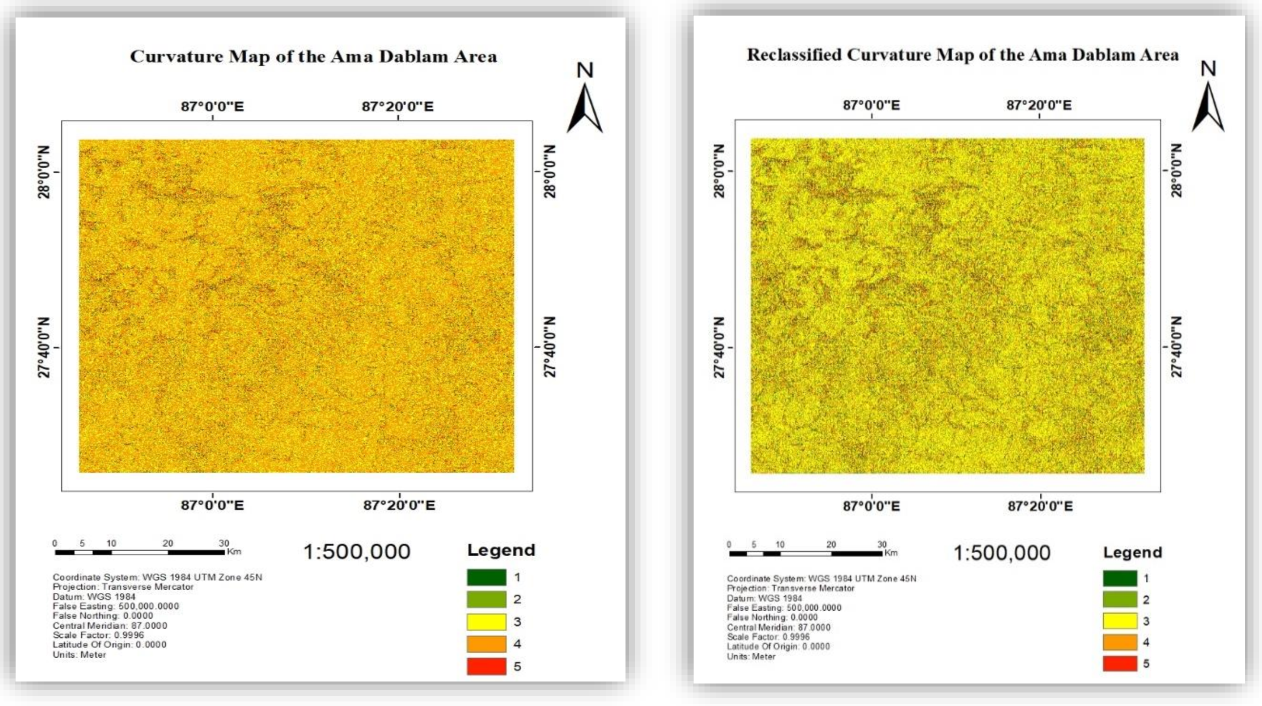
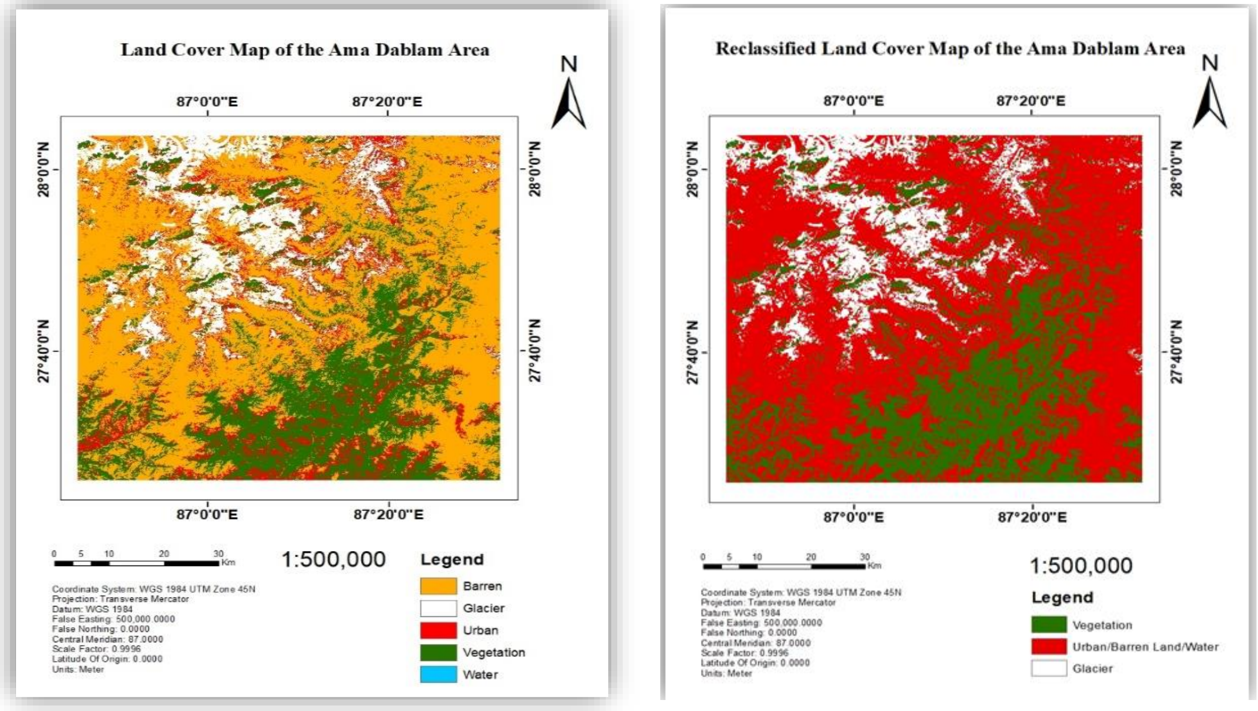
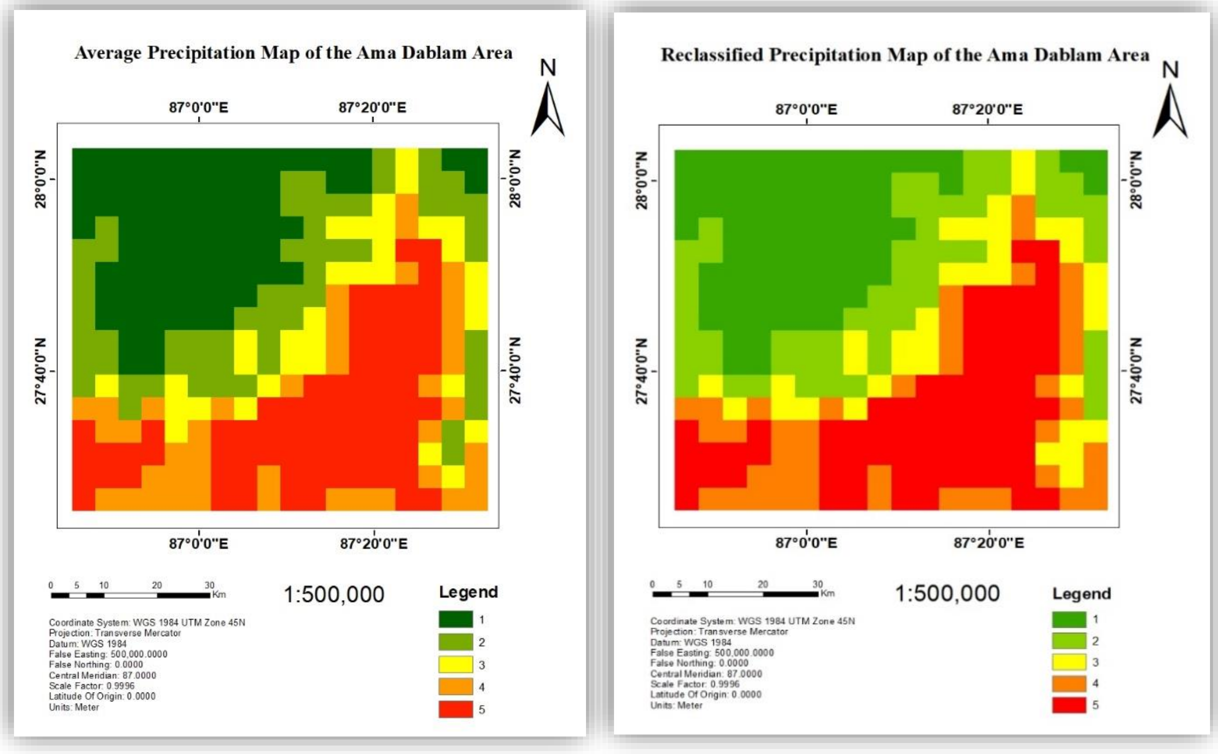


Figure 30: Curvature and Reclassified Curvature of the Study Area II


Land Cover Map of the Ama Dablam Area

Reclassified Land Cover Map of the Ama Dablam Area

Figure 31: Land Cover and Reclassified Land Cover of the Study Area II


Average Precipitation Map of the Ama Dablam Area

Reclassified Precipitation Map of the Ama Dablam Area

Figure 32: Average Precipitation and Reclassified Precipitation of the Study Area II

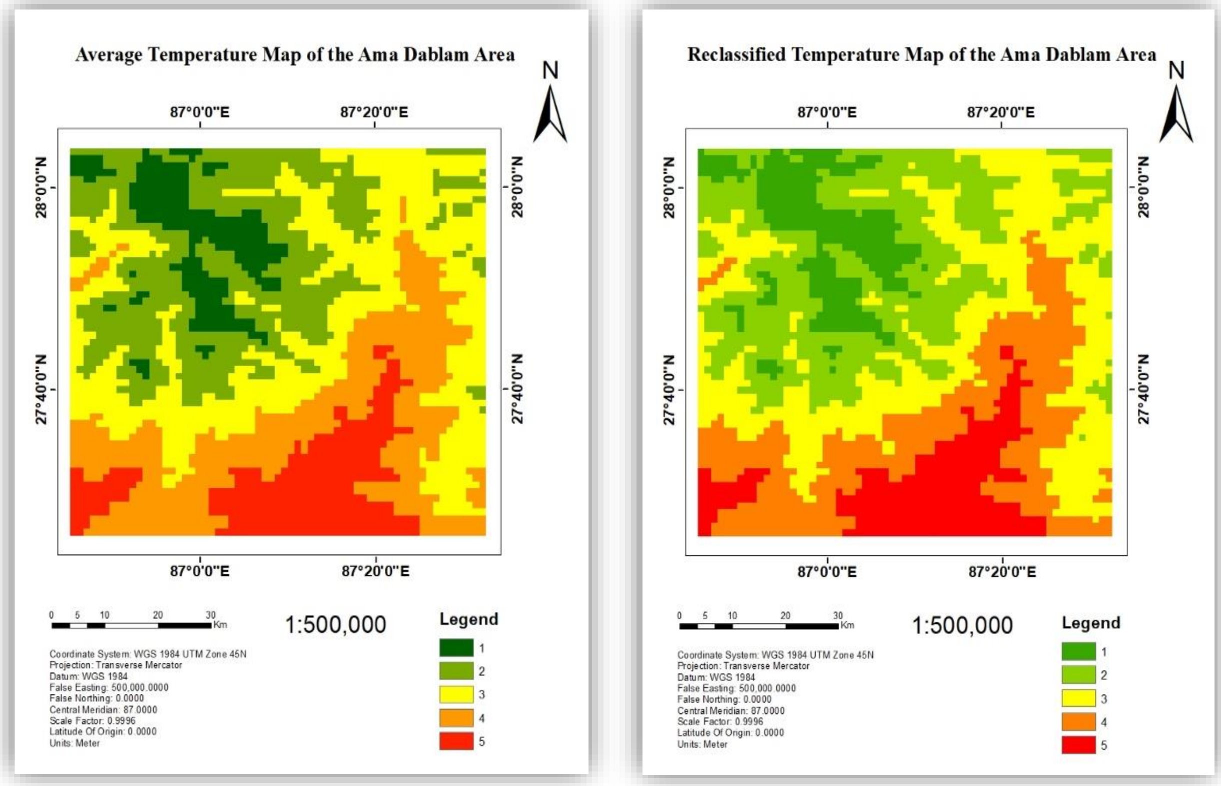


Figure 33: Average Temperature and Reclassified Temperature of the Study Area II

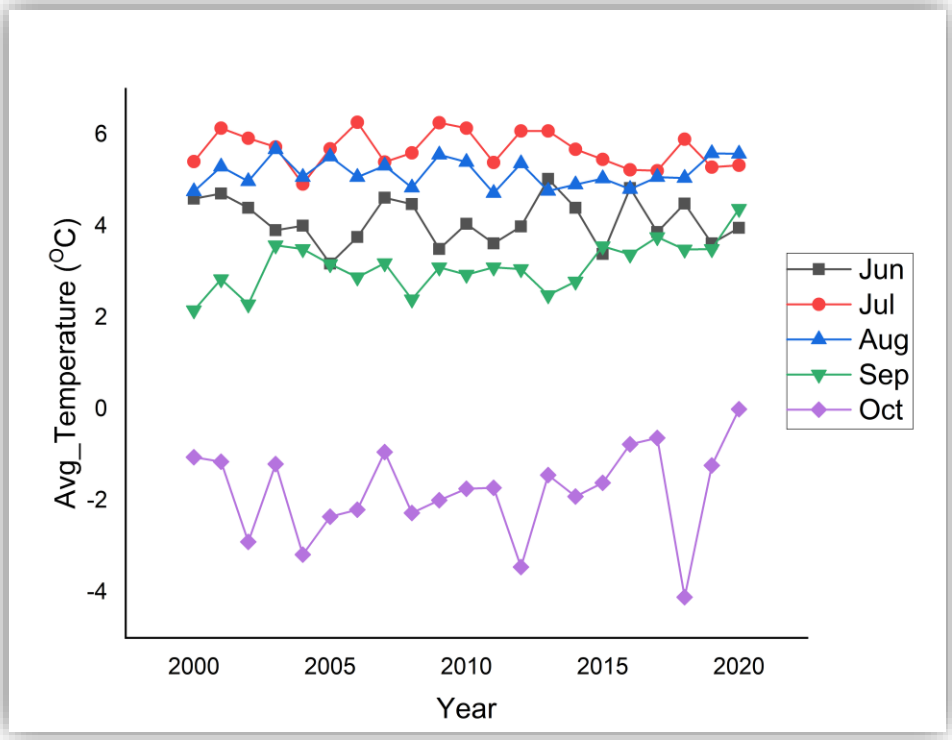


Figure 34: Average temperature of different months of the Study Area-II

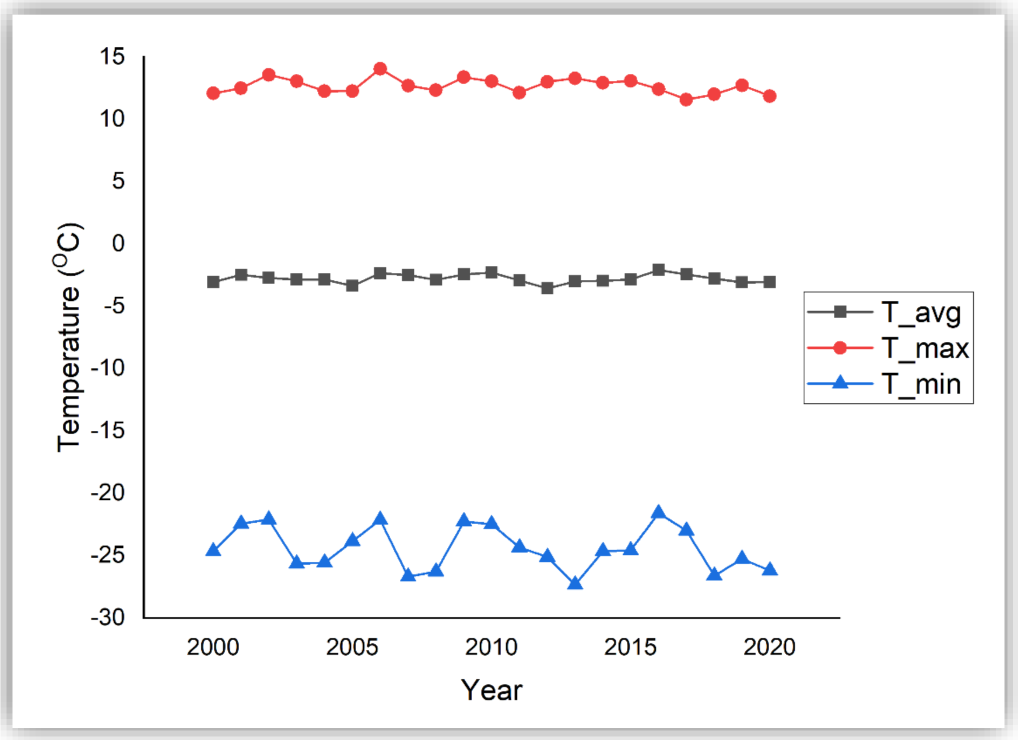


Figure 35: Variation of average temperature over the period of 20 years of Study Area- II

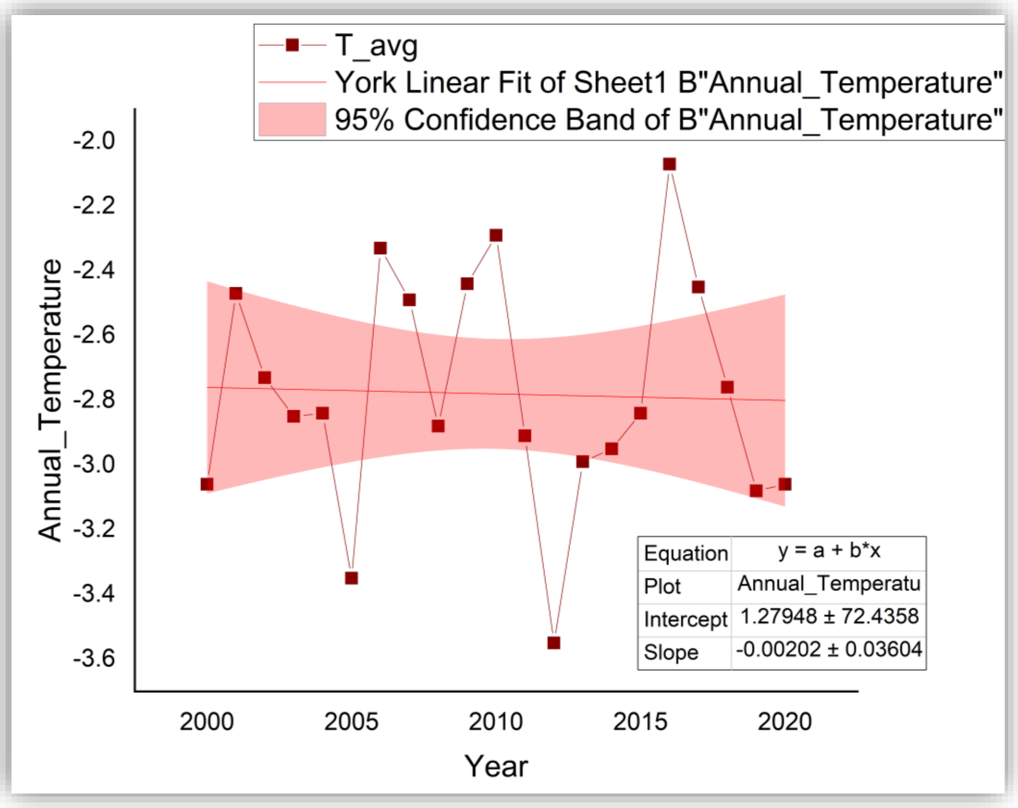


Figure 36: Variation of average temperature over the period of 20 years of Study Area-II

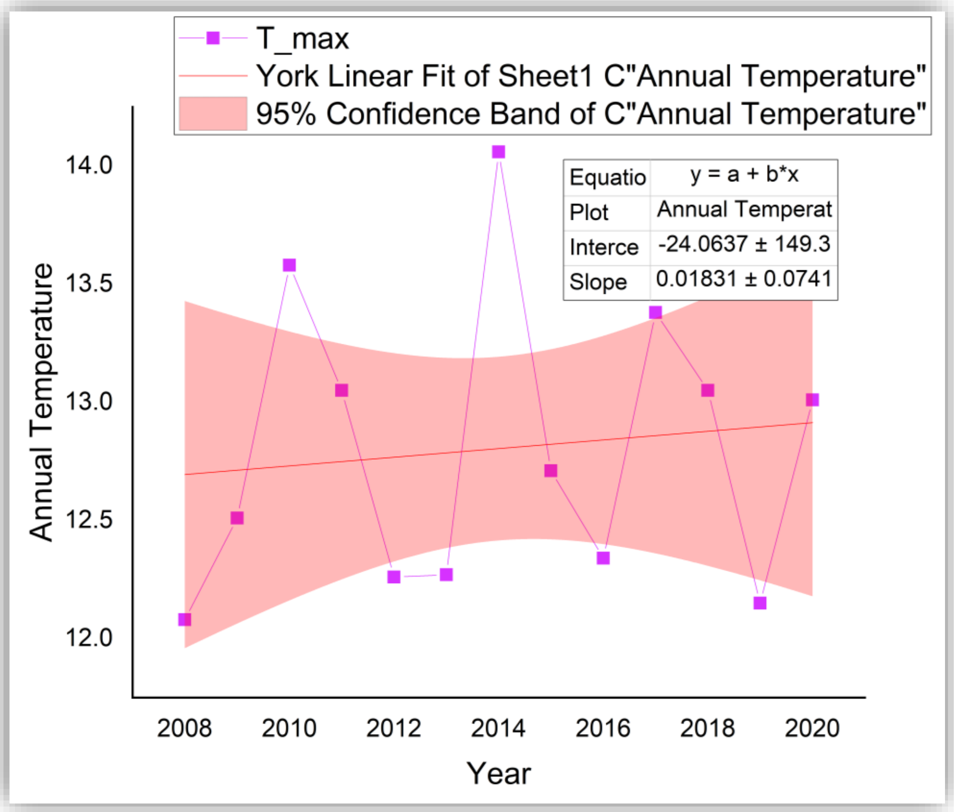


Figure 37: Variation of maximum temperature over the period of 20 years of Study Area-II

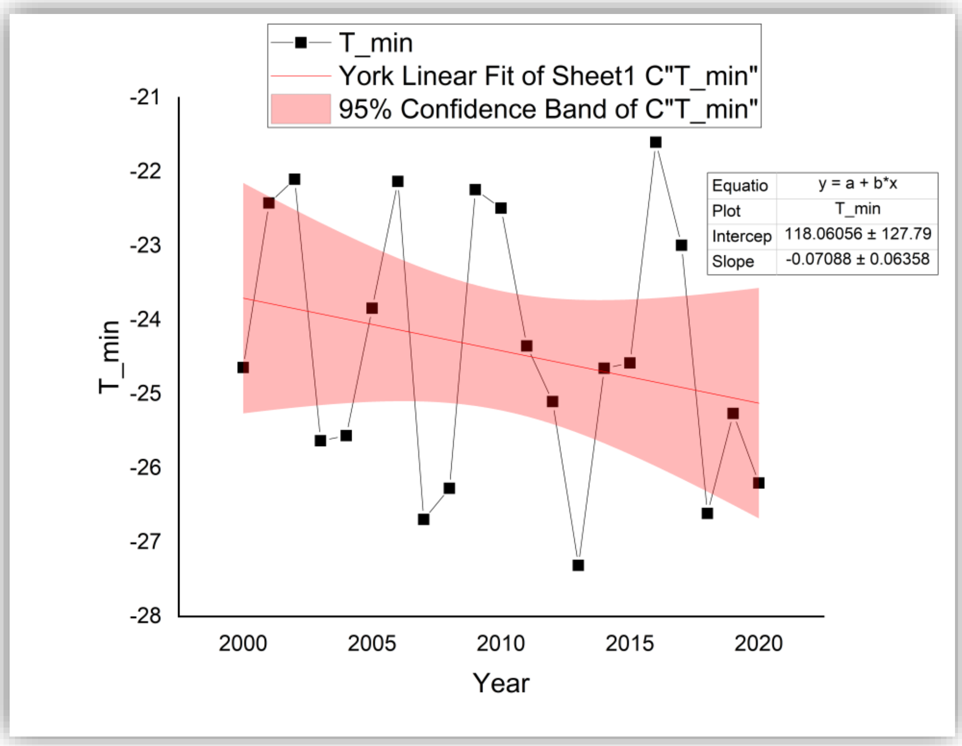


Figure 38: Variation of minimum temperature over the period of 20 years for Study Area-II

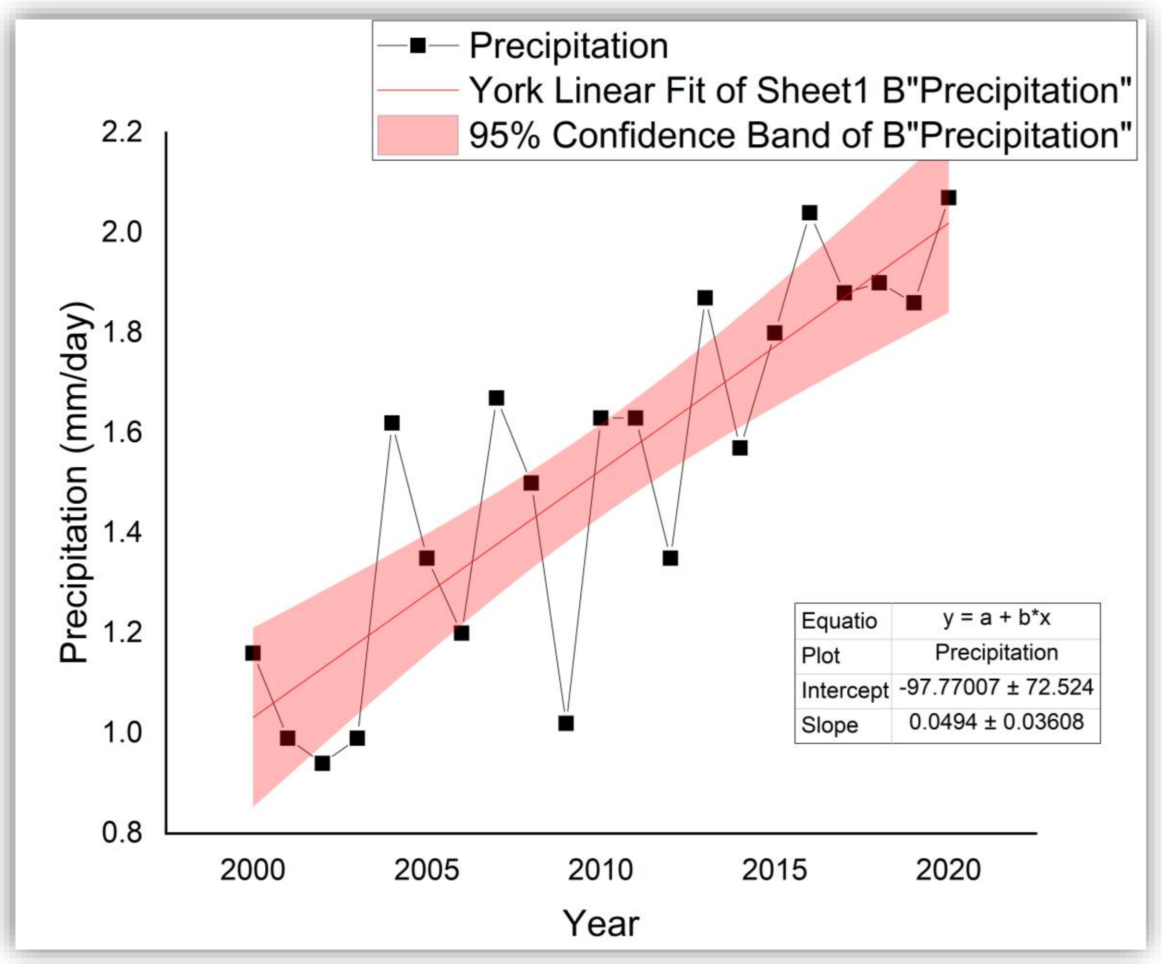


Figure 39: Variation of average annual precipitation over the period of 20 years for Study Area-II

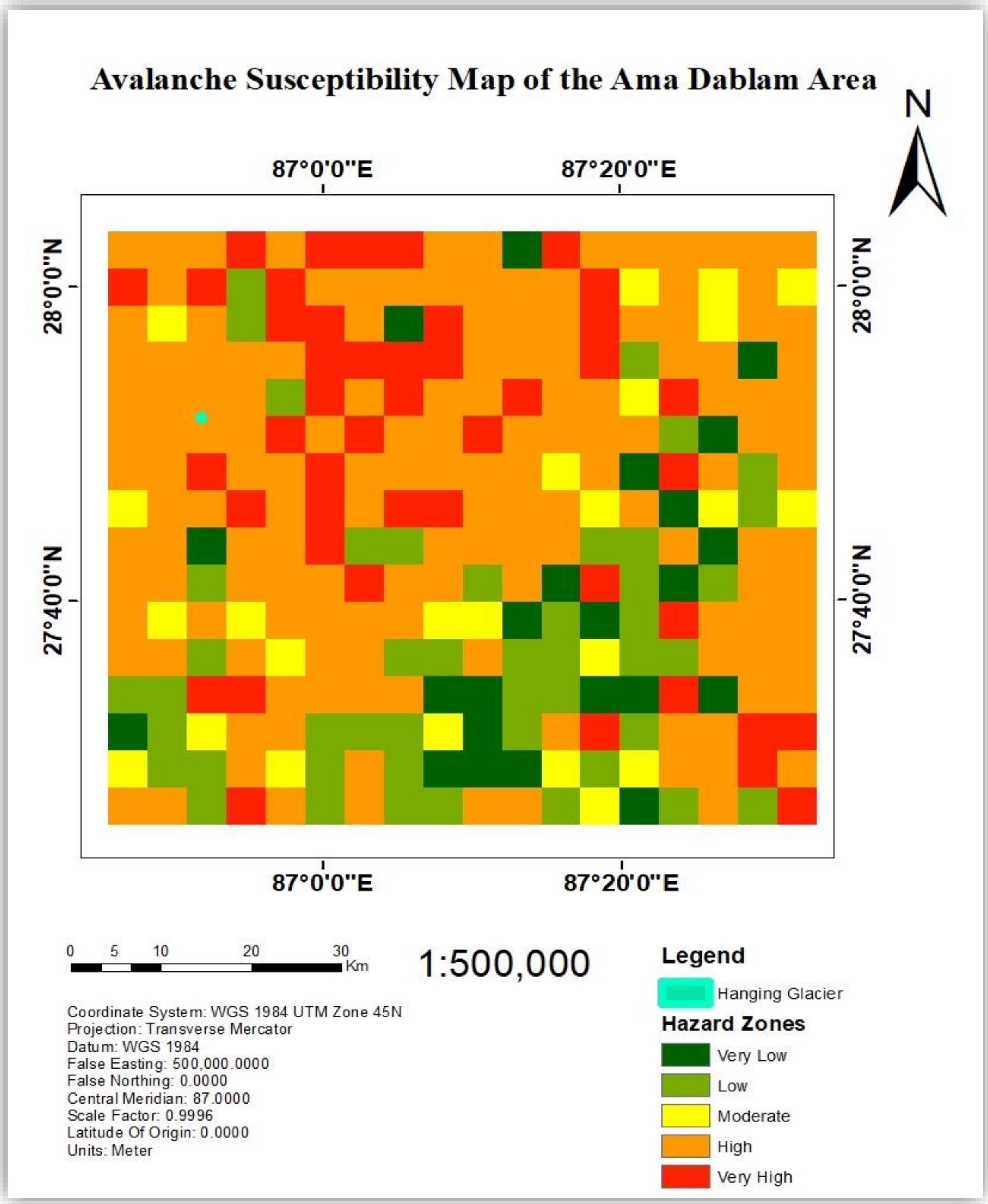


Figure 40: Avalanche Susceptibility Map of the Study Area II

Table 4: Avalanche Zone in various category of the Ama Dablam *Area*

Hazard Zone	Area (m^2)	Area (%)
Very Low	43878.40	8.32%
Low	87814.04	16.65%
Moderate	39096.29	7.41%
High	284867.76	54.01%
Very High	71776.92	13.61%
Grand Total	527433.43	

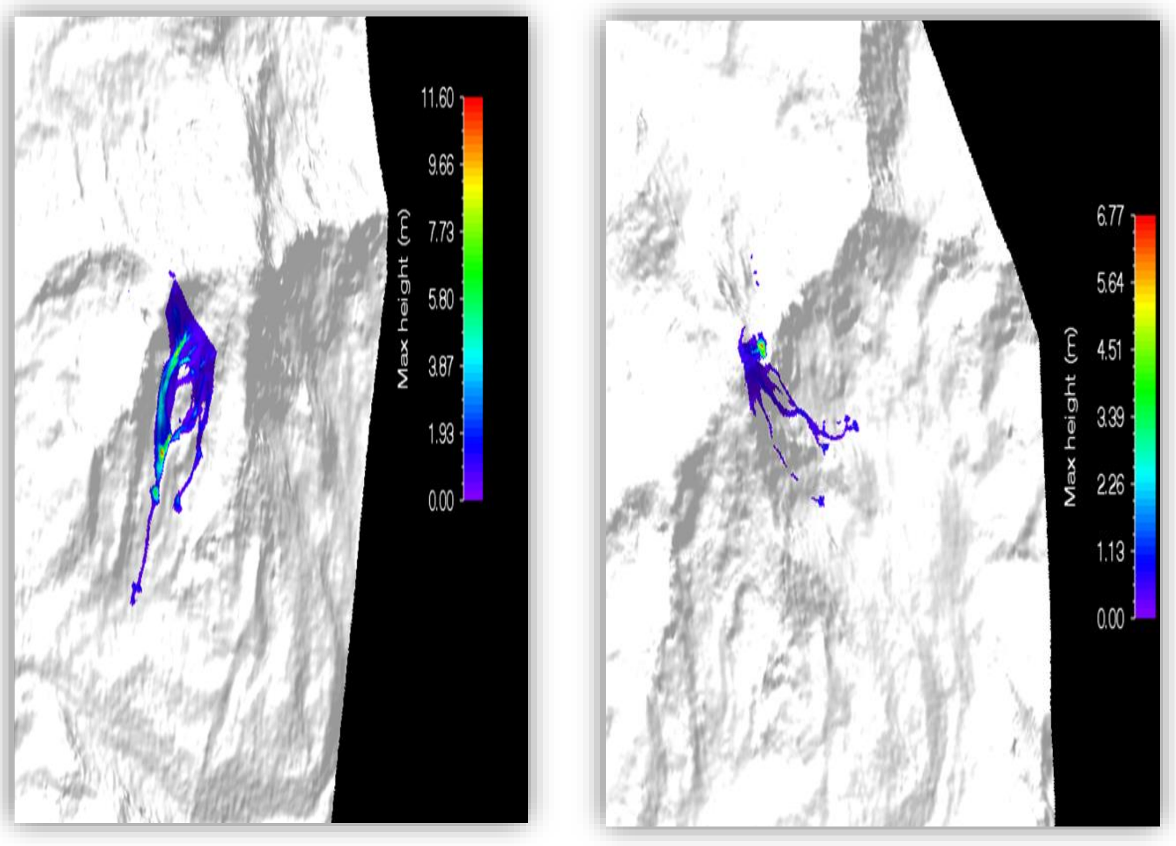


Figure 41:3D view of simulated flow: Height of the Study Area II (1st) & (2nd) respectively

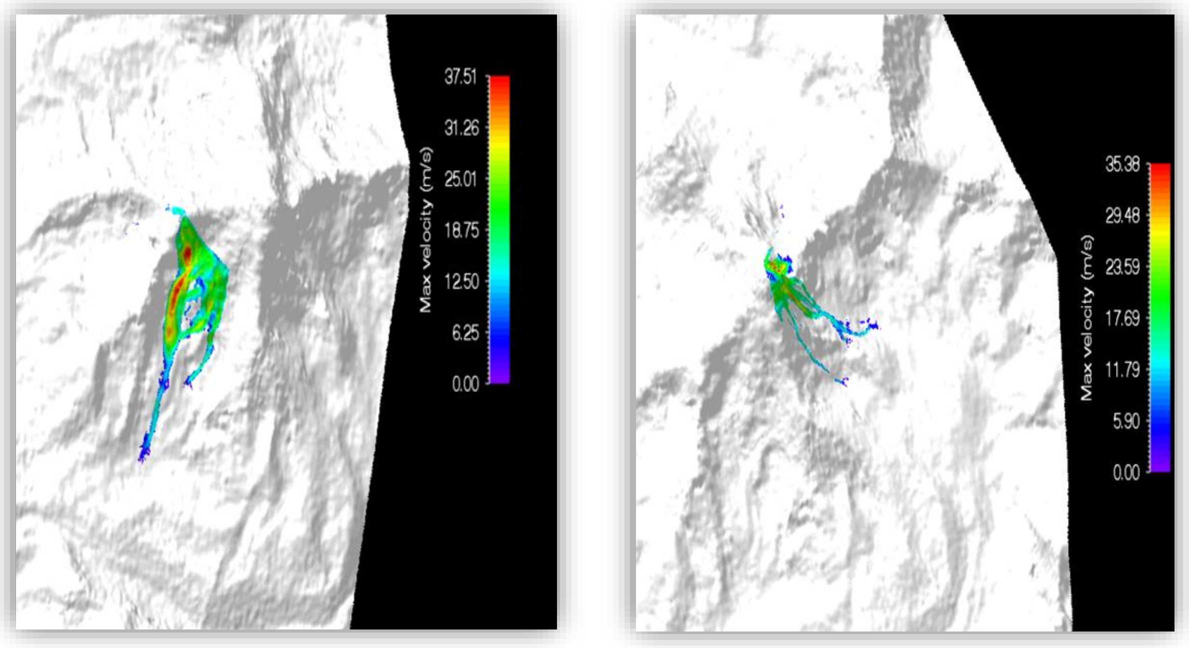


Figure 42:3D view of simulated flow: Velocity of the Study Area II (1st) & (2nd) respectively

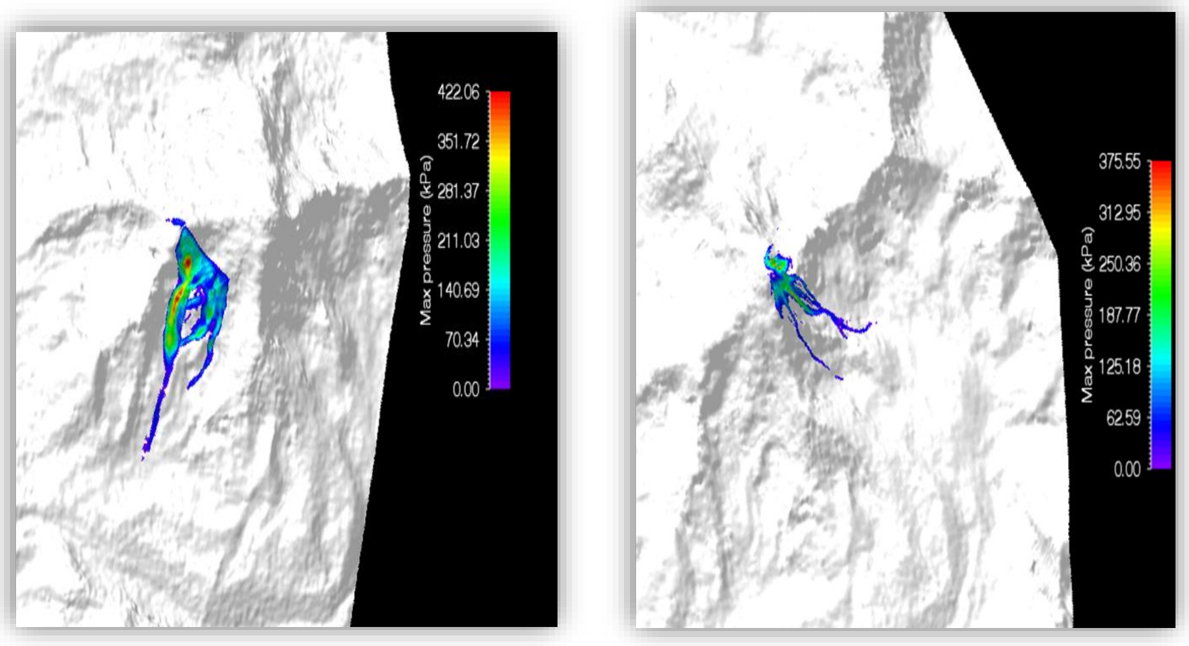


Figure 43:3D view of simulated flow: Pressure the Study Area II (1st) & (2nd) respectively

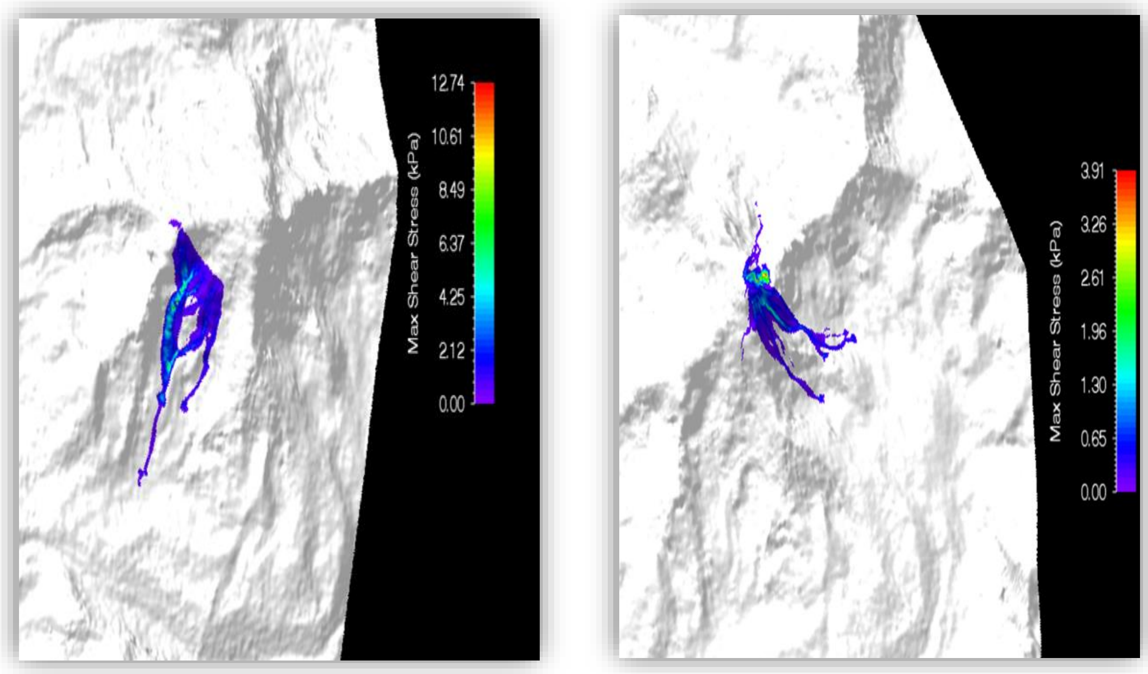


Figure 44:3D view of simulated flow: Stress the Study Area II (1st) & (2nd) respectively

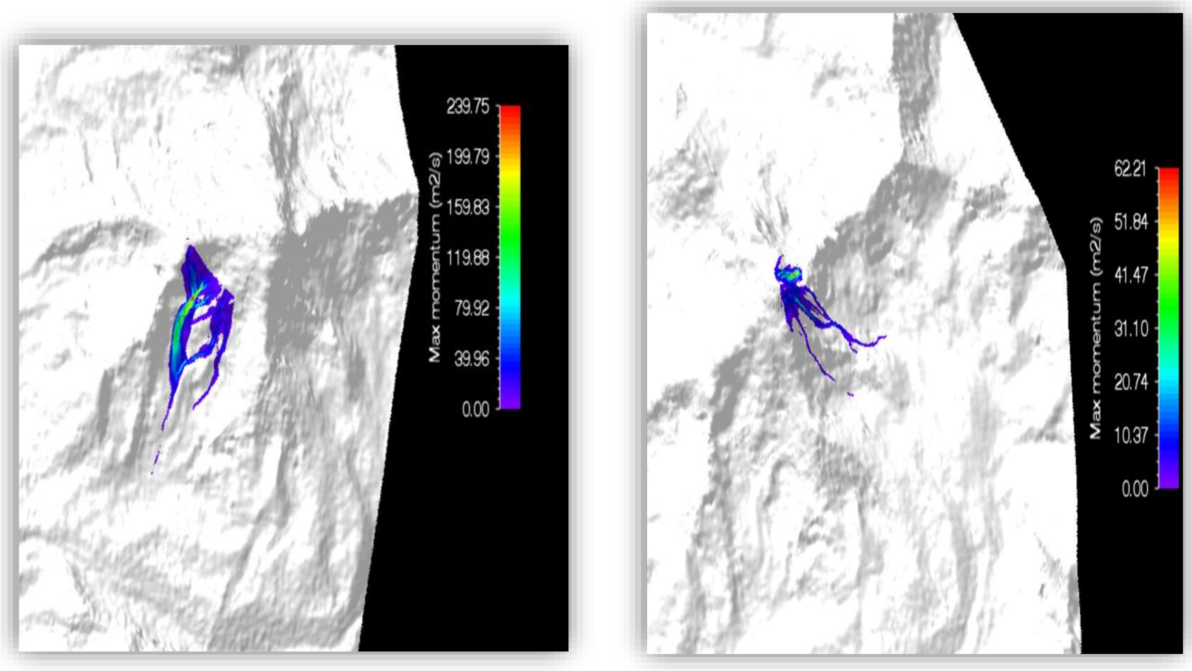


Figure 45:3D view of simulated flow: Momentum of the Study Area II (1st) & (2nd) respectively

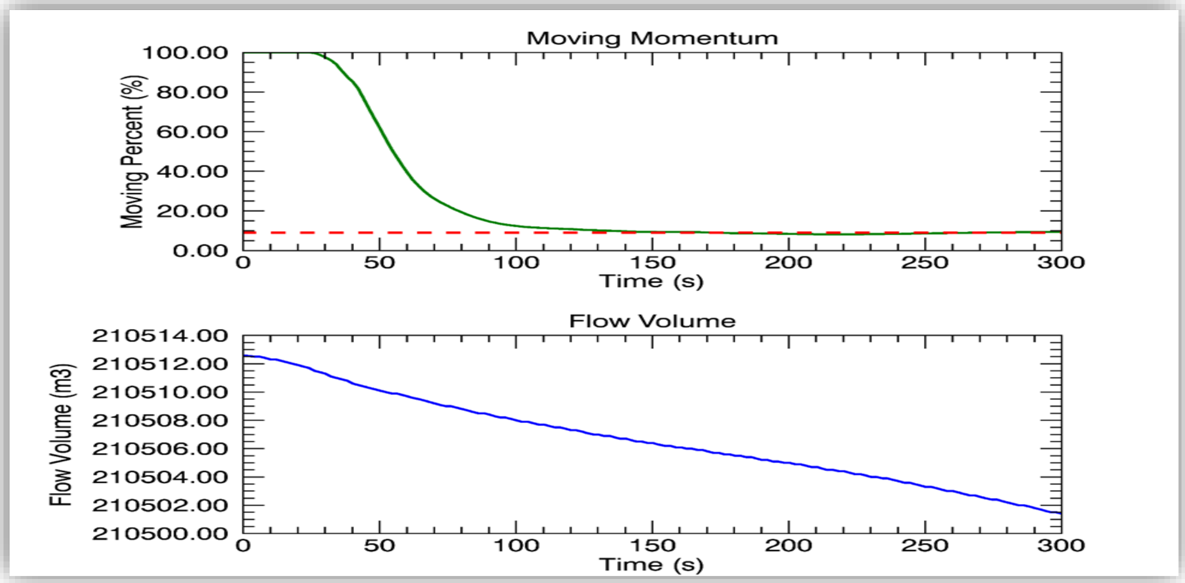


Figure 46: Moving Momentum and Flow Volume Profile of the Study Area II (1st)

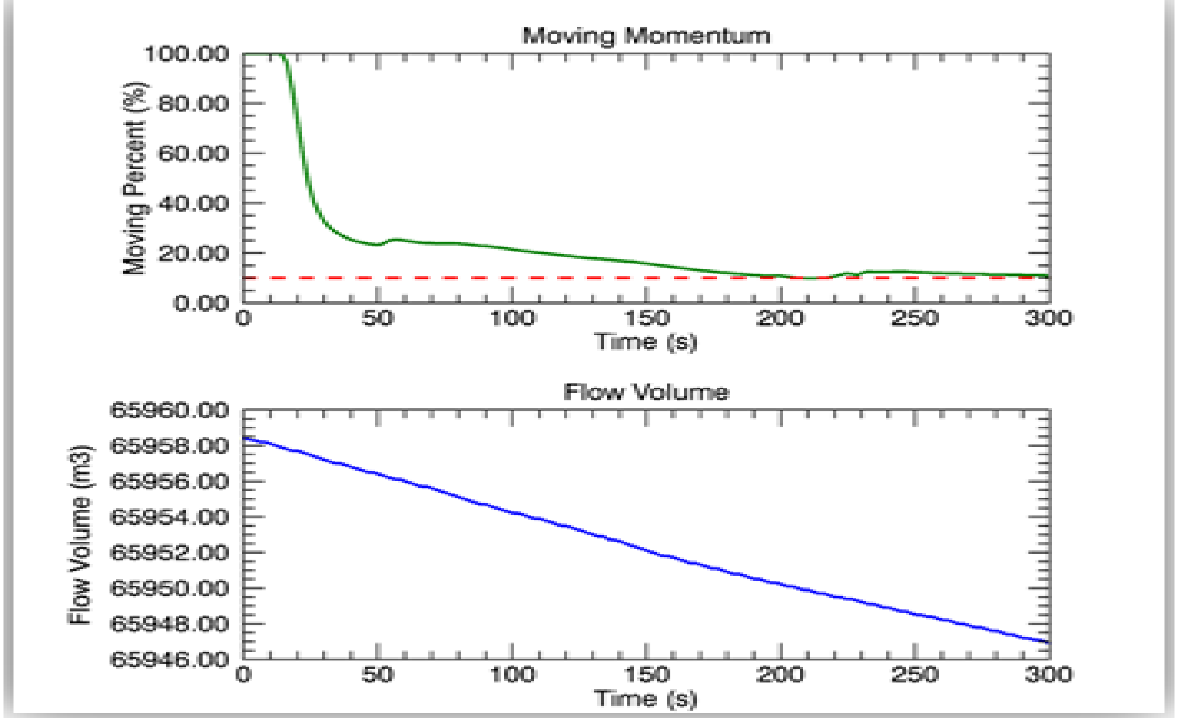


Figure 47:Moving Momentum and Flow Volume Profile of the Study Area II (2nd)

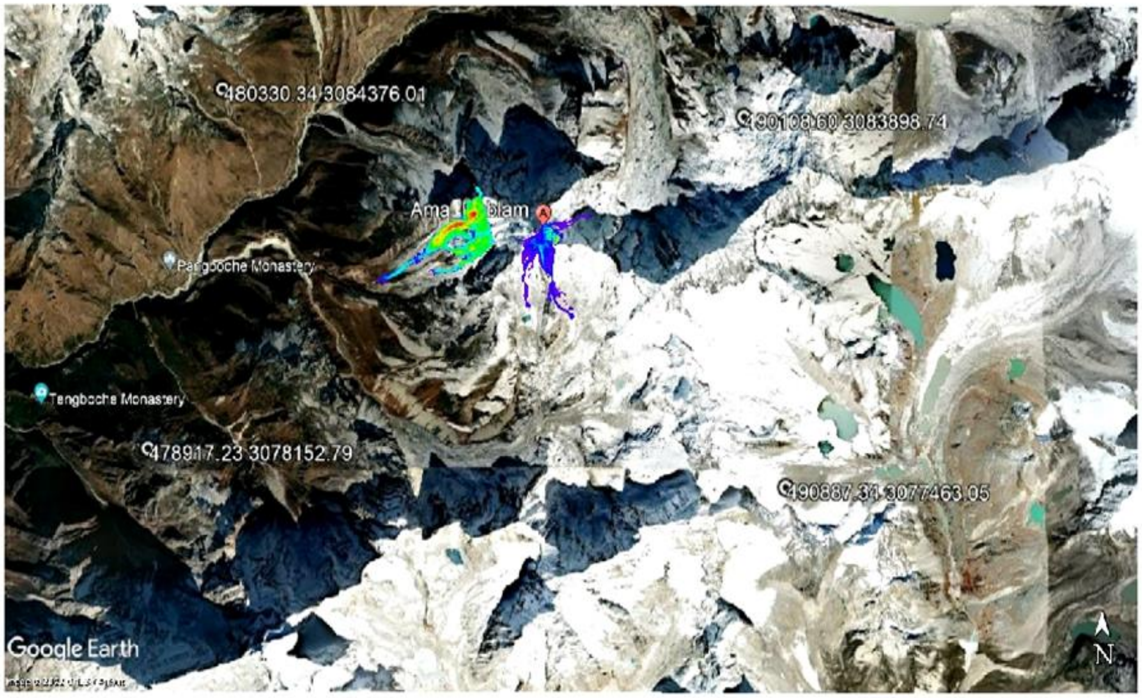


Figure 48: Simulated result of the Study Area II (1st) & (2nd) on Google Earth

VALIDATION AND PREDICTABILITY

On February 7, 2021, a disastrous debris flow happened in the Chamoli district of Uttarakhand, India, at the upper glacier area of Raunthigad. Along the Dhauli Ganga and Rishiganga Rivers, this incident had disastrous effects downstream. Approximately 200 people lost their lives in the catastrophe, which also severely damaged two hydropower projects. The right half of a hanging glacier that covered 0.59 square kilometers broke off, causing an ice-rock avalanche and setting off the debris flow. Infrastructure located along the river's path was largely affected by the flood.

This started with the construction of a 13.2 MW small hydropower project on the Rishiganga and continued with the demolition of a bridge that across the river. At an elevation of 1800 meters above sea level, the 520 MW Tapovan-Vishnugad hydroelectric project was severely damaged by the flood 4 kilometers downstream on the Dhauliganga River. During the Tapovan-Vishnugad project, the tunnel under construction became a significant disaster site, killing over 50 people and leaving over 150 unaccounted for.

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.

CHAPTER V

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.

Furthermore, avalanche susceptibility mapping has been crucial in predicting future locations that are likely to have avalanches. In particular, the study has determined the primary input topographical parameters—such as aspect, slope, elevation, and curvature—as well as climatic parameters—such as temperature and precipitation—that are accountable for the hazard. Furthermore, it has been demonstrated that the AHP technique has an impact on the weighting of factors in relation to their relative contribution to danger. Here, the area having maximum slope at high elevation are more likely to be vulnerable to be susceptible to avalanching. Furthermore, by identifying relationships across spatial extent, the research contributes to enhancing public safety while mountain climbing and helps mitigate the varied impacts of avalanches by identifying places that are susceptible to avalanches. Clear comprehension of the connection between the avalanche hazard and the ensuing causative topographic elements has also been made possible thanks in large part to the research.

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 the high-altitude area 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 potentially 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 time along with regular and continuous supervision and plotting of glacier maps.
- Limiting the renewable energy source mainly: hydropower project construction besides the area of human residence.
- New technology to be used for the setup of early warning system for glacier/snow avalanche.

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 scientist, geologist and geographers. Together with, community level awareness programs regarding nature-based solution such as large-scale afforestation programs should be launched

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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]

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

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