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Master Degree Thesis

Climate-Driven Evolution of Glacier-Moraine Systems: Integrated Surveying and Numerical Modelling of the Valpelline and Melamchi Events.

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Abstract

Climate change has a direct influence on glacier environments. As the world gets warmer, glaciers are melting faster than ever before. When the glacier body moves downward, it starts to melt, leaving behind ridges of loose rocks and dirt called moraines. During heavy rainfall, these unconsolidated sediments are often unstable and can collapse, turning into dangerous downstream flows of water and loose material known as debris flows. Moraine failures and debris flows change valley morphology and threaten people living downstream depending on the intensity of flow and volume. Understanding glacier environments and the dynamics of moraine behaviour has become increasingly important in recent years. Therefore, predicting the initiation and propagation of debris flows originating from moraine failures requires robust numerical modelling capable of reproducing both slope instability and post-failure dynamics.

In this thesis, an integrated engineering workflow is applied for the assessment of moraine instability, combining geomorphological survey, mapping, monitoring, stability analysis, and dynamic runout modelling. The core challenge lies in addressing the stability of the Tza de Tzan lateral moraine located in the Valpelline region in the Western Italian Alps, where the objective is to evaluate the stability of the moraine surface under dry and saturated conditions and to back-calculate the runout behaviour of a massive $1.8 \times 10^6\ m^3$ volume of material after the collapse. Multi-temporal Digital Surface Models derived from drone photogrammetry before and after the debris flow event were used to define pre-failure geometry, estimate erosion thickness, and entrainment conditions for numerical simulations. Digital Surface Model (DSM) differencing identified surface lowering of more than 50 meters at the source and progressive erosion and deposition in the downstream valley, effectively mapping the “invisible” erosion.

The limit-equilibrium method using Slide2 (Rocscience) software is used to compare the pre-failure conditions and calculate the Factor of Safety under dry and saturated rainfall scenarios. This analysis quantifies the reduction in factor of safety associated with increased pore-water pressures. The post-failure condition and evolution of the debris flow were reconstructed through back-analysis using the depth-averaged DAN3D model. Model parameters were calibrated through iterative simulations using frictional and Voellmy rheologies. The DAN3D code successfully reproduces the observed runout distance, bulking volume, and deposition patterns when spatially variable basal resistance and erosion laws are applied.

In addition, this study includes a comparative evaluation against observations from the 2021 Melamchi flood in Nepal. This case is taken as a reference event from a high-mountain Himalayan region, where earthquake-weakened and rainfall induced moraine failure serves as a source of downstream cascading events and debris flow, which travelled over 50 kilometers downstream. The study further discusses how differences in data availability between Alpine and Himalayan regions influence modelling strategies and risk evaluation approaches.

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1. Introduction

Problem Statement

High mountain areas are among the most affected environments due to climate change. Glacier systems have undergone highly retreat and change in geomorphology, making them sensitive in high mountain region. These transformations in glacier environment has direct influence on stability of moraine due to melting of buried ice, thermal conditions and slope alteration. This thesis focuses on the study of stability problems in morainic structure through the survey, mapping, monitoring and modelling techniques and comparison of one case of Alps with recent case of Nepal's Himalaya. By applying methods within the recent case of Alps and Himalayas, aims to develop the effective approaches under changing climatic conditions.

1.1 Background

Glaciers are the most powerful tool shaping high mountain landforms, which influence both geomorphology and hydrology. When glaciers move downward, the interaction between ice movement, erosion, and deposition changes the mountain terrain, producing a number of geomorphic features such as ridges, valleys, and morainic accumulations. Over some decades, climate change has changed the shape of glacier systems, which respond more rapidly to glaier systems than any other. Over some decades, glacier retreat has been widely recorded in many regions, faster than before. It reflects the ongoing impact of rising temperatures and makes this area of study very important because it is changing the mountain setting. (IPCC, 2021; Harrison et al., 2025. Almost 10% (671 million people) of the global population lived in high mountain regions in 2010, based on gridded population data and this population is expected to grow to 736–844 million across the shared socioeconomic pathways by 2050.

In recent years, reports show that glacier retreat has become one of the most visible areas of global climate change. Due to rising air temperatures and changes in precipitation patterns, the ice melting process has sped up, leading to a continuous loss of glacier mass in almost all mountain regions. Some research from the Alps, Andes, and Himalayas shows that glaciers are melting at very fast rates, exposing new landforms and altering the geomorphic balance of high mountain environments (Zemp et al., 2019). When the ice melts, it leads to a loss of stability in the glacier and morainic system, resulting in the formation of morainic ridges, slopes, and valley deposits. These processes also reshape mountain landscapes and at the same time influence slope stability and water systems, highlighting the need for continued research on glacier-related geomorphic change (IPCC, 2021).

When glaciers move downstream, they carry rock boulders and sediments within their mass, which are later deposited as accumulations of these materials. The landforms created by such sediment accumulation are known as moraines. These morainic ridges serve as evidence of past glacier fluctuations and climatic conditions. However, in recent times, many of these morainic structures left behind by glacial activity have become unstable due to the melting of buried ice and the influence of ongoing climate change. Such instability can lead to surface deformation, material collapse, and the reactivation of debris, posing geomorphic and social risks in high mountain regions. It is therefore essential to understand the formation, composition, and stability of morainic ridges, and modern survey, mapping, and monitoring techniques are vital for effective risk assessment and for providing valuable information under current climatic conditions (Benn & Evans, 2010; Etzelmüller & Hagen, 2020).

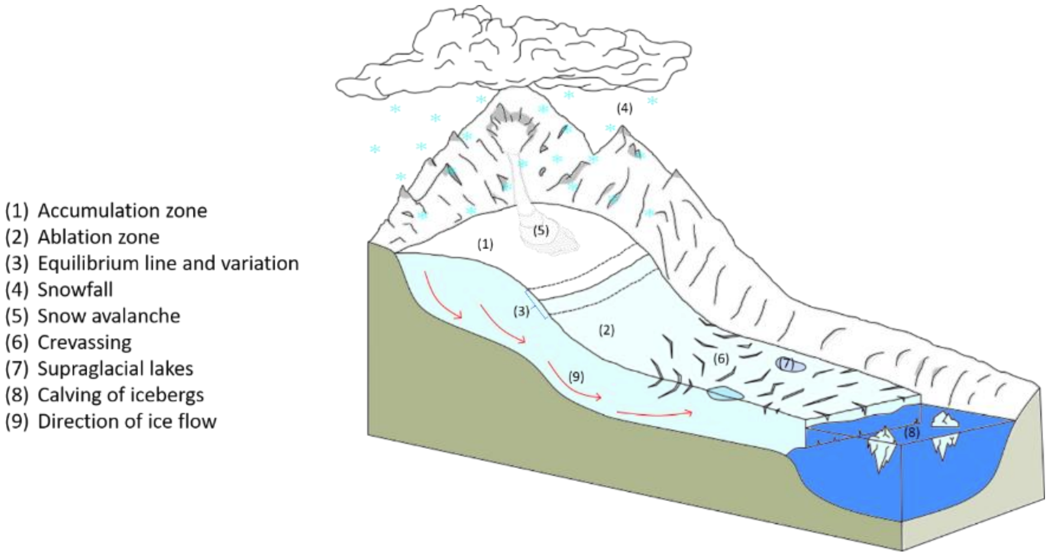

Figure 1.1Schematic of glacier zones and moraine formation. (world meteorological organization)

The Alps and the Himalayas are most dynamic mountain regions, which have long-term glacial and periglacial processes. Alps are the very few mountainous regions which have been extensively studied for a very long time, hence well-documented glacial and morainic systems. Many areas of the Alps show evidence of slope instability, debris reactivation, and instability linked to morainic structures due to climate change. Recent studies in the European Alps have shown that terrain instability leads to more frequent rockfalls, debris slides, and moraine fragmentation due to glacier retreat and permafrost degradation (Ritter et al., 2011; Mourey et al., 2022). These processes not only change the geomorphic balance in alpine regions but also have a direct influence on human activity. In contrast, Himalayas have higher elevations and monsoon-dominated climate, host large debris-covered glaciers, where morainic ridges and slopes are difficult to access and less monitored. Climate has also shown visible effects in the Himalayas, which have increased the risk of moraine destabilization and related hazards. Comparing these two regions is an opportunity to analyze a wide range of high mountain regions, similarities and differences in geomorphology, moraine formation, and related risks due to climate change.

It is essential to understand the stability of morainic ridges in these mountain regions, which have been affected by the global rise in temperature. By combining field-based surveys with modern techniques, it becomes easier to identify the patterns of change in the stability of moraines and the risks associated with these unstable structures. This approach not only gives insights into glacier–landform interactions but also provides valuable ideas for hazard management and land-use planning in high mountain remote areas of countries like Nepal. This thesis focuses on the comparative study of glacial and morainic systems under current climatic conditions.

1.2 Problem Context and research aim

Currently, there are many ongoing studies on glacier retreat and its consequences, but the study of unstable morainic ridges remains less understood, particularly in the high mountain regions of the Himalayas. The rapid rise in temperature causes ice melt and slope deformation, raising concerns about the stability of moraine deposits and their potential geological and social risks. Both in the Alps and the Himalayas, studies show that many hazards have occurred recently due to moraine instability. Therefore, the aim of this thesis is to analyze the stability problems of morainic ridges in the Alps and the Himalayas that show evidence of instability. The study focuses on identifying the main factors affecting moraine stability, studying different survey, mapping, and monitoring methods for risk assessment, and evaluating the similarities and differences between the two regions to better understand moraine stability issues under changing climatic conditions.

1.3 Organization of Thesis

This thesis is organized into six main chapters. **Chapter 1** introduces the background, problem context, and research aim of the study. **Chapter 2** presents a literature review on glacier geomorphology, moraine formation, and similar studies conducted in high mountain regions. **Chapter 3** introduces the methodologies. **Chapter 4** discusses the debris flow context, study site and result of GIS based survey, mapping, monitoring and debris flow modelling techniques. Finally, **Chapter 5** provides the discussion, conclusions and recommendations based on the research findings, highlighting the importance of this study for risk assessment in high mountain environments.

2. Glacier–Moraine Systems under Climate Change

This chapter introduces the main scientific concepts related to glacial processes and landform development by reviewing past studies. It is fundamental to have a solid knowledge of how glacier systems form, evolve, and interact with climatic and geological factors. The study begins with the scientific concept of the glacial system, describing its formation, dynamics, and geomorphic effects, and introduction and comparison of geomorphological characteristics of two key mountain ranges: the European Alps and the Himalayas. Furthermore, discussion on moraine formation, its types, glacier retreat under climate change, and the resulting stability issues is required for the assessment of mountain hazards.

2.1 The Glacial System and Geomorphology

2.1.1 Formation and Structure of Glaciers

Glaciers are large moving ice formed over a very long period when the accumulation of snow exceeds melting and evaporation. In the cold and high mountain regions, a high amount of snowfall and compression transform snow first into granular firm and then into dense glacial ice. This transformation of snow into ice is due to compaction and recrystallization processes under the pressure of overlying snow layers (Benn & Evans, 2010). The formation and life of a glacier depend mainly on climate, temperature, and precipitation, along with local geological factors such as slope, aspect, and elevation (Cuffey & Paterson, 2010).

A glacier is composed of two main parts: the accumulation zone and the ablation zone. The upper part of a glacier, where snow and ice are gradually collected mainly through snowfall and avalanches, is the accumulation zone, while the ablation zone is where ice is lost through melting at the lower part of the glacier. The balance between these two zones is important because it determines whether the glacier advances, retreats, or remains stable (Andrews, 1975). The line separating them is called the Equilibrium Line Altitude (ELA), at that point the total gain and loss of ice are equal (Hock, 2003). A positive mass balance indicates glacier growth, while a negative one leads to retreat. The mass balance can be expressed as a function of precipitation, melting, and the surface energy balance:

$$M = f(P, L, B)$$

where M is mass balance, P is solid precipitation, L is latent heat of melt, and B is the surface energy balance.

The ELA changes its position due to climate variation, and it is an important indicator of glacier health and mass balance (Cuffey & Paterson, 2010). If the accumulation of ice is greater than ablation, the glacier expands, and if ablation dominates, it starts to retreat.

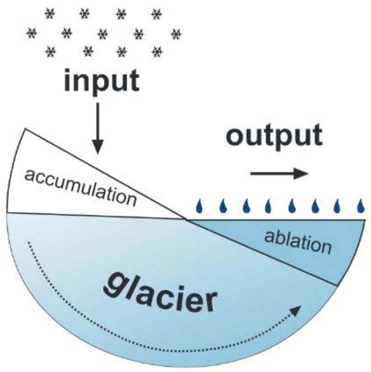

Figure 2.1Glacier as input-output systems (Winkler et al. 2010, after Winkler 2009)

Glaciers vary depending on their thermal condition and external form. Glaciers are classified based on temperature into three types: temperate, polar, and polythermal. Temperate glaciers are near the melting point and have some meltwater, which increases the movement of the glacier and erosion of bedrock, while polar glaciers are in a frozen state with limited motion. Polythermal glaciers have characteristics of both temperate and polar glaciers. According to their shape and location, glaciers are also divided by other names. Alpine glaciers form in mountains, continental glaciers cover large areas such as Antarctica and Greenland, piedmont glaciers are found on flat plains, and tidewater glaciers flow directly into the sea and calve icebergs. Some unique types of glaciers, such as rock glaciers and ice aprons, occur in different mountain settings (Knight, 1999; Benn & Evans, 2010; Hambrey & Lawson, 2000).

Table 2.1 Classification of Glaciers (modified from IPCC, 2021; Benn & Evans, 2010)

Type	Description	Location/Example	Dominant Climate
• **Alpine**	Valley glaciers formed in mountainous regions	Alps, Andes	Temperate
• **Continental**	Ice sheets covering large areas	Antarctica, Greenland	Polar
• **Piedmont**	Valley glaciers spreading on flat plains	Alaska	Temperate
• **Tidewater**	Glaciers flowing directly into the sea	Norway, Alaska	Maritime
• **Rock glacier**	Ice–debris mixture in permafrost terrain	Alps, Andes, Himalayas	Cold mountain

Glacier type and process of formation determine the interaction with the mountain landscape. Glacier movement, erosion, and the development of new landforms are influenced by the climate, composition, and mass balance of the glacier (Benn & Evans, 2010). Understanding these physical characteristics is essential to explain the dynamic behaviour of glaciers and their role in shaping mountain geomorphology in regions like the Alps and the Himalayas (Cuffey & Paterson, 2010).

2.1.2 Glacier Dynamics and Movement

Glacial flow and movement are a complex phenomenon, in which gravity helps ice masses move downslope. This movement of ice masses develops from the internal deformation (creep) due to pressure and basal sliding over the underlying substrate (Jiskoot et al., 2011; AntarcticGlaciers.org, 2024). Due to water present at the base of temperate or polythermal glaciers, it increases the speed of flow. In temperate or polythermal glaciers, due to basal sliding, typically the fastest movement occurs with the help of meltwater present at the base (Jiskoot et al., 2011).

Modern geological studies have emphasized another mechanism for glacial movement, which is subglacial or substrate deformation. In this process, unconsolidated sediment or till deforms under shear stress and contributes significantly to increasing the flow velocity (Lyell Collection, 2021). When the basal temperature is below the pressure melting point, as in cold-based ice, horizontal flow is negligible and the glacier thickens instead. Warm-based ice shows the opposite characteristics; it produces meltwater which acts as a lubricant, accelerating basal sliding and sediment deformation, so it increases overall glacier movement (Taylor & Francis Online, 2024).

Additionally, these flow mechanisms also control the transport, accumulation, and deformation of sediments that form morainic ridges and different types of glacial deposits. So, it is essential to understand glacier dynamics to know the geomorphic evolution of mountain landscapes and the condition of morainic structures (Benn & Evans, 2010).

2.1.3 Geomorphic Processes of Glaciers

The movement of glaciers acts as one of the powerful agents of erosion and landscape formation in mountain regions. During the movement of glaciers downslope, it modifies the surface beneath the glacier by processes of erosion, transportation, and deposition (Benn & Evans, 2010). Plucking and abrasion are two main erosion processes in this movement. Plucking takes place when glacier ice freezes onto bedrock; during the movement, it pulls pieces of bedrock away, while abrasion happens when rock fragments beneath the glacier mass fixed with the ice grind and polish the valley floor. After a long time, these processes create typical glacial landforms such as U-shaped valleys, cirques, and fjords (Anderson & Anderson, 2010).

Glaciers act as major sediment transport systems ranging from very fine materials to large boulders. These materials can be carried from the glacial surface (supraglacial), mixed with ice (englacial), and along the base (subglacial) (Knight, 1999). When ice starts to melt, these transported materials are deposited below to form moraines, drumlins, and outwash plains. Due to this continuous process, it shapes the geomorphology of mountainous landscapes. Therefore, understanding these geomorphic processes provides a solid structure to explain the evolution of moraines (Benn & Evans, 2010).

2.1.4 Major Glacial Landforms

The glacier's movement results in changing the shape of mountain landscapes and forming a variety of landforms. The action of erosion creates U-shaped valleys, cirques, arêtes, and fjords; these are the typical features seen in formerly glaciated mountain regions. When glaciers widen and deepen the pre-existing river valley, it forms a U-shaped valley, while cirques are bowl-shaped landforms created after the accumulation of ice at the head of the glacier. When several cirques erode toward each other, they leave sharp ridges and pointed peaks, creating arêtes and horns. These features act as evidence of past ice ages, giving us clues for current glacier research (Benn & Evans, 2010).

In contrast, when glaciers melt and release the debris they carried, they create depositional landforms. These landforms include moraines, drumlins, eskers, and outwash plains (Anderson & Anderson, 2010). Moraines are the most common and important depositional features, consisting of unsorted materials such as clay, sand, gravel, and boulders deposited along the sides, middle, or end of glaciers. Past glacier advances and retreats can be studied from the shape and size of moraines. Over time, these depositional structures contribute to the evolution of ridges and slopes in mountainous regions like the Alps and the Himalayas. Currently, these landforms have been studied to interpret glacial history and assess moraine stability under changing climatic conditions (Benn & Evans, 2010)

2.1.5 Importance of Studying Glacial Geomorphology

Glacial geomorphology shares necessary information about how glaciation shapes the Earth's surface and impacts the environment and climate. To understand present-day glacier behavior, the study of glacier landforms is very important, which was influenced by past climatic conditions, glacier advances, and retreats. The deposition of materials during the glaciation period also acts as natural records of environmental change and offers proof of ice movement, sediment transport, and meltwater flow (Benn & Evans, 2010; Anderson & Anderson, 2010).

The study of glacial geomorphology is not only important for academic research but also for practical applications of risk assessment, natural hazard reduction, and land management. Due to climate change, there is a direct effect in the Alps and the Himalayas in the form of glacier retreat and permafrost degradation, which is increasing the risk of slope failure, moraine collapse, and glacial lake outburst floods (Haeberli et al., 2017). Therefore, the study of geomorphology of glaciers is important to identify unstable zones, plan monitoring strategies, and assess the long-term effects of climate change.

2.2 Geomorphology of the Alps and the Himalayas

The European Alps and the Himalayas share the same formation mechanism. During the continental collision, high mountain regions were formed, which were later shaped by glaciation during the Quaternary period. However, there are differences in their tectonic activity and climate, which is the reason for the distinct types of geomorphic hazards in these two high mountain regions.

2.2.1 Geological and Tectonic Background

The geomorphology of the Alps and the Himalayas is strongly influenced by their geological and tectonic evolution. During the continental collision in both regions, it led to large-scale crustal deformation and uplift. Both the Alpine mountain range and the Himalayan mountain range were formed, and it is still an ongoing process. About 50 million years ago, from the convergence between the African and Eurasian plates, the Alps formed, while the collision between the Indian and Eurasian plates formed the Himalayas. The convergence of continental plates created complex lithological and structural settings that are still evolving through faulting, folding, and uplift (Le Fort, 1996; Ballèvre et al., 2018).

In the Alps, the present-day complex geological structure is made of sedimentary, metamorphic, and crystalline rocks arranged in several tectonic zones such as the Helvetic, Penninic, and Austroalpine domains (Schmid et al., 2004). In the Alps, continuous uplift with the combination of glaciation has produced deep valleys, steep slopes, and a well-developed glacial environment. Conversely, the Himalayan mountain structure consists of massive thrust systems and active tectonic activity with the formation of rocks including schists, gneisses, and sedimentary sequences. Ongoing seismic activity and continuous uplift of the Himalayas make it the most dynamic mountain system on Earth (Yin & Harrison, 2000).

By understanding the geological settings of these regions, it helps in the study of the geomorphic development of glaciers. In addition, it influences erosion and sedimentation patterns and affects moraine and slope stability.

2.2.2 Geomorphic Characteristics of the Alps

Mountain region of the Alps is one of the well-studied mountain systems in the world and gives a clear example of the connection between glacial, geological, and climatic processes. After multiple glaciations during the Quaternary period, the Alpine landscape resulted in steep peaks, deep U-shaped valleys, cirques, hanging valleys, and moraine ridges. Due to repeated advances and retreats of ice, it has strongly shaped its geomorphology. The Last Glacial Maximum (LGM), around 20,000 years ago, covered almost the entire Alpine region and changed the landscape of the Alps (Ivy-Ochs et al., 2008; Ehlers et al., 2011).

Alpine glaciers are mainly composed of temperate glaciers, which means ice is at or near the pressure melting point, enhancing both erosion and sediment transport during movement and retreat. These continuous glacier retreats in recent times have created a wide range of glacial landforms such as lateral and terminal moraines, rock glaciers, and outwash plains. In addition to the formation of new landforms, interaction between glaciers, permafrost, and steep slopes has increased the risk of rockfalls, debris flows, and moraine instability (Cossart et al., 2010; Haeberli et al., 2017). These processes have a direct influence on the increase of natural hazards that require detailed study and monitoring plans in Alpine regions.

2.2.3 Geomorphic Characteristics of the Himalayas

Mountain range of Himalaya is one of the youngest and most active mountain systems on Earth. The Himalayas is characterized by steep relief, elevation, and strong tectonic movement. Glaciers in the Himalayas are different than Alps, it is dominated by debris-covered glaciers, large moraine, and glacial lakes, which shows its vast geomorphic condition. Glaciers in Himalayas lie at altitudes above 5000 meters and expand to deep valleys, which forms complex landforms shaped by monsoon and continental climatic conditions (Bolch et al., 2012; Richardson & Reynolds, 2000).

Climate change has influenced Himalayas more than any other regions, its shape has been controlled by combination of active uplift, precipitation during monsoon period, and temperature variability. At the same time, due to climate change glacier retreat is higher, and erosion and sediment transport has reshaped the geomorphology of region. When the glacier is covered by thick debris cover it reduces surface melting, but it leads to ice-cored moraine during retreat, and due melting of buried ice there increases instability (Frey et al., 2010). Mass movement in this region is frequent, those movements increase the risk of rockfalls, debris flows, and moraine dam failure posing significant risks to downstream valleys and settlements (Petley et al., 2010). The Himalayan glaciers are monitored poorly due to limited accessibility and difficult terrain, highlights the need for improved survey and monitoring techniques to reduce the hazard related to moraine failure.

Figure 2.2 Tsho Rolpa Glacial Lake in Dolakha, Nepal

2.2.4 Geomorphology comparison: Alps vs. Himalayas

The process of formation of the Alps and Himalayas is almost the same, formed by continental collision but with significant differences in their geomorphology, climatic conditions, and type of glacier. The Himalayas are younger, higher, and influenced by monsoon and continental climates, while the Alps are older than the Himalayas, more eroded, and located in a temperate climatic zone. These differences have affected the type of glaciers found in the two different regions and their geomorphic evolution (Le Fort, 1996; Yin & Harrison, 2000).

The Himalayas represent a high rate of compressional strain and uplift due to a dynamic environment, which is balanced by extremely high rates of denudation. Due to this dynamic behaviour combined with monsoonal climate, it results in a higher rate of sediment production. This production of a large amount of sediment causes the potential for large-scale hazards, specifically glacial lake outburst floods (GLOFs). In contrast, hazards in the Alpine region are driven by permafrost degradation. The structural instability and complexity of the Alps are due to local instabilities, with lower sediment activity and a slower rate of landscape change compared to the monsoon-fed Himalayan system (Haeberli et al., 2017; Frey et al., 2010).

Table 2.2 Comparison of Geomorphic and Climatic Characteristics of the Alps and the Himalayas (IPCC, 2021; Benn & Evans, 2010; Kuhle, 2007; Haeberli et al., 2017)

Parameter	Alps	Himalayas
Formation	Formed by convergence of African and Eurasian plates (~50 Ma)	Formed by collision of Indian and Eurasian plates (~45–50 Ma, ongoing)
Age	Older mountain system	Younger and tectonically more active
Elevation	Average 2,500–4,800 m	Average 4,000–8,848 m
Dominant Rock Type	Metamorphic, sedimentary, and crystalline rocks (Helvetic, Penninic, Austroalpine zones)	Schists, gneisses, sedimentary sequences, and granites (Higher, Lesser, and Tethyan Himalaya)
Tectonic Activity	Moderate, mostly inactive faults	Very active, with major thrusts (Main Central Thrust, Main Boundary Thrust)
Climate Type	Temperate; influenced by Atlantic systems	Monsoon and continental; strong altitudinal variation
Glacier Type	Mostly temperate glaciers	Largely debris-covered and polythermal glaciers
Glacial Processes	Strong glacial erosion and valley formation	Rapid sediment production, moraine formation, and slope instability
Major Hazards	Permafrost degradation, rockfalls, and debris slides	Moraine-dammed lake outbursts (GLOFs), landslides, and debris flows
Research Condition	Well-monitored and documented	Poorly monitored, limited accessibility

2.3 Moraine Formation and Types

moraines are the results of glacier movement and deposition of sediments. Formation of moraine serves both record of past glacier activity and significant risk of hazard in modern times.

2.3.1 Formation of Moraines

Accumulations of unconsolidated glacial debris (till) that form as a result of movement of glacier and process of melting are moraines. When the glacier moves downward, it carries rock fragments, sediments, and other materials from the valley walls and bed, later deposited due to ice melt and loss of carrying capacity. The sources of these materials are mainly three types: supraglacial debris carried on the ice surface, in englacial it traps debris within the ice, and subglacial debris transported at the base of the glacier (Benn & Evans, 2010; Anderson & Anderson, 2010).

When the glacier starts to melt, those materials accumulate and form the distinct ridges known as moraines. Depending on the flow dynamics of the glacier, melting rate, and local topography, moraines have different shapes and positions. The final form of morainic structures also depends on the processes of ice melting and sediment deformation. Moraines also serve as important indicators of past glacier activities in high mountain environments such as the Alps and the Himalayas; in addition, they provide evidence of climatic variation and patterns of glacier melting (Ivy-Ochs et al., 2008; Eyles, 1983).

2.3.2 Types of Moraines

Moraines are classified into different types depending on their position to the glacier and the deposition process.

Lateral moraines: These are the ridges of deposited debris at the side of the glacial flow, which are pushed outward by the glacier. These ridges have the maximum height of the glacier surface and have a slope angle of 70 degrees or more (Benn & Evans, 2010).

Medial moraines: These moraines form where two tributary glaciers meet at one point. It combines the lateral moraines of respective glacier flows into a single central ridge (Anderson & Anderson, 2010).

Terminal moraines: Terminal moraines, also called end moraines, mark the furthest advance of the ice where it melts. The study of these moraines is important because they form massive natural dams that can create moraine-dammed lakes (Eyles, 1983).

Ground moraines: When the glacier moves forward, it leaves an irregular blanket of till, which creates small rolling hills and plains (Benn & Evans, 2010).

2.3.3 Morphological and Climatic Significance of Moraines

Moraine serves as a valuable past geomorphic record that preserves the history of glacial activity allowing researchers to study of past glaciation. Height, slope, and composition of sediments shows the process of glacier movement, the rate of ice melt and the depositional environment during different climatic periods (Benn & Evans, 2010; Anderson & Anderson, 2010).

In mountain regions, moraines also play a crucial role in understanding the effects of climate change. If the moraines and moraine-like structures have a buried ice, when it starts to melt it destabilizes those ridges, leads to surface deformation, slope failure and in some case failure of moraine dam. In some cases, in the Himalayas, due to this type of instability of moraine dam it poses significant risks, when that moraine dammed lakes sudden blast, it triggers floods and debris flows, which is risky for the downstream settlements and infrastructure (Frey et al., 2010; Richardson & Reynolds, 2000).

2.4 Climate change and glacier retreat

World glaciers are dramatically changing due to climate change. This is the starting time of a major shift in the shape of the land in high mountain regions, experts have called this a paraglacial crisis (Ballantyne, 2002; Curry, 2000). This is a big ongoing adjustment to the landscape where ice is disappearing.

2.4.1 Evidence of Global Glacier Retreat

Over the past century, according to many studies, worldwide glaciers are retreating consistently, which is the most visible indicator of global climate change (IPCC, 2021). Glacier mass balance is largely negative in most of the mountain regions. Between 1961 to 2016, global ice melt contributed significantly to the modification of the landscape and global sea-level rise. Since 1976, 9 trillion tonnes of ice have retreated, which has caused a 2 cm mean sea-level rise (Zemp et al., 2019).

The European Alps have been well documented since the last century, where most of the glaciers lost more than 50% of their volume of ice. Similar to the Alps, since the 1970s, the Himalayan glaciers are also thinning and retreat have been recorded; it is mainly due to temperature rise and reduced accumulation at higher elevations (Bolch et al., 2012; Haeberli et al., 2017). These changes have resulted in the risk of moraine-dammed lake outburst floods in the Himalayas. This trend of consistent reduction of glacier mass is mostly influenced by changing climate patterns and global temperature rise, which is the most critical indicator of environmental change in high mountain regions (IPCC, 2021).

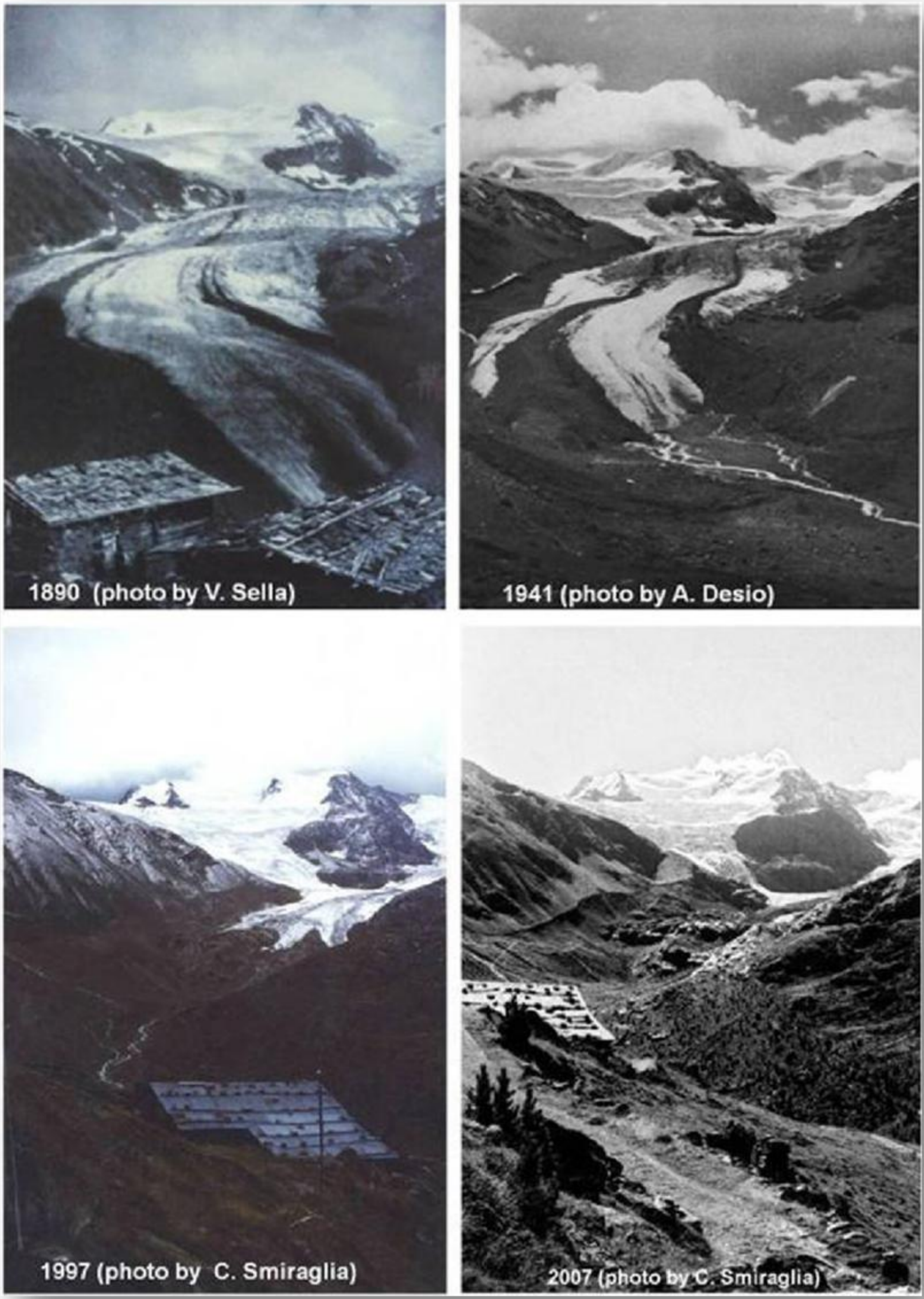

Figure 2.3Comparison of photos showing the strong retreat witnessed by Forni Glacier. The photos were taken in 1890 (by V. Sella), in 1941 (by A. Desio) and in 1997 and 2007 (by C. Smiraglia), respectively

2.4.2 Impacts of Temperature and Precipitation Change

Temperature and precipitation are the main climatic factors which control glacier mass balance. When the amount of snowfall decreases in the mountain region, it reduces the snow accumulation in the upper part of the glacier, and similarly, at the lower part, a rise in temperature significantly increases the ice melting, both lead to faster retreat of the glacier. Both in the Alps and Himalayan mountain region, due to reduced winter snowfall and variable monsoon precipitation, produced uneven glacier responses; some glaciers retreat faster while some others remain stagnant due to debris cover. Stability of moraine is also controlled by these climatic variations and reshape the overall geomorphic evolution of glacier environment (IPCC, 2021; Bolch et al., 2012; Haeberli et al., 2017).

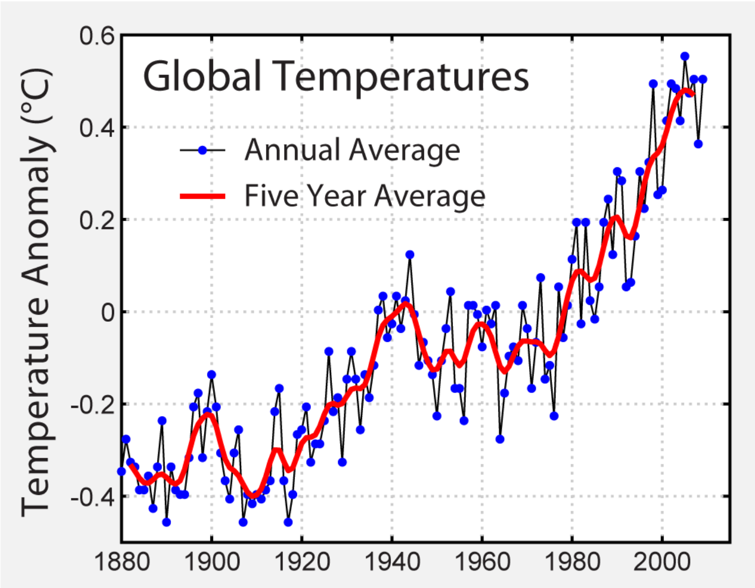

Figure 2.4 Global temperature anomalies (1880–2000) showing a consistent warming trend.(AntarcticGlaciers.org (2023))

2.4.3 Effects on Geomorphology and Landscape Evolution

The retreat of glaciers triggered due to warming triggers a rapid geomorphological response called the paraglacial crisis (Ballantyne, 2002; Curry, 2000). Glacier environments in alpine and Arctic areas are currently undergoing this adjustment. Due to changes in thermal and hydraulic boundary conditions, moraines are being subjected to failure. This means that when the temperature rises, it increases the melting of ground ice (permafrost), leading to shear strength reduction, increased pore water pressure, and internal piping, which reduce the stability of the moraine slope. This leads to an increase in potential mass movements far beyond normal rates. In both the Alps and the Himalayas, such transformations reshape the mountain geomorphology, emphasizing the need for monitoring and hazard assessment (IPCC, 2019; Haeberli et al., 2017).

2.5 Moraine Instability and Related Hazards

2.5.1 Causes of Moraine Instability

nstability of moraine is mainly influenced by factors such as geological, geomorphological, and climate. The most common cause of moraine instability is the melting of buried ice within the body, which is responsible for the surface deformation, subsidence, and internal collapse of the ridge. When the climatic pattern changes, it affects the hydrological regime of moraine deposits, leading to an increase in pore water pressure and lowering of shear strength. At the end, the presence of unconsolidated and poorly sorted sediments, permafrost degradation, and steep slopes of ridges contribute to instability (Benn & Evans, 2010; Haeberli et al., 2017).

In addition to the internal factors, some external factors like intense rainfall and seismic activity can cause the failure of moraine and large-scale debris movement. These combinations of internal and external factors pose the reactivation of unstable morainic structures and risks to downstream areas (Richardson & Reynolds, 2000; Frey et al., 2010).

2.5.2 Slope Failure and Mass Movement Processes

Slope failure occurs due to the unbalance between driving forces like gravity and pore water pressure exceeding the resisting forces of shear strength and cohesion. When buried ice melts or as rainfall infiltrates loose sediments, it increases the pore pressure, reducing the effective stress and helping the slope movement. Failure mechanisms are such as shallow landslides, debris slides, rotational slumps, or large-scale debris flows depending on the water content and composition of sediments in the moraine (Benn & Evans, 2010).
In the Alpine and Himalayan regions, thawing permafrost and intense monsoon rainfall also increase the frequency of slope failure. Once the moraine starts to fail, this can mobilize the total area of the moraine, and the resulting unconsolidated sediments may block the stream, form temporary lakes, and later it can transform into high-velocity debris flows. Continuous rainfall and heavy runoff can erode the moraine surface causing heavy floods and debris flow downstream. Continuous permafrost degradation further speeds up the process, reshaping the landscape and creating geomorphic hazards (Haeberli et al., 2017; Frey et al., 2010; Richardson & Reynolds, 2000).

2.5.3 Geomorphic and Social Risks in High Mountain Regions

Moraine instability and related mass movement is a serious issue in mountain regions and for the residing inhabitants. GLOF hazards are the main risks related to moraine instability, as they can release huge volumes of water and debris downstream. In some recent cases in the Alps and Himalayas, such events have caused loss of life, damage to infrastructure, and long-term modification of the landscape. Historical records confirm the catastrophic potential; GLOFs were responsible for approximately 32,000 deaths in Peru during the 20th century (AntarcticGlaciers.org, 2024) Some characteristics of the Himalayas, such as steep terrain, active tectonics, and heavy monsoon rainfall, increase the likelihood of moraine failure, while in the Alpine region the main triggering phenomena are permafrost degradation and glacier retreat. Climate change has increased the chance of such hazards by destabilizing the morainic slopes. Therefore, it is essential to have knowledge of potential moraine failure in relation to social risk to develop effective approaches such as early warning systems, hazard mapping, and sustainable mountain management strategies which can reduce potential hazards (Richardson & Reynolds, 2000; Huggel et al., 2004; Haeberli et al., 2017).

3. Integrated Methods for Moraine Instability Assessment

3.1 Conceptual Framework for Method Comparison

Moraine instability is the result of the interaction of geomorphological, climatic and mechanical processes and it acts at different spatial and temporal scales. As described in Chapter 2, glacier retreat, melting of buried ice, changes in thermal conditions and changes in water balance slowly change the internal structure and the surface of moraine deposits, which increases the susceptibility to deformation, which leads to failure of moraines. These complex factors result in difficulty assessing moraine-related hazards by one single investigation method.

Due to this, an integrated methodological framework is therefore required to assess moraine instability. In this study, four main categories of investigation methods are discussed: survey, geomorphological mapping, monitoring, stability and runout modelling. Each of these methods gives the behaviour of moraine in a specific way and complementary information can be collected and presents limitations on data availability and site accessibility. (Benn & Evans, 2010; Etzelmüller & Hagen, 2020)

Survey and geomorphological mapping are the basis of moraine instability assessment by identifying the landforms, deformation features on the moraine, and areas of interest. Monitoring approaches analyse the temporal changes such as surface deformation, erosion, and volume variation, where multi-temporal data are available. Stability modelling provides information about failure initiation by analysing the balance between driving and resisting forces, while post-failure behaviour is assessed by runout modelling. Runout modelling focuses on flow propagation, erosion, and deposition processes of the debris. Modelling of such unstable moraine surfaces requires simplifications and assumptions, and their reliability mainly depends on the quality of available data. (Hungr et al., 2014)

Application of these methods depends significantly on mountain environments. Availability of data and better accessibility benefit Alpine regions. It allows more quantitative application of both observational and modelling techniques. In contrast, limited access and less data availability make the Himalayan environment less studied. The comparative evaluation of these methods under different data availability conditions is adopted as a conceptual framework in this thesis. It is an already established approach in geomorphological hazard assessment; the methodological framework is the combined use of observed data and modelling techniques that is applied to contrasting mountain conditions.

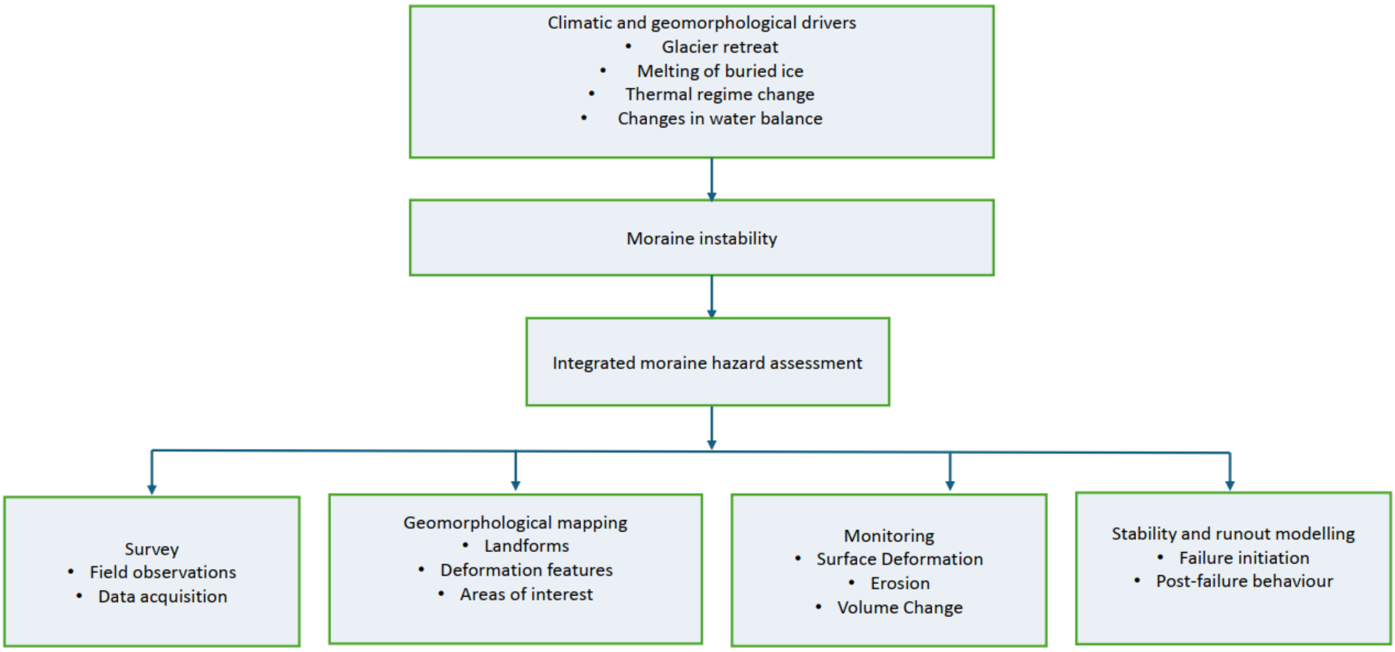

Figure 3.1 Conceptual framework illustrating the integrated methodological approach used to assess moraine instability.

3.2 Survey Methods

It is the first step to provide direct information on site-specific geomorphological conditions in the assessment of moraine instability and information about moraines. Field-based surveys are used for identification of surface features such as scarps, cracks, tension zones, and displaced blocks, which are commonly connected to unstable moraine deposits. These surveys are very important to identify active or potentially unstable moraine surfaces and to define areas of interest for further study.

In glacial environments, surveys also contribute to analysing material characteristics, which include grain size distribution, degree of consolidation, and information on buried ice. Site investigations provide visual evidence of irregular surface morphology, which can suggest internal degradation processes related to glacier retreat and permafrost thaw. (Benn & Evans, 2010; Etzelmüller & Hagen, 2020).

Table 3.1Characteristics and limitations of field-based moraine investigations.

Feature / Region	**Alpine Environments**	**Himalayan Environments**	**Data Contribution to Stability**
Accessibility	High (infrastructure-supported)	Low (remote, extreme relief)	Determines frequency of monitoring
Key Surface Indicators	Scarps, cracks, vegetation shifts	Large-scale displacements, boulders	Identification of active instability
Subsurface Data	Direct sampling, GPR, boreholes	Often restricted to visual proxies	Grain size, ice content, consolidation
Survey Frequency	Repeated/Seasonal	Occasional/Post-event	Analysis of temporal degradation
Primary Limitation	Cost of high-tech instrumentation	Logistical and safety constraints	Need for remote sensing integration

The effectiveness of survey methods depends on site accessibility and safety conditions. Relatively easier access and proper infrastructure often help repeated field surveys and detailed ground observations in Alpine regions, but Himalayan environments are more difficult to access and are characterized by extreme topography, remoteness, and logistical constraints, which limit frequent direct field investigations. This results in Himalayan regions often being restricted to rapid assessments and post-event observations.

Despite these limitations, remote sensing techniques support the collection and interpretation of data and modelling techniques in moraine instability assessment. However, surveys alone are not sufficient for quantitative assessment of moraine deposit stability, and correct integration of mapping, monitoring, and modelling approaches is needed within a comprehensive methodological framework.

3.3 Geomorphological Mapping Approaches

Mapping of glacier–moraine systems provide spatial information on landforms, surface processes, and morphological relationships for assessing moraine instability. It identifies and classifies morainic ridges, channels, erosion zones, and depositional areas, which are very important for understanding the spatial extent and potential instabilities.

In glacial environments, mapping is commonly based on the interpretation of remote sensing data such as satellite imagery, aerial photographs, and digital elevation models (DEMs). Remote sensing data define moraine boundaries, slope, aspect, runout paths, and geomorphic indicators of instability over large and very remote areas (Benn & Evans, 2010). To record the regional geomorphological setting and local instability features, multi-scale mapping approaches are useful. When combined with field surveys, it is easier to validate mapping results and improve the reliability of interpretations. However, in areas where field measurements are difficult, mapping mainly relies on remotely sensed data, increasing uncertainty in subsurface conditions.

The use of geomorphological mapping varies between mountain regions. In the Alps, high-resolution topographic data and repeated surveys allow detailed and accurate mapping of morainic features. However, the use of medium- to coarse-resolution satellite data in Himalayan regions may limit the identification of small-scale moraine features. Despite these limitations, geomorphological mapping is a key method for moraine instability assessment, as it provides essential information for monitoring strategies and modelling tools. (Etzelmüller & Hagen, 2020).

Figure 3.2 Moraine landforms in a glacial environment from the Manang region, Nepal, illustrating lateral moraines and depositional ridges typically mapped using remote sensing and field observations. Image from Wikimedia Commons.

3.4 Monitoring Strategies and Indicators

Monitoring provides information on the temporal evolution of geomorphological processes. Monitoring focuses on detecting changes over time, such as surface deformation, erosion, and volume variation, making it very important for moraine instability assessment. In glacial and periglacial environments, monitoring uses multi-temporal datasets derived from remotely sensed data, such as digital elevation models (DEMs), satellite imagery, and aerial photographs. By using DEM differencing, it identifies elevation changes, erosion and deposition areas, and high deformation of moraine surfaces, and provides indicators of instability development. (Etzelmüller & Hagen, 2020).

Monitoring approaches can also include indirect indicators of instability, such as changes in runout patterns, terrain roughness, or the formation of cracks and movements over time. These monitoring data are very useful where continuous measurements are not feasible. The accuracy of monitoring results depends on data resolution, acquisition frequency, and georeferencing. Alpine regions benefit from repeated surveys and long-term datasets, whereas in the Himalayas very limited or irregular monitoring data restrict the ability to track continuous instability processes.

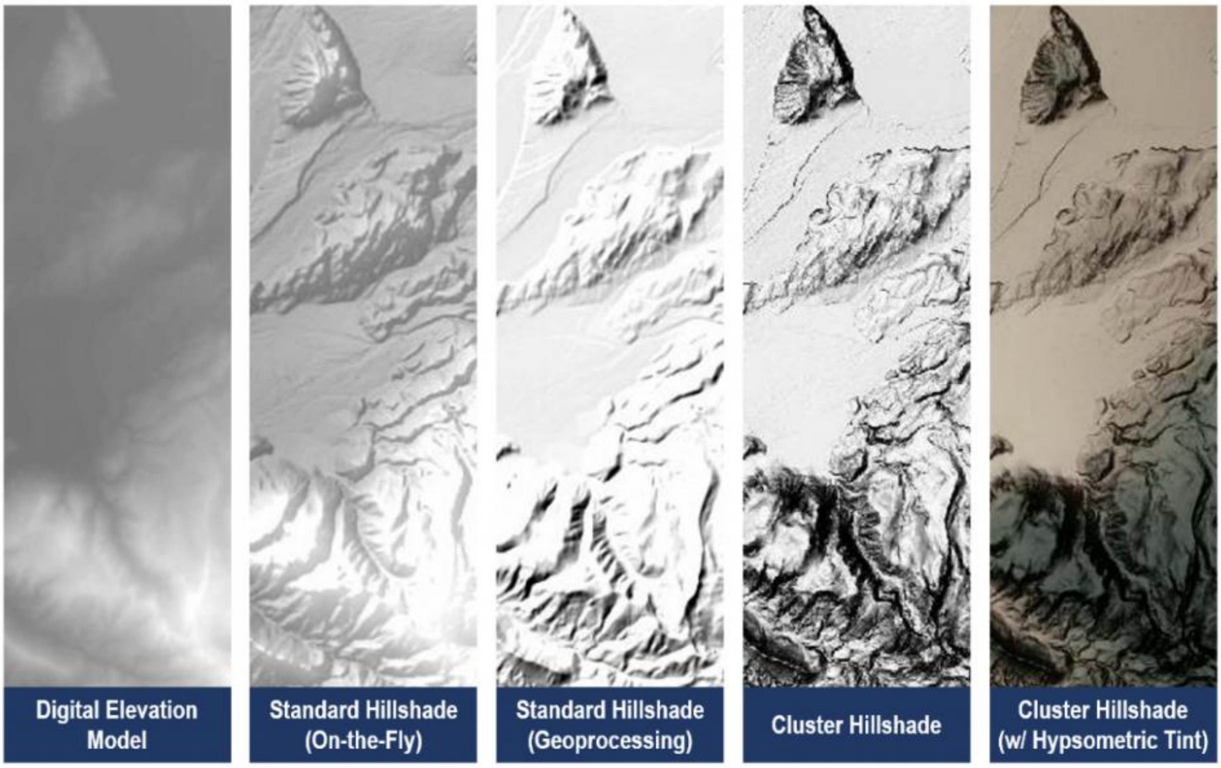

Figure 3.3 Example of digital elevation model (DEM)–derived hillshade visualization illustrating terrain representation used in multi-temporal monitoring. Image from USGS.

3.5 Stability Modelling (Limit Equilibrium Method)

In the limit equilibrium method, it uses the assumption that the failure surface is along a predefined slip surface, and the overall equilibrium of the slope is evaluated by balancing driving and resisting forces or moments acting on the potential sliding mass. There are different formulations and methods that allow for the calculation of driving and resisting equilibrium conditions, while soil and debris resistance is evaluated by simplified models, such as the Mohr–Coulomb failure criterion.

In the context of moraine instability, the modelling approach is firstly used to investigate the sensitivity of slope stability and its variation with material properties, pore water pressure conditions, and external effects such as rainfall or groundwater rise. This study helps in the identification of potentially unstable slope configurations and provides an estimation of the factor of safety under different conditions.

However, limit equilibrium modelling has several simplifying assumptions, such as results being mainly dependent on the selection of slip surfaces and input parameters, and the neglect of three-dimensional effects and stress–strain behaviour. Therefore, this tool is more useful for screening and comparative purposes rather than a predictive representation of failure processes.

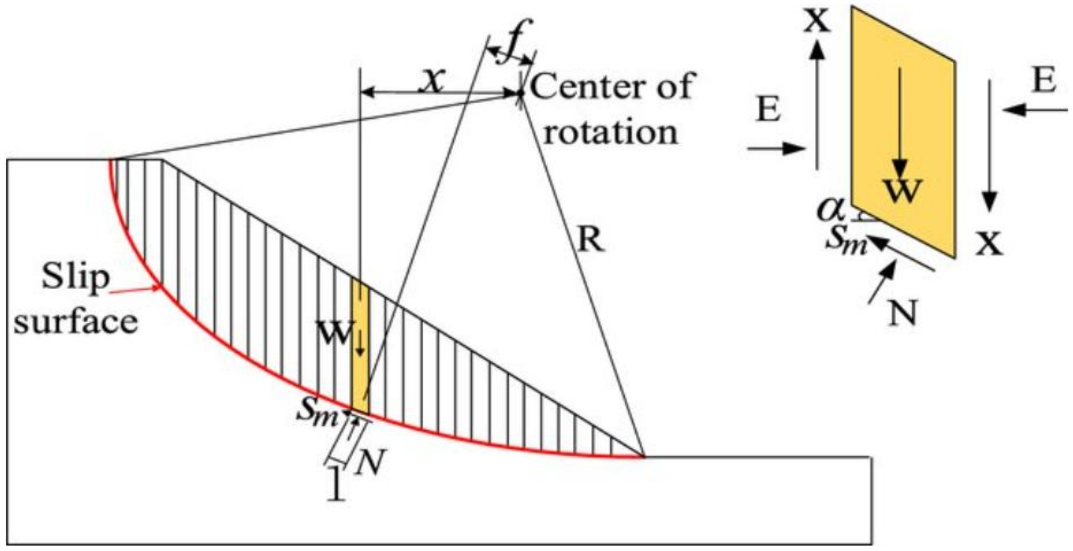

Figure 3.4 Schematic illustration of the limit equilibrium method for slope stability analysis, showing a predefined slip surface and the forces acting on a potential sliding mass (adapted from the geotechnical literature).

3.5.1 Theoretical Basis and Assumptions

The limit equilibrium method is a well-established approach for slope stability calculation (Fredlund and Krahn, 1977; Duncan et al., 2014). The method is founded on the assumption that a slope loses stability along a predefined slip surface and can be assessed by calculating the equilibrium between driving and resisting forces or moments acting on the potential sliding mass.

In this method, resisting forces are defined using simplified shear strength models; the most common method is the Mohr–Coulomb failure criterion, which defines material resistance as a function of cohesion, friction angle, and normal stress (Terzaghi et al., 1996). The factor of safety is therefore defined as the ratio between the available shear strength of the material and the mobilized shear stress along the assumed failure surface. Generally, the analysis is performed under static conditions and is most commonly represented in two dimensions (Duncan et al., 2014).

- **Factor of Safety (FoS):**

The factor of safety (FoS) is defined as the ratio between the available shear strength and the mobilised shear stress along the assumed failure surface:

$$\mathrm{FoS} = \frac{\text{Available shear strength (resisting)}}{\text{Mobilised shear stress (driving)}}$$

Table 3.2 Stability classification based on factor of safety (FS) values

Value	Stability Status	Meaning
FS > 1.0	**Stable**	Resisting forces exceed driving forces
FS = 1.0	**Critical/Limit Equilibrium**	The slope is at the point of failure
FS < 1.0	**Unstable**	Driving forces exceed strength; failure is expected.

- **Failure criterion**: Shear strength is commonly represented using the Mohr–Coulomb failure criterion:

$$\tau = c' + (\sigma n - u)\tan\phi'$$

where τ is the shear strength, c' is the effective cohesion, σ_n is the normal stress, u is the pore water pressure, and ϕ' is the effective friction angle (Terzaghi et al., 1996).

- **Limit equilibrium formulation using Mohr–Coulomb criterion**

For a potential slip surface, the factor of safety can be expressed as:

$$\text{FoS} = \frac{c' + (\sigma_n - u)\tan\ \phi'}{\tau}$$

where:

- c'= effective cohesion
- σ_n= normal stress acting on the slip surface
- u= pore water pressure
- ϕ'= effective friction angle
- τ= mobilised shear stress along the slip surface

3.5.2 Model Inputs and Applicability

The selection of parameters is the main challenge in the case of moraine deposits. Complex depositional processes during glaciation and varying degrees of consolidation result in a wide range of possible parameter values (Duncan et al., 2014; Haeberli et al., 2017).

Slope geometry: The geometry of the slope (moraine deposit) is defined using various methods such as field surveys, digital elevation models, or geomorphological mapping. Geometry controls the location of potential failure surfaces and the shape of the assumed slip surface (Duncan et al., 2014).

Friction angle: For moraine deposits, the friction angle typically varies between 30° and 45°, depending on grain size distribution, clast angularity, density, and degree of interlocking (Mitchell and Soga, 2005). Surface vegetation and root reinforcement also play a role in parameter selection and may locally increase apparent friction.

Cohesion: Effective cohesion is generally assumed to be low for unconsolidated moraine debris, commonly ranging between 0 and 30 kPa. If the presence of buried ice or partially frozen tills is observed, cohesion may need to be increased. However, apparent cohesion due to ice cementation is highly sensitive to temperature and is rapidly lost during thawing (Haeberli et al., 2017).

Pore water pressure ($\boldsymbol{u}$ or $\boldsymbol{R_u}$): The main triggering factor for moraine instability is pore water pressure. Stability analyses commonly investigate sensitivity to rising groundwater levels or increasing pore pressure ratios (R_u) to simulate rainfall infiltration, snowmelt, or meltwater accumulation (Fredlund and Krahn, 1977). Variations in pore water pressure reduce effective stress and shear resistance along potential failure surfaces.

Table 3.3 : Summary of the main input parameters commonly used in limit equilibrium slope stability analyses of moraine deposits and their relevance for moraine instability assessment.

Parameter	Symbol	Typical range / description	Relevance for moraine stability
Friction angle	ϕ'	30°–45°	Controls shear resistance
Cohesion	c'	0–30 kPa	Low resistance of unconsolidated debris
Unit weight	γ	Site-dependent	Controls driving forces
Pore water pressure	u / Ru	Variable	Main triggering factor
Slope geometry	–	DEM / profiles	Controls slip surface geometry

Given the uncertainty associated with material properties and hydrological conditions, sensitivity analysis is required for limit equilibrium modelling in glacial environments. This approach is suitable for identifying and assessing pre-failure stability and potentially unstable slopes. Such configurations are defined prior to erosion or runout modelling, which are addressed separately in subsequent modelling stages.

3.5.3 Slide2 Rocscience software

Slide2 is a two-dimensional slope stability analysis software developed by Rocscience. The software uses limit equilibrium formulations for the evaluation of slope stability and the calculation of the factor of safety (Rocscience, 2023). The software provides an integrated environment for geometry definition, material assignment, dry and saturated conditions, and factor of safety calculation.

Geometric representation: Slide2 uses two-dimensional geometry under plane strain assumptions. Slope profiles are defined in two ways: surface topography and subsurface stratigraphy. This allows the modelling of layered deposits, such as upper layers consisting of moraine deposits and underlying materials, in order to evaluate potential failure surfaces within the defined geometry (Duncan et al., 2014).

Slip surface search methods: In Slide2, both predefined and automated slip surface search methods can be used for the evaluation of potential failure surfaces. Common approaches include circular and non-circular failure surface searches, which allow the identification of critical slip surfaces associated with minimum factors of safety (Fredlund and Krahn, 1977).

Material and hydraulic inputs: Material properties are assigned to predefined material layers or zones using simplified strength models consistent with limit equilibrium assumptions. Groundwater conditions are defined through the assignment of water tables, piezometric lines, or pore pressure distributions. This allows the assessment of hydrological effects on slope stability under different hydrological scenarios (Duncan et al., 2014).

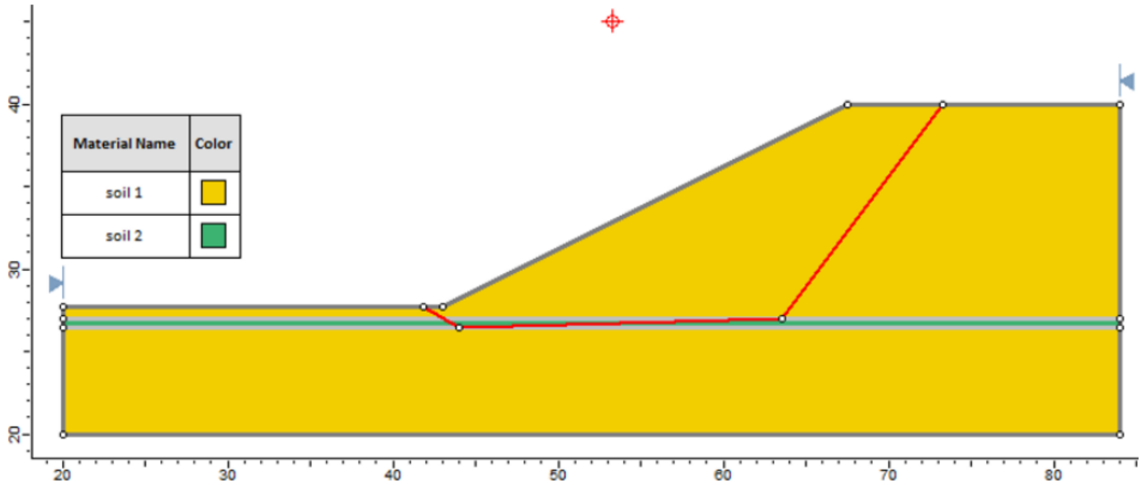

Figure 3.5 Example of a two-dimensional slope geometry setup in Slide2, showing material zoning (Rocscience)

Analysis output: Slide2 provides the primary output in the form of the factor of safety associated with each analysed slip surface. Additional outputs include visualisation of critical failure surfaces, force distributions, and sensitivity to changes in input parameters, which support comparative stability assessments.

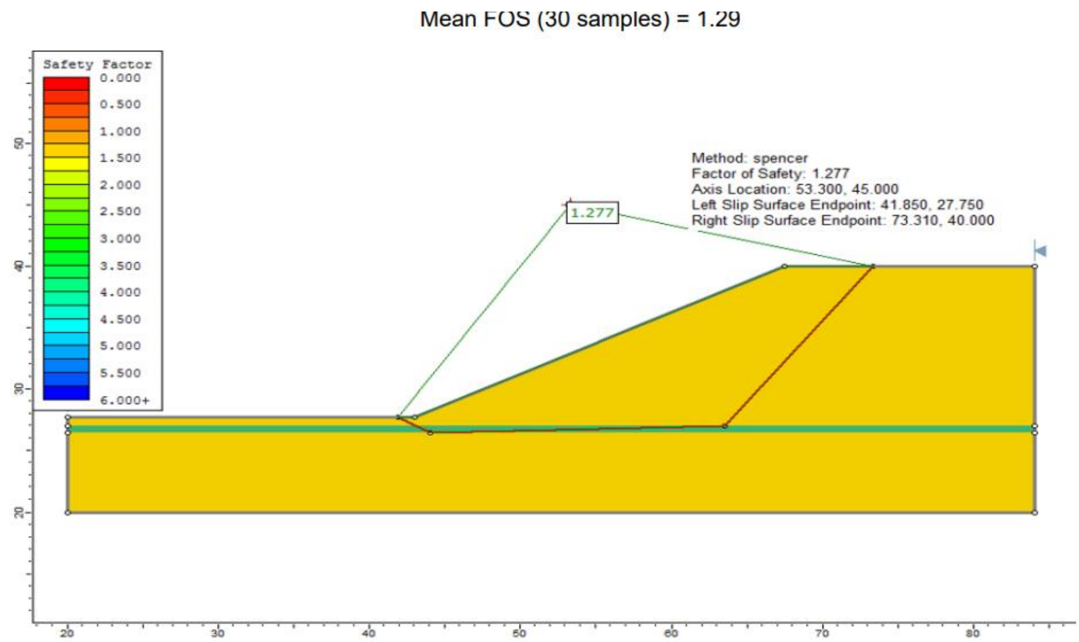

Figure 3.6 Example of limit equilibrium slope stability results obtained using Slide2 (Rocscience)

Limitations: Slide2 does not provide information on deformation, failure propagation, or time-dependent processes. Three-dimensional effects of topography and material heterogeneity are simplified through the use of a two-dimensional representation.

3.6 Runout Modelling (DAN3D)

DAN3D (Dynamic Analysis of Landslides in 3D) is a semi-empirical code based on continuum mechanics, designed specifically for extremely rapid landslides and debris flows.

3.6.1 Governing Principles of DAN3D

DAN3D simulates rapid landslides and debris-flow runout over complex terrain in 3D. This model is based on a depth-averaged, Lagrangian numerical model, that uses the **equivalent fluid approach** to simulate the runout of rapid landslides. Lagrangian numerical model is adapted from the concept of smoothed particle hydrodynamics. In this model, landslides and debris flows are simulated as moving masses that are represented as flowing layers whose behaviour is governed by the conservation of mass and momentum (Hungr and Evans, 1996; McDougall and Hungr, 2004). The equivalent fluid approach replaces the heterogeneous material with an equivalent fluid; it can represent the real properties of the material. a comparasion of the prototype material and the equivalent fluid is shown in the figure 3.7.

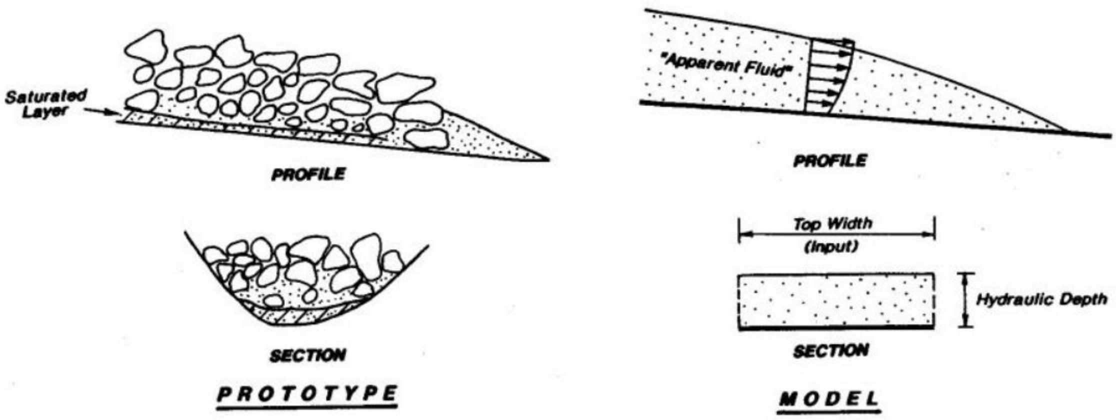

Figure 3.7 Comparasion of hategerous material with the equivalent fluid. (Hungr 1995)

In this approach, vertical velocity variations are neglected, but the internal velocity profile of the moving mass is averaged over the flow thickness, which allows the efficient simulation of large-scale runout processes (McDougall and Hungr, 2004). DAN3D strongly controls flow motion through the underlying topography using a digital elevation model, which governs flow direction, spreading, and deposition patterns.

The depth-averaged formulation used in DAN3D is efficient for modelling long runout distances and large affected areas. At the same time, this model simplifies internal deformation processes and stress–strain behaviour, which are not explicitly resolved within the model.

3.6.2 Rheological Framework

In DAN3D, the behaviour of flow is controlled through basal resistance laws, which means that resisting forces control flow thickness and velocity. These rheological parameters define flow mobility, runout distance, and deposition patterns and represent a key component of runout modelling (Hungr and Evans, 1996; McDougall and Hungr, 2004).

Frictional (Coulomb-type) rheology: A constant friction coefficient is used as the basal resistance term, and it is assumed that basal shear resistance is proportional to the normal stress acting on the base of the moving mass (Hungr and Evans, 1996). The basal shear stress is expressed as:

$$\tau = \sigma_n(1 - r_u)\tan\,\phi$$

where:

- $\tau$is the basal shear stress (resistance),
- $\sigma_n$is the total normal stress acting on the bed,
- $r_u$is the pore pressure ratio, and
- $\phi$is the basal friction angle.

Frictional rheology is suitable for coarse-grained materials such as moraine deposits, relatively dry or low fluid-content materials, where resistance of the moving mass is mainly friction-controlled. In this study, the frictional model is applied for the calibration of initial model parameters and to evaluate runout length using frictional rheology.

Voellmy rheology: The Voellmy rheology adds an additional velocity-dependent resistance term to the frictional rheology to account for turbulent effects in highly mobile flows. The basal shear stress (McDougall and Hungr, 2004; Voellmy, 1955) is expressed as:

$$\tau = \sigma_n(1 - r_u)\tan\,\phi + \frac{\gamma v^2}{\xi}$$

where:

- $\tau$is the basal shear stress (total resistance),
- $\sigma_n(1 - r_u)\tan\,\phi$represents the **frictional component**, in which $\sigma_n$is the total normal stress, $r_u$is the pore pressure ratio, and $\phi$is the basal friction angle,
- γ is the unit weight of the flowing material,

- v is the flow velocity, and
- ξ is the turbulence coefficient (Voellmy coefficient).

Voellmy rheology enables the simulation of enhanced mobility and long runout distances, mainly in channelised debris flows. In this study, the Voellmy model is adopted to simulate highly mobile runout behaviour of the flow and to compare the observed runout and deposition pattern with simulation results.

Even though DAN3D allows several types of rheology, this thesis focuses on frictional and Voellmy theologies, which are suitable for moraine-rich debris flows and are most used in current research. For lower mobility and initial runout behaviour, the frictional model is used, while the Voellmy model is applied to simulate highly mobile flows and longer runout distances. This combined approach supports a comparative assessment of runout behaviour under varying conditions. Detailed calibration and parameter selection are addressed in the following chapter.

3.6.3 Entrainment and Bulking Concept

Entrainment is described as the process by which basal surface material is incorporated into the moving debris during runout, leading to an increase in flow volume and mobility. In moraine deposits and moraine-derived debris flows, the entrainment process plays an important role in controlling runout distance and deposition patterns (Hungr and Evans, 1996; McDougall and Hungr, 2004).

In the DAN3D code, entrainment is implemented through erosion-based formulations. In this process, basal material is eroded, removed from its original position, and added to the flowing debris mass during motion. This results in bulking of the flow and modifies its dynamic behaviour as the flow progresses (McDougall and Hungr, 2005).

In moraine environments composed of unconsolidated glacial deposits; bulking effects are very high due to the high potential erosion rate. The parameters controlling entrainment may be defined spatially to distinguish between source areas, transport channels, and depositional zones, allowing a simplified but realistic representation of runout behaviour (Pichler, 2011).

3.6.4 Model Inputs for DAN3D

DAN3D runout modelling requires the definition of a set of inputs such as geometric, material, rheological, and numerical parameters that describe the initial conditions and behaviour of the moving mass. The quality and consistency of these input data determine the reliability and effectiveness of the model results (McDougall and Hungr, 2004; Pichler, 2011).

Topographic data: This is the fundamental input for DAN3D modelling, as the movement, spreading, and deposition of the flow are primarily controlled by surface morphology. Digital elevation model (DEM) and digital surface model (DSM) are used in the .grd file format to define the slope gradient, flow paths, channel confinement, and depositional areas. The accuracy and resolution of the DEM strongly influence the modelled runout behaviour, particularly in complex terrain (McDougall and Hungr, 2004; Pichler, 2011).

Grid-based input files (GRD files):

In DAN3D, GRD files are grid-based raster files; they allow spatially distributed information into the model software. GRD files are used for the representation of topography, source geometry, and spatial variability in material or entrainment properties. This approach provides flexibility in modelling heterogeneous terrain and different geomorphological conditions along the flow path. Typical GRD inputs in DAN3D include elevation grids for topography, thickness grids for initial source geometry, and erosion grids for defining spatial variability in entrainment (McDougall and Hungr, 2004; Pichler, 2011).

Creation of GRD files:

GRD files are created from the DSM or DEM data using geographic information system (GIS) software. To ensure compatibility with the DAN3D software, raster grids are prepared with the same resolution, extent, and coordinate reference system for all the GRD files. During preprocessing, grids may be clipped, resampled, or reclassified to represent specific modelling inputs such as source areas or channel paths (Pichler, 2011).

It should be prepared carefully to avoid errors in grid alignment, resolution, or value assignment, as differences in any value can affect the simulation results. For this reason, preparation of the grid files is a critical step in DAN3D setup (McDougall and Hungr, 2004). For this study, QGIS software is used to prepare the source, thickness, and erosion .grd files with 10 m resolution derived from DSM.

Rheological parameters:

As described in the previous section, rheological parameters are used to control flow velocity, runout distance, and deposition patterns. Rheological parameters are often constrained through back-analysis rather than direct measurement due to natural variability and uncertainty. The selection of rheological parameters represents a key source of uncertainty in runout modelling using the DAN3D code (McDougall and Hungr, 2004; Pichler, 2011).

Additional numerical and simulation inputs

To control the simulation, additional inputs are required that control the model resolution, stability, and computational performance (McDougall and Hungr, 2004).

Number of particles:

The moving mass of material is discretised into a finite number of particles, which represent the flowing material. This number influences the spatial resolution and smoothness of the flow.

Time step:
To control numerical stability and accuracy, the time step needs to be defined. Lower time steps improve the simulation accuracy but increase computational time, while larger time steps may lead to numerical instability.

Simulation time:
It controls how long the runout process is simulated. Simulation time must be sufficient to allow the flow to reach the final deposition zone and come to rest.

These parameters balance computational efficiency and model accuracy and are typically derived from model calibration and modelling experience rather than direct physical measurement.

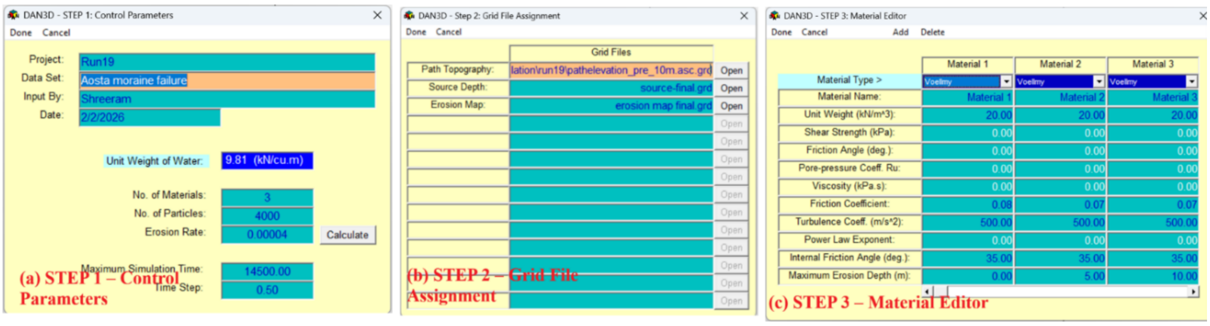

Figure 3.8 DAN3D model setup workflow showing (a) control parameters and numerical settings, (b) assignment of topography, source depth, and erosion input grids, and (c) definition of material properties and rheological parameters (DAN3D)

3.6.5 Back-analysis and Predictive Use

Using DAN3D back-analysis, many model parameters are derived that cannot be directly measured in natural environments. In this approach, model parameters are adjusted iteratively to reproduce model output, which is later compared with the characteristics of observed and documented events such as runout distance, inundation extent, and deposition patterns (Hungr and Evans, 1996; McDougall and Hungr, 2004).

The primary objective of back-analysis is to verify rheological and entrainment parameters within physically reasonable ranges and to assess the sensitivity of model results to parameter variations (Pichler, 2011). When a satisfactory agreement between observed and simulated runout behaviour is achieved, the calibrated model can be applied for predictive or scenario-based simulations. In the context of predictive modelling, it is used to study potential future events while acknowledging the uncertainty associated with parameter selection under different initial and triggering scenarios (McDougall and Hungr, 2004; Pichler, 2011). Therefore, model output from DAN3D is interpreted as a scenario-based assessment rather than deterministic predictions.

4. Study Area and Modelling Application

4.1 Alpine Study Area: Valpelline Region

Located in the Aosta Valley, north-west Italy, the Alpine study area Valpelline region is extended from the high mountain region of the Pennine Alps and the Grand Combin massif, which is characterised by strong relief and a wide elevation range. It develops starting from the Aosta Valley region, with a main direction North-East – South-West, until reaching the town of Bionaz, near the Swiss border, with an extension of approximately 60 km (Regione Autonoma Valle d'Aosta, 2018).

This region shows a pronounced glacial morphology with U-shaped sections, steep ridges, and massive deposits of glacial and fluvio-glacial origin (Benn and Evans, 2010). Due to the past and recent glaciation, a wide range of unconsolidated sediments is distributed along the slopes and valley floors, providing enough glacial till and morainic ridges for slope instability and debris-flow processes (Deline et al., 2015).

High-elevation areas of the Valpelline region host several small glaciers and associated moraine systems (Zekollari et al., 2019). Due to climate change and ongoing glacier retreat, it has modified the landscape and local hydrological conditions, which increase the exposure of moraine deposits (Haeberli et al., 2017). Seasonal snowmelt and heavy rainfall events in this region have changed the groundwater condition and pore-water pressure within unconsolidated materials (Beniston et al., 2018).

Since this Alpine region is composed of steep topography, glacial deposits, and variable hydrological changes, the Valpelline region is suitable as an Alpine setting for the study of moraine instability and debris-flow hazards (Stoffel and Huggel, 2012).

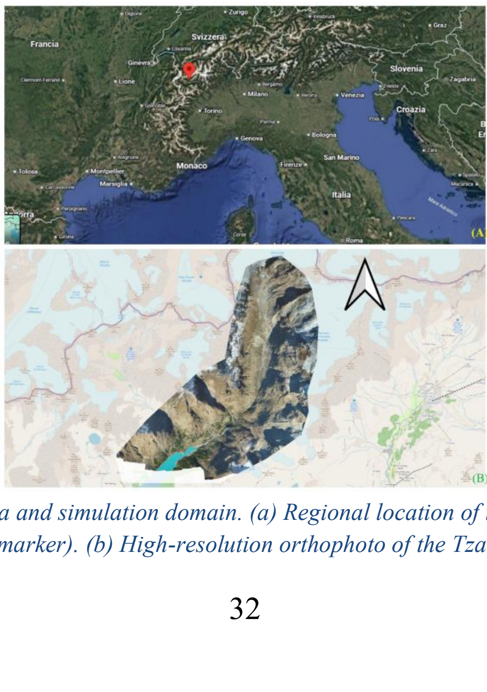

Figure 4.1 Overview of the study area and simulation domain. (a) Regional location of the study site within the Western Alps (indicated by the red marker). (b) High-resolution orthophoto of the Tza de Tzan glaciar area.

4.2 Tza de Tzan Glacier Area and Moraine System

The source area of detachment of moraine is in the Tza de Tzan glacier area in the upper Valpelline region, close to the Italian Swiss border within the Pennine Alps (Regione Autonoma Valle d'Aosta, 2018). This area represents a small Alpine glacier at a high-elevation environment, and it has undergone significant retreat in recent decades, which is consistent with the observed retreat pattern in the western Alps (Zekollari et al., 2019; Haeberli et al., 2017). The Place-Moulin Dam, a hydroelectric artificial dam built in the 1950s and 1960s, which is the final depositional area followed by the runout channel originating from this mountain region. (CVA S.p.A.; Regione Autonoma Valle d'Aosta, 2018).

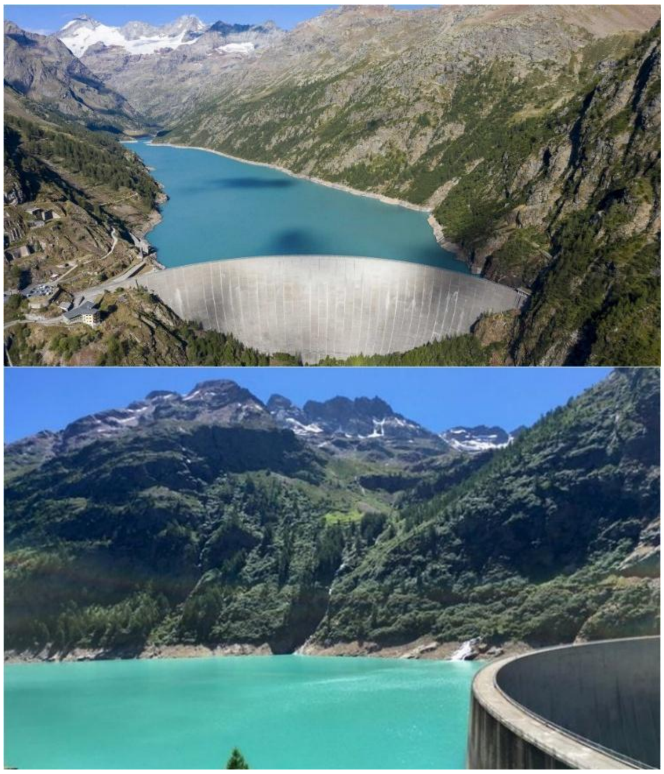

Figure 4.2 View of the Place-Moulin reservoir and dam within the Valpelline valley (CVA S.p.A)

This glacier area is accompanied by unconsolidated and heterogeneous glacial debris, generally found in moraine deposits. Large amount of moraine material consists of a wide grain-size distribution and loose packing, making it sensitive to hydrological forcing and erosion processes (Benn and Evans, 2010; Deline et al., 2015).

During intense rainfall events and periods of snowmelt, heavy surface drainage and surface runoff interact with these loose moraine deposits, locally enhancing erosion and instability potential (Deline et al., 2015; Beniston et al., 2018).

Like other glacial environments, pronounced glacier retreat and associated geomorphological changes have been seen in the Tza de Tzan glacier area. Figure 4.3 compares the historical and recent photographs of the Tza de Tzan glacier, where an excessive amount of melting shows concern over environmental and climate change. Some studies indicate that until the mid-20th century the Tza de Tzan glacier formed a single ice body with the Grandes Murailles glacier, but since 1850 it has experienced a cumulative frontal retreat of approximately 7 km. Recent studies in the Tza de Tzan glacier indicate that about 1.2 km of ice has retreated since 2002, which shifted the glacier front upward approximately 400 m in elevation (AostaSera). As visible in Figure X, this reduction of glacier mass led to increased exposure of unconsolidated moraine deposits, enhancing the risk of natural instability and sensitivity of the nearby landforms.

Figure 4.3 Comparison of historical and recent photographs of the Tza de Tzan glacier area illustrating long-term glacier retreat.

4.3 Moraine Instability and Debris-Flow Event (Alpine Case)

Instability of moraine deposits and collapse was seen in the upper Valpelline region on 29 June 2024 after intense rainfall and hydrological saturation, when a large section of the lateral moraine associated with the Tza de Tzan Glacier detached and mobilised as a debris-flow event (Costa, MSc thesis; AostaSera, 2024). After the collapse of the moraine slope, it affected the adjacent proglacial area and quickly transitioned into a debris-flow movement that travelled downslope along the valley floor and reached the Place-Moulin Dam (CVA S.p.A.; Regione Autonoma Valle d'Aosta, 2018).

Post-event observations show that the collapsed moraine deposit and associated material were transported via the Torrente Buthier de Valpelline, impacting the landscape and changing the morphology of the area (Costa, MSc thesis). In the immediate aftermath, CVA reported that a volume of approximately 2.5 million cubic metres of water and debris reached the Place-Moulin Dam, flows of over 112 cubic meters per second for more than 4 hours causing a rise in the lake level of about 4 m (AostaSera, 2024). After this event, dam outlets were partially obstructed due to heavy logs and sediments (CVA S.p.A.). The final estimated damage due to debris flow was 2.8 million euros.

Figure 4.4 Field photograph showing post-event conditions of the lateral moraine and evidence of erosion.

After the event, geomorphological changes along the proglacial plain and valley corridor were observed around the downstream channel. Documented reports of this event show that, due to erosion and deposition along the channel, trails and infrastructure were damaged, and widespread redistribution of unconsolidated debris occurred throughout the valley (Legambiente, 2024; Regione Autonoma Valle d'Aosta, 2018).

This is a documented instability event related to climate-change-driven glacier retreat and provides information on moraine collapse evolving into debris-flow activity in the Alps Modelling of stability and runout and their impacts are presented in subsequent sections.

4.4 Survey, Mapping, and Monitoring of instability features

Results derived from the geomorphological mapping, monitoring of the moraine system, and multi-temporal DSM analysis for the assessment of the Tza de Tzan moraine system are discussed in this section. The results are based on the available field observational data and interpretation of orthophotos and digital surface models, which give basic information for the stability and runout modelling presented in the next part.

4.4.1 Data Acquisition, Available datasets

The remote sensing data, aerial data acquisition, and primary photogrammetric processing were not performed as part of this thesis work. The datasets used in this study were acquired and processed by the DIATI GlacierLab of the Politecnico di Torino, in collaboration with DigiSky, Torino. In this study, these datasets developed by DIATI are used as the fundamental inputs for analysis and modelling (Costa, 2025).

Survey Background and Data Origin

A Tecnam P92 JS ultralight aircraft was used for the aerial survey. The aircraft was equipped with a Phase One iXM-RS150F metric camera (150 megapixels, 50 mm focal length), which ensures high-quality data capture suitable for alpine geomorphology studies (Costa, 2025).

Figure 4.5 Aerial survey platform and imaging sensor employed for the acquisition of photogrammetric datasets used in this study

Two datasets were selected from GlacierLab for this research:

DSM and Orthophoto 2022 (baseline): Acquired in September and October 2022.
DSM and Orthophoto 2024 (monitoring): Acquired on November 11, 2024

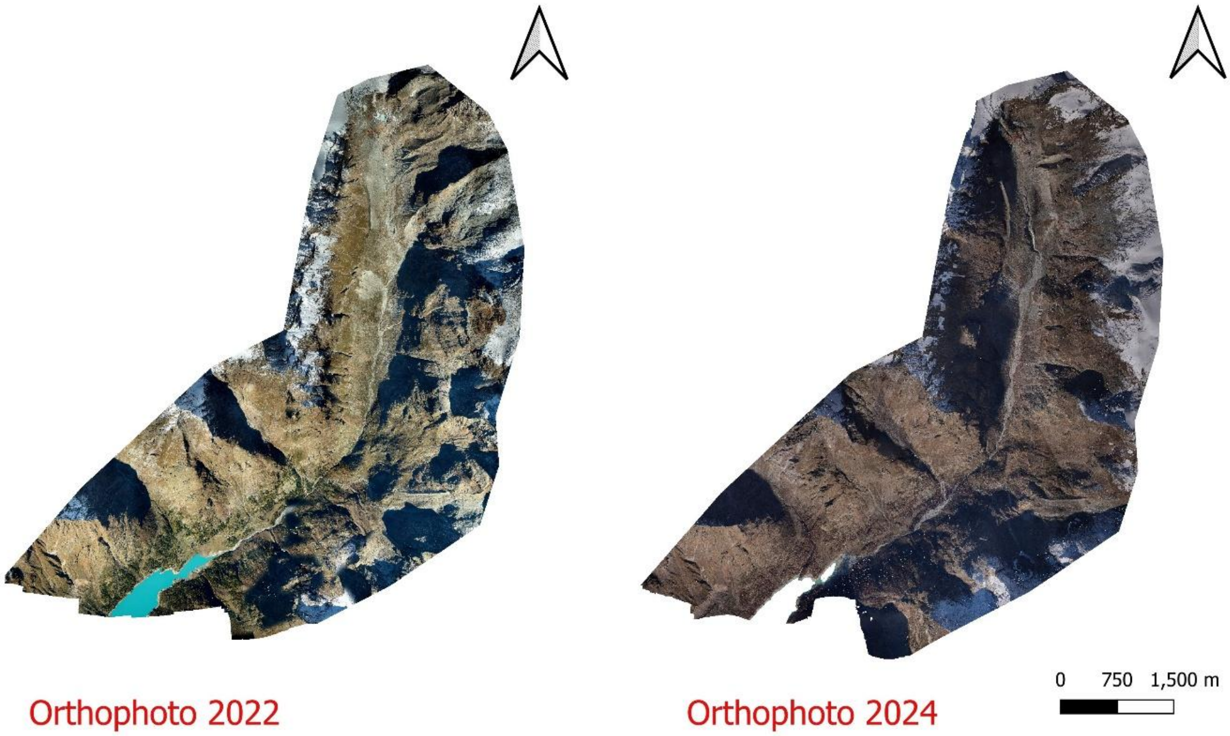

Figure 4.6 Orthophotos of the study area acquired in 2022 and 2024

Data Quality and Working Resolution:

Resolution and resampling: Although the original products generated by GlacierLab were rich in quality, for this study DSMs and orthophotos were resampled to a spatial resolution of 0.5 m. This resolution is considered appropriate for the monitoring and modelling, balancing the need for topographic detail for numerical simulations (Slide2 and DAN3D).

4.4.2 Geomorphological Mapping Results

Mapping of the glacial environment discussed in this study was carried out using high-resolution orthophotos and DSM-derived products such as hillshade and slope maps. The identification of the moraine system and downstream affected channel and depositional area is the focus of mapping.

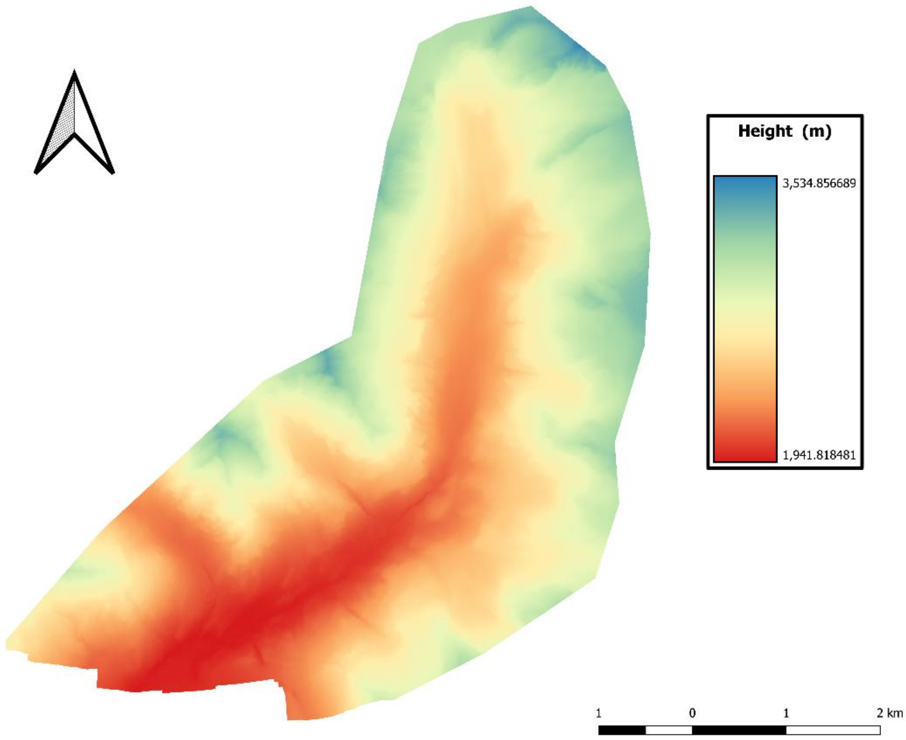

Figure 4.7 Topographic representation of the study area derived from the 2022 DSM, used to support geomorphological mapping.

Some of the mapping features are moraine crest, steep moraine faces, erosional scarps, downstream channel, main erosion zones, and depositional flat zones. Near the area where the moraine collapsed, features such as steep and irregular surface morphology were observed, which indicate zones potentially prone to instability. In the downstream section from the glacier and moraine system, a well-defined but narrow channel connecting the source area to the depositional zone toward the Place-Moulin Dam is observed.

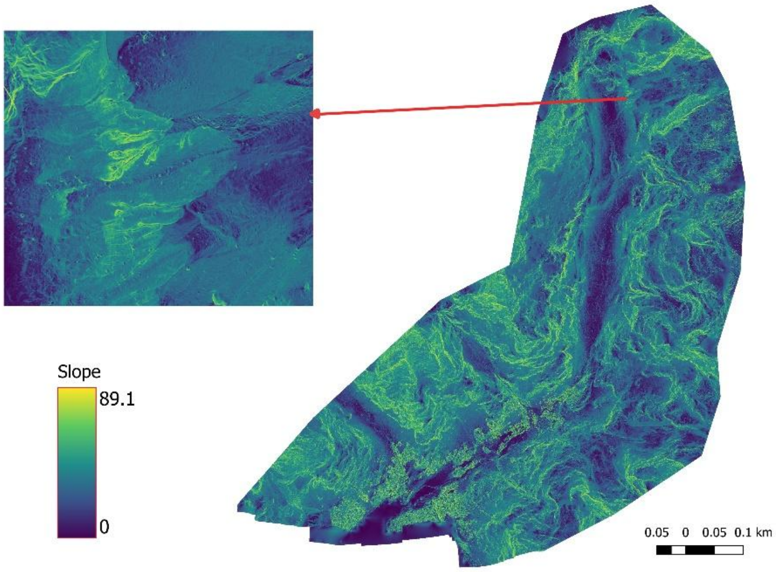

Figure 4.8 Slope distribution of the study area derived from the 2022 DSM, used to support geomorphological mapping.

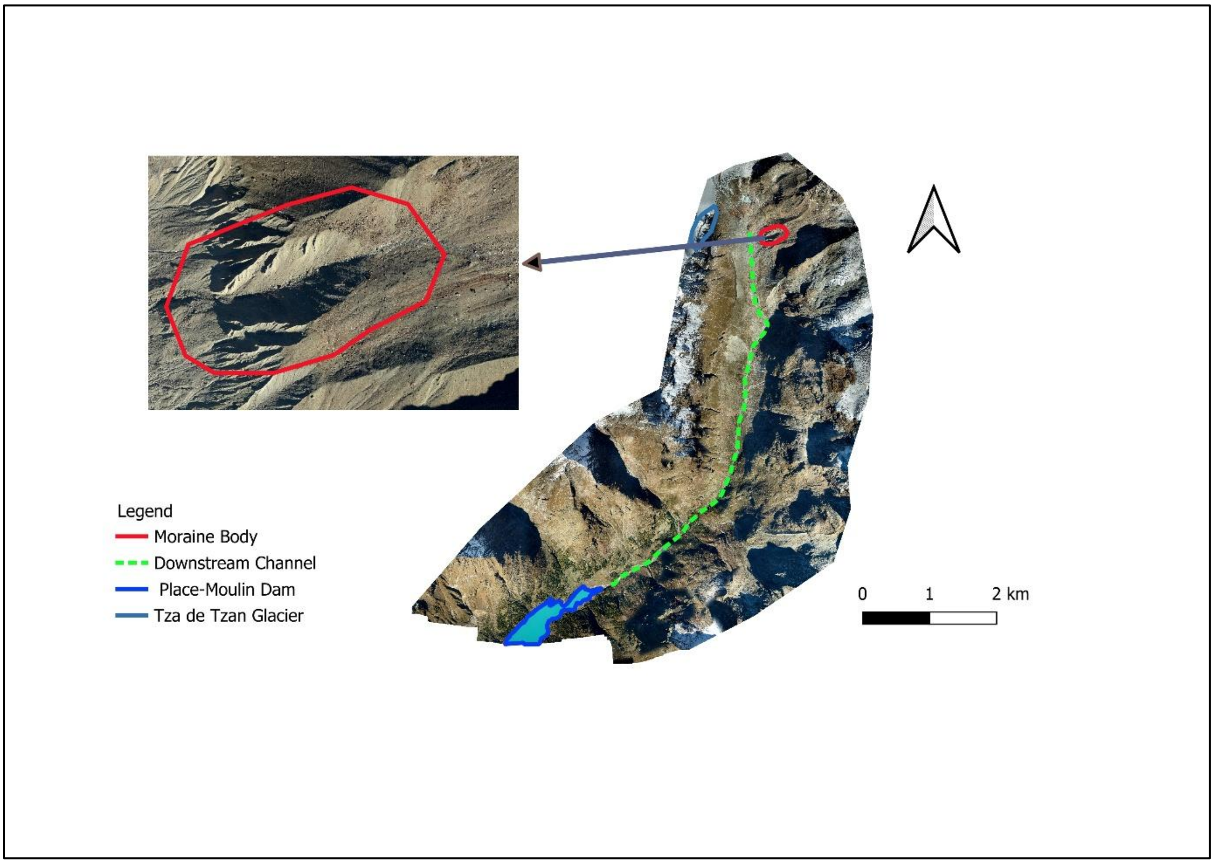

Figure 4.9 Geomorphological mapping of the study area based on orthophoto interpretation, showing the mapped moraine body, downstream channel, glacier extent, and the location of the Place-Moulin Dam.

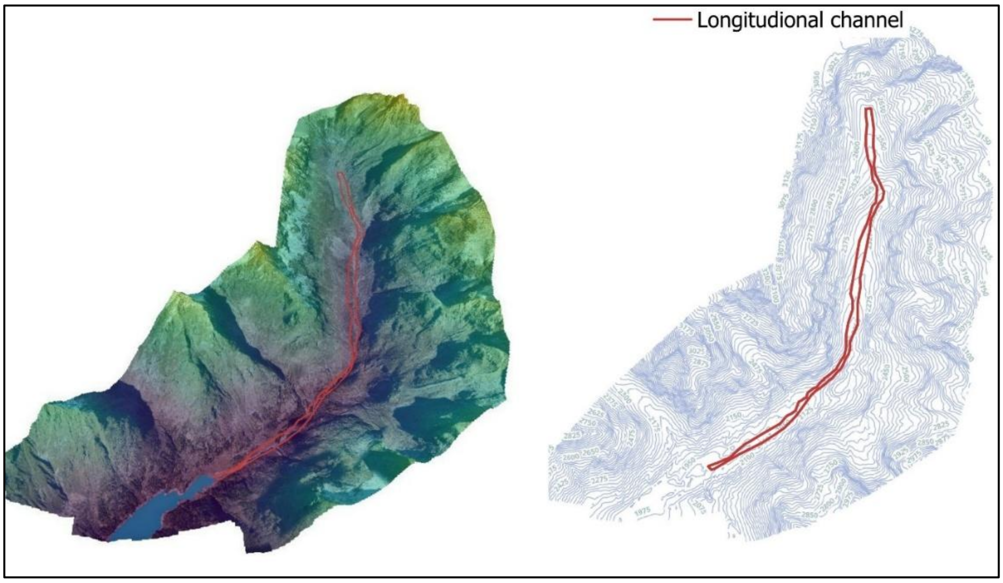

Figure 4.10 3D topographic view and 2D contour map of the study area with the mapped longitudinal channel.

4.4.3 DSM Differencing and Morphological Changes (2022–2024)

Change in local morphology between pre- and post-observed moraine instability was assessed by comparing DSMs generated from aerial photogrammetric surveys. The DSM differencing tool was used to identify and evaluate zones of surface lowering and accumulation, allowing the spatial distribution of erosion and deposition.

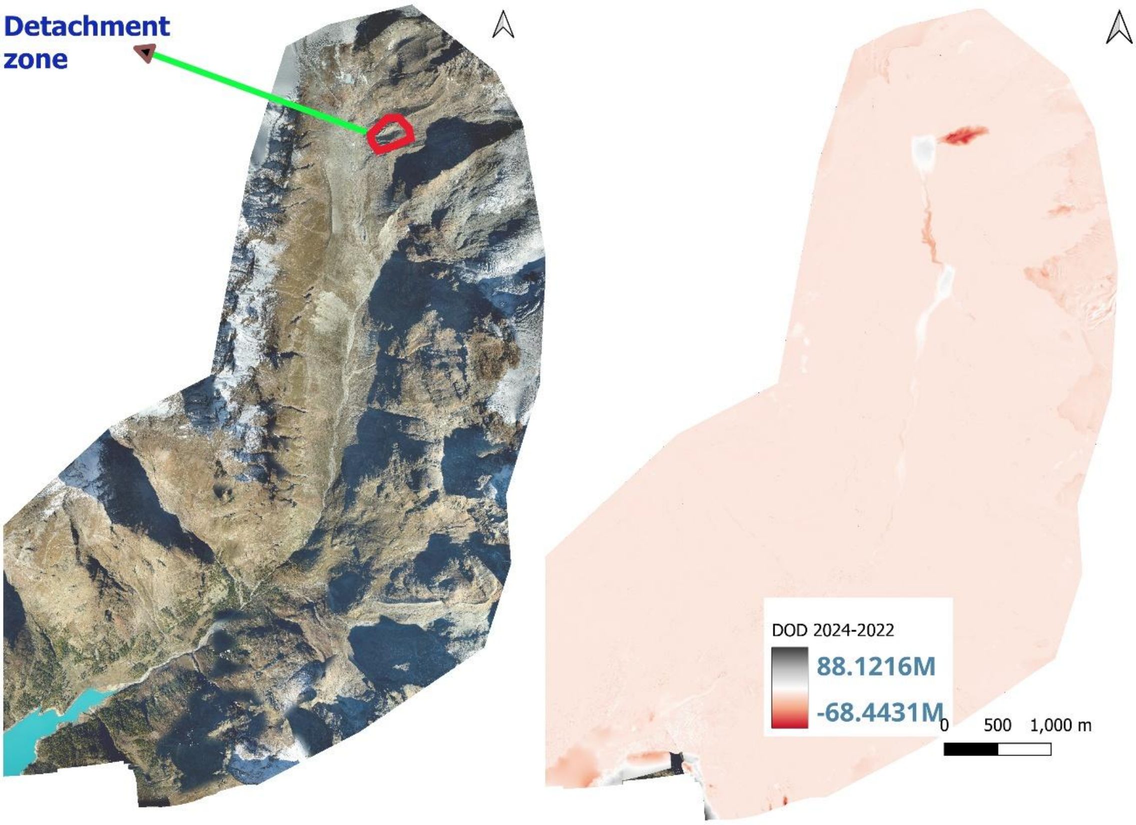

Figure 4.11 DSM of difference (DoD) between 2024 and 2022 derived from aerial photogrammetric surveys.

Figure 4.11 shows, the elevation difference analysis provide evidence of surface lowering within the moraine body of a more than 50 m, and heavy deposition just below the erosion area, which follows the channel toward the final deposition zone. Similarly, both erosion and deposition patterns are seen along the channel before reaching the Place-Moulin Dam. These patterns suggest a distribution of sediments along the channel, and a high volume of debris finally deposited in the dam.

4.4.4 Source-Area Delineation and Instability Features

Based on the previous results of DSM differencing and geomorphological mapping, the main source area associated with this debris flow was located at the upper portion of the channel. Evidence of recent erosion was observed in this glacial system.

The comparison between the two survey epochs indicates progressive surface lowering in this sector, which suggests ongoing material mobilization. The delineated source area was used to define the internal geometry for stability modelling and to estimate the volume of potentially unstable material. A GIS-based volume calculation carried out in QGIS on the delineated source area shows an estimated unstable volume of approximately **1.8×10^6 m³**.

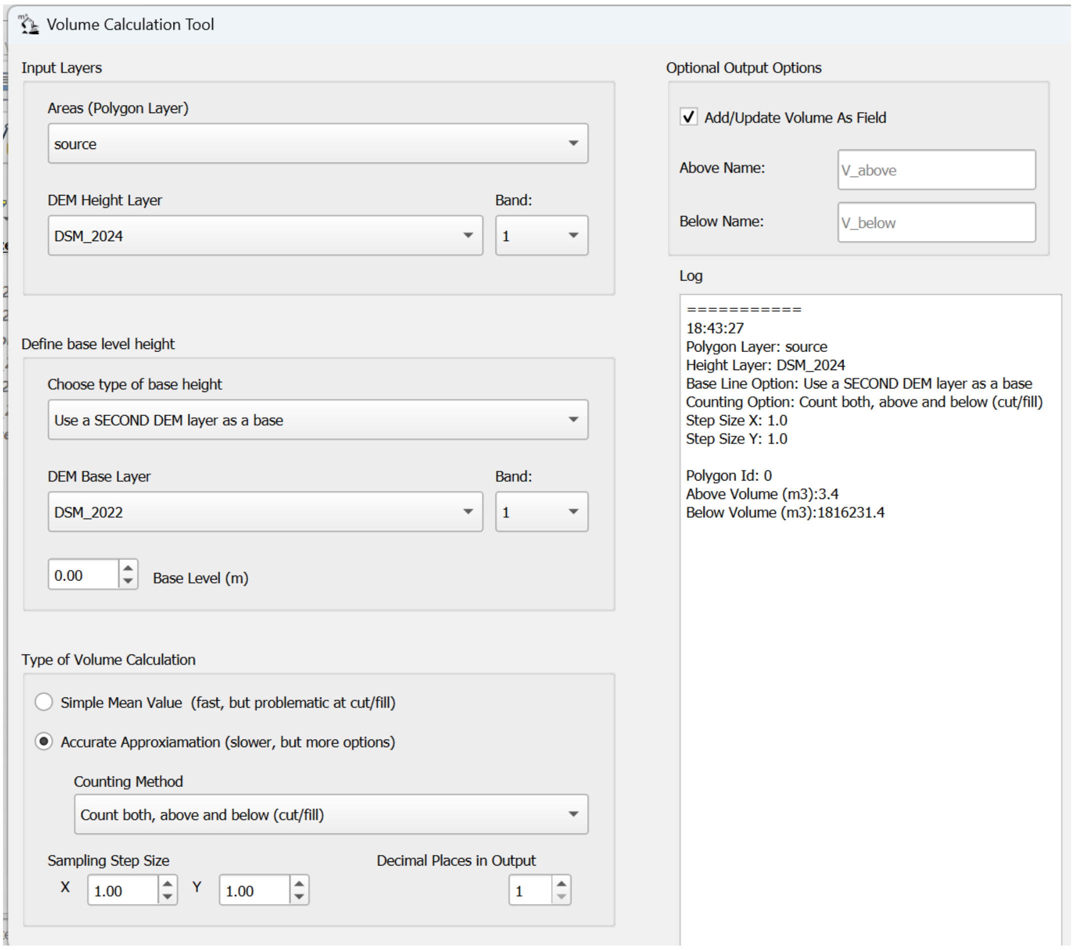

Figure 4.12 QGIS-based volume calculation of the delineated source area using DSMs from 2022 and 2024.

4.4.5 Channel Geometry, observed erosion and depositional Pattern

The downstream reach linking the moraine source area to the Place-Moulin Dam shows a clear longitudinal profile, with slope and channel confinement changing along its course. The channel geometry was characterized using profiles extracted from the DSM together with detailed orthophoto interpretation.

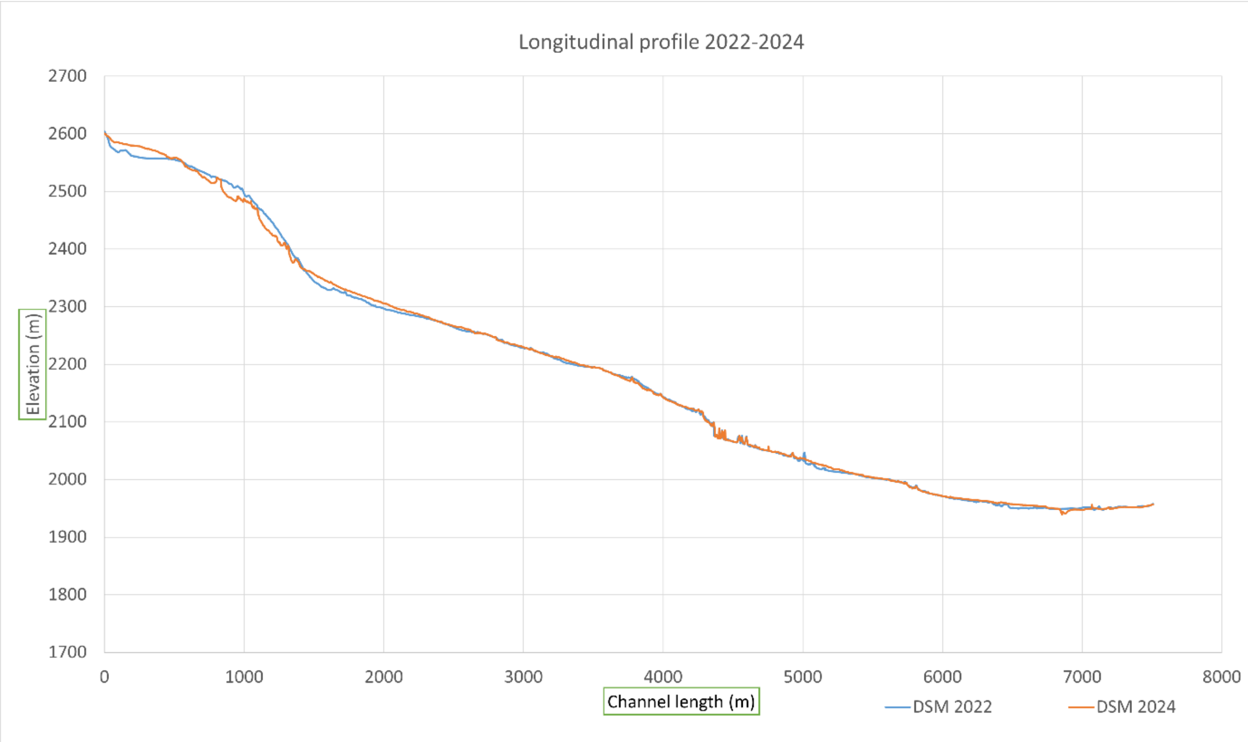

Figure 4.13 Comparison of longitudinal channel elevation profiles derived from the 2022 and 2024 DSMs.

The channel slope just below the source area is characterized by a wide and flat geometry. Progressively steeper slopes and narrower confinement channel, which Favor erosional processes and sediment entrainment. Downstream near the Place-Moulin Dam, the channel is wide and flat, which facilitates sediment deposition. Depositional areas are particularly evident in zones where the channel transitions into lower-gradient terrain.

Different sections were extracted to further characterize the morphological changes in source zone and downstream channel. Figure 4.14 shows the location of the extracted sections and comparison of pre and post event geometry.

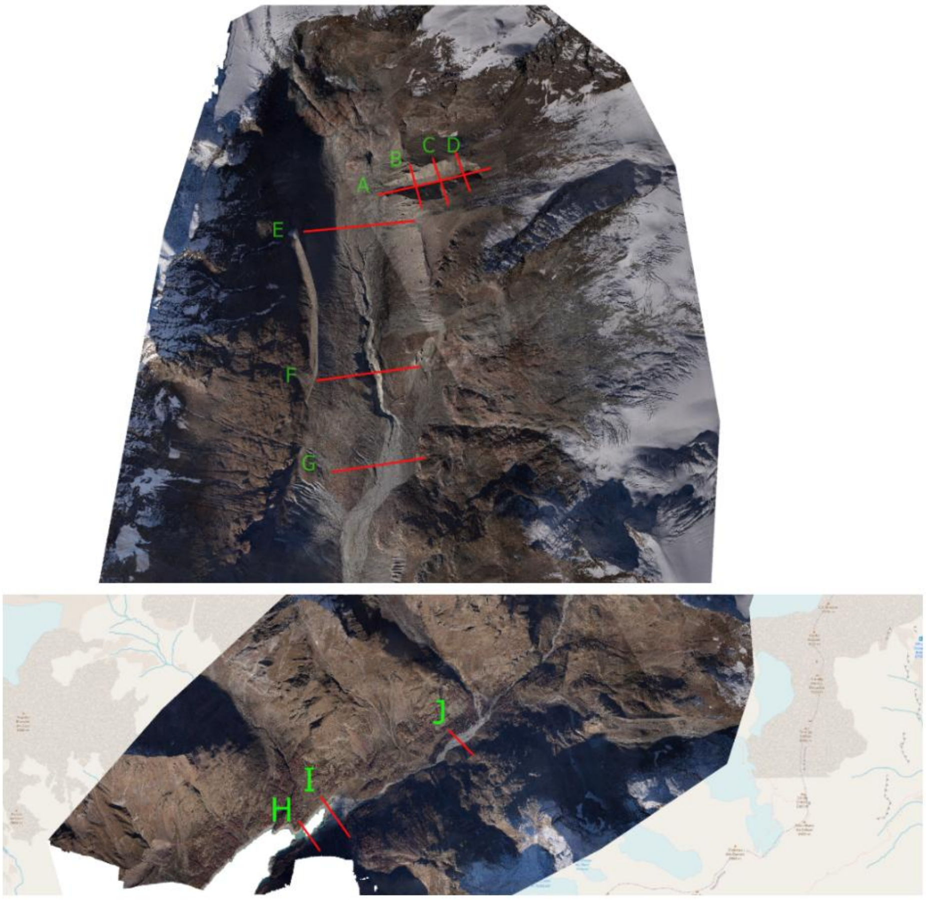

Figure 4.14 Locations of sections analyzed

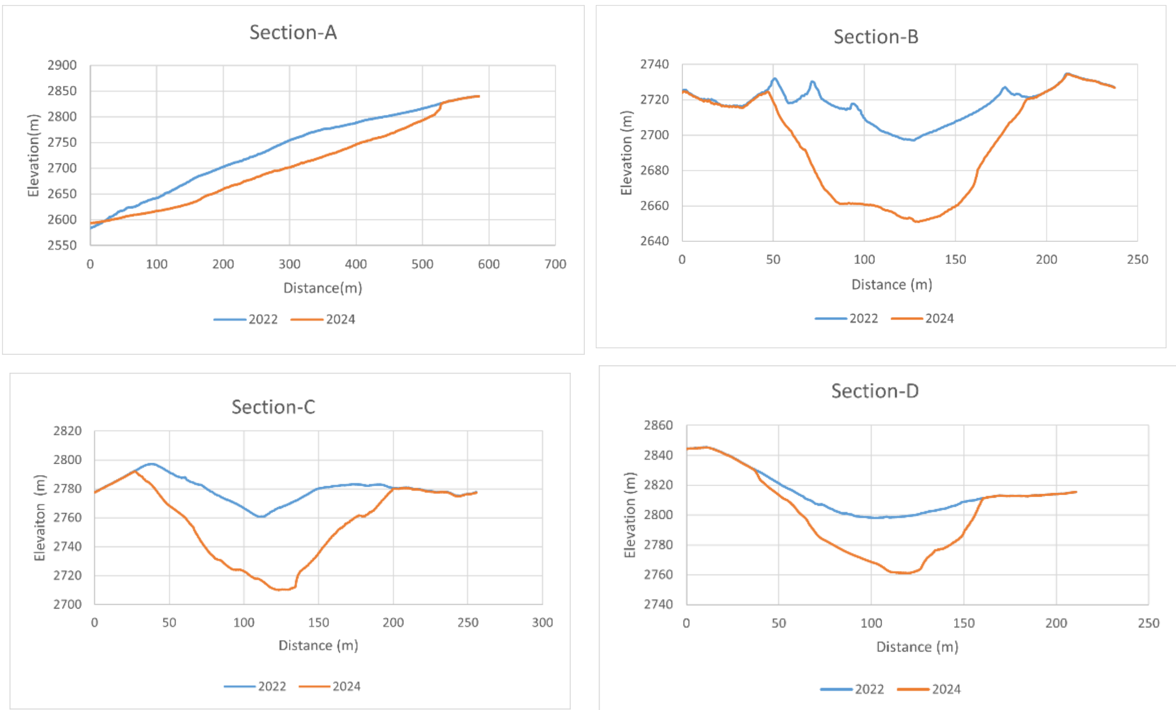

Figure 4.15 Comparison of pre- and post-event profile for sections A–D located in the upper source area.

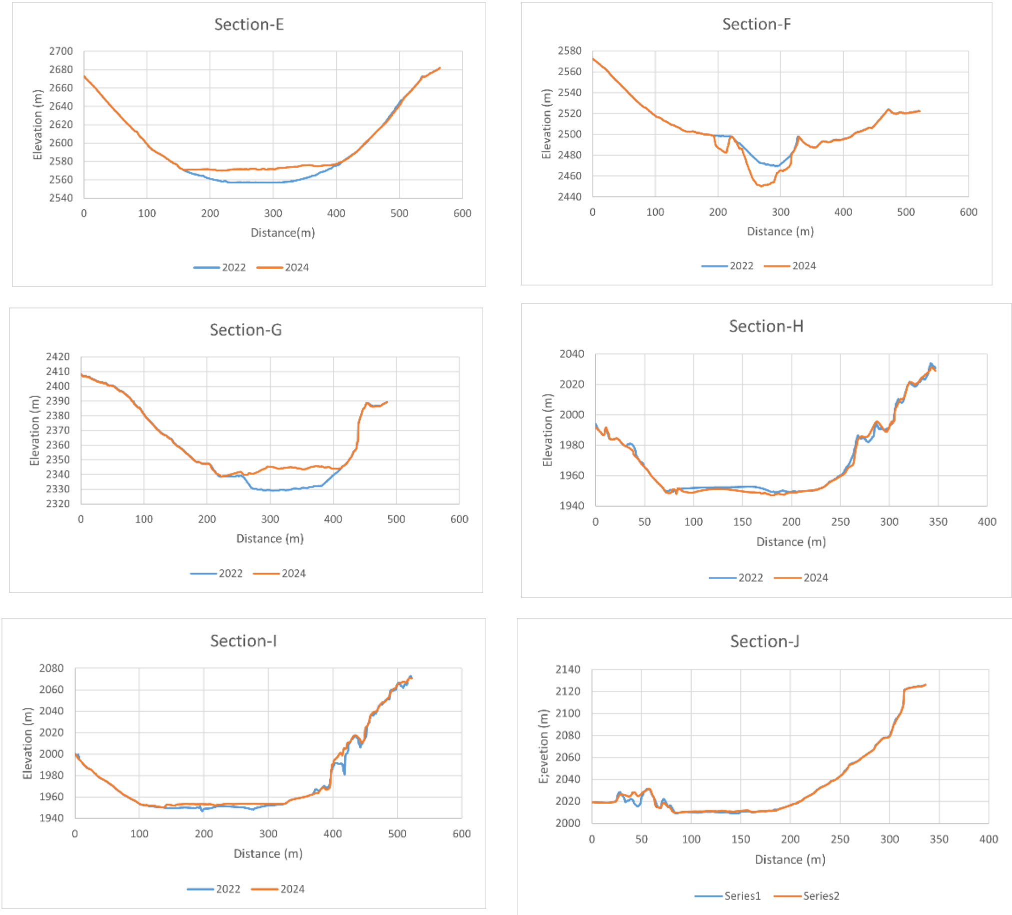

Figure 4.16 Comparison of pre- and post-event profile for sections E–G located in the upper channel section and sections H-J located in final deposition zone near dam. .

Figure 4.15 and Figure 4.16 highlight the morphological changes around the source zone and along the flow path. Cross sections (Sections A–D) located within the source area show surface lowering, indicating erosion associated with the sliding zone. Figure 4.16 provides a combination of channel erosion and localized aggradation, which reflects spatial variation of erosion and deposition along the confined channel and near the Place-Moulin Dam. This documents redistribution of moraine deposits from near the source area toward the downstream valley.

4.4.6 Monitoring Observations and Field Evidence

Field observations carried out by Legambiente, the Comitato Glaciologico Italiano, and ARPA Valle d'Aosta after the event clearly provide additional evidence that supports the interpretation derived from remote sensing data (Aostasera). Field inspections after the event show fresh debris, exposed unconsolidated material, and localized erosion features near the moraine body and along the channel. Although continuous instrumental monitoring data are limited, the combined use of field evidence and DSM analysis allows for a robust reconstruction of recent morphological evolution.

Figure 4.17 post-event field observations showing erosion scarps, incised channel sections, and unconsolidated moraine material along the debris-flow path. (GlacierLab polito, Aostasera)

4.4.7 Summary of Observational Constraints for Modelling

The results based on survey, mapping, and monitoring present essential constraints for numerical modelling of moraine instability and the debris-flow event. The identification of the source area, active erosion and deposition zones, along with the characterization of channel geometry, provides the basis for numerical modelling using DAN3D.

This section confirms the presence of moraine instability in the Tza de Tzan moraine system and justifies the application of numerical models to investigate instability mechanisms and debris-flow propagation.

4.5 Stability Modelling (Slide2)

4.5.1 Aim of stability modelling application

The objective of stability modelling using Slide2 (Rocscience) software is to evaluate slope stability under dry and rainfall-induced saturation conditions. This analysis is focused on pre-erosion stability, comparing dry with saturated conditions representative of intense rainfall on June 2024, which triggered the instability and moraine failure.

This modelling is intended to evaluate relative change in Factor of Safety rather than producing exact failure geometry or timing. This type of comparative approach is essential to assess the sensitivity of natural slopes to hydrological forcing (Iverson, 2000; Hungr et al., 2014).

4.5.2 Model geometry and section selection

The representative cross-section of the slope is extracted from the pre-event DSM, as shown in Figure (figure number). The section is located within the moraine, where DSM differencing identified active erosion, surface lowering, and possible instability. The cross-section of the representative slope was oriented approximately parallel to the main slope direction and was also positioned inside the source area to evaluate critical slope configurations.

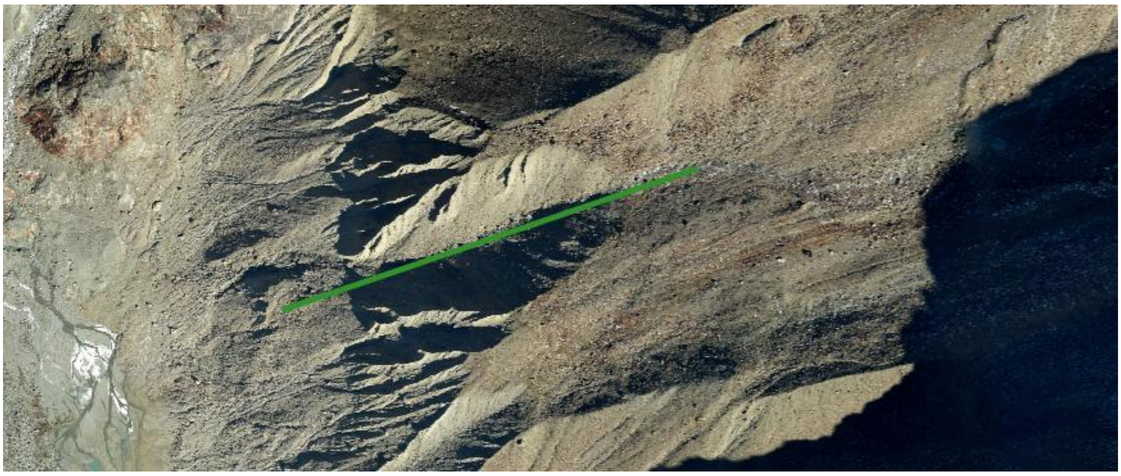

Figure 4.18 Selected cross-section (green line) used for slope stability analysis of the moraine slope.

4.5.3 Input Parameters and Hydrological Scenarios

The input parameters for Slide2 to evaluate the Factor of Safety in different geological conditions were defined from the literature for alpine moraine deposits, as detailed in Chapter 3. Constant values were used to evaluate the hydrological effect on the moraine slope (Iverson, 2000).

Two main hydrological scenarios were analysed:

- a dry or pre-event condition, representing baseline stability prior to rainfall, and
- a saturated condition, with increased pore water pressure after intense rainfall infiltration.

This approach allows a direct comparison of stability of moraine deposits and slope behaviour (Duncan and Wright, 2005).

Table 4.1 input geotechnical parameters used for slope stability modelling of moraine deposits under dry and saturated conditions.

Material Name	Unit Weight (kN/m³)	Saturated Unit Weight (kN/m³)	Strength Type	Cohesion (kPa)	Friction Angle φ (°)	Water Surface
Moraine deposits	20	23	Mohr–Coulomb	1	35	Water Table
Bedrock	25	—	Mohr–Coulomb	500	45	None

4.5.4 Stability Results

Slide2 provides the Factor of Safety under dry and saturated conditions for the analysed cross-sections. For dry conditions, the Factor of Safety is over value, which shows a stable slope before rainfall. Under saturated conditions, a significant reduction in the Factor of Safety is observed, which indicates instability of the moraine slope.

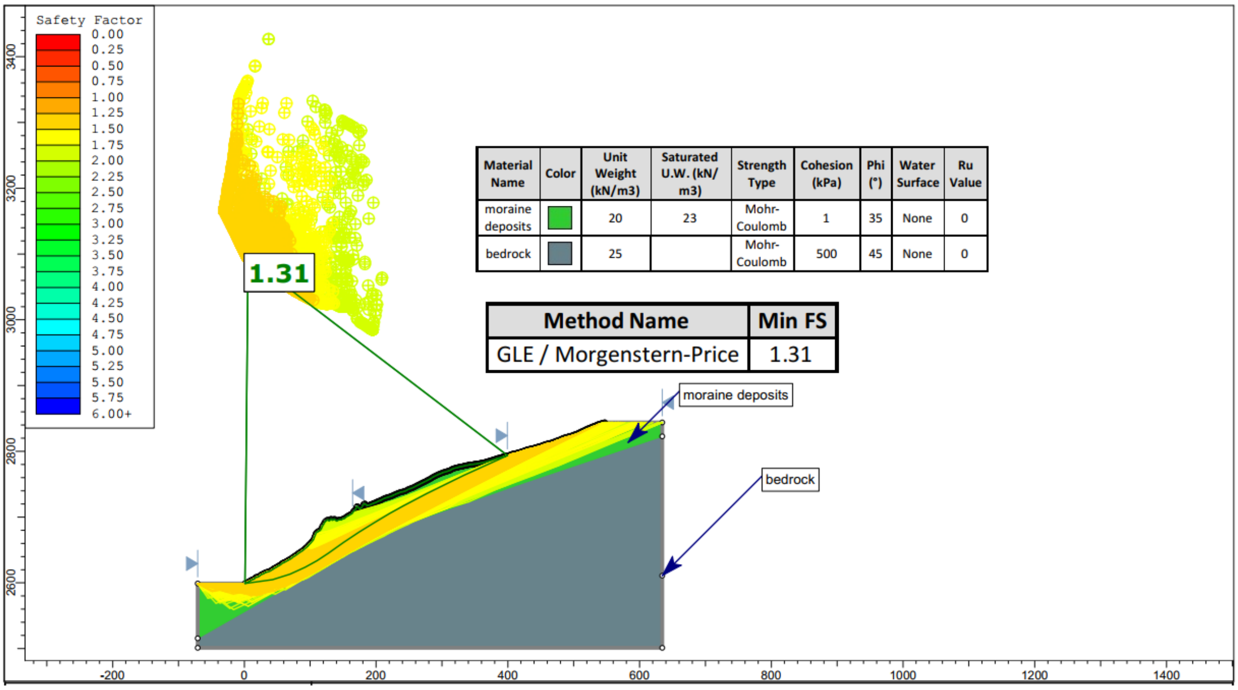

Figure 4.19 Slope stability analysis under dry conditions using Slide2, showing the critical slip surface and minimum factor of safety (FS = 1.31) computed with the Morgenstern–Price method.

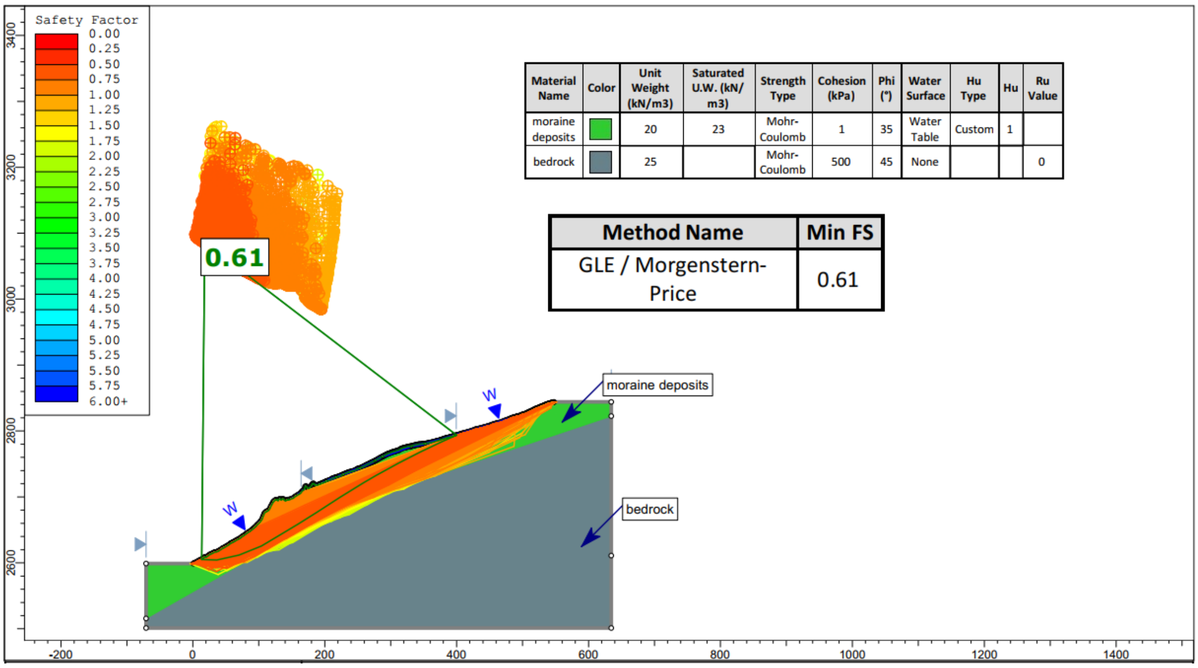

Figure 4.20 Slope stability analysis under saturated conditions including the water table, showing the critical slip surface and minimum factor of safety (FS = 0.61) computed using the Morgenstern–Price method, indicating unstable slope conditions.

Slide2 results shows a minimum factor of safety of **1.31** under dry conditions, indicating marginally stable slope conditions, whereas the factor of safety decreases significantly to **0.61** under saturated conditions, indicating slope failure. These results highlight that the reduction in stability is strongly influenced by pore water pressure, indicating that rainfall-induced saturation is sufficient to promote slope instability. The location of critical slip surfaces from the Slide2 stability analysis approximately corresponds to areas where erosion and surface lowering were observed through DSM differencing.

4.6 Runout modelling

4.6.1 Aim of Runout Modelling

In this thesis, DAN3D is used for a back-analysis of the debris-flow event that occurred in the Aosta Valley in June 2024. The primary objective of this modelling is to reconstruct the debris-flow behaviour, such as debris-flow propagation, runout extent, and depositional pattern, based on post-event observations and results from DSM differencing (McDougall and Hungr, 2004; Hungr and McDougall, 2009). Back-analysis studies in debris-flow research are commonly applied to calibrate controlling factors and parameters by reproducing data-rich events under known boundary conditions, and they do not predict future scenarios (Hungr et al., 2014).

Back-analysis will evaluate whether the DAN3D code can reasonably reproduce the observed downstream impact toward the Place-Moulin Dam. The analysis focuses on the post-failure stage of stability modelling by investigating debris-flow dynamics after initiation. This runout modelling does not provide a predictive hazard assessment; rather, it investigates the consistency between the characteristics of the observed event and the modelled runout behaviour (McDougall and Hungr, 2004; Hungr et al., 2014).

4.6.2 Model Setup and Initial Conditions

The pre-event Digital Surface Model is used to define the basal topography for the DAN3D model simulation. The computational domain is used as a .grd file in order to capture the full debris-flow propagation path, and includes the moraine source area, the downstream channel network, and the erosion grid toward the Place-Moulin Dam (McDougall and Hungr, 2004; Hungr and McDougall, 2009).
The unstable moraine zone is used as the initial source area, which is defined based on the results of DSM differencing and stability modelling presented in Sections 4.4.4 and 4.5. From the DSM differencing, approximately the maximum surface lowering and erosion depth was identified as 50 m. The upper moraine and the channel head section are used as the source area. The initial released volume calculated by DSM differencing is about 1.8 million cubic metres (McDougall and Hungr, 2004).

When calibrating the model behaviour and parameter values, initial conditions were kept constant across all simulations. This setup therefore provides a simplified but physically consistent representation of the pre-failure terrain, which is a required condition for back-analysis of debris-flow events.

4.6.3 Calibration Strategy and Rheological Models

Model simulation was calibrated through a back-analysis approach, where simulated debris-flow behaviour was compared with pre- and post-event DSM differencing and depositional patterns (McDougall and Hungr, 2004; Hungr and McDougall, 2009). While maintaining the initial conditions constant, initial rheological parameters were taken from the literature and systematically adjusted in order to reproduce the documented flow behaviour (Hungr et al., 2014).

In this study, two rheological formulations were tested in DAN3D: a frictional rheology and the Voellmy rheology. In the frictional rheology, flow resistance is described through a basal friction coefficient, while the Voellmy rheology extends this by introducing an additional velocity-dependent turbulent resistance term. This term allows for higher mobility and longer runout distances of debris flows moving in confined alpine channels (Hungr et al., 2014).

The main objective of this calibration strategy is to identify parameter sets that can reproduce the overall characteristics of the real debris-flow event. Determining unique material properties or exact rheological values is not a primary focus of this study.

4.6.4 Frictional Rheology Simulation (Baseline Run)

A baseline simulation using frictional rheology was conducted in DAN3D to evaluate debris-flow behaviour under constant basal resistance without entrainment. The model was initialized with the mapped source geometry and pre-event topography, allowing the mass to propagate downslope under friction-controlled conditions. The principal input parameters used in this simulation are listed in Table 4.2.

Table 4.2 Principal input parameters for the DAN3D frictional baseline model.

γ [kN/m³]	φb [°]	φi [°]	Es [m⁻¹]	V₀ [m³]
20	12	35	0	1.81×10^6

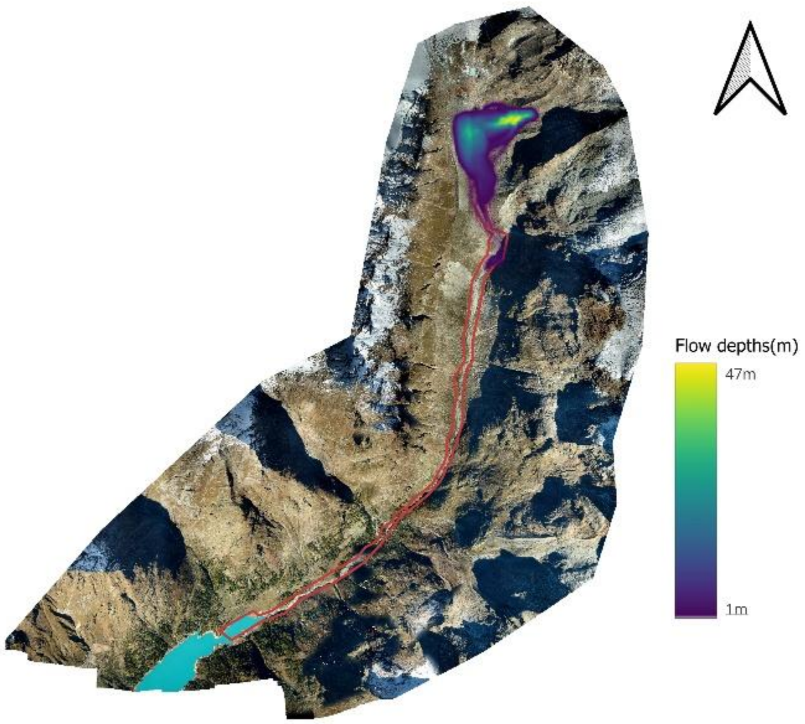

Figure 4.21 Spatial distribution of maximum flow depth simulated using frictional rheology.

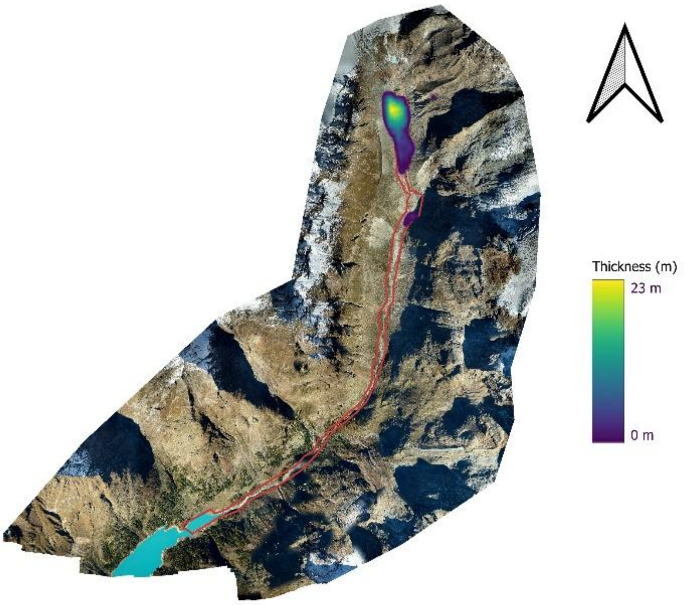

Figure 4.22 Final deposit thickness simulated using frictional rheology.

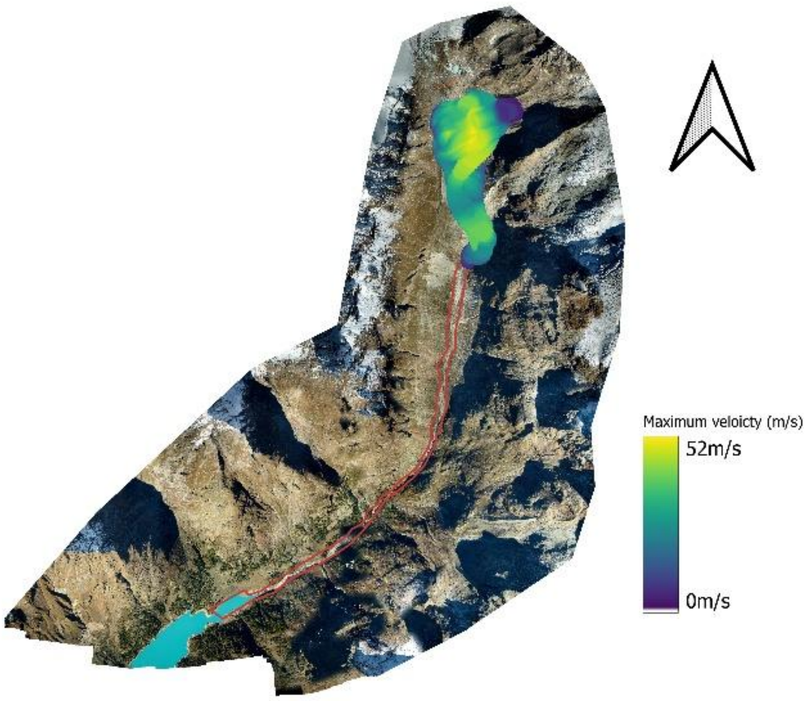

Figure 4.23 maximum velocity simulated using frictional rheology.

The frictional simulation shows restricted mobility, with the flow stopping within 280 seconds and travelling less than 1 km, considerably shorter than the observed runout. This behaviour indicates that frictional resistance alone cannot reproduce the documented event. Therefore, a more advanced rheological approach using the Voellmy model was adopted for subsequent simulations.

4.7 Voellmy Rheology

4.7.1 Voellmy (no entrainment)

This simulation evaluates debris-flow mobility using Voellmy rheology without incorporating erosion or entrainment processes. The objective is to assess the influence of basal friction and turbulent resistance on flow propagation and deposition patterns.

Table 4.3 Parameters used for the simulation

γ [kN/m³]	*f* [-]	ξ [m/s²]	φ_i [°]	Es [m⁻¹]	V_0 [m³]
20	0.08	500	35	0	1.81×10^6

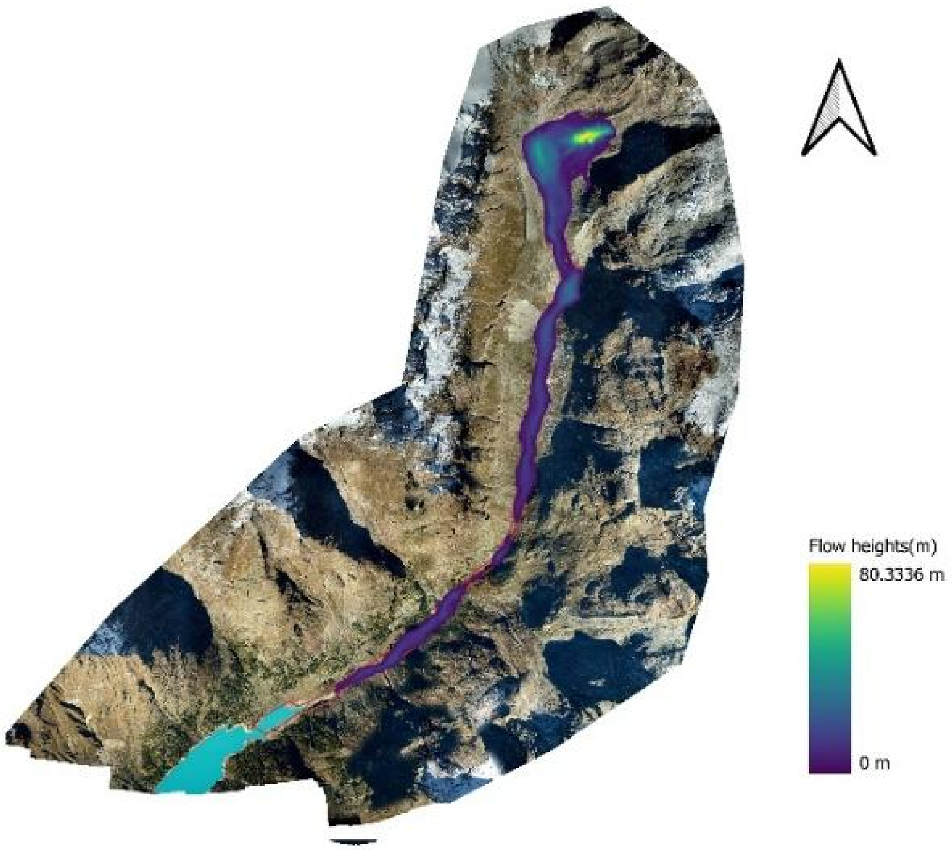

Figure 4.24 Maximum flow depth distribution simulated using Voellmy rheology without erosion.

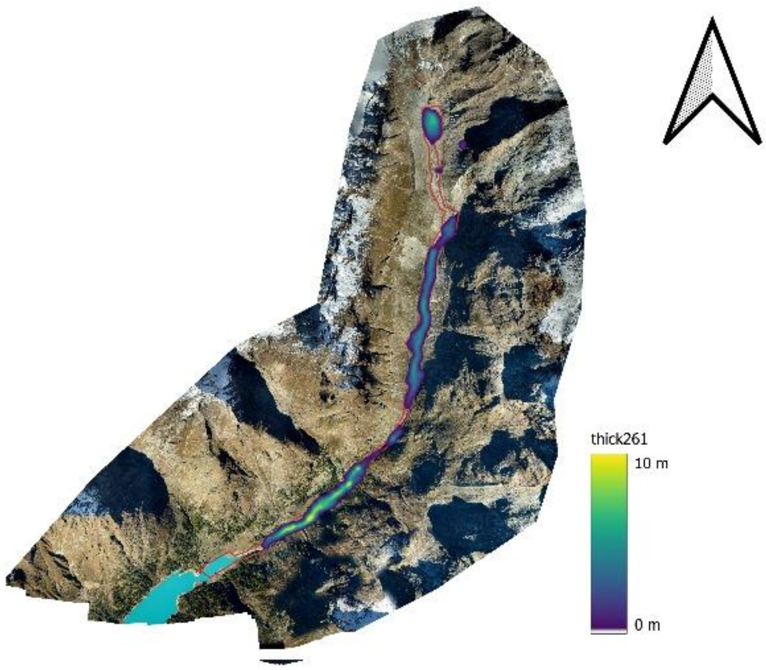

Figure 4.25 Maximum flow depth distribution simulated using Voellmy rheology without Es.

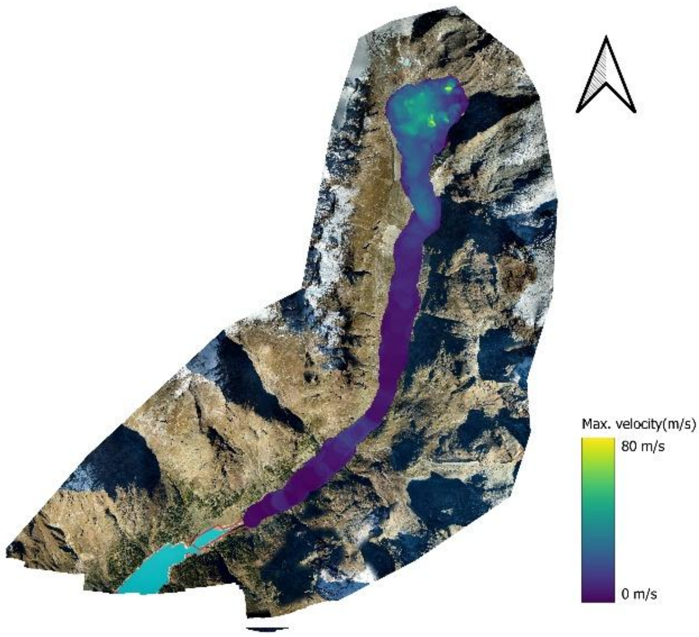

Figure 4.26 maximum flow velocity simulated using Voellmy rheology without erosion.

The results show runout distances comparable to the real event, but unrealistic deposition patterns and excessive velocities. The lack of entrainment keeps the simulated volume equal to the initial release, while observations show a larger volume reaching the downstream lake. Therefore, erosion processes are necessary for realistic debris-flow modelling.

4.7.2 Voellmy Rheology with Erosion

A preliminary simulation incorporating Voellmy rheology and erosion was performed to evaluate the effects of entrainment and material zonation on debris-flow mobility. This run served as an intermediate calibration stage prior to the final model optimization.

Model parameters were defined using field evidence and representative values reported in previous debris-flow studies. Mechanical properties were assigned to reflect moraine material behaviour, while Voellmy friction and turbulence coefficients were adjusted to simulate realistic flow mobility. Erosion was incorporated to account for channel entrainment, and three material zones were used to represent spatial variability in surface conditions. The key input parameters are summarized in Tables 4.4 and 4.5.

Table 4.4 Global input parameters for DAN3D simulation

Parameter	Value
Number of materials	3
Number of particles	4000
Time step	0.5 s
Erosion rate	0.00004 m^{-1}

Table 4.5 Material-dependent rheological parameters

	Source	Channel banks	Flow path
Rheology	Voellmy	Voellmy	Voellmy
Friction coefficient (*f*)	0.08	0.07	0.07
Turbulence coefficient ξ (m/s^2)	500	500	500
Unit weight γ (kN/m^3)	20	20	20
Internal friction angle φ_i (°)	35	35	35

These parameters were selected to improve flow mobility while maintaining realistic debris-flow behaviour. Voellmy rheology was adopted to account for both frictional and turbulent resistance. Moderate friction coefficients reduced basal resistance and promoted downstream propagation, while the turbulence coefficient ($\xi = 500$ m/s^2) controlled excessive acceleration. Uniform material density and internal friction were used to represent typical moraine properties. The three-material zonation allowed spatial variation in resistance conditions, improving flow routing and deposition patterns.

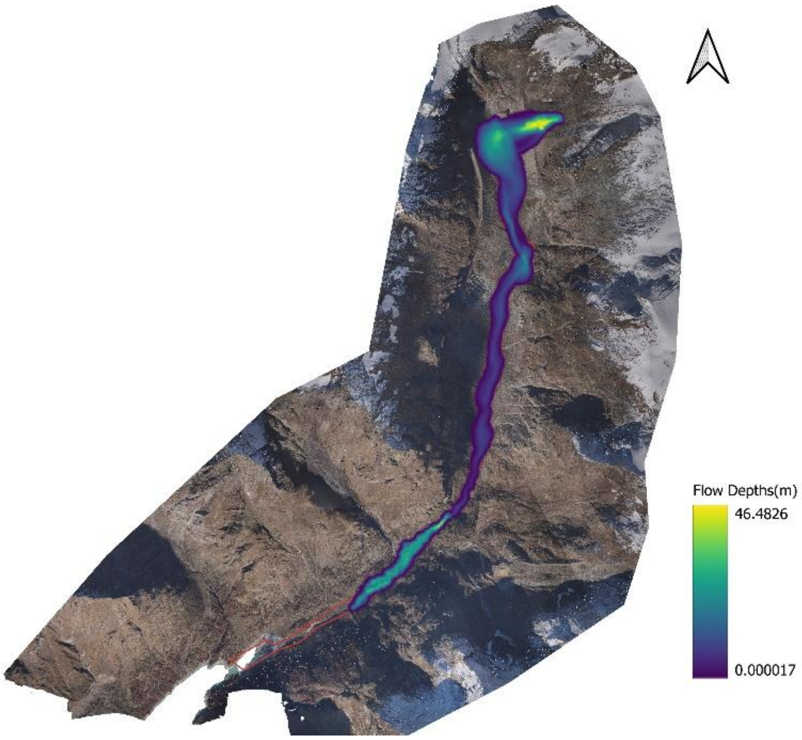

Figure 4.28 Maximum flow depth distribution produced by the preliminary Voellmy–erosion simulation.

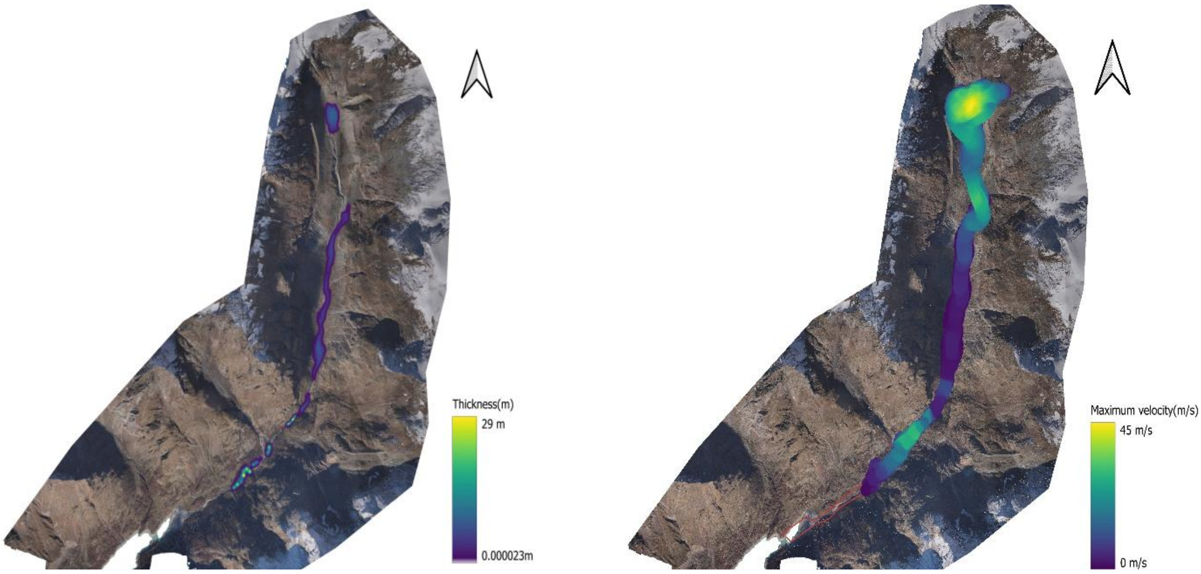

Figure 4.27 Final deposit thickness and maximum flow velocity distributions produced by the preliminary Voellmy–erosion simulation.

Despite using a turbulent coefficient (ξ) of 500 m/s^2 and incorporating erosion, the simulated flow did not reach the downstream dam location. After approximately 14,000 seconds (≈ 3.9 hours), the flow remained confined within the valley, and the final simulated volume (≈ 2.2×10^6 m^3) was lower than field-based estimates. These discrepancies indicate that further parameter calibration was required.

4.7.3 Final Calibrated DAN3D Simulation

A final calibrated DAN3D simulation was conducted using Voellmy rheology with erosion to reproduce the observed debris-flow behaviour. The model included three material zones and incorporated entrainment processes to simulate volume growth. Flow mobility was governed by calibrated friction parameters, a turbulence coefficient of 400 m/s^2, and an erosion rate of 0.00004 m^{-1}, enabling improved representation of runout and deposition patterns.

Table 4.6 Input control parameters

Parameter	Value
Number of materials	3
Number of particles	4000
Rheology	Voellmy
Time step	0.5 s
Erosion rate	0.00004 m^{-1}
Turbulence coefficient (ξ)	400 m/s^2
Initial volume	1.81×10^6 m^3
Final volume	2.45×10^6 m^3
Simulation duration	14,500 s (≈ 4.0 h)

Table 4.7 Material-specific rheological parameters

Parameter	Material 1 (Source)	Material 2 (Channel Banks)	Material 3 (Main Channel)
Rheology	Voellmy	Voellmy	Voellmy
Unit weight γ (kN/m^3)	20	20	20
Friction coefficient (*f*)	0.08	0.10	0.06
Turbulence coefficient ξ (m/s^2)	400	400	400
Internal friction angle φ_i (°)	35	35	35

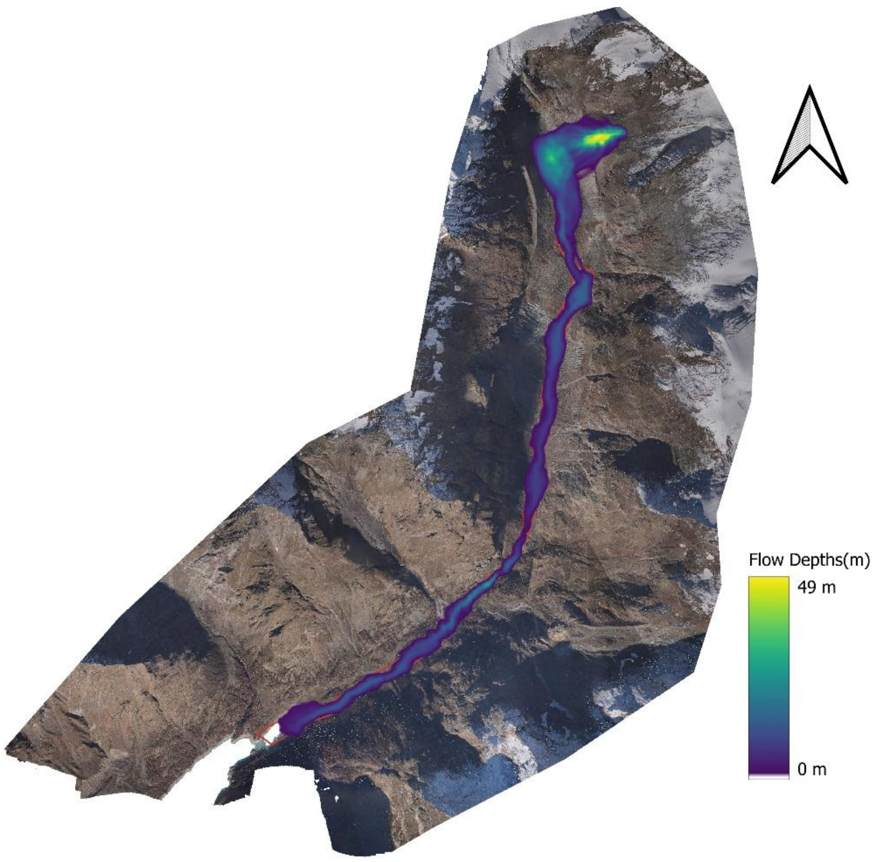

Figure 4.29 Maximum flow thickness from the final calibrated Voellmy–erosion simulation (ξ = 400 m/s²).

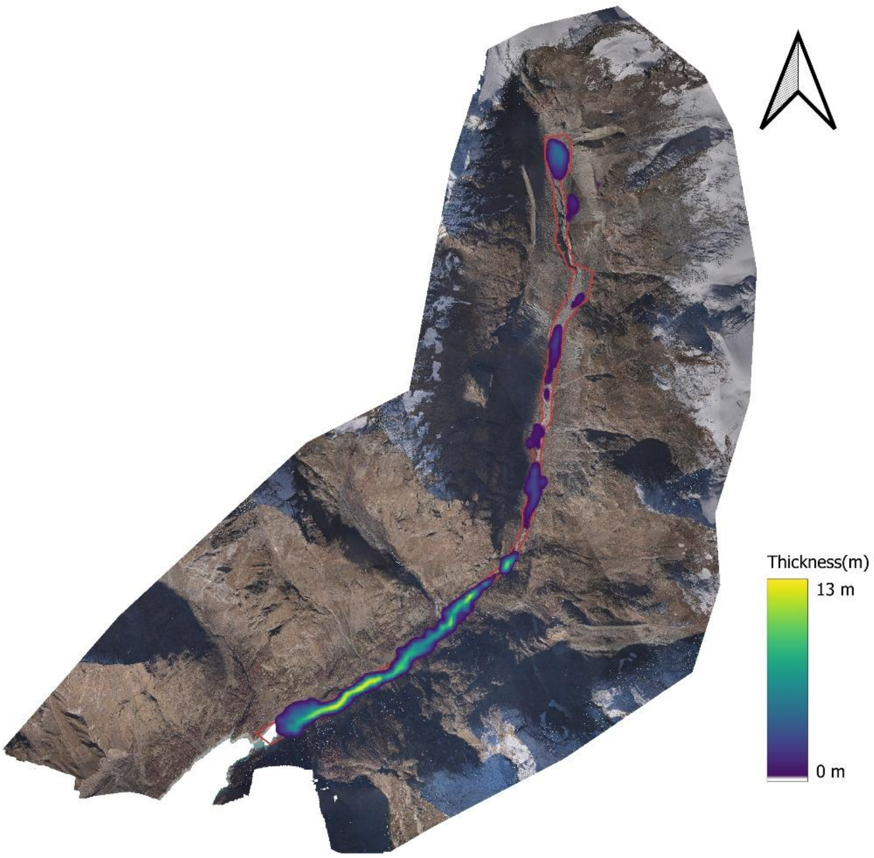

Figure 4.30 Final deposit thickness from the final calibrated Voellmy–erosion simulation (ξ = 400 m/s²).

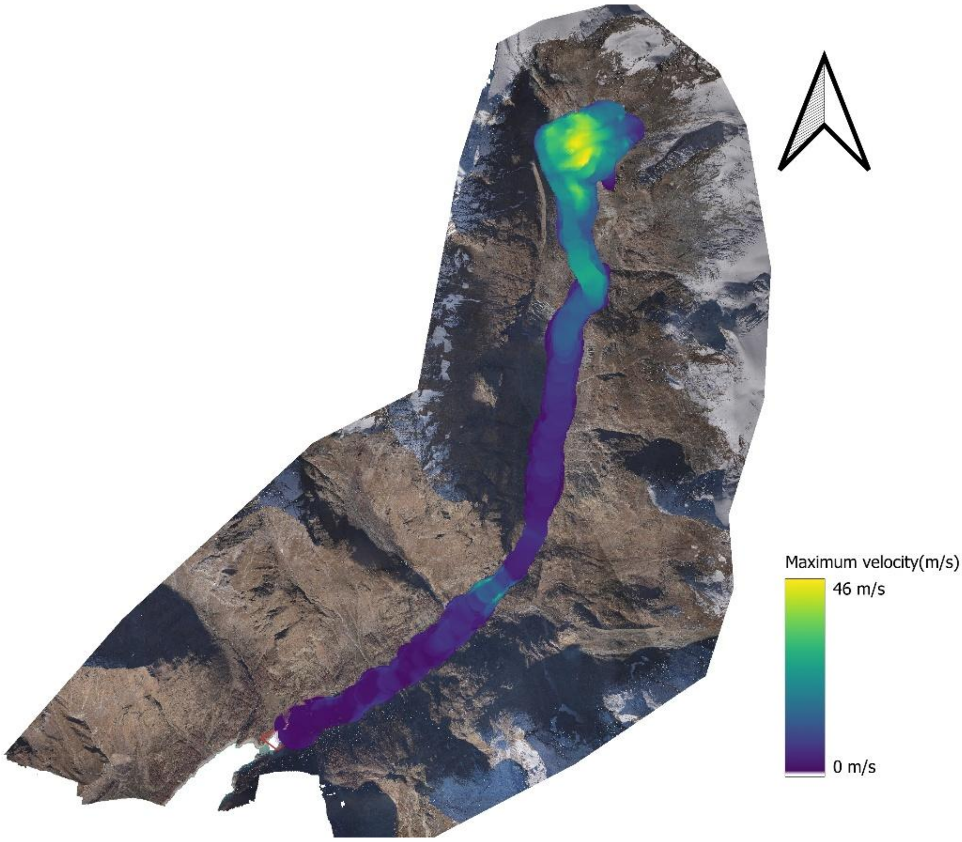

Figure 4.31 Maximum flow velocity from the final calibrated Voellmy–erosion simulation (ξ = 400 m/s²).

The behaviour of the final calibrated simulation is primarily controlled by the selected rheological and erosion parameters. The friction coefficient (*f*) strongly influenced flow mobility, where lower values in the main channel reduced basal resistance and allowed longer downstream propagation, while higher values in the source and bank zones limited excessive spreading. The turbulence coefficient ($\xi = 400$ m/s²) regulated flow acceleration and prevented unrealistically high velocities, producing stable and physically consistent motion along the channel. Incorporation of erosion enabled progressive entrainment, leading to volume growth and improved runout towards the downstream dam. Additionally, the use of three material zones allowed spatial variation in resistance conditions, improving flow confinement and deposition patterns. Together, these parameters produced realistic runout distance, velocity distribution, and final deposition consistent with field observations.

Overall, the final calibrated simulation reproduces the observed runout distance, flow path, and deposition patterns with good agreement. The simulated temporal evolution confirms realistic debris-flow propagation, indicating that the selected rheological and erosion parameters adequately represent the event dynamics.

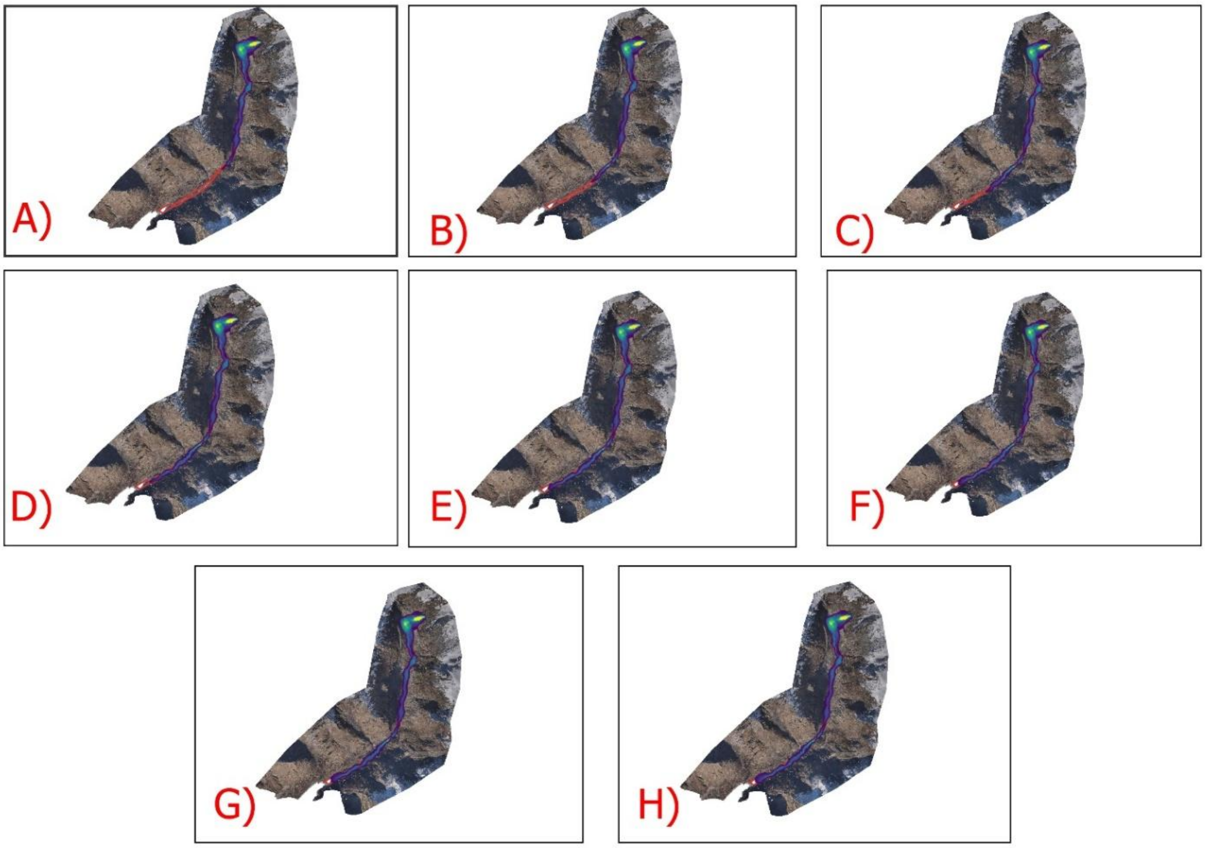

Figure 4.32 Time-series maps of debris-flow propagation from the final calibrated Voellmy–erosion simulation showing progressive downstream movement of the flow (A = 15min, B = 30min, C = 50mins, D = 100min, E = 150min, F = 3hr, G = 3.5hr, H = 4hr).

The sequence (fig. 4.32) shows the gradual downstream propagation of the debris flow from the source area to the valley outlet. The flow initially moves rapidly along the steep upper slopes, then becomes more channelized and elongated as it travels downstream. In the final stages, the flow front approaches the dam while deposition increases along the lower channel due to energy loss.

4.8 Melamchi flood: Himalayan debris flow event

4.8.1 Study Area and Event Overview (Melamchi, Nepal)

The Melamchi Valley is in central Nepal within the Indrawati River basin, which drains the southern flank of the Jugal Himal range in Nepal. The source of water in the Melamchi River is in high-altitude glaciated and paraglacial mountain terrain. This Himalayan region is characterized by large volumes of unconsolidated sediments that are stored in moraines, valley fills, and relict landslide deposits. During the monsoon period, several lines of evidence show that this region exhibits instability under intense hydrometeorological forcing (ICIMOD, 2021; Graf et al., 2024).

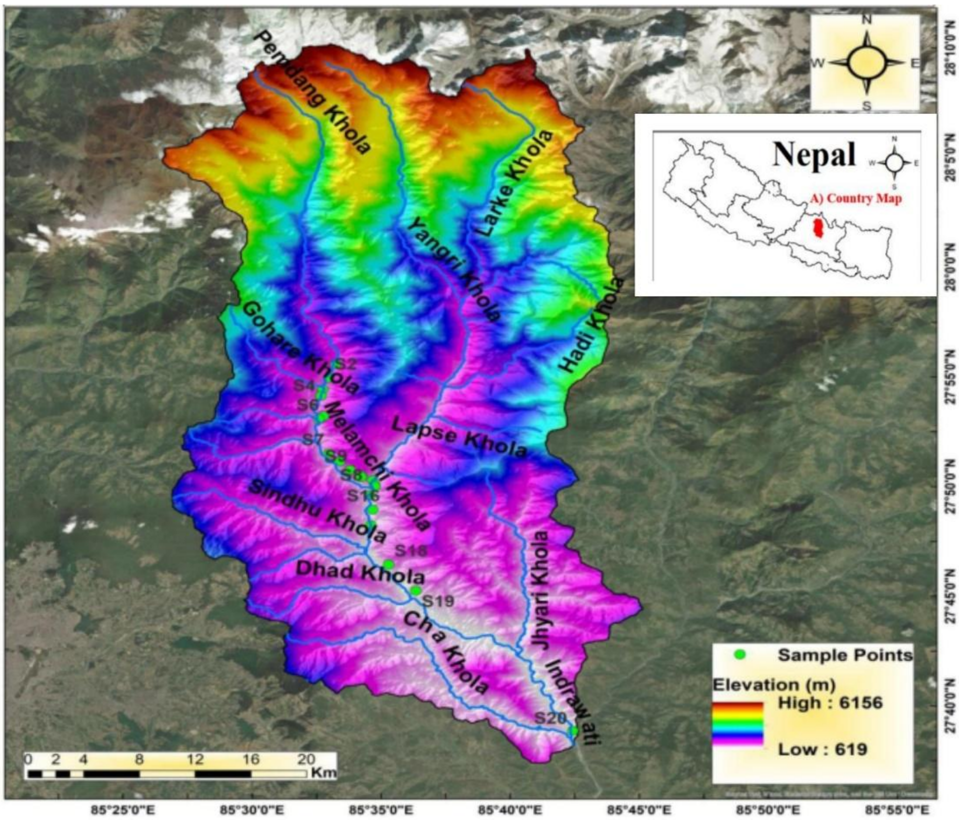

Figure 4.33 Digital elevation model (DEM) of the Melamchi River catchment showing the main tributaries, elevation range, within the Indrawati River basin, central Nepal.

On 15 June 2021, after several days of intense rainfall, an extreme sediment-laden flood–debris-flow event was seen that affected the Melamchi River system, which had been previously weakened by the 2015 Gorkha earthquake. Recent studies in this area indicate that the debris-flow event was not caused by a single glacial lake or landslide-dam failure, but instead developed as a cascading process, followed by progressive erosion and remobilisation of landslide- and moraine-derived deposits (Maharjan et al., 2021; Chen et al., 2023). The overall event evolution is summarised conceptually in Figure 4.34 illustrating the sequence of erosional and depositional processes from the upper glacial source areas to downstream populated zones.

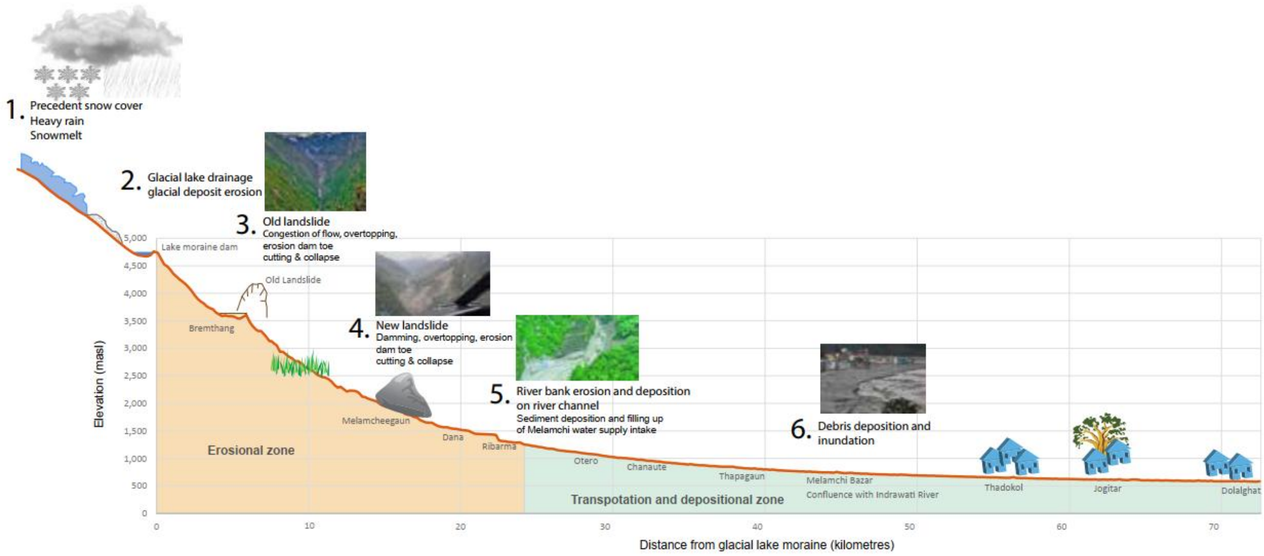

Figure 4.34 Conceptual longitudinal profile of the Melamchi–Indrawati River system illustrating the sequence of processes involved in the 15 June 2021 event, from rainfall and snowmelt in the upper catchment to downstream sediment deposition and inundation (Source: ICIMOD 2021; Chen et al., 2023).

Remote sensing analyses document large-scale erosion involving moraine deposits, gullying of valley fills, and reactivation of earthquake-damaged slopes in the upper catchment. Mobilised sediment in the upper tributaries was entrained and transported downstream into the Melamchi River, producing a debris-flow–like flood carrying heavy sediment for several tens of kilometres, reaching the Melamchi–Indrawati confluence at Melamchi Bazaar (Chen et al., 2023; Graf et al., 2024).

Figure 4.35 post-event aerial view of Melamchi Bazaar showing extensive riverbed aggradation, channel widening, and sediment deposition following the 15 June 2021 debris-flow event.

The event caused severe impacts in downstream populated areas. Reported losses after the event include at least 20–25 fatalities some missing, widespread displacement of several villages, destruction of hundreds of houses, and major damage to bridges, roads, and the Melamchi Water Supply Project headworks. Economic losses of several hundred million USD were reported, although the figures vary depending on assessment methods and timing (ICIMOD, 2021; Duwadi et al., 2024). More than 10 m of riverbed aggradation and deposition was reported in downstream areas such as Chanaute, Galthumg, and Melamchi Bazaar, reflecting the exceptional sediment transport during the event (Chen et al., 2023).

Figure 4.36 Before-and-after views of Chanaute Bazaar

In this study, the Melamchi 2021 debris-flow event is considered a Himalayan high-mountain reference case of moraine and glacial-deposit instability that led to a large-scale debris-flow event triggered by extreme rainfall. For the Himalayan case, the main focus is placed only on the role of moraine instability and debris-flow sediments in the source area rather than on detailed downstream runout dynamics. Due to the lack of pre-event monitoring data and consistent high-resolution topography in the region, this case is discussed only for comparison with a similar case from the Alpine region.

Figure 4.37 debris-flow inundation, channel aggradation, and infrastructure damage in the Melamchi Valley after the June 2021 event.

4.8.2 Survey and Remote Mapping Evidence

Evidence of moraine and glacial-deposit instability

According to published reports, a major contributor to downstream sediment supply was erosion of moraine and glacial valley-fill deposits in the upper catchment (Chen et al., 2023; Graf et al., 2024). Mapping results show progressive incision, gullying, and remobilisation of unconsolidated glacial sediments, and there is no clear evidence of a single glacial lake outburst flood (GLOF) event (Chen et al., 2023). These observations support the interpretation that this was a cascading event, where sediment transfer processes were driven by extreme rainfall acting on sediment-rich high-mountain terrain (Maharjan et al., 2021; Graf et al., 2024).

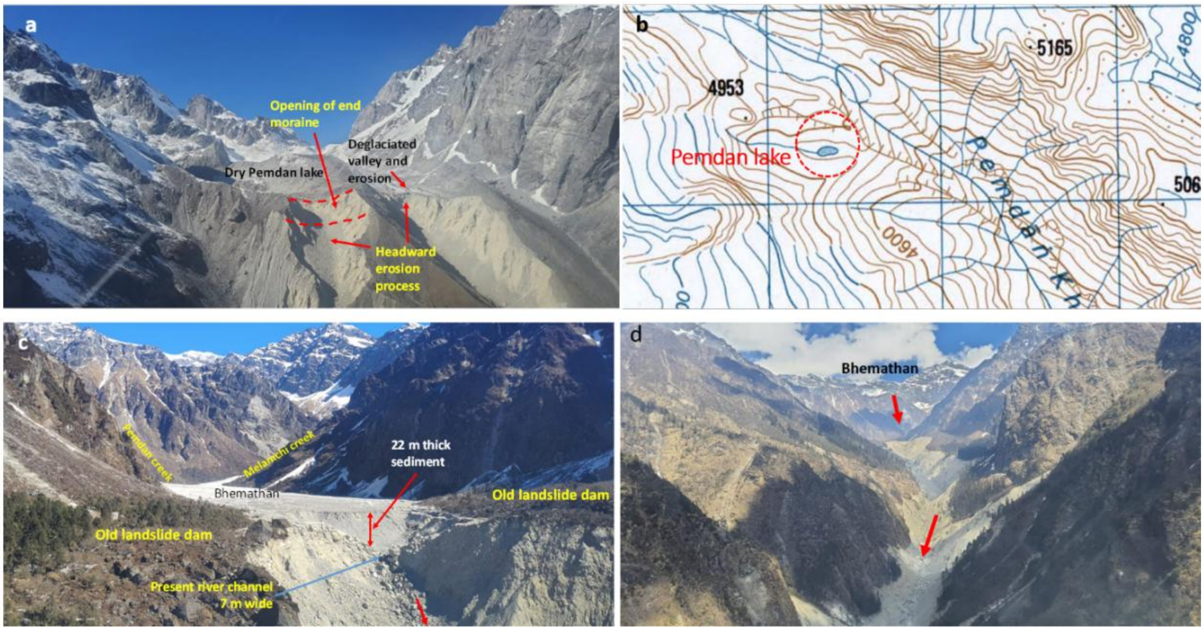

*Figure 4.21 Field and topographic evidence illustrating key geomorphic processes contributing to sediment mobilisation and debris-flow development in the Melamchi catchment during the 2021 event: **(a)** Opening of the end moraine and headward erosion in the former Pemdang Lake area. **(b)** Topographic setting of the Pemdang Lake. **(c)** Old landslide dam and thick sediment accumulation showing channel incision. **(d)** Downstream valley reach illustrating sediment transfer and debris-flow propagation.*

Remote sensing datasets used for event assessment

Existing remote sensing analyses indicate that high-resolution optical satellite imagery and stereo satellite-derived digital elevation models (DEMs) were primarily used for analysis of the 2021 Melamchi event (Chen et al., 2023; Graf et al., 2024). According to published studies, pre- and post-event DEMs were analysed to quantify the spatial pattern of erosion and deposition along the Melamchi River corridor (Chen et al., 2023). This indicates widespread erosion in the upper catchment near glacial moraines, including glacial valley-fill deposits, which was followed by downstream erosion and channel aggradation (Graf et al., 2024; Chen et al., 2023).

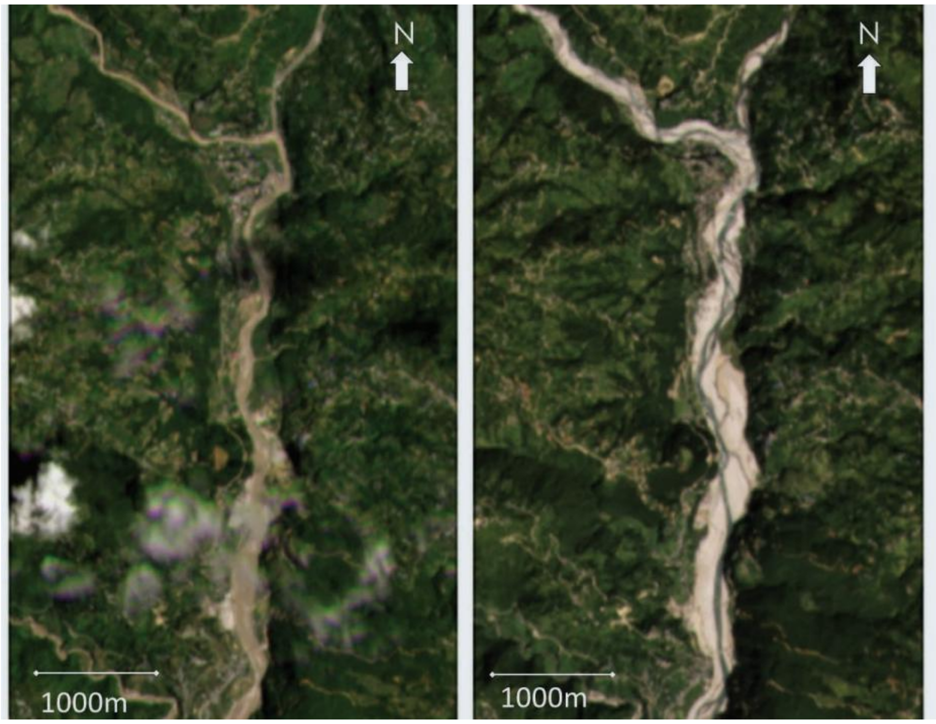

Figure 4.22 Pre- and post-event PlanetScope optical satellite imagery of Melamchi Bazaar showing channel widening and extensive sediment deposition before (August 2020) and after (October 2021) the 15 June 2021 debris-flow event.

Spatial distribution of sediment source areas

Remote sensing mapping shows that the debris-flow event was not only caused by a single moraine failure or glacial lake failure, and sediment sources were distributed across multiple headwater tributaries (Chen et al., 2023; ICIMOD, 2021). Satellite-based inventories reported erosion of unconsolidated moraine deposits and reactivation of earthquake-damaged slopes along the channel which crate (Chen et al., 2023). In particular, the major sediment source zone, the Pemdang Khola and nearby tributaries, is repeatedly discussed in the literature (ICIMOD, 2021; Chen et al., 2023).

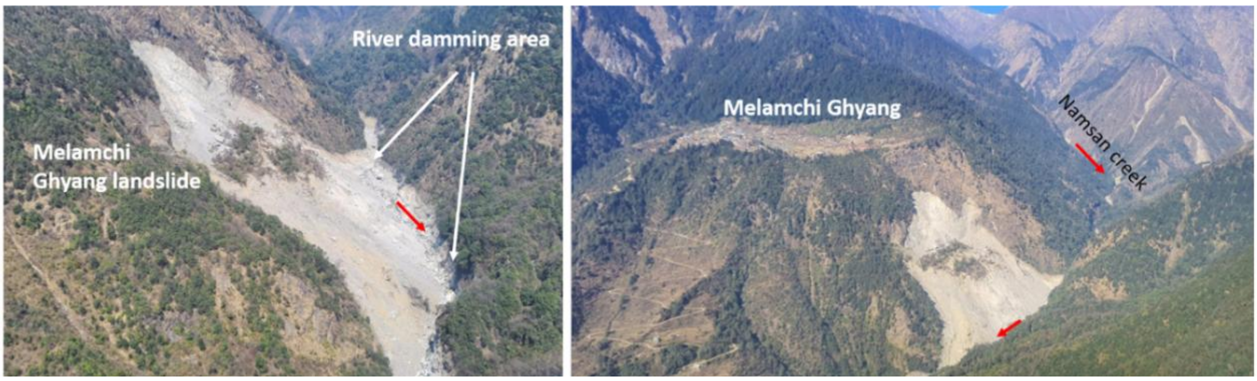

Figure 4.38 Landslide-induced river damming and sediment sources in the Melamchi Ghyang area

Sediment volume and sediment budget interpretation

Published analyses suggest that sediment volumes mobilised were very large, at a multi-million cubic metre scale (Graf et al., 2024; Chen et al., 2023). Erosion in the upper catchment was accompanied by downstream deposition and sediment export into the Indrawati River system (Graf et al., 2024). However, exact sediment volume estimation is uncertain and varies between studies due to limited data availability and DEM baseline quality (Graf et al., 2024; Chen et al., 2023).

Data limitations for detailed moraine stability assessment

In this study, the Himalayan moraine instability event is discussed as a reference case for comparison with the debris-flow event of the Valpelline region. Due to limitations in the availability and quality of datasets, it is not possible to perform back-analysis and flow modelling using DAN3D. Previous studies note that the lack of pre-event high-resolution topography and limited UAV coverage in high-mountain regions introduce significant uncertainty in runout modelling and geomorphic interpretation (Graf et al., 2024; Chen et al., 2023).

4.8.3 Methodological Constraints and Interpretation

Method applicability under data-limited Himalayan condition

Data availability, accessibility, and terrain conditions play a major role in moraine instability assessment. The application of integrated survey, mapping, monitoring, and modelling methods is strongly controlled by data constraints in difficult high-mountain environments, mainly in the Himalayan region (ICIMOD, 2021; Graf et al., 2024). In the Himalayan region, satellite remote sensing provides regional-scale geomorphic interpretation, but it is not sufficient for detailed monitoring of slope-scale stability assessment (Chen et al., 2023; Graf et al., 2024).

Implications for Stability Modelling

The slope and moraine ridge conditions were strongly influenced by damage from the 2015 Gorkha earthquake (ICIMOD, 2021; Maharjan et al., 2021). Due to this, strength parameters such as cohesion or rock mass quality may be significantly reduced compared to Alpine conditions. Without this consideration, classical Mohr–Coulomb stability analysis may overestimate slope stability (Maharjan et al., 2021).

Implications for DAN3D Flow Modelling

The Melamchi debris-flow event travelled a very long distance, exceeding 50 km, and showed very high mobility (Chen et al., 2023; Graf et al., 2024). The behaviour of this debris-flow event suggests low effective basal resistance and strong sediment entrainment along the Melamchi River (Graf et al., 2024). Since the Himalayan region does not have reliable data on pre-event volume and channel erosion, it is difficult to calibrate model parameters in DAN3D. In comparison, the Valpelline case allowed calibration of friction and erosion parameters using high-resolution DSM data and mapped volume changes.

Limitations for stability modelling and back-analysis

Since the Himalayan region, especially the high-mountain area of the Melamchi Valley, is less monitored and has very limited available datasets for stability modelling and back-analysis, physically based modelling approaches require reliable input data such as material properties, pore-pressure conditions, and detailed pre-event topography (Graf et al., 2024; Chen et al., 2023). Due to these incomplete or spatially inconsistent datasets, the Melamchi case is limited for effective slope stability back-analysis and numerical flow modelling. Therefore, modelling using DAN3D is not considered reliable within the scope of this thesis (ICIMOD, 2021; Graf et al., 2024).

Relevance of the Melamchi case for this thesis

In this thesis, the Melamchi event is used as a Himalayan case to support comparison with the Alpine moraine instability and debris-flow event in the Valpelline region. This study mainly focuses on the application of methodology and its limitations rather than performing quantitative modelling, which allows comparison between data-rich Alpine environments and data-limited Himalayan environments for the study of integrated hazard assessment approaches.

5. Discussion and Conclusions

5.1 Discussion: Comparing Alpine and Himalayan Dynamics

The result of this thesis shows that the fundamental physical processes, such as ice-core melting and increases in pore-water pressure due to climate change, control moraine instability globally, but the resulting hazards and responses are strongly shaped by regional environmental contexts such as channel shape, flow volume, downstream settlements, and differing data conditions.

The Alpine debris-flow event documented in this thesis in the Valpelline region has suitable high-resolution, multi-temporal Digital Surface Models (DSMs), enabling a precise back-analysis using DAN3D. The initial detachment volume of approximately 1.8×10^6 m^3 was successfully reproduced using numerical modelling. Stability modelling of the morainic surface confirms that intense rainfall is the primary triggering factor of this event, where the Factor of Safety (FoS) decreased from stable conditions.

In comparison to the 2021 Melamchi event in Nepal, it shows a cascading hazard occurring due to climate change within a data-limited Himalayan environment. Unlike the single-source failure observed in the Alpine debris-flow case, the Melamchi event involved multiple sediment sources starting from moraine failure due to intense rainfall to erosion of destabilized slopes by the 2015 earthquake, generating a complex process chain which moved more than 50 km downstream from the upper Himalayan region.

A significant monitoring gap between two similar events in the Alps and Himalayas highlights that more focus is needed in the Himalayan region for a proper hazard assessment plan. Hazard assessment in the Himalayan region relies heavily on post-event satellite imagery and rapid remote-sensing analysis due to extreme topography, remoteness, and limited accessibility. Whereas high infrastructure support and repeated field surveys in the Alpine region allow detailed monitoring and model validation.

5.2 Methodological Contributions

The integrated engineering workflow applied in this thesis, combining geomorphological mapping, DSM differencing, and numerical modelling using Slide2 and DAN3D, proved robust for assessing moraine-related hazards.

Stability analysis: Stability modelling using Slide2 confirmed that rainfall-induced saturation is sufficient to trigger instability in unconsolidated moraine deposits by significantly reducing the Factor of Safety.

Runout modelling: Runout simulations using DAN3D successfully reproduced the observed debris-flow travel distance, channelized flow behaviour, and deposition patterns near the Place-Moulin Dam when calibrated with Voellmy rheology.

Volume quantification: Multi-temporal DSM differencing proved essential for identifying and quantifying geomorphological changes that are not directly visible in field observations, revealing surface lowering exceeding 50 meters in the Tza de Tzan source area.

5.3 Final Conclusions

The results of this study demonstrate that glacier retreat due to climate change is accelerating paraglacial landscape adjustment, which increases the risk of sediment-rich debris-flow hazards in high-mountain regions.

• **Hydrological forcing:** Rainfall-induced pore-water pressure increase remains the most critical short-term triggering mechanism for moraine collapse in both Alpine and Himalayan environments.

• **Baseline data quality**: The availability of high-resolution topographic and monitoring data represents the primary requirement for reliable predictive modelling and hazard assessment.

• **Integrated methodologies:** Combining geomorphological investigation, remote sensing, and numerical modelling is essential to capture the complex interactions among climatic, geological, and mechanical processes governing moraine instability.

By documenting and reconstructing recent moraine-failure events, this thesis provides a scientific foundation for improving hazard evaluation strategies in remote mountain regions. The proposed integrated framework supports risk mitigation planning and contributes to protecting downstream communities and critical infrastructure under ongoing climate change.

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