Assessment of Glacier and Permafrost Hazards in Mountain Regions

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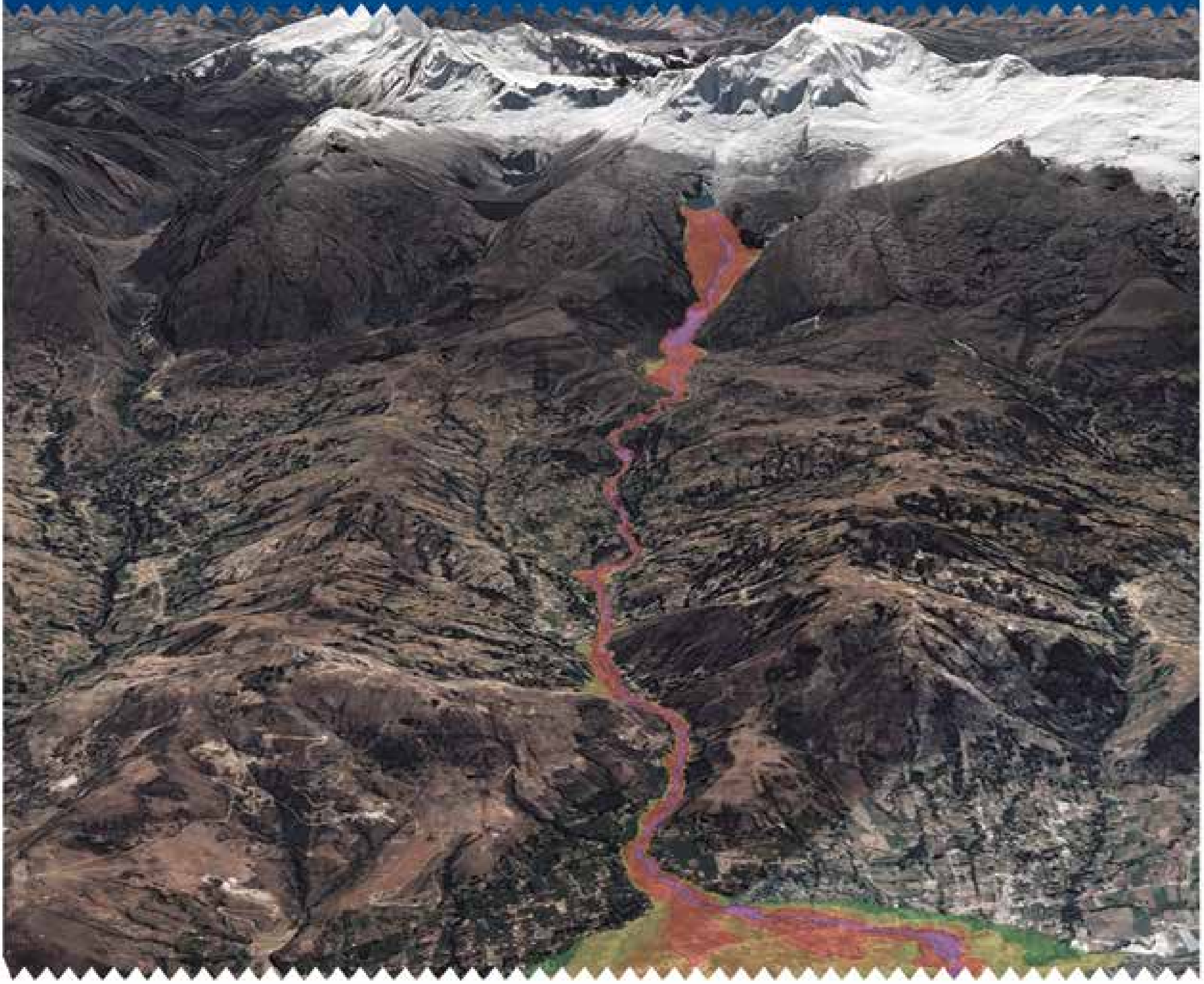

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Figure on cover page

Oblique view of the GLOF hazard map for the Chucchún catchment and the city of Carhuaz, Cordillera Blanca, Peru (cf. Schneider et al. 2014). Background: GoogleEarthTM.

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IMPORTANT NOTE

ACKNOWLEDGEMENTS

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CONTENTS

INTRODUCTION

Hazards relating to glaciers and permafrost occur in most mountain regions of the world and are a threat to lives, livelihoods, and sustainable development within some of the world's most vulnerable communities. In view of rapid global warming and related changes in the sensitive mountain cryosphere, landscapes are evolving and new threats are emerging. Coupled with the ongoing expansion of people and their infrastructure into high mountain valleys there is an increasing potential for societal losses and far-reaching disasters. Recognising the need for a structured and comprehensive approach to hazard assessment underpinned by latest scientific understanding, the Joint Standing Group on Glacier and Permafrost Hazards in High Mountains (GAPHAZ) of the International Association of Cryospheric Sciences (IACS) and the International Permafrost Association (IPA) has produced this technical guidance document as a resource for international and national agencies, responsible authorities and private companies. The work has been substantially supported by the Swiss Agency for Development and Cooperation (SDC) through the Glaciares+ Project.

1. SCOPE OF THE REPORT

In the context of a warming and evolving mountain landscape, this technical guidance document focusses on hazards that are directly conditioned or triggered by contemporary changes in mountain glaciers and permafrost. Emphasis is given to catastrophic mass flows that can travel far downstream or downslope, potentially leading to cascading processes and impacts. This includes ice avalanches and other glacier instabilities, rock or mixed rock-ice avalanches, para- or periglacial debris flows, and outburst floods from glacial lakes. In addition, we address glacier- and permafrost-related hazards that produce localised and on-site threats, such as land subsidence and deep instabilities. The treatment of hazards is not intended to be complete for the mountain environment, although potential interactions with phenomena such as snow avalanches and fluvial flash floods are discussed.

As a technical guidance document for practitioners and experts from a range of institutions, the end-user is expected to possess reasonable background knowledge and expertise in the field of hazard assessment. In this regard, the document is not intended to provide fundamental step-by-step prescriptive guidance. Rather, in direct alignment with one of the stated goals of the GAPHAZ Standing Group, the overall aim of the document is to provide a concise compilation of the state of knowledge and best practices related to glacier and permafrost hazard assessment. Internationally, the level and development of guidelines or standards on hazard assessments in different countries varies widely. While this document collects best practices to develop and propose robust approaches it may not always be fully in line with existing national or regional practice. Coordination with responsible authorities and stakeholders is recommended.

In the assessment of factors that can condition or trigger hazardous glacier and permafrost hazards, we focus on interlinking atmospheric, cryospheric, geological, geomorphological, and hydrological processes. The focus here on conditioning and triggering factors is to primarily determine where events are expected to occur, and the associated likelihood of an event occurring, as input for hazard mapping and associated planning purposes. Determining more precisely when an event might occur (i.e., forecasting and early warning) is outside the scope of this document. The role of anthropogenic factors such as engineering works which may directly influence, e.g., the stability of a slope or natural dam, or the volume of a lake, are also not addressed here, but should be an inherent component of any hazard assessment where human influence on the natural environment is evident. Furthermore, the document does not address other risk components, such as exposure and vulnerability of assets and people.

2. CLIMATE CHANGE AND EVOLVING MOUNTAIN LANDSCAPES

Today, a primary challenge concerning the anticipation and assessment of hazards in icy high-mountain regions is the fundamental paradigm change induced by effects from continued global warming. Disappearance of glaciers, permafrost degradation, landscape evolution and corresponding changes in inter-connected surface processes are cumulative developments. They lead far beyond historical precedence. Future conditions will in many places be far removed from the past and present and therefore limit the value of historical event inventories. Quantitative, future-oriented and scenario-based system approaches must therefore be applied (Allen et al., 2016; Schaub et al., 2013). However, modelling future high-mountain landscapes with their complex systems of interacting surface processes and landforms is a young, emerging research field, and uncertainties are inherently large. Individual components within the complex system have strongly diverging characteristics in their response to climate change. Glacier recession is rapid, if not accelerating, in most parts of the World (Vaughan et al., 2013; Zemp et al., 2015). By comparison, due to slow heat diffusion and retarding effects from latent heat exchange in subsurface ice, permafrost degradation is a slow process with long-term commitments, unless thermocast processes evolve. Many mid-latitude mountain ranges may largely lose their glaciers within decades (Huss and Hock, 2015; Zemp et al., 2006). Corresponding glacial landscapes will turn into periglacial landscapes characterised by slowly degrading permafrost, numerous new lakes and pronounced dis-equilibrium conditions concerning vegetation cover, slope stability and sediment cascades. In view of the large uncertainties involved with anticipating such conditions, focused monitoring using advanced space borne, air-borne and terrestrial technology is required, coupled with regular re-assessment of the general conditions and rapidly evolving hazard situations. The formation of new lakes located within increasingly close proximity to steep and de-stabilizing mountain headwalls has the potential to greatly enhance regional risks from far-reaching flood waves (Haeberli et al., 2016). Corresponding hazard and risk management relating to low-probability events with extreme damage potential is especially difficult for planning, policymaking and decision taking. Furthermore, the expected penetration of humans with their infrastructure for tourism, traffic or hydropower, etc., into previously un-accessible or even avoided high mountain areas must be taken into account. A long-term perspective to hazard and risk assessment in high mountain landscapes thereby requires intensive trans-disciplinary communication and cooperation.

3. KEY DEFINITIONS

Hazard is defined herein as the potential occurrence of a natural physical process or phenomenon that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage. This definition aligns with that of the climate adaptation (IPCC, 2014) and disaster risk reduction communities (UNISDR, 2009). In this report, we consider only those hazards that are directly conditioned or triggered by contemporary changes in mountain glaciers and permafrost.

Technically, hazard is assessed as a function of the probability that an event will occur and the expected intensity (magnitude) of the event:

$$\text{Hazard} = f\,(\text{probability, intensity})$$

Intensity is defined at a given site using a process-specific physical unit (see also impact), whereas magnitude may be used more generally over a range of scales.

Susceptibility is a relative measure of the likelihood (or probability) that a hazard will occur or initiate from a given site, based on intrinsic properties and dynamic characteristics of that site. The concept of susceptibility has a long history in landslide hazard assessment, and results are often expressed as susceptibility maps (Highland and Bobrowsky, 2008). Susceptibility has an inverse relationship with stability, i.e, an unstable lake dam could indicate that a given glacial lake is highly susceptible to outburst flooding.

Impact is used in this guidance document as a general term to refer to the potential physical threat produced by a hazard event. This component of the hazard assessment identifies the potential extent of the affected area, and provides information on the intensity of the expected event in terms of, e.g., inundation heights, velocities etc, providing the basis for hazard mapping.

A scenario in the context of glacier and permafrost hazard assessment describes a potential event of a given magnitude together with its corresponding estimated probability of occurrence. By considering several possible scenarios in the hazard assessment (typically small, medium, and large scenarios), the results can account for a range of outcomes and their inherent uncertainties. Scenarios for hazard assessment are valid for current conditions but may also incorporate future conditions under a changing climate. It is worth mentioning that in the context of climate change the term scenario refers to different future outcomes, such as greenhouse gas emission scenarios, that try to capture different pathways of climate change mitigation and are then translated into different scenarios of atmospheric warming (Moss et al., 2010). Corresponding time horizons are typically decades to end of the 21st century. It is important to note the difference between climate change scenarios and the scenarios used in hazard assessments (as those described above). For some processes, climate change scenarios can directly feed into the development of scenarios for hazard assessment, but in other case, linkages with climate change are not so well established. This subject of this document is at the interface of the hazard and climate change communities, and it is therefore recommended to clarify and specify the scenario type and time horizon applied in any study, and communicate this information clearly with stakeholders and other actors.

4. DOCUMENT STRUCTURE

Following the introduction provided in Part I of the guidance document, a review of key processes and their interactions will be provided in Part II. The intention of this review is to provide the reader with the latest state-of-the-art knowledge needed to inform the subsequent hazard assessment presented in Part III. After being introduced to the conceptual framework of the hazard assessment, the reader is then guided systematically through the core components of the hazard assessment. Key factors to be considered within the susceptibility assessment are outlined in a series of check-list tables, providing a valuable resource for practitioners (1). Throughout the guidance document, reference is made to case-studies and examples from the international literature. Finally, further technical details on available modelling tools for the hazard assessment are provided in Appendix 2, with a complete listing of literature cited in this document given in Appendix 3.

I. KEY PROCESSES AND INTERACTIONS

Figure 1: A large rock avalanche (~12 x 10^6 m^3) fell from the east face of Aoraki/Mt Cook on December 14, 1991. The failure reduced the elevation of New Zealand's highest mountain by ~30 m (Photo: Ian Owens, 16/12/91).

In this part of the document we provide a concise summary of latest scientific understanding of key hazard-related processes occurring in the glacier and permafrost environment. The intention is not to provide a comprehensive review, but rather to arm the reader with sufficient physical understanding to inform any subsequent hazard assessment. This includes a description of wide-ranging catastrophic mass flows that can occur in a high mountain environment, and the underlying preconditioning and triggering processes. We then explore spatial and temporal characteristics of the processes, emphasizing potential interactions that may exacerbate hazard potential.

1. CATASTROPHIC MASS FLOWS

The term "catastrophic mass flows" encompasses various hazardous geomorphic processes occurring in high mountain environments, primarily consisting of downslope and downstream movements of snow, ice, water, rock and debris. While key process types are distinguished in the discussion below, it must be noted that a key characteristic of catastrophic mass flows occurring in high mountain landscapes is the frequent interaction and transformation that occurs between processes, as material is entrained or deposited along the path, and as snow or ice melts (see also section 2.2).

1.1. ROCK AVALANCHES

Rock avalanches refer to bedrock slope failures that involve high velocity downslope flow-like movement of fragmented source material, which has originated from an intact rock mass (Hungr et al., 2001). Hence, there is a clear distinction from rockfalls, which involve smaller-scale dislodgement of loose bedrock, although terminology is often used interchangeably in the literature, and rockfalls can escalate to destabilize a much larger rock mass. Rock avalanches are documented across all mountain regions and are a primary agent of denudation in high mountain areas due to steep topography, high relief, unstable geological structures and seismicity interacting with transient climate-driven glacial, para- and periglacial processes (Evans and Delaney, 2015). Resulting impacts and societal consequences can be far-reaching, as the mobility of high mountain rock avalanches is enhanced due to lower friction and incorporation of additional mass as the flow travels over snow and ice covered terrain (Deline, 2008; Evans et al., 2009; Evans and Clague, 1988; Schneider et al., 2011).

Geotechnical factors (lithology and structure) determine the overall ability of a slope to resist the stresses that are acting upon it, and therefore also govern the geometry that a slope can maintain. These factors are largely static or changing slowly over geological time-scales, and hence are considered as primary conditioning agents that determine the inherent strength of a slope. The initial failure of rock-mass is classified according to three mechanisms, requiring an unfavourable configuration of the joints and bedding (Hoek and Bray, 1981). Plane sliding occurs when the failure plane is exposed in the rock face (so called “daylighting”), dipping at an angle greater than the angle of internal friction of the rock mass. Wedge failures occur when two discontinuities intersect to create a wedge, whereby the angle of the cliff face is greater than the angle of the potential slip surface. Toppling is rather more complex, involving the rotation of blocks or columns of blocks about a fixed base. In general, joints weaken a rock mass, providing not only a potential failure surface, but also pathways for water flow and heat transfer, and exposing increased surface area to weathering processes. Hence, large rock avalanches have frequently initiated from heavily fractured and dilated source material (e.g., Cox et al., 2015; Deline et al., 2011; McSaveney, 2002). Certain lithological units may be inherently linked to predominating mechanisms and magnitudes of failure, and rock avalanche inventories have revealed a preferential clustering of events where large-scale structural discontinuities occur, such as along lithological boundaries and fault zones owing to changes in engineering properties (e.g., Allen et al., 2011; Fischer et al., 2012). These same studies have shown that rock avalanches have predominated from very steep slopes in the range of 40 - 60°.

Although para- and periglacial controls on bedrock stability are complex, operating on a range of spatial and temporal time-scales, there is nonetheless compelling empirical evidence indicating a temporary increase in slope instability following deglaciation, and for enhanced instability from within zones of warm or marginal permafrost (Deline et al., 2015). In glacial or formerly glaciated environments, large slopes have been eroded at their lower flanks by glacial and/or fluvial action. Subsequent retreat of glacial ice leads to a debutressing effect where the support provided by the ice is removed (Ballantyne,

Figure 2: Rock avalanche and related debris flows at Pizzo Cengalo, Bondasca valley and Bondo, southern Swiss Alps. A: view of the rock slope failure zone after the slide of 23 August 2017 of ca. 3 million m^3. In 2011 a rock avalanche of ca. 1.5 million m^3 occurred in the winter (27 December 2011) from the same site. Immediately after 23 August 2017, debris flows started from the toe of the rock slope failure and entrained significant material of the rock avalanche (B) and caused heavy impacts in the downstream community of Bondo (C) (Photos: swisstopo, VBS, SDA).

2002). As a consequence of this unloading, stress-release fracturing can develop in the bedrock, creating new planes of failure (McColl, 2012), while previously insulated surfaces are exposed to hydrological and hydraulic changes, and altered regimes of mechanical and thermal erosion (Haeberli et al., 1997; Wegmann et al., 1998). Freeze-thaw weathering, for example, is capable of extending and weakening pre-existing fractures within the rock mass (Matsuoka and Murton, 2008). Linkages between atmospheric warming, permafrost degradation and slope instability have been postulated based on physical process understanding (Gruber and Haeberli, 2007) and field evidence, including the visual recognition of ice within failure zone of recent rock avalanche events (Dramis et al., 1995; Haeberli et al., 2004), the predominance of events from within zones of marginal or warm permafrost (Allen et al., 2011; Bottino et al., 2002; Noetzli et al., 2003), and timing of events during periods of unusually warm atmospheric conditions (Allen and Huggel, 2013; Coe et al., 2017; Gruber et al., 2004; Paranunzio et al., 2016; Ravanel et al., 2010). Coupled with this evidence, laboratory studies have also shed light on rock and ice mechanical properties in response to warming, demonstrating that the shear strength of both ice-bonded and ice-free fractures decreases with temperatures close to 0° (Davies et al., 2001; Krautblatter et al., 2013).

Triggering mechanisms for high mountain rock avalanche events are rarely established with any certainty, owing to the remoteness of the source areas and lack of reliable data in many regions. Many of the world's great mountain ranges are formed at active tectonic margins, where earthquake generated rock avalanches are common (e.g., Hewitt et al., 2008; Keefer, 1994; Xu et al., 2016). Heavy precipitation is a well-established trigger of landslide activity from lowland hillslopes, and has been linked to some recent high mountain rock avalanche events (Hancox and Thomson, 2013; Paranunzio et al., 2016). Particularly in the European Alps, where some of the most rapid atmospheric warming over the past century has been observed, many recent rock avalanche events also appear to have been preceded by extremely warm temperatures prevailing on the order of days to weeks (Allen and Huggel, 2013; Paranunzio et al., 2016). These events are typically of small to moderate size, and may be linked to rapid thawing of permafrost, active layer thickening, or rapidly rising pore and cleft water pressures from melting snow and ice. However, it is important to note that many large rock avalanches have occurred spontaneously without any obvious meteorological or seismic trigger, when the progressive degradation in rock mass strength in response to long-term static fatigue and various conditioning processes appears to reach some intrinsic threshold (e.g., Eberhardt et al., 2004; Hancox et al., 1999; McSaveney, 2002).

1.2 ICE AVALANCHES AND OTHER GLACIER INSTABILITIES

Ice avalanches originate primarily when ice detaches a) from the steep frontal section of a glacier (so-called cliff situations), or b) from a sloping glacier bed (so-called ramp or slab situation) (Alean, 1985). Several broad factors determine the occurrence of a catastrophic break-off and its magnitude. These include the shear strength at the base of the glacier ice (related to thermal and hydrological conditions), the inclination and shape of the basal slope, and the tensile strength of the glacier body itself (Evans and Delaney, 2015). In general, ramp-type instabilities arising from cold-based glaciers require a steeper critical sliding surface (as a proxy for the bed of small and steep glaciers) than for polythermal or temperate glaciers. Cliff-type situations on the other hand are rather associated with a sudden steepening or break in the bed topography.

Faillettz et al. (2015) combined monitoring and modelling to further elucidate thermal controls on glacier stability, and distinguished three settings:

1. Cold-based glaciers that are entirely frozen to their bedrock, where the instability results from the progressive increase of internal damage due to the change in glacier geometry (mass gain and thickening towards the front). In this case, the final mechanical rupture occurs within the ice, typically a few metres above the bedrock.
2. Poly-thermal glaciers that are partly frozen onto their bedrock with the presence of a temperate zone. In this case, the final rupture occurs directly on the bedrock in the temperate area of the glacier and can possibly propagate through the ice. Liquid water is present in the glacier (but not flowing) and plays a key role in the development of the instability.

3. Temperate steep glacier tongues subject to sliding on their bedrock. In this case, the final rupture occurs directly at the bedrock, and flowing water is present at the interface between the glacier and the bedrock. The instability results mainly because of rapid changes in subglacial water pressures, and requires a critical geometrical configuration (steep slope, no frontal abutment, and convex bed topography).

These underlying processes imply a significant topo-climatic influence on glacier stability, as glacier beds typically steepen and basal freezing increases with altitude and/or reduced air temperatures. Hence, a change in air temperature can alter the potential for ice avalanches through both a direct influence on the thermal regime of the glacier, and indirectly through changing geometry of the glacier. Regardless of how the failure initiates, as the ice mass moves downslope it disintegrates to produce a high-velocity, highly mobile flow of fragmented ice. Total runout distances are broadly related to initial detachment volume, although significant entrainment, flow transformation and cascading processes are possible (see section 2.2). As a general assumption, cliff-type situations are normally associated with smaller, frequent and repetitive events, and to some extent represent a natural ablation process for these glaciers. While large volumes are unlikely, impacts into glacial lakes and subsequent displacement waves are a significant and common threat, especially in cirque basins where lakes are forming beneath steep glaciated headwalls. Ramp-type situations produce less frequent but larger ice avalanches, capable of reaching and impacting downstream areas.

Large-volume (>106 m^3) ice avalanches are rare phenomena and have been reported from the European Alps, North America, the Andes, the Himalayas and Tibet (Schneider et al., 2011). Collapses of large parts of relatively flat valley-type glaciers are extremely rare. Examples have occurred at Kolka glacier in the Russian Caucasus (2002) (Evans et al., 2009; Haeberli et al., 2004; Huggel et al., 2005), where the glacier had been destabilised by a series of ice and rock avalanches from the steep slopes behind, and recently with the exceptional twin ice avalanche events in the Aru Cru Range, Tibet (2016) (Tian et al., 2017). Process understanding is still limited, although surging behaviour has been linked to some cases and was clearly observed prior to the events in Tibet. Proposed causal mechanisms contributing to such catastrophic detachments are related to increasing stresses and decreasing strength of the glacier system, including loss of shear resistance at the glacier bed due to the development of extreme water pressures from precipitation or melt processes (particularly in polythermal bed conditions), mass loading due to snow accumulation, and mass redistribution or loading from other mass movements landing on the glacier ice (Evans and Delaney, 2015).

Enhanced movement of the glacier and formation of tension cracks and crevassing at the surface is a frequent, but not essential, precursor of ice avalanche activity, and instabilities can occur without clear precursory signs (Faillettaz et al., 2016). Ice avalanches may also be triggered spontaneously by earthquakes. While in most cases this likely involves failure within the underlying bedrock (e.g. Huascaran disaster of 1970, Peru), there are also examples where minimal rock debris has been evident in the resulting avalanche deposit (van der Woerd et al., 2004). For example the recent 2015 Langtang disaster is considered primarily as an earthquake triggered snow-ice avalanche (Fujita et al., 2016). Due to changes in water pressures and reduction in shear strength, both heavy precipitation and extremely warm melt periods are also considered to be potential triggers of ice avalanche activity.

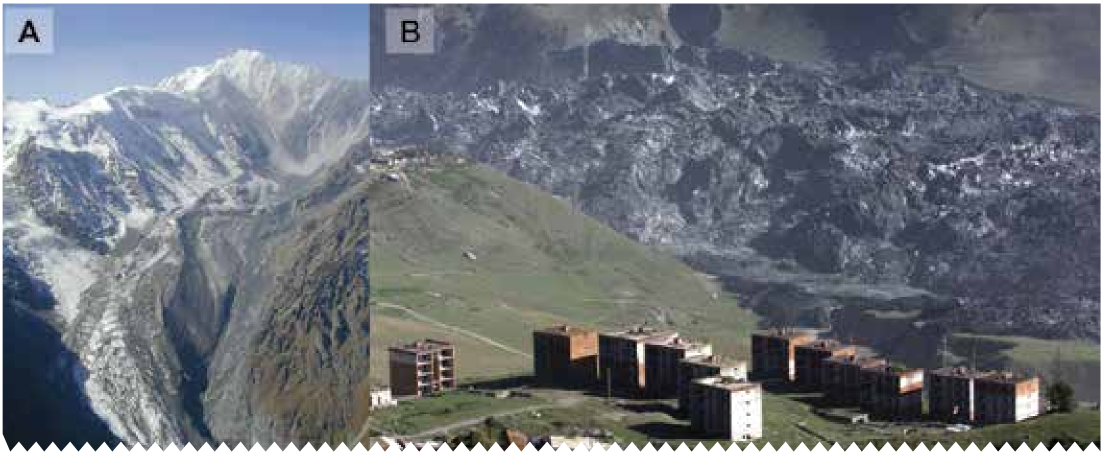


Figure 3: On 20 September 2002 the Kolka glacier in the Caucasus (North Ossetia, Russia) collapsed, resulting in a >100 million m^3 ice-rock avalanche that travelled 19 km downstream, transformed into a debris flow, causing some 140 casualties and massive damage. A: view of the collapsed Kolka glacier and initial trajectory of the avalanche. B: massive ice and debris deposits of the avalanche at Karmadon (Photos: I. Galushkin and Keystone).

1.3 GLACIAL LAKE OUTBURST FLOODS

The term Glacial Lake Outburst Flood (GLOF) is used here to refer to the catastrophic release of a water reservoir that has formed either at the side, in front, within, beneath or on the surface of a glacier. Dam structures that impound the water reservoir may be composed primarily of glacial ice, morainic debris, or bedrock.

Ice-dammed lakes can develop at the margin of an advancing (or surging) glacier, when side-valley's or depressions at the side of the glacier become truncated and blocked. Many such lakes formed in high mountain regions during the Last Glacial Maximum (LGM) and more recently during and following the Little Ice Age (LIA). Over time, as the glaciers retreat, the support of the ice dam is removed and the lake may drain catastrophically, or remain trapped behind lateral moraines of the former glacier. The recent 2013 GLOF disaster in Kedarnath, India, involved failure of such a lake (Allen et al., 2015). As previously confluent glaciers retreat, new lakes may develop in a freshly uncovered glacier forefield, dammed downslope by a remaining glacier. Subglacial lakes forming beneath glaciers are most well-known from Iceland where the formation (and drainage) is linked to geothermal and volcanic activity. Outbursts from ice-dammed water reservoirs within or beneath a glacier, including drainage of supraglacial ponds through englacial channels, have also been described across most mountain regions of the world, where linkages with heavy precipitation events or enhanced melt during warm weather have been noted (Benn et al., 2012; Huss et al., 2007; Richardson and Reynolds, 2000a; Rounce et al., 2017). Recent studies from the Tien Shan have shown that the size and lifetime of supraglacial lakes are controlled by the timing of connectivity to the englacial drainage network, with frequent monitoring required to assess rapidly evolving threats (Narama et al. 2010; 2017).

Sub- or englacial drainage occurs primarily through tunnels that become widened through thermal and mechanical erosion. What exactly initiates this outflow of water is often not well understood, but hydrostatic flotation of the glacier dam as the impounded water volume reaches some critical level is one possible mechanism. Outburst floods relating to tunnel enlargement typically develop more slowly and with smaller peak discharges than other GLOF mechanisms where lake volumes are comparable. More rapid sub- or en-glacial drainage events have been documented, although the involved mechanisms are not well understood.

The widespread retreat of mountain glaciers since the LIA has resulted in the formation of lakes trapped behind proglacial moraines, some of which may be spectacularly large with volumes of up to 100 million m^3, and depths exceeding 200 m (Cook and Quincey, 2015). These lakes can occupy steep cirque basins, or valley floors. For long, flat, debris-covered valley glaciers, which respond to a negative mass balance by thinning rather than by terminus retreat (e.g., Quincey et al., 2007; Richardson and Reynolds, 2000b), large lakes typically develop through the gradual expansion and coalescence of supraglacial ponds. Owing to the unconsolidated nature of morainic debris, which can be ice-cored, dam structures (up to 100 m in height) can be weak and prone to breaching via several mechanisms. Firstly, seepage, removal of fine sediment, and erosion on the downstream face of the dam can result from the hydraulic gradient across the dam. Degradation of ice cores in the dam can reduce the internal stability of the dam and therefore increase the susceptibility to dam failure. Secondly, retrogressive channel erosion (e.g. from wind-induced wave action, or break-through of a temporary outlet channel blockage) may incise the barrier and trigger overflow. Thirdly, rapid inflow of water (from rain or snowmelt) or the generation of displacement waves from mass movements (ice or rock avalanches) into the lake may increase water flow through the outlet channel and initiate incision. In either the case of rapid inflow of water or a mass movement generated floodwave, the hydrological, geomorphological, and geological characteristics of the surrounding slopes and watershed area of the lake become fundamental components of the hazard assessment. Earthquakes can trigger mass movements into a lake, or may directly destabilise a dam structure. However, empirical evidence is surprisingly scarce, and the 2015 Gorka earthquake in Nepal did not cause any significant moraine dam instability, perhaps in part due to the positioning of the lakes in flat valley-floor locations where ground acceleration was generally less (Kargel et al., 2016).

Figure 4: On June 16 and 17, 2013, devastating debris flows destroyed the village of Kedarnath, Uttarakhand, northern India. Most damage and significant loss of life occurred on June 17 when a small lake dammed at the lateral margin of the Chorabari glacier (blue arrow) overtopped and breached, following several days of extremely heavy rainfall. Unusually rapid spring snowmelt and runoff into the lake in the prior month was likely also a key factor (Photo: Vaibhav Kaul).

Once a channel is incised across a moraine dam and lake outflow increases, erosion is enhanced and the breach enlarged, lake flow increases further and a self-enhancing process is enabled (Figure 5). Typically, this continues until a point when outflow drainage starts to decrease along with shear stresses applied to the ground, and erosion processes are attenuated and eventually stopped. The composition (e.g, clast size, buried ice, vegetation) and geometry (e.g., height, width, slope) of the dam are crucial not only for the initial stability of the dam, but also as controls of the rate of erosion and final depth of any breach, which in turn are important determinants for the flood hydrograph. While there are some examples of moraine dams breaching soon after a lake has formed (O'Connor et al., 2001), dams may fail years to decades later, or persist for centuries or longer to become permanent, stable landscape features. In most cases, moraine breaches result in a significantly reduced lake water level, and the resulting enlarged channel typically prevents new threats from developing except when the lake is further enlarged and deepened, e.g. due to continued glacier recession and thinning. Furthermore, in rare instances, displacement waves from large mass movements can overtop a moraine dam and cause an outburst event without actually breaching the dam, meaning that the threat of secondary events remain. For bedrock dammed lakes, overtopping waves are the only mechanism by which a catastrophic flood may be initiated, as the dam structures themselves are considered stable.

Figure 5: Photo taken during the breach of a moraine dam, Gruben glacier, Valais, Switzerland, with substantial erosion and channel enlargement underway (Photo: H. Roethlisberger, 1970).

Once initiated, GLOFs tend to entrain large amounts of sediment, with the potential to transport massive boulders, particularly in the upper reaches where channel gradients in high mountain catchments are often steep. This is particularly true for floods from moraine dammed lakes, which frequently transform into debris or hyperconcentrated flows following the entrainment of material from the moraine and immediate downstream channel. Typically, stream channel slopes in excess of 6 – 9° are required to sustain such flows (Huggel et al., 2004a), with deposition of sediment occurring in gentler reaches. Due primarily to their large flow depths and locally high energy gradients, GLOFs produce erosive forces far greater than typical meteorological floods would for the same stream conditions. However, unlike meteorologically driven floods, GLOFs tend to rapidly attenuate downstream which has implications for potential impacts and losses (Schwanghart et al., 2016b). Downstream attenuation of the floodwaters is linked to the initial volume and duration of the breach/outburst event, with small volume short duration events attenuating most rapidly. However, in long stream channels such as in the Himalayas and the Andes, dynamic flow transitions are often observed for GLOFs, from initial debris flow types to hyperconcentrated flows and possibly back to debris flows depending on channel slope and availability of erodible material. Flood paths extending up to 100 km and even more have been observed (Carey et al., 2012; Cenderelli and Wohl, 2003; Schwanghart et al., 2016b).

1.4 DEBRIS FLOWS

While debris flows are commonly initiated from the outburst of steep moraine dammed lakes (see section 1.3), other non-outburst related debris flows in high mountain landscapes can originate from steep moraines, talus slopes at the foot of eroding rockwalls, from destabilised rock glacier tongues, and from fluvioglacial deposits within steep stream channels (Evans and Delaney, 2015). Once mobilised, debris flows consist of fast flowing mixture of sediment and water, comprising of one or several pulses (Iverson, 1997). The amount of sediment is variable, but typically amounts to 50 - 70% by volume. Diagnostic features include a substantial erosion capacity, transportation of large boulders, poorly sorted deposits and levee formation in response to flow deceleration on flatter terrain (Hungr et al., 2001). Peri- and para-glacial zones are favourable for debris flow initiation owing to the abundant supply of loose, unconsolidated material, coupled with steep topography, melting of snow and ice, and heavy convective or monsoon precipitation (Allen et al., 2015; Chiarle et al., 2007; Evans and Clague, 1994; Jomelli et al., 2007). Trigger mechanisms commonly include high summer temperatures and related melting of snow and ice, and/or heavy precipitation (Chiarle et al., 2007; Jomelli et al., 2007). For example, about 600 debris flows were triggered by heavy precipitation in the Swiss Alps during 1987, with more that 50 % of these events originating in zones that had deglaciated within the previous 150 years (Rickenmann and Zimmermann, 1993; Zimmermann and Haeberli, 1992). Similarly, studies in Southern Russia have demonstrated enhanced debris flow activity associated with recent rapid deglaciation and exposure of morainic material, with source areas often characterised by thermokarst features which can become oversaturated with meltwater or surface runoff (Seinova et al., 2011; Stokes et al., 2006). Cold permafrost bodies can act as a barrier to groundwater percolation leading to local saturation in the overlying non-frozen material (Zimmermann and Haeberli, 1992). Thawing permafrost in non-consolidated material leads to a loss of cohesion and increase in pore water pressure, and slumping where massive ground ice bodies disappear (Harris, 2005). Because re-vegetation of deglaciated terrain is slow, peri- and paraglacial landscapes can remain unprotected against erosion over extensive time periods of several decades or more (Kääb et al., 2005).

A strong seasonality to debris flow activity has been identified, with events occurring more frequently in summer and autumn in the European Alps (Rebetez et al., 1997; Stoffel et al., 2011), and during summer in the Caucasus (Perov et al., 2017). Not only is triggering from heavy convective precipitation or melt-related processes more likely during these warmer months, but also sediments are less likely to be frozen and hence, the availability of material for erosion is greater. Particularly in permafrost environments, there is a close association between debris flow activity and development of the active layer. Hence, following gradual top-down thawing of the near-surface material, slopes become most prone to instability by late summer or autumn. However, critical precipitation thresholds required to trigger an event may actually be smaller earlier in the summer when the active layer is shallower and already saturated from spring snow-melt (Schneuwly-Bollschweiler and Stoffel, 2012).

Figure 6: Debris flow originating from glacial moraines/till above the town of Tyrnyauz, Russia, July 2000. The most probable trigger of the debris flow was considered to be an outburst from an englacial cavity (Photo: A. Aleinikov).

1.5 MASS FLOWS FROM ICE-CAPPED VOLCANOES

Mass flows from ice-capped volcanoes have led to some of the largest disasters worldwide. Most prominently in recent history, a medium-sized eruption in 1985 of Nevado del Ruiz volcano, Colombia, melted substantial amounts of snow and ice, producing lahars (volcanic debris flows) that killed more than 20,000 people in the city of Armero some 70 km downstream of the volcano (Pierson et al., 1990; Voight, 1990). Five years earlier, in 1980, the catastrophic eruption of ice-capped volcano Mt. St. Helens generated a flank collapse and volcanic blast including massive ice and rock avalanches and lahars, devastating large areas around and downstream of the volcano (Waitt et al., 1983). Following these tragic and seminal events much research efforts have been invested in studying processes and interactions of volcanic activity with snow and ice, and associated hazards.

Figure 7: Glacier covered Nevado del Huila in the Cordillera Central of Colombia erupted in 2007 and 2008 after a longer quiescent period. Water melted by impacts of volcanic activity on glaciers produced massive lahars that travelled more than 100 km downstream. Efforts in hazard assessment, risk management and early warning effectively prevented large loss of life (Photo: INGEOMINAS/Geological Survey of Colombia, April 2008).

Lahars are the most far-reaching hazard from ice-capped volcanoes and can reach more than 150 km downstream of the volcano (Worni et al., 2012), and can involve tens of millions of m^3 of volume with peak discharges up to several tens of thousands of m^3s^{-1}. For instance, at Nevado del Ruiz in 1985 the total lahar volume was estimated at 90 million m^3 with a peak discharge of 48,000 m^3s^{-1} and velocities in the range of 5-15 m/s. Total volume of the 1956 lahar from Bezymyannyi volcano (Kamchatka Peninsula) was even larger, at 500 million m^3 (Seynova et al., 2017). Lahars can be produced both by eruption and non-eruption related processes on ice-capped volcanoes (Major and Newhall, 1989):

- Pyroclastic flows, i.e. a mixture of hot, dry rock fragments and hot gases moving at high speeds, are most effective in melting snow and ice that then can form potentially large lahars.
- Lava flows can produce melt when overrunning snow and ice but heat flow is generally much slower and less effective than with pyroclastic flows.
- Heat flow at the base of glaciers can be produced by subglacial eruptions or geothermal heat flow. Large amounts of water can accumulate subglacially, depending on topography and subglacial drainage system, and eventually drain catastrophically such as most prominently known from Iceland where this type of large sudden floods are termed jökulhlaups (Björnsson, 2003; Roberts, 2005).
- Ejection and deposition of ash and other eruption products on glaciers can hardly result in lahar generation but have important effects on the ablation and mass balance of glaciers. Crater lakes are a potential source of large floods, with triggers related to both eruptive and non-eruptive volcanic activity as well as snow and ice related dynamics.

A recent study has identified 144 ice-capped volcanoes, as well as 226 volcanoes with stable snow cover around the globe (Seynova et al., 2017). In terms of geographic distribution of ice-capped volcanoes and related hazards the Cordilleras of the Americas are a hotspot, with several additional important locations on the Aleutians, Kamchatka, Japan, New Zealand and Iceland. Hazard assessment studies have been performed for several ice-capped volcanoes in the Andes, Mexico and the USA, following a range of methods that necessarily need to consider the interactions of the volcanic and glacier systems (Huggel et al., 2007b; Künzler et al., 2012; Thouret, 1990; Waythomas et al., 2009).

1.6 OTHER RELEVANT PROCESSES

In addition to the processes described in Sections 1.1 – 1.5 various other natural hazards are occurring in the high mountain para- and peri-glacial environment. Deep-seated gravitational slope deformation of moraine walls and steep mountain flanks is a gradual and often long-term paraglacial process, with significant implications for onsite infrastructure (Deline et al., 2015). While rates of movement are typically very slow (centimetres to metres per year), if conditioning of the slope further deteriorates, triggering thresholds will lower and rapid, catastrophic failure can occur (McColl and Davies, 2013). In this context, earthquakes are important, providing a potential trigger for all types of catastrophic mass movement (e.g., Shugar et al., 2012; van der Woerd et al., 2004), but also owing to their cumulative effect on slope stability and landscape evolution, enhancing erosion and sediment delivery from high mountain systems (e.g., Howarth et al., 2012; Schwanghart et al., 2016a). Snow avalanches occur throughout all mountain regions of the world, and well established assessment procedures and scientific understanding are built on many decades of research and community exchange (for example, the International Snow Science Workshops date back to the 1950s). As such, snow avalanches are not explicitly considered in the context of glacier or permafrost hazards. However, the importance of accounting for snow entrainment within mixed ice/rock/snow avalanches is acknowledged (Schneider et al., 2011), while the recent Langtang disaster in Nepal has highlighted the devastation that can occur when large snow avalanches detach from steep glaciated headwalls (Fujita et al., 2016).

Finally, fluvial flash floods (often referred to as mountain torrents) are also not addressed in this document, although such events may be enhanced by spring snow or ice melt, and large storm events may trigger a devastating convergence of fluvial flash flooding and GLOF activity (Allen et al., 2015; Das et al., 2015). Hence, in view of the wide-ranging hazards that can affect the high mountain environment, integrative cross-disciplinary approaches are typically required for hazard assessment at

2. PROCESS INTERACTIONS AND DYNAMICS

2.1 SPATIAL AND TEMPORAL DIMENSION OF PROCESSES AND HAZARDS

Glacier and permafrost hazards are characterised by wide-ranging spatial and temporal dimensions (Figure 8). At one end of the continuum, small volume icefalls and rockfalls occur on an almost daily basis in dynamic mountain environments, particularly during warm summer months when event frequencies can be closely linked to diurnal warming and melting. The threats from such hazards are typically localised within the high-mountain environment, but can be of concern, for example, where large numbers of recreationalists (such as mountaineers) traverse through exposed routes (Temme, 2015). At the other end of the continuum, comparatively rare, yet large magnitude avalanches of ice and/or rock have the potential to obtain large runout distances and thereby threaten people and infrastructure located far downstream (Schneider et al., 2011), particularly where events transform or where process chains are initiated (see Section 2.2).

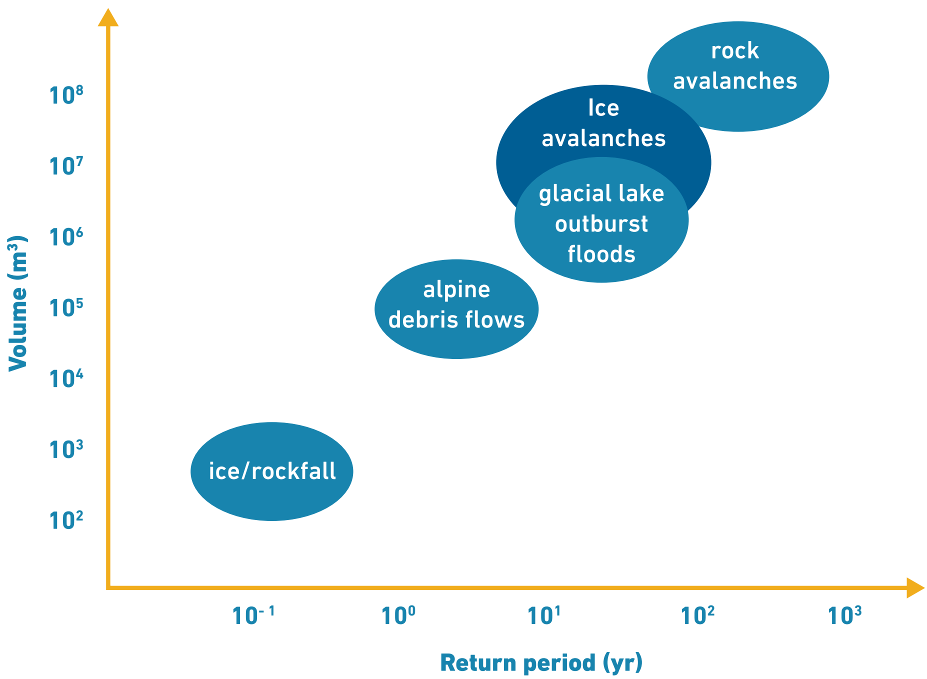


Figure 8: Characteristic volumes and return periods of different slope failures and mass movements in high mountain and cryosphere areas (Huggel et al., 2012). The figure is generalised, and does not exclude that given events may occur much more frequently. For example, some glacial lakes can develop rapidly or refill seasonally, to produce repetitive and frequent outburst events

In this document, we address both processes that condition or predispose, and those processes that directly trigger hazard events or chain reactions. Climate change is unique in this regard, as related changes in the cryosphere and hydro-meteorology induce complex influences on erosion and landscape stability, operating on a range of spatial and temporal scales. Considering the example of bedrock instability, geological structure and slope topography are typically considered as static preconditioning factors, yet both may be responding slowly to glacial recession and debutressing on time-scales of centuries to millennia (McColl, 2012, see also Part III). Such processes lead to a gradual reduction in the shear strength of a slope, while shorter duration hydrometeorological extremes such as heavy precipitation or snow-melt produce a more rapid response in slope stability. At intermediate time-scales (e.g. as related to accelerated warming of the past century), one might consider processes such as thawing of permafrost at depths of metres to tens of metres, or disappearance of small glaciers. Processes that can cause abrupt reductions in shear strength (including earthquakes) can only act as a trigger of slope failure where the shear strength is already sufficiently low, and near to some critical threshold (Figure 9). Hence, the assessment of glacier and permafrost hazards must consider the long-term evolution of landscape dynamics and interacting processes, both from historical and forward-looking future perspectives.

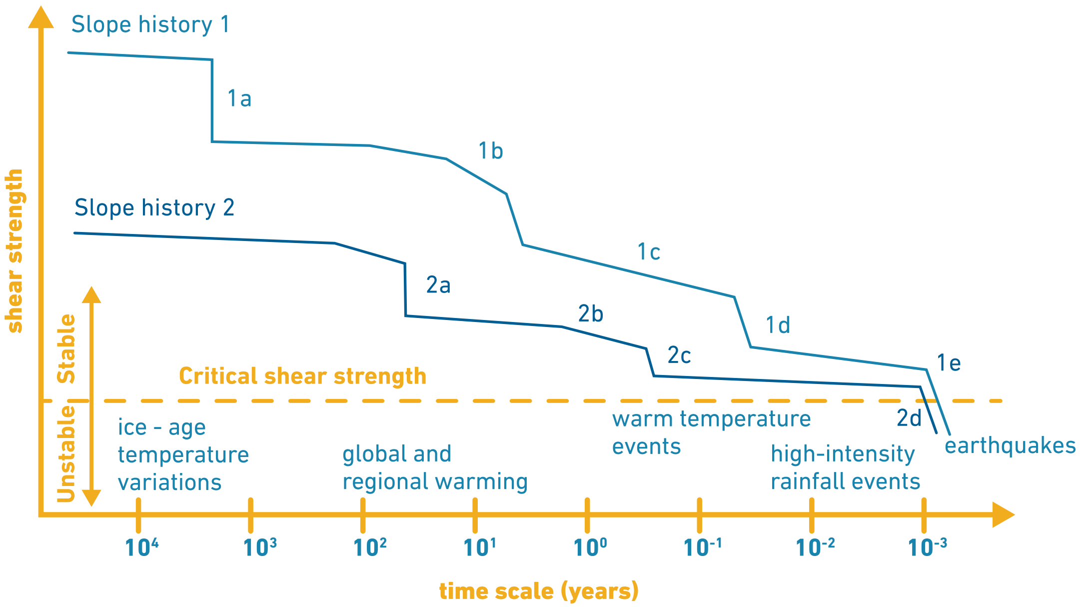


Figure 9: A conceptual sketch showing the long-term evolution of stability for two slopes. The dashed line indicates the critical shear strength threshold below which the slope is unstable and a failure could be triggered (from Huggel et al., 2010). Both slope evolutions are characterized by processes that produce a gradual decrease in shear strength (e.g. glacial recession since the Last Glacial Maximum), and abrupt reductions in shear strength (e.g. hydro-meteorological extremes or earthquakes). Slope 2 has a lower initial shear strength due, for example, to rock type or structure.

2.2 PROCESS CHAINS AND COMPOUND EVENTS

A distinguishing characteristic in the assessment of glacier and permafrost hazards is the need to consider interacting processes and their cumulative downstream impacts. In fact, some of the most devastating and far-reaching disasters in high mountain regions have involved such process chains, starting as ice and/or rock avalanches and processing downstream as debris, mud, or hyper-concentrated flows (e.g., Huggel et al., 2005; Lliboutry et al., 1977). The interaction between processes may be immediate (i.e., seconds to minutes), as in the case of a mass movement impacting into a lake and causing an outburst flood. For other interactions, such as the damming of a lake by a landslide deposit or surging glacier, the resulting secondary hazard may evolve on time-scales of days, weeks, months or even years (for more information on landslide dammed lakes see e.g, Schneider et al. 2013; Korup and Tweed 2007).

One example of a typical process chain, involving mass movement of ice or rock into a glacial lake, has been well described by several authors (e.g., Worni et al., 2014) (Figure 11), and is gaining increasing

Figure 10: Trajectory and deposits of the 6 August 2010 rock avalanche and debris flow at Mount Meager, British Columbia, Canada. The avalanche initiated in volcanic rocks with a volume of 53 million m^3 and transformed into a debris flow that travelled some 10 km downstream where it blocked the Lillooet River (Roberti et al., 2017). Exceptional erosion, run-up and superelevation features of the mass flow are clearly visible (Photo: T. Spurgeon).

importance in view of new lakes forming in close proximity to steep, destabilising mountain flanks (Haeberli et al., 2016). A key challenge for hazard assessment is that while different scientific and engineering communities have developed modelling approaches for individual processes (e.g., wave generation, dam breach, flow propagation), these approaches were never designed for integrative GLOF modelling. Schneider et al. (2014) have provided one of the first coupled mass flow and lake impact model implementations as a basis for hazard mapping in Peru. In this example, the largest uncertainties relating to the overtopping wave emerged not from the coupling of various models, but rather stemmed from the initial scenario definition for the rock/ice avalanche (Schaub et al., 2015), emphasising the importance of the initial slope stability assessment. Recent attempts aim at providing model approaches that are capable of simulating the entire chain of interacting processes with two-phase mass flow models (Kafle et al., 2016). On larger times scales (months to years or longer), there are important connections between rockfall, rock avalanches and debris flow activity. Increased availability of unconsolidated and easily erodible sediment such as from rock avalanche deposits can strongly change debris flow activity (Frank et al., 2015; Tobler et al., 2014).

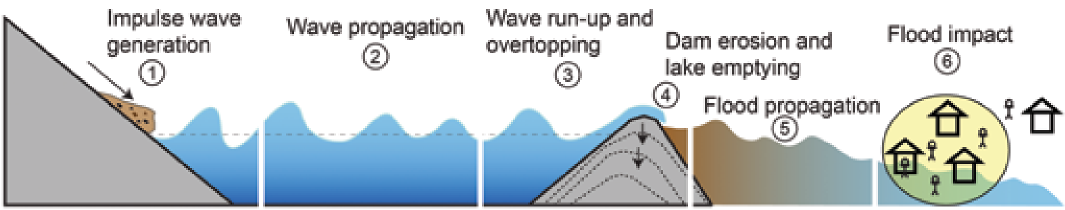


Figure 11: Schematic sketch showing a typical glacial lake outburst chain resulting from an initial mass movement (from, Worni et al., 2014). (1) A mass movement (ice, rock or debris) enters a lake, producing (2) a displacement wave that (3) overtops and (4) incises and erodes the dam area. (5) A flood then travels downstream where (6) populated areas and infrastructure are exposed. Note that displacement waves can be catastrophic with or without erosion of the dam area, and as such, can threaten also apparently stable bedrock dammed lakes.

II. HAZARD ASSESSMENT

In this main component of the guidance document we outline a systematic approach for the assessment of glacial and permafrost hazards. Following an introduction to the assessment framework, we address two underlying core requirements for hazard assessment, namely, the importance of developing and maintaining inventories of past events, and in the context of a rapidly changing climate, the need for robust climatic data to underpin the assessment. Based on the state-of-the-art presented in Part II, we then guide the reader through the key considerations and latest methodological approaches for the assessment of glacier and permafrost hazards in mountains, with an emphasis on hazard mapping.

1. FRAMEWORK AND CORE CONCEPTS

1.1 ASSESSMENT FRAMEWORK

Two core components (or outcomes) of the hazard assessment process are distinguished:

- Susceptibility and stability assessment: Identifying where from, and how likely hazard processes are to initiate.
- Impact assessment: Identifying the potential threat from the hazard for downslope and downstream areas, and providing the scientific basis for decision making and planning.

Note that we concern ourselves here with the potential physical impact only, whereas any assessment of societal impacts, damage, and losses, falls within the realm of risk assessment and is outside the scope of this document. The framework is not prescriptive, but rather is intended to guide the practitioner and expert systematically and comprehensively through the assessment process. At each stage of the assessment, various tools and methodologies are available and should in each case be tailored to the local context and needs. The framework is also intended to be generic enough to guide assessment studies at a range of scales, from regional to local site-specific. The scale of any assessment will depend on the questions being investigated, e.g., what hazard does a particular lake pose (site-specific), or how hazards threaten hydropower development in a particular river basin (regional scale). As a study advances from considering susceptibility and stability through to impact assessment, the relevance and usefulness for local authorities tasked with disaster risk reduction and climate change adaptation generally increase.

Where data and expertise allow, an ultimate end-goal could be the development of physical-numerical model-based hazard maps, validated and fine-tuned with field studies, and translated into recommendations for planning. However, we recognize that this may not be feasible or desirable in all cases, and other valuable outcomes can be foreseen based on simplified first-order approaches and expert assessment.

1.1.1 Susceptibility and stability assessment

We provide guidance for a wide-ranging assessment of the atmospheric, cryospheric, and geotechnical factors that condition and trigger a hazard event (see section 2). Conditioning factors encompasses static and inherent characteristics of the site, but also those dynamic factors that gradually increase the susceptibility of a site over time. Triggering factors are thereby reserved for those processes that directly initiate movement or transform a site from a stable to unstable state. How relevant certain factors are for susceptibility or stability will vary from one region to another, and expert judgement is needed to determine whether or not more emphasis (weighting) should be applied to some factors in the local assessment of susceptibility. For example, if an inventory of past rock avalanches in a region shows that all events occurred from within a certain lithological zone, this factor might be strongly weighted in the assessment of slope stability.

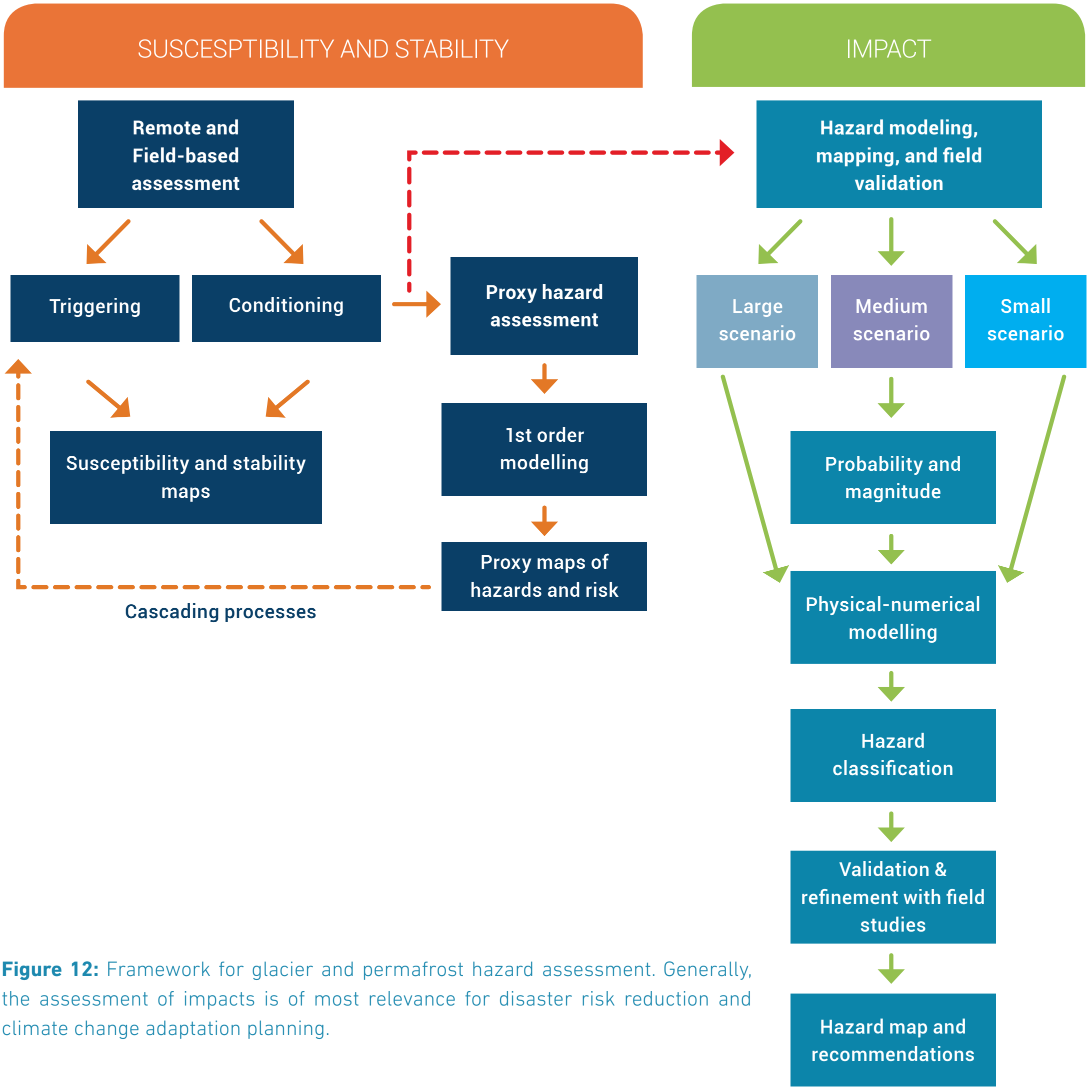


Figure 12: Framework for glacier and permafrost hazard assessment. Generally, the assessment of impacts is of most relevance for disaster risk reduction and climate change adaptation planning.

Conditioning and triggering factors inform not only about where and how likely an event is to initiate, but also provide insight on possible magnitudes that may be involved. Hence, the susceptibility and stability assessment provides a basis for identifying and prioritizing where subsequent impact studies will be focused (e.g. focusing on highly susceptible or unstable slopes), while the information gathered during this stage will also feed directly into the scenario development and hazard modeling within the impact assessment phase. Typically, approaches to susceptibility assessment at basin or larger scales are based on remotely derived information, with GIS used to overlay the various susceptibility factors so that a pixel-based semi-qualitative classification can be implemented. Where critical threats are recognized, and field access or very high resolution remote sensing are feasible, site-specific data can be used to drive quantitative analyses, such as slope stability or slope kinematic models.

1.1.2 Impact Assessment

Our framework recognizes that many larger-scale studies (e.g. district or regional) have tended to go beyond susceptibility and stability assessment, using simple models and empirical approaches to estimate downstream flow paths and possible runout distances, but falling short of the quantified information required for hazard mapping (e.g., Allen et al., 2016; Rounce et al., 2016). Here we categorize this intermediate step as the proxy hazard assessment, the main outputs of which are indicative maps of potential hazard or risk. The first-order models used are often empirically derived, but not physically based, and hence cannot provide information such as flow heights, impact pressures, velocities etc, as required for comprehensive hazard mapping. Nonetheless, such models are valuable in that their simplicity allows multiple (e.g., hundreds) of potential event paths to be simulated, and hence resulting maps can serve as a first-order indicator of potential threats and as a basis for prioritizing further local investigations and hazard mapping. For cascading processes, such first-order modelling can also feed back into the susceptibility assessment, identifying, e.g., where lakes are located within the potential runout path of an ice or rock avalanche.

Where critical situations are identified (e.g., where susceptibility is high and/or where the proxy hazard assessment has identified key threats), hazard modelling and mapping is likely to be undertaken. Hazard mapping, in the context of this guidance document, refers strictly to the assessment of hazard as defined on the basis of the probability that an event will occur, and the expected intensity of the given

Hazard = f (probability, intensity)

Hazard mapping typically draws upon historical records to establish frequency – magnitude relationships that can then be used as a basis for scenario development and hazard modelling, e.g., hazard mapping for a given river floodplain might be conducted for a 20-year flood event with an established peak discharge of 1000 $m^3 s^{-1.}$ For hazards originating in high mountain environments, the ability to establish reliable frequency – magnitude relationships is limited by three factors:

- Hazards originate often in remote, inaccessible locations, meaning even large events may have passed unnoticed and dates are poorly constrained for the historical record.

- The cryosphere is changing rapidly and in some cases conditions are already beyond any historical precedence, meaning frequency – magnitude relationships are of decreasing significance.
- Many events can occur only once (e.g. complete incision of a moraine dam), and hence, frequency – magnitude relationships may not apply at all.

Given these limitations, a semi-qualitative approach to scenario development is recommended whereby scenarios of three different magnitudes (e.g., small, medium, and large) are linked to corresponding best estimates of the likely probability of occurrence (e.g., low, medium, high). The fundamental basis for the scenario development should be the information gathered during the susceptibility and stability assessment, augmented where possible with best understanding of past events occurring in the region or other areas. We highlight the importance of including a worst-case scenario, i.e., the largest magnitude event that could be anticipated, the probability of which will be determined based on the information sources described above. Particularly for the anticipation of new or emerging threats under a changing climate, worst-case scenarios provide a conservative approach with which to capture the various sources of uncertainty inherent in future projections. A toolbox of physical-numerical models can then simulate for each scenario the potential downslope/downstream hazard event (see Annex II), providing key parameters such as flow heights, impact pressures, and velocities, as required for intensity mapping and hazard classification. Scenario development, modelling approaches, and hazard classification and mapping procedures for both single events, and more complex process chains are outlined in Sections 3.2 – 3.4

1.2 THE ROLE OF HAZARD INVENTORIES

Inventories of past catastrophic mass movements are a fundamental prerequisite for the assessment of hazard and risks. Through investigation of the distribution, type, and pattern of past hazard events, understanding of triggering and conditioning processes can be improved, the susceptibility assessment optimized, and the impacts better constrained (Carrivick and Tweed, 2016). Identifying and cataloging hazards occurring in high mountain regions is challenging because 1) there are few eye-witnesses, 2) cloud, shadow, and/or snow cover can obscure remotely sensed imagery, 3) glacial and fluvial erosion can rapidly remove evidence of mass movement processes, 4) accumulations of ice/snow disappears rapidly (within days/weeks), and 5) fresh debris (e.g. from a landslide) deposited on top of older debris covered surfaces (e.g. glacial moraine) can be difficult to recognize.

Systematic glacial and permafrost hazard inventories are most developed for the European Alps, where researchers can draw on a long history of scientific monitoring and where mountaineers, hut wardens, and other regular users of the mountain landscape are engaged in data collection (Fischer et al., 2012; Ravanel and Deline, 2011; Temme, 2015). As a consequence, process understanding and many empirical rules defining, e.g., starting zone characteristics or runout distances are based largely on data coming from the European Alps (Haeberli, 1983; Huggel et al., 2004a), and often only very large events from other more remote mountain regions are well documented. For GLOFs, efforts have recently been undertaken to establish an international database of events (http://glofs-database.org/), which will aid understanding of GLOF processes and impacts across different physical and social environments

(Vilímek et al., 2014). In order to assess changes in processes over time, hazard inventories should span a minimum of 30 years (i.e., typical length of a climatological reference period), with shorter records unlikely to yield statistically robust trends. In this regard, reconstruction of historical events through, e.g., dendrogeomorphological techniques, can substantially improve the baseline knowledge on hazard processes and particularly frequency-magnitude relations (Stoffel and Bollschweiler, 2008). Using GLOFs as an example, we outline the information below that would typically be captured within a GLOF hazard inventory. See Section 2 for a comprehensive overview of the type of information required to understand the triggering and conditioning of other mass movement processes.

The main physical parameters of the international GLOF database are as follows (Vilímek et al., 2014):
Glacial lakes:

- name
- coordinates (longitude, latitude, altitude)
- location (mountain range, valley)
- lake type (supra-, pro-, peri-, subglacial, etc.)
- dam type (bedrock-dammed, moraine-dammed, ice-dammed, combined dam)

Flood following dam failure or overflow:

- date of occurrence
- probable trigger
- outburst mechanism(s)
- flood volume
- peak discharge
- downstream reach (also influenced by downstream topography)
- flow type/sediment load

1.3 ASSESSING THE CLIMATIC BASELINE

Changes in mean and extremes of the atmosphere (mainly temperature and precipitation) and the resulting impacts on the cryosphere are important conditioning and/or triggering factors for many flood and mass movement processes (see Section 2). Characterizing such changes is therefore a challenge considering that hydro-meteorological data are scarce in many remote mountain regions. To some extent, freely available gridded climatological datasets can serve as a surrogate for ground-based measurements, with satellite-derived precipitation estimates from TRMM or IMERG being used extensively in the assessment of landslide and GLOFs that have occurred over the past ca. 20 years (e.g., Allen et al., 2015; Mathew et al., 2014). However, both under- and over-estimation of actual precipitation quantities are possible from such datasets. For temperature, reanalyses products can provide a coarse estimate of possible large-scale anomalies, or commonly, temperature trends are extrapolated vertically and horizontally from the nearest available station data (often some 100 km or more in remote regions). While many authors have used such extrapolations to infer melt and thaw-related influences on triggering or conditioning, the associated uncertainties in these studies are large. Similarly, studies have often referred to a mass movement trigger as being "unusually heavy precipitation", "extremely warm temperatures" etc., without there being any statistical basis for these statements. Ideally, both mean and extreme climate conditions should be defined locally based on a reference period of 30 years or more (Seneviratne et al., 2012), and at least within any given region, a common time period should be used for this definition. Recently, Paranunzio et al. (2015, 2016) have introduced a statistical approach to detect the anomalies of climate parameters (temperature and precipitation) associated with rockfall occurrences in the Italian Alps, providing a robust tool for investigating factors which condition and trigger slope instability at high elevation.

Given these considerations and challenges, as part of any long-term strategy for monitoring and assessing related hazards, establishment of automatic weather stations (including snow measurement) and stream gauges should be undertaken, ideally at multiple elevations within a catchment. Particularly for consideration of future changes, local station data are required to down-scale results from global or regional climate models. Procedures for remotely monitoring glacial changes, including lake formation, are well established, and recent inventories are available for most mountain regions of the world. These inventories should be updated at regular intervals. Permafrost, as a sub-surface phenomenon can hardly be assessed remotely, and therefore permafrost conditions are commonly inferred using modelling approaches, ranging from simple empirical rules to physically based numerical models (e.g., Boeckli et al., 2012; Etzelmüller et al., 2001; Fiddes et al., 2015). For critical sites, temperature sensors may be installed at or below the ground surface, or geophysical surveys conducted to validate modelling results and monitor changes over time (e.g., Gruber et al., 2003; Hauck, 2013).

2. SUSCEPTIBILITY AND STABILITY ASSESSMENT

Below we outline the main factors to be considered and corresponding methodological approaches to be applied within the susceptibility and stability assessment for various glacier and permafrost hazards. We broadly group these factors as relating to the cryosphere or to the geotechnical and geomorphological setting, while recognizing that there are strong interlinkages between the various factors. This information is summarized in Appendix 1, Tables 1 – 5.

2.1 ROCK AVALANCHES

Physical characterization of the bedrock structure and strength are essential for the evaluation of slope stability. However, because rock avalanches initiate from some of the steepest, inaccessible high mountain slopes, assessment approaches must often rely on remote sensing applications. Where critical threats are recognized, and field access or very high resolution remote sensing is feasible, site-specific information on geotechnical and other factors can be used to derive static, kinematic, or dynamic models to assess the stability of the slope.

2.1.1 Cryospheric Factors

Various approaches exist to model permafrost conditions, ranging from simple empirical relationships between mean annual air temperature (MAAT) and slope topography, to advanced numerical models that estimate ground surface temperature (e.g., Boeckli et al., 2012; Fiddes et al., 2015; Gruber et al., 2004). For a slope susceptibility assessment, a particular interest is to identify bedrock areas where permafrost is likely to be warm (marginal), i.e, where ground surface temperatures are ~0°. Related investigations typically focus on a critical range of around -1.5 – 0 °C. In significantly colder or warmer slopes, thawing permafrost is less likely to be a relevant factor, although cannot be excluded, particularly where the presence of hanging glaciers and related transfer of latent heat through the firn of the accumulation zone can induce strong thermal perturbations. Model results provide only a proxy indication of actual permafrost conditions, while local geophysical (e.g., Electrical Resistivity Tomography) measurements can provide semi-direct information on thermal conditions, ice content and unfrozen water at depth (see Hauck, 2013 for an overview of geophysical processes). The disappearance or thinning of glacier bodies on or below steep rock faces can be best quantified from repeat satellite, aerial or terrestrial imagery, and used to infer related thermal and mechanical (e.g., debuttressing) effects on the slope.

2.1.2 Geotechnical and geomorphic factors

Any bedrock slope stability assessment must begin with fundamental understanding of the local geotechnical conditions, and in particular the orientation and condition of bedding, foliation, joints, faults and other discontinuities (Hoek and Bray, 1981). Where larger scale geological maps are available, these can serve as a first guide and some geotechnical characteristics can be inferred based on mapped lithological units and structures, particularly where historical landslide inventories provide a strong scientific basis for linking certain lithological units with structural conditions and failure processes (e.g., Allen et al., 2011). Similarly, where large scale discontinuities occur (e.g., along fault zones, or lithological boundaries), unfavorable conditions may be inferred. Subsequently, high resolution remote sensing (including laser scanning) and/or field mapping are required to facilitate a more detailed assessment of structural discontinuities. Various geotechnical assessment schemes for rock slope stability have been developed (see Pantelidis, 2009 for an overview), of which common input requirements may be broadly grouped as:

- Rock mass strength and quality (intact rock strength, erosion, weathering etc.)
- Condition of the discontinuities (filled with breccia, presence of water, ice etc.)
- Geometric characteristics of the discontinuities (dip, orientation, spacing etc.)
- Condition of the slope (irregularities, vegetation cover etc.)
- Geometry of the slope (slope angle, aspect, height etc.)

It is not possible here to review the detailed requirements of a geotechnical assessment, and generally a high level of expert knowledge is required to determine whether or not conditions or geometries are favorable or unfavorable for bedrock stability. The susceptibility classification should be informed primarily by local geotechnical knowledge and understanding of past landslide activity in the given region. In general, where inventories have been analyzed, the highest susceptibility arises on very steep slopes (~40 - 60°) where discontinuities are frequent (heavily fractured), dilated, weak, and with geometrical configurations which can cause a planar, wedge, or toppling event (Allen et al., 2011; Fischer et al., 2012; McSaveney, 2002). Seismicity can be both a conditioning and triggering factor for slope failure and needs to be considered in seismically active regions. Documented evidence of enhanced rockfall activity is a strong indicator of unfavorable conditions and may escalate to trigger a larger slope failure.

2.2 ICE AVALANCHES AND OTHER GLACIER INSTABILITIES

Ice avalanches are a challenge for hazard assessment because key processes are generally evolving rapidly within or beneath the glacier and hence are difficult to directly observe or monitor. Assessment therefore relies heavily on proxy indicators that can be observed or inferred from the glacier surface, often using remote sensing techniques. Because some instabilities occur repetitively from the same glacier, an inventory of past events can be highly insightful for susceptibility assessment. Some factors may only become detectable in the weeks or days prior to an ice avalanche event, therefore being less relevant for hazard assessment and mapping, and rather more useful for early warning purposes.

2.2.1 Cryospheric Factors

Glacier type, thermal characteristics and bed slope are among the most important factors to be considered in the assessment of ice avalanche susceptibility. Cold glaciers typically imply internal rupture mechanics while temperate and polythermal glaciers also involve basal sliding instabilities (Faillettaz et al., 2015). According to the failure mechanisms involved, ice avalanches from cold-based glaciers occur from steeper slopes than from temperate glaciers. As a rough, empirically based approximation, cold-based glaciers require a minimum slope of >45°, compared to a critical angle of 20 – 25° for temperate glaciers (Alean, 1985). In the absence of direct ice temperature measurements, the thermal state of the glacier may be estimated based on a on a power relationship with mean annual air temperature MAAT (Huggel et al., 2004a). For small and relatively thin glaciers, the slope of the glacier surface provides a reasonable approximation for the glacier bed topography, and can be used to identify critical angles or bed features (e.g. sudden breaks in topography or lack of supporting abutments). Geophysical surveys (e.g., ground penetrating radar) provide direct measurements of bed slope for individual glaciers, while for larger glaciers, modeling techniques exist for estimating glacier bed topography (e.g., Linsbauer et al., 2012).

The identification of potential ice avalanche starting zones can also be aided by differentiating between cliff or ramp type situations (Alean, 1985; Pralong and Funk, 2006), as this determines which other factors and attributes need to be considered in the susceptibility analyses, and says something about the likely frequency and magnitude of any possible events. While cliff-type situations may be highly susceptible to frequent small avalanches, avalanches from ramp-type situations may be less likely, but much larger if they do occur. New emerging threats can be anticipated where glaciers are retreating towards topographically less favorable positions (e.g., a steeper slope with no abutment).

Photogrammetry techniques (e.g, using optical imagery, Synthetic Aperture Radar - SAR, Light Detection and Ranging - LIDAR), including DEM comparisons and feature tracking, can be used to quantify changes in glacier geometry and dynamics. Larger scale changes may be observed at basin scales, while specific glaciers can also be analysed using terrestrial or aerial imaging. A thickening of mass towards the front of a hanging glacier can be indicative of critically unstable geometry, while an increase in surface velocity may also be evident in the weeks prior to a mechanical failure (Faillettaz et al., 2015). In general, the emergence of large crevasses running across the full width of a glacier give an early indication of the possible extent of unstable ice that may detach downslope. Surging glaciers are characterized by a rapid increase in velocity by an order of magnitude or more, heavy crevassing and thickening of the glacier tongue. In very rare cases, surge-type glaciers have been observed to generate massive collapses. Thermo-mechanical modeling, optical and SAR based satellite remote sensing can support stability assessment but the capabilities for early detection of upcoming collapses are limited.

In addition to MAAT-based estimates, permafrost modelling can help determine where glaciers are likely to be cold, temperate or polythermal. Where permafrost is warm or absent, water at the ice-rock interface is likely and instabilities can arise on less inclined slopes. However, hanging glaciers are known to have a complex distribution of englacial temperatures. On vertical, impermeable cliffs, the ice can be as cold as the surrounding bedrock, whereas on less steeply inclined upper accumulation zones, permeable firn layers are strongly warmed by latent heat from percolating and refreezing meltwater (Haeberli et al., 1997). In areas with MAAT exceeding –10 to –12°C, firn is usually temperate (Hooke et al., 1983) and the ice/bedrock interface behind the cold cliff remains at phase equilibrium temperature, which can induce deep-seated thermal anomalies within the underlying bedrock, and hence contribute to conditioning of ice/rock avalanches (Haeberli et al., 1997, 2004). Changes in the thermal properties of a glacier such as induced by climatic variability and global warming can have important effects on the stability.

2.2.2 Geotechnical and geomorphic factors

Because large ice-rock avalanches can result from failure in the underlying bedrock, ice and rock avalanche hazard should always be assessed in an integrated fashion. In addition to those factors that affect the underlying bedrock stability, the potential frequency and magnitude of seismicity in the region should be assessed, as a potential direct trigger of ice avalanche activity. The stability of glaciers during large seismic events is not fully understood but existing observations suggest a high strength of glaciers to seismic energy, typically higher than for bedrock or snow (avalanches), or soil, probably related to the plasticity of glacier ice.

2.3 GLACIAL LAKE OUTBURST FLOODS

Various schemes have been proposed for assessing the susceptibility of glacial lakes, mostly drawing on remotely sensed information to characterize semi-quantitatively the cryospheric environment, lake and dam area, and other geotechnical and geomorphic characteristics of the upstream catchment area of the lake (e.g., Huggel et al., 2002; McKillop and Clague, 2007; Worni et al., 2013). The potential for unstable rock and/or ice (section 2.1 – 2.2) to impact into a lake can be determined based on worst-case runout distances (see section 3.1 for details). Assessment approaches have mostly been developed and tailored towards regional implementation, and in particular for moraine dammed lakes, for which McKillop and Clague (2007) provide a comprehensive overview of many of the relevant susceptibility factors that may condition or trigger an outburst event (Figure 13). Our guidance below is largely based on this work, but is expanded to consider a fuller range of factors relevant for ice, moraine, and bedrock dammed lakes. The final susceptibility rating for any given lake is typically based on a simplified empirically-based classification scheme, or a statistical approach may be possible where a sufficient historical inventory of events is available. For sub or englacial drainage of ice-dammed lakes, process understanding remains rather limited and robust assessment criteria are lacking.

2.3.1 Cryospheric Factors

Key overarching determinants of GLOF susceptibility and the resulting event magnitude are the size of the glacier lake, the outburst mechanism (and related hydrograph), and the characteristics of the downstream torrent (determined by channel inclination and debris availability). Large lakes obviously can produce potentially greater flood magnitudes, but larger lakes also are more susceptible to impacts from rock and ice. Lake area is easily quantified from remotely sensed imagery. On the other hand, direct measurements of lake volumes are rare owing to the difficulties and danger involved in surveying lake bathymetries in remote regions. Approaches using small unmanned boats with sonar instrumentation provide a safe and cost-effective option for surveying critical lakes, providing detailed bathymetries. For regional to basin scale studies, a first-order estimate of lake volume can be derived from empirical equations that link mean lake depths with lake area (Fujita et al., 2013; Huggel et al., 2002; O'Connor et al., 2001). Consideration of the geomorphological context (e.g. moraine-dammed, supraglacial, or ice-dammed) has been shown to considerably improve such first-order estimates of lake volume (Cook and Quincey, 2015). Future threats can be anticipated where lakes expand or newly develop within depressions in the glacier bed. Possible locations of large overdeepenings can be established from morphological criteria (Frey et al., 2010) or derived from modelled bed topography (e.g, Linsbauer et al., 2016), although future lake volumes can only be estimated to within an approximate order of magnitude.

Glacier dynamics (advance, retreat, calving, downwasting, and surging) can be monitored over large areas using remote sensing and photogrammetry, and should be combined with regular monitoring of lake development and updating of the lake inventory. Permafrost conditions need to be characterized for both the surrounding steep bedrock slopes (see rock avalanche susceptibility assessment), but also for the dam area of the lake to infer the presence and likely condition of any ground ice in the dam structure (ice-cored moraine or rock glacier) that may be highly susceptible to further warming and melting. For critical dam structures, geophysical techniques can then be employed to more precisely determine the subsurface thermal conditions.

Whereas supraglacial drainage networks can be observed at the surface, the connectivity of lakes to a sub or englacial system can only be established through observation of past drainage events, field experimentation (e.g. dye-tracing) or modelling.

2.3.2 Geotechnical and geomorphic factors

A distinction is made between those factors that are critical to the stability of the lake dam and those that determine the hydrological response of the lake catchment area, and thereby influence the susceptibility to precipitation or melt-triggered outburst events.

With high resolution optical imagery (such as available from google earth) and corresponding high quality digital terrain models, it has become possible to quantify various physical characteristics of the dam and catchment area remotely over large spatial scales. However, precise geometric measurements (e.g. dam freeboard or dam height) and in situ characteristics (e.g., ice-core, lithology) can only be obtained through local site investigations.

GIS tools can be used to determine the upstream catchment area of each glacial lake, and quantify key hydrological characteristics therein (Allen et al., 2015). While empirical evidence linking catchment characteristics with GLOF susceptibility remains limited, it can be assumed that lakes fed by a steep, fast-draining catchment area are more susceptible to rapid inflow from precipitation or snowmelt. The same tools may be used to assess the topographic and geomorphological characteristics of the downstream flood path below the lake.

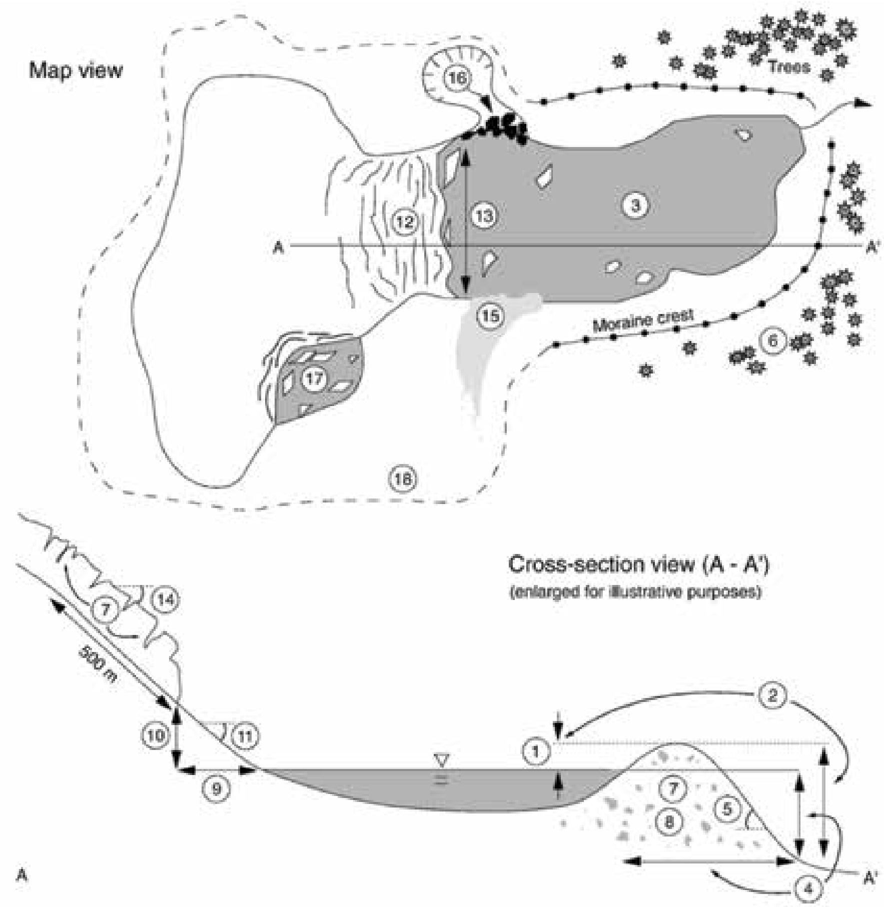


Figure 13: Summary of factors relevant to the stability of moraine dammed glacial lakes, as presented by McKillop and Clague (2007). These include: (1) lake freeboard, (2) lake freeboard-to-moraine crest height ratio, (3) lake area, (4) moraine height-to-width ratio, (5) moraine downstream slope steepness, (6) moraine vegetation coverage, (7) ice-cored moraine, (8) moraine lithology, (9) lake–glacier proximity (horizontal distance), (10) lake–glacier relief (vertical distance), (11) slope between lake and glacier, (12) crevassed glacier snout, (13) glacier calving front width, (14) glacier snout steepness, (15) snow avalanches, (16) landslides, (17) unstable lake upstream, and (18) watershed area.

2.4 DEBRIS FLOWS

The occurrence of debris flows is strongly controlled by topography, the type of sediment reservoir, and the related physical geomorphological characteristics of the reservoir. Here we focus on the susceptibility assessment for debris flow source areas that have formed as a result of glacial and permafrost-related processes, and/or where cryospheric processes (melting of glaciers, snow, or permafrost) could trigger a debris flow. Debris flows caused by glacial outburst events are covered under section 2.3. In general, para- and peri-glacial environments are characterized by abundant steep, unconsolidated sediment, and hence are highly susceptible environments for debris flow activity, which may be trigged by excessive meltwater or heavy precipitation.

2.4.1 Cryospheric Factors

Changes in glaciers can be assessed as described under section 2.2.1, drawing on remote sensing analyses at regional to basin scales to help identify where glacier retreat is exposing new zones of loose, unconsolidated sediment, or where thinning is destabilizing adjacent moraines. Likewise, for permafrost, modelling and field approaches as described under section 2.1.1 can be used to characterize not only the permafrost conditions of the sediment reservoir, but also of the surrounding headwalls from which the sediment may be derived. Slope deformation, as measured from terrestrial surveys or remote sensing, also provides an indication of permafrost conditions. Key parameters within the reservoir to consider include the depth and seasonal thawing of the active layer (influence on depth of erosion), as a determinant of the timing and also the possible magnitude of a debris flow. Cold permafrost bodies acting as a hydrological barrier at depth within the reservoir could be identified with geophysical techniques, and may demarcate a zone of possible oversaturation within the overlying sediment during periods of excessive water input. Snowpatches, as a source of meltwater can be mapped from remote sensing or during field studies, and are most critical when located in the contact area between a rock face and talus slope (Huggel et al., 2004a). Frost-weathering is strongly dependent on elevation and aspect, with enhanced rates of rockfall activity and sediment production observed on shaded slopes, and in areas of permafrost (Sass, 2005). Various temperature-based indices can be used to derive frost-weathering potential for any given location, and the influence of contemporary climate change on frost-weathering can be assessed (e.g., Jomelli et al., 2004, 2007).

2.4.2 Geotechnical and geomorphic factors

A key distinction is typically made between sediment reservoirs that are active and those that are considered relict (Sattler, 2014). Active reservoirs are continuously replenished by weathering, mass movements, or fluvial processes. Such reservoirs, (e.g. talus slopes, sediment filled channels/gullies, landslide deposits from channel slopes) typically produce relatively low magnitude events, because the volume of material is often limited (supply-limited), and because the reservoir must regenerate before a subsequent event can occur, associated frequencies may also be low. Conversely, relict debris reservoirs are no longer replenished by active processes, and may have formed over long time periods. Related debris flows from these reservoirs (e.g. moraines, fluvial terraces, or landslide deposits), can attain very large magnitudes, as an abundant amount of sediment is available for entrainment (supply-unlimited), and events may reoccur at high frequencies until the large supply of sediment is eventually exhausted. Rock glaciers may provide both types of reservoirs, depending on the activity of the landform.

For sediment reservoirs fed by mechanical and thermal erosion of an adjacent rockwall the assessment should consider the relevant factors for rock avalanche susceptibility, with factors such as joint density, tectonic wear by uplift and folding, and dip direction all influencing rates of sediment production. Likewise, certain lithologies (e.g. sedimentary rocks) have been shown in some studies to be more susceptible to frost weathering than crystalline rocks (André, 2003). The physical properties of the sediment reservoirs themselves (e.g., particle size distribution, permeability, and shear strength) can only be directly assessed through field studies, although certain characteristics may be inferred from the lithology of the source material. Empirical relationships are, however, not well established, are sometimes contradictory, and depend partly on the resulting trigger mechanism. The unconsolidated, poorly sorted, loose, porous and rather permeable nature of morainic sediment has been consistently linked to high levels of instability.

Studies have shown that the percentage of vegetation in a catchment area is an important controlling factor on both debris flow frequency and magnitude, enhancing the stability of a reservoir, establishing downstream channels, and reducing surface runoff (e.g., Greenwood et al., 2004). For freshly emerging paraglacial environments or periglacial landscapes, vegetation is lacking, enhancing susceptibility in these zones.

Slope gradient within the source area can be considered fundamental for sediment accumulation and debris flow initiation. Costa (1984) defined 15° - 20° as a common lower threshold for debris flow initiation, while observed slope angles generally range between 20° - 45° (Corominas et al., 1996). Upper bounds relate to the angle of repose for talus and other debris, and steeper slopes are generally covered with sediment which is too thin or too locally restricted to be of any concern. In addition, topographic breaks (e.g, convex steep slope with a more gentler concave lower section) may represent zones of enhanced susceptibility due to a concentration of runnoff on the lower gradient slopes (Larsson, 1982). Such zones are often found at the contact between a rockwall and talus slope, where late lying snow patches may also be evident in the shaded topography (Huggel et al., 2004b).

Local seismicity should be assessed in relation to both direct triggering of debris flows (liquefaction), and in relation to conditioning of debris flows, through enhanced rockfall activity and sediment delivery from weakened slope structures.

2.5 ON-SITE PERMAFROST HAZARDS

On-site permafrost hazards relate to infrastructure that is partly or entirely placed in the vicinity or on top of permafrost- and glacier-affected frozen rock masses or debris. Changes in permafrost and glacier dynamics may derive from atmospheric warming but as well from human-environment interaction. Both can act to alter the thermal, mechanical and hydrological regime in rock masses and debris in permafrost and glacier areas (Gruber and Haeberli, 2007; Haeberli, 2005; Krautblatter et al., 2013).

The resulting changes in stability and water dynamics affect high-alpine (i) transport infrastructure, i.e. cable cars, railways, cogwheel trains, tunneling infrastructure, (ii) housing and gastronomy infrastructure, i.e. hotels and alpine huts and (iii) leisure and sports infrastructure, i.e. ski and climbing infrastructure. Typical hazards include slow and fast subsidence, water inundations, rockfalls and rock slope failures, differential creep affecting infrastructure and surroundings (Fischer et al., 2010, 2013; Phillips et al., 2016; Pogrebiskiy and Chernyshev, 1977). Due to the sensitive nature of the affected frozen rock masses or debris slopes, small environmental or human-induced system changes can onset widespread hazards and lead to cost-intensive countermeasures, restructuring or abandoning of the infrastructure.

First careful attempts have been made to develop recommendations or guidelines for constructions to avoid on-site permafrost hazards (Bommer et al., 2010). Some countries have also started to collate systematical inventories of infrastructure potentially endangered by permafrost degradation and glacier retreat, e.g. more than 1700 objects have been identified in France, with 10% thereof classified at high risk (Duvillard et al., 2015). Structural countermeasures are presently developed, including advanced anchoring and grouting systems that avoid heat transmission and excessive loading extruding ice from frozen rock masses (Lin et al., 2015; Phillips, 2000; Pläsken et al., 2017).

2.5.1 Cryospheric Factors

The mechanical stability of perennially frozen rock slopes depends on the strength of the intact rock with ice-filled porosity, the strength of the rock-ice interfaces in fractures and the strength of ice in fractures. All three factors strongly decrease from -5°C and 0°C (Arenson et al., 2007; Davies et al., 2001; Krautblatter et al., 2013). Repeated freezing and sustained ice segregation at subzero temperatures lead to material fatigue and can heavily degrade the mechanical strength of intact bedrock (Jia et al., 2015; Murton et al., 2016). Rock masses are exposed to high levels of rapidly varying stresses. These evolve due to elevated hydrostatic pressures in perched water above permafrost bodies and elevated cryostatic pressures deriving from ice segregation (Fischer et al., 2010; Jia et al., 2017).

The mechanical behavior, subsidence and creep of ice-rich debris sites is controlled by stress conditions (downhill forces and loading), proportional ice and debris (impurity) content, ice temperature, water content in the ice, as well as water and heat supply to the ice body (Arenson et al., 2016; Arenson and Springman, 2005b; Budd and Jacka, 1989). Recent inventories show the potential for hazardous rapid accelerations of rock glaciers up to meters and decameters per year (Kääb et al., 2007; Kenner et al., 2014).

2.5.2 Geotechnical and geomorphic factors

In addition to a number of geomorphological, geological and geotechnical properties that influence all rock slopes, permafrost-distribution, glacier- and snow-dynamics can significantly influence the stability of permafrost rock slopes and respond quickly to climatic fluctuations (Fischer et al., 2010; Fischer and

Huggel, 2008). The influence of permafrost dynamics on rock slope stability is only considered in detail in a few studies. The presence of ice in the detachment zone of instabilities has often been reported (Dramis et al., 1995; Gruber and Haeberli, 2007). Relationships between permafrost dynamics and landslide events were in some cases deduced from a reconstructed thermal field. Huggel (2009) states that the detachment zones of rock-ice avalanches can be correlated with thermal disturbances caused by the thermal interaction of permafrost and glacial ice, volcanic/geothermal effects and climate change. These relations were, e.g. suggested for the Kolka-Karmadon slide, Caucasus (Haeberli et al., 2003), Iliamna avalanches, Alaska (Huggel et al., 2007a), Mt. Steller avalanche, Alaska (Huggel et al., 2008) and Monte Rosa failure, Italia (Fischer et al., 2006). The sensitivity of permafrost to atmospheric warming and the subsequent enhanced activity of rockfall events were demonstrated in the European Alps during the hot summer of 2003 (Gruber et al., 2004). Furthermore, a spatial relationship between permafrost degradation and rockfall was detected by Noetzli et al. (2003) for the European Alps, and by Allen et al. (2009) for the Southern Alps, New Zealand. In southeast Alaska, Coe et al., (2017) have linked a recent increasing frequency of large, highly mobile rock-avalanches to degradation of mountain permafrost.

From a mechanical point of view, the presence of permafrost can increase shear stress due to changing hydrostatic pressure and cryostatic pressure, i.e. by ice segregation. Thawing permafrost can also act to decrease shear resistance of rock masses as thawing alters the mechanical behaviour of intact rock, crack propagation, and frictional processes of rock-rock contacts, rock-ice contacts and ice/frozen fill-material (Krautblatter et al., 2013).

In terms of shear stress, the permeability of frozen fissured rock is one to three orders of magnitude lower than the permeability of identical thawed rock (Pogrebiskiy and Chernyshev, 1977). The combination of perched groundwater and deep-reaching unfrozen fracture systems causes significant problems for tunnel structures by inundating water in permafrost rocks e.g. at the Aiguille du Midi (France) and at the Jungfrau (Switzerland) in 2003, as well as for the Kunlun Mountain tunnel of the QingHai-Tibetian railway track (Hasler et al., 2008; Tang and Wang, 2006; Wegmann, 1998). Hydrostatic pressures due to the sealing of rock surfaces by ice can play a vital part in the destabilisation of rock slopes as shown by coupled hydro-mechanical modelling of the 3x105 m^3 Tschierva rock avalanche in 1988 (Fischer et al., 2010), and the observed outflow of pressurised water rock slopes, e.g. at the scarps of Kolka-Karmadon and Mt. Steller subsequent to failure (Haeberli, 2005; Huggel et al., 2008). Ice segregation requires a sub-zero temperature gradient (-3°C to -6°C), water supply and an intercrack pressure slightly above the stress corrosion limit. These conditions frequently coincide at the base of the active layer above the permafrost table (Hallet et al., 1991; Murton et al., 2006). Heaving pressures of 20 to 30 MPa exceed even the tensile strength of strong rocks and can cause crack propagation (Hallet et al., 1991; Jia et al., 2017).

In terms of shear resistance, ice-filled fractures respond to different mechanical processes acting individually, in succession or in combination: (i) friction/fracture along rock-rock contacts, (ii) friction/fracture along rock-ice contacts, (iii) fracture/deformation of cleft ice, and if present (iv) deformation of frozen infill material. For saturated intact rock, Mellor (1973) could show a drop in uniaxial compressive strength varying from 20% to 50%, and a drop of the tensile strength varying from 15% to 70%. This drop correlates to rock porosity and water content and corresponds to changes in Poisson's ratio, Young's modulus and joint stiffness; it is more pronounced for tensile strength than for compressive strength (Glamheden, 2001; Inada and Yokota, 1984). Simultaneously, also fracture toughness, subcritical fracture propagation and friction significantly change along frozen bedrock fractures (Dwivedi et al., 2000; Krautblatter et al., 2013; Li et al., 2003). The behaviour of polycrystalline cleft ice under constant load is dependent on the stress-strain conditions and the rate of loading. Ice demonstrates elastic and ductile creep behaviour (primary, secondary and tertiary creep) without failure when slowly compressed. The shear strain rate is controlled by the shear stress and is dependent on temperature, crystal orientation, impurities, water content etc. Exceeding certain thresholds for stress level, strain rate or strain level, ice deforms in a brittle and ductile-brittle manner until complete fracture occurs (Sanderson, 1988). In constant strain shearing experiments on ice-concrete samples, the shear stress at failure of ice-filled fractures is a function of temperature and normal stress, i.e. that shear strength of the fracture declines with increasing temperature of the ice between -5°C and 0°C (Davies et al., 2000). In more realistic constant stress shearing experiments, the failure of the sample occurs at the connection between ice and concrete and the shear stress at failure is controlled by normal stress and temperature (Guenzel, 2008; Krautblatter et al., 2013). Fractures in permafrost bedrock with frozen infill material can presumably be related to studies on permafrost soils. Arenson et al. (2007) concluded that the volumetric ice content and strain rate are key factors for the strength characteristics of frozen soils. The strength increases as ice content decreases because of enhanced friction between solid particles. Ice is the bonding between particles and provides cohesion resulting in a stiffer behaviour at the beginning of shearing at low confining stress compared to unfrozen samples. At high strain rates, the resistance of frozen soil is similar to that of unfrozen soil. At strain relaxation, the ice-bonding heals itself due to refreezing and causes a strengthening of the sample (Arenson and Springman, 2005a).

To constrain mechanical models for on-site permafrost hazards, laboratory testing of mechanical stability of materials in frozen condition can be essential (Arenson et al., 2007; Jia et al., 2015; Krautblatter et al., 2013). Geophysical methods can provide fast insights and can help to monitor relevant geotechnical and permafrost conditions (Hauck et al., 2011; Heincke et al., 2006; Hilbich et al., 2008; Keuschnig et al., 2016; Krautblatter and Draebing, 2014; Magnin et al., 2015). LiDAR, SAR and remote sensing techniques are capable of rapidly detecting the spatial dimension of subsidence and mass movements as well as the temporal evolution if applied repeatedly (Kenner et al., 2014).

For on-site hazards, the impact occurs at the site of instability, and not downslope or downstream as in the case of, e.g., a GLOF or avalanche. Hence, from a practical perspective, there is a less clear distinction made between the susceptibility or stability assessment, and the impact assessment. We therefore recommend performing the following key assessment steps (see also Table 5):

- Geological, geotechnical and hydrogeological reconnaissance of potential predestined subsidence or mass movements structures as well as potential hydrological problems
- Reconnaissance of permafrost conditions and change; here geophysical methods can provide a fast initial judgement and monitoring tool
- Geomechanical analysis or modelling of combined rock-ice mechanical stability and hydrogeological assessment of future problem.

3. IMPACT ASSESSMENT

3.1 PROXY HAZARD ASSESSMENT

Under proxy hazard assessment we include those approaches that provide a first indication of the extent and threat of natural hazards, but where hazard intensities are not physically modelled. Typically these approaches combine empirical estimates of possible event magnitudes (e.g. avalanche volume or flood volume and peak discharge) and runout distances, with simple hydrological models or flow routing algorithms that capture the main downstream or downslope path of the mass movement (Allen et al., 2016; Horton et al., 2013; Huggel et al., 2003; Rounce et al., 2016; Watson et al., 2015). Such approaches have been widely applied in glacier and permafrost hazard research over the past decade, and serve multiple purposes:

- As an intermediary step to identify potential hazard or risk hotspots where further studies, field investigations and process-based modelling and hazard mapping can be focused.
- As an alternative to process-based modelling and hazard mapping, where the quality and resolution of data prevents a more sophisticated approach.
- Identification of potential cascading processes and chain reaction events.
- For early anticipation of future threats.

GIS-based flow-routing models require minimal computing requirements even for large-scale applications (e.g. entire mountain range), and are typically implemented using freely available digital elevation data with a grid resolution of 30 – 90m (e.g, ASTER GDEM or SRTM). The key limitation of these approaches is their inability to capture the actual physical behavior of mass movements, such as overtopping of barriers in the flow path or flow transformations, and physical parameters such as flow heights, impact pressures, velocities, etc are not modeled. Rather, these models provide only a coarse estimation of the possible downslope or downstream area that may be affected by a given event. Where modeled paths intersect with other potential hazard source areas (e.g., lakes, or steep unstable debris accumulations), the likelihood of secondary events or flow transformations can be anticipated.

A key concept for the proxy hazard assessment is the empirically derived angle of reach or overall trajectory slope (measured from the start to end point), which is often used to define the maximum runout distance that a mass movement could attain. Where possible, practitioners should define runout distances using comparable events for the same or similar study environment. For first-order assessments in the European Alps, angles of approximately 17° have been defined for ice avalanches, 11° for debris flows, and 2 - 3° for floods with little debris entrainment (Huggel et al., 2004a). Rock avalanche mobility is strongly influenced by volume, water, and ice content, with some of the largest events recorded globally having attained angles as low as 6° (Schneider et al., 2011).

3.2 SCENARIO DEVELOPMENT

Scenarios in the context of glacier and permafrost hazard assessment refer to expected event frequencies and magnitudes. A scenario is inherently forward looking but does not necessarily consider a comprehensive set of future drivers of hazards, such as climate change and related impacts on the cryosphere. The definition of the time horizon for which the defined scenario is valid should therefore be explicitly stated. If the scenario is intended to be valid over longer time periods (several decades), one needs to appropriately consider the respective future climatic changes which can themselves be based on different climate scenarios (e.g., as related to low and high greenhouse gas emissions). Hence, hazard scenarios can be independent of, or linked to climate change scenarios, depending on the time horizon for which the hazard assessment is to be considered valid.

As outlined in the introduction to the assessment framework, the goal of the scenario development is to establish three feasible scenarios for the process-based hazard modelling, where the potential mass or volume initiated in a small, medium, or large event is estimated, and a corresponding best estimate of the probability of such an event occurring is assigned. Importantly, these scenarios typically consider only the mass or volume of the initial event, while subsequent entrainment of material along the flow path can be assessed by downstream or downslope modelling.

The expert can establish possible event scenarios based upon the following primary sources of information:

- Information compiled during the basin to site specific susceptibility/stability assessment.
- Inferences based on local historical inventories and field evidence from past events.
- Inferences based on evidence and process understanding from the international literature.

The expert will ideally draw primarily upon the quantitative information coming out of the susceptibility and stability assessment, supported where possible and necessary with field studies, available historical information, international evidence and process understanding to assign probability levels to the three scenarios. In view of rapidly changing environmental conditions, scenario development should incorporate latest understanding on changing glacial and periglacial landscapes, and resulting implications for event frequencies and magnitudes (see also Part I). It should be clearly defined for which time period the scenarios are considered relevant (e.g., 5 or 10 years), after which time the scenarios would need to be reevaluated and the assessment repeated.

The following possible approaches for scenario development are foreseen:

- Probabilities are specifically assigned based on careful consideration of the underlying susceptibility and stability assessment. All probability – magnitude combinations are possible.
- A simple inverse frequency-magnitude relationship is applied, with the large scenario assigned the lowest probability, and the small scenario the highest probability.
- Where there is an insufficient basis or reasoning to distinguish probabilities it may be feasible to maintain the same probability level across all 3 scenarios, i.e., all three scenarios are considered equally likely.

In view of possible extreme events characterized by very low probabilities but very large dimensions, a single “worst-case” scenario can be proposed. This could be appropriate, for example, for a very large volume lake that is deemed to have very-low probability of an outburst. According to the hazard modelling results (see section 3.2) the potential land area affected by such a worst-case event could be marked as an area of residual danger.

It is not possible to be prescriptive about how scenarios should be established, and considerable expert judgement is required. It is also recommended that scenarios be discussed and defined with responsible authorities of the area. For instance, whether and how a “worst-case” scenario is modeled should be part of a discussion with authorities and responsible institutions because it involves a political and societal decision. A “worst-case” may be included as the modeled large scenario, included separately as a residual danger (as described above) or not modeled at all. Uncertainties surrounding the scenarios should be communicated in a clear, open, transparent and reproducible way. The examples below serve to further illustrate how the expert may approach the challenge of scenario development for key processes.

Example 1: Rock avalanche

In the case of potential bedrock instabilities, the expert will draw on the stability assessment and specific factors such as the geometry of discontinuities and their orientation relative to the slope topography to help determine the thickness of the bedrock slab, wedge, or blocks that could initially fail. This might then be assigned as the small scenario with high probability. Where this zone of instability is supporting a much larger flank (e.g., a buttress situation), failure of the entire flank could constitute the large scenario. Depending on the geotechnical configuration, it may be determined that the small and large scenarios are of equal probability, or the stability of the upper flank may be sufficiently favorable that a lower probability is assigned to the large scenario. Where high resolution site-specific data are available, slope kinematic modelling can provide a quantitative basis for scenario development. Where there is a lack of local geotechnical observations, potential scenarios may be inferred from past landslide activity in a given basin, and certain lithological units may be associated with characteristic failure mechanisms, depths, and volumes. For example, thinly bedded structures may be more predisposed to frequent small volume rockfalls rather than large catastrophic failures.

Example 2: Ice avalanches

Determining the mass of ice that may be involved in any potential ice avalanche is difficult. In some cases crevasse patterns have been used to map potential detachment zones (Schaub et al., 2015), but this may prove unreliable in other instances. Where large crevasses cut across a glacier and the area downslope shows signs of increasing velocity, there can be increased confidence in defining the zone of instability (Faillettaz et al., 2015). Huggel et al. (2004a) proposed a simple approximation for cliff-type situations based on evidence from the Swiss Alps (Figure 14), where volume is established from the cliff length (L), width (W), and thickness/depth (D). Where these values cannot be obtained from remote sensing, topographic maps, or field studies, reasonable values were found to be approximately in the range of 10 – 20 m for width (as the point at which cliff-type glaciers usually break off behind the ice front), and the thickness in the range of 50 – 60 m. How such values hold for other mountain regions is unclear. For ramp-type situations, maximum volumes in the order of 5 x 10^6 m^3 are suggested for the

Alps (Huggel et al., 2004a), but these values have been exceeded by an order of magnitude in other regions worldwide, in particular where entire glacier tongues have detached (Evans et al., 2008; Huggel et al., 2010; Tian et al., 2017). This highlights that empirical rules provide useful guidance only, and provide no guarantee that exceptional events will not occur.

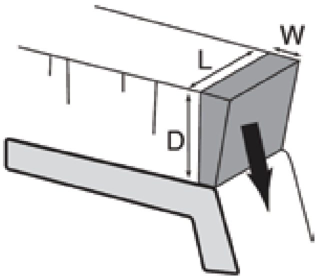


Figure 14: Estimation of ice avalanche volume for a cliff-type situation, based on length (L), width (W), and thickness/depth (D) of the unstable block.

In the absence of further local evidence a typical inverse frequency-magnitude relationship may be reasonably applied for ice-avalanches. This is likely most robust for cliff-type glaciers, where small and frequent avalanches represent a natural ablation process.

Example 3: Glacial lake outburst floods

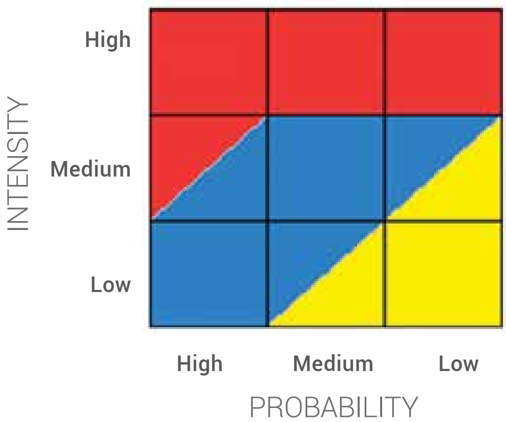
Scenarios for glacial lakes are complex, owing to the various trigger mechanisms, lake types, and dam compositions. For bedrock-dammed lakes, where the only likely outburst mechanism is a mass movement triggered impact wave, a first approximation of the likely displaced water volume will be equal to the potential incoming mass. In this case, the associated probabilities will likewise be linked to the ice and bedrock stability assessment for the surrounding slopes. For moraine-dammed lakes, the large scenario will involve complete incision of the dam and drainage of the total lake volume, the likelihood of which will depend primarily on the dam geometry, with steep, narrow dams most susceptible to irreversible erosion. Due to the self-enhancing nature of dam incision, a large scenario may be considered equally probable as a small scenario for critical dam structures. For more favorable dam geometries, a reduction in outflow and cessation of erosion can occur well before the full lake volume has been emptied, making smaller scenarios more probable for impact-triggered events, and also events triggered by seepage and piping. Because extreme hydro-meteorological events by definition occur less frequently than more moderate events, inverse frequency-magnitude relationships may also be reasonably applied for precipitation or snowmelt triggered outburst events.

Based on empirical evidence, maximum flood discharge is correlated with lake volume (Huggel et al., 2002). For moraine dammed lakes, the determining factor is the rate and extent of breach development which can be simulated with modeling approaches (e.g. BASEMENT) where high resolution topography and bathymetric data are available. Typically, ice-dammed lakes draining sub- or en-glacially produce small floods relative to similar sized moraine-dammed lakes. However, for scenarios involving mechanical fracturing of the ice, peak discharge may be comparable as for moraine dammed lakes, while large lakes trapped behind surging glaciers may produce exceptionally large magnitude and high probability events (Harrison et al., 2014).

3.3 HAZARD INTENSITY MODELLING AND CLASSIFICATION

The availability of numerical modelling tools for simulating catastrophic mass movement scenarios has significantly increased over recent years, and provides a basis for physically based mapping of event intensities for each hazard scenario (see Appendix 2, for an overview of commonly applied models). There is no best-approach, and selected models should align to local requirements, resources, and data availability.

To link the scenario modelling with a corresponding hazard level, a matrix-based approach to hazard classification is favored, as for instance employed within the Swiss codes of practice (after Raetzo et al., 2002). The matrix is comparable to classification schemes used in several other countries (e.g., Fiebiger, 1997; García et al., 2003; Humbert, 1977; Jakob, 2005; Vallance et al., 2003). For each scenario, the 3-by-3 matrix links the modelled flood or mass movement intensities with the assigned probability level for that scenario, to establish a danger or hazard level (Figure 15). Multiple scenarios (e.g., small, medium, large scenarios) can then be overlaid and fine-tuned through field mapping to arrive at a hazard map. The common framework can be applied for various processes (floods, debris flows, landslides, avalanches etc.), and remains flexible enough in that the underlying probability and intensity levels can be calculated in various ways, and with various levels of quantification depending on the scale of the assessment.



Red	High hazard
Blue	Moderate hazard
Yellow	low hazard

Figure 15: Matrix based approach for linking the susceptibility assessment (probability) with the scenario-based intensity modelling, to arrive at a hazard classification. Colors are usually subject to nationally defined standards.

According to the Swiss practice, qualitative intensity classes are based on quantitative measures of process intensities (see Table 1) and relate to potential damage the event could cause to people and property (if they were present). Note, however, that this is hypothetical only, and does not actually consider whether or not people and property are exposed to the simulated event (as would be considered under a risk assessment).

High intensity: people and animals would face threat of injury inside buildings; heavy damage to buildings or even destruction of buildings would be possible.

Medium intensity: people and animals would face threat of injury outside buildings, but would face low threat levels inside buildings; lighter damage to buildings should be expected.

Low intensity: people and animals would be slightly threatened, even outside buildings (except in the case of stone and block avalanches, which could harm or kill people and animals); superficial damage to buildings could be expected.

Various quantitative criteria can be used to define these intensity classes using one or more outputs from the model simulations. Taking the example of debris flow, studies have shown that the impact pressure mainly depends upon velocity, although flow depth is also important. Hence, some authors have chosen to combine both factors to determine the resulting flow intensity (Hürlimann et al., 2006; Schneider et al., 2014). For other processes, such as rockfall or avalanches, impact pressures may be a direct output from the modelling. Indicative values proposed in Switzerland for defining the hazard intensity classes for different high mountain processes are given in Table 1. These definitions should serve as general guidance only, and other definitions may be in use depending on national guidelines. Note that for some processes not all three intensity classes are valid, e.g., in the impact zone of a rock avalanche the intensity is always considered high. Likewise for debris flows, low intensities are not considered, according to the Swiss guidelines.

Table 1. Indicative values for the intensity classification for various high mountain hazards as used in Swiss practice (after, Hürlimann et al., 2006; Raetzo et al., 2002). E Kinetic energy; v Velocity; h flow depth or height of the deposit.

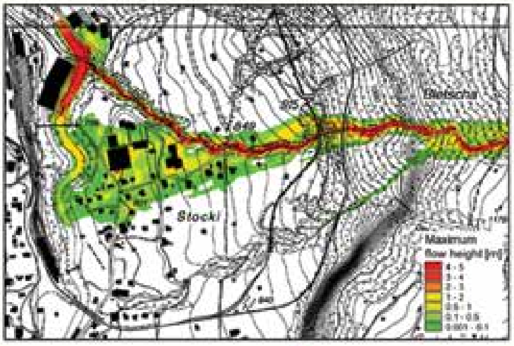
Phenomena	Low intensity	Medium intensity	High intensity
Rockfall	E < 30 kJ	30 < E < 300 kJ	E > 300 kJ
Rock avalanche			E > 300 kJ
Landslide	v≤2cm/year	v: dm/year (>2cm/year)	v > 0.1 m/day for shallow landslides; displacement > 1m per event
Debris flow (single parameter)		h < 1 m	h > 1 m
Debris flow (multiple parameter)		h < 1 m or v < 1m/s	h > 1 m and v > 1m/s

Box 1 provides an illustrative example of applying hazard intensity modelling and classification for mapping of debris flow hazard. The raw output from the numerical hazard modelling and classification should be considered as a preliminary hazard map only, which must necessarily be validated with, and compared to, field-based hazard mapping and historical archives. As outlined under the scenario development, extremely rare and potentially large magnitude events are not included within the matrix classification approach. Such very low probability events are typically classified with a zone of residual danger where modeled intensity levels are high (in Switzerland, for instance, this zone extends to include events with a return period of >300 years). The implications of the final classified hazard levels and appropriate management responses will vary based on the local societal, governance, and legal context.

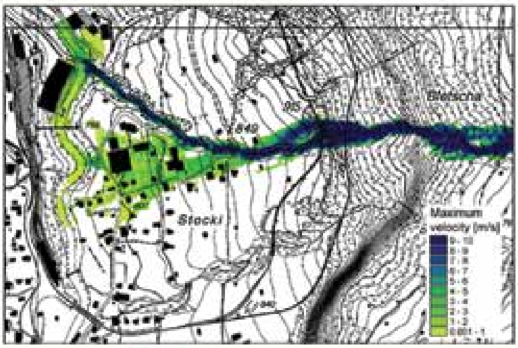
Box1: Illustrative example for debis flow hazard modelling and mapping

Medium scenario:

Maximum flow height h [m] : Probability = medium

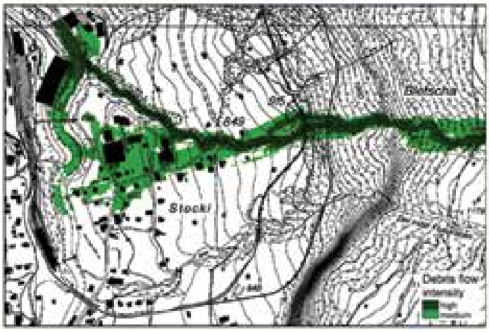


Maximum velocity v [m/s]



Debris flow intensity

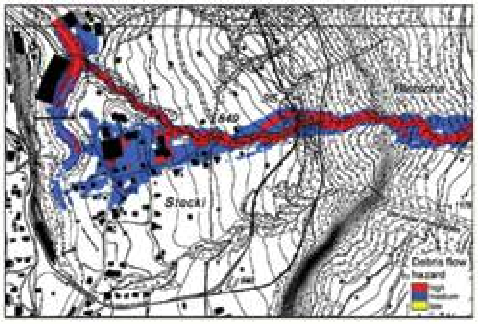
Step 1:
Numerical modelling and classification of event intensity for given scenario



			MAX VELOCITY		
			High	Medium	Low
			> 1 m/s	0 - 1 m/s	-
MAX FLOW DEPTH	High	> 1 m			
	Medium	0 - 1 m			
	Low	-			

Debris flow hazard

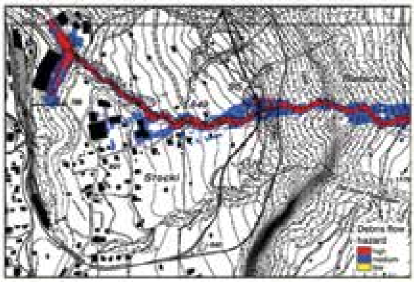
Step 2:
Preleminary hazard classification based on intensity and probability for given scenario



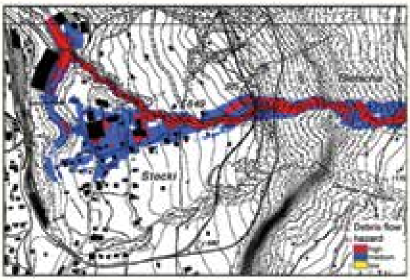
		PROBABILITY		
		High	Medium	Low
INTENSITY	High			
	Medium			
	Low			

Preliminary hazard maps

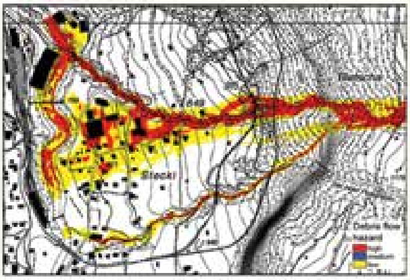
Small scenario:
Probability : high



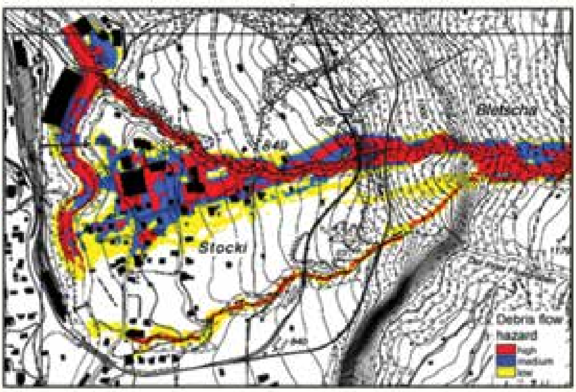
Medium scenario:
Probability : medium



Large scenario:
Probability : low



Pre - Final hazard maps



Step 3:
Repeat steps 1 and 2 for all scenarios and overlay results into pre - final hazard map.

Final hazard map subject to verification and revisions based on field studies and in - line with needs of local authorities.

3.4 PROCESS CHAINS AND COMPOUND EVENTS

There are limited published examples of comprehensive hazard assessments that have been undertaken for potential coupled processes of downstream cascading mass movements. However, in view of rapid environmental changes and formation of new lakes exposed to impacts of destabilized rock and ice (Haeberli et al., 2016), such events are of growing importance for disaster risk reduction and adaptation planning. Simulating process chains with physically based, fully coupled models is an emerging field of research (e.g., Domnik et al., 2013; Pastor et al., 2009; Worni et al., 2014) while other studies have combined separate models for different stages of the process chain (e.g., Schneider et al., 2014; Westoby et al., 2014). This latter approach has been most comprehensively described for Lake 513 in the Cordillera Blanca, Peru, where Schneider et al. (2014) simulated lake-outburst flow scenarios triggered by rock/ice avalanche impact waves as a basis for hazard mapping. Their study serves to provide illustrative guidance here. The first requirement is to define the stages that could occur within the given process chain, and for each stage select the appropriate modelling approach. In the example of Lake 513, five stages were defined based on a past event from the lake:

- Combined rock/ice avalanche flowing into Lake 513.
- Impact wave triggered by the rock/ice avalanche, which overtopped the bedrock dam.
- Formation of a debris flow by lateral erosion and sediment entrainment, with subsequent deposition on a downstream fan.
- Continuation of the flow as a hyperconcentrated flow.
- Initiation of a secondary debris flow due to an increase in channel gradient, flow velocity and erodibility of the material.

Whereas the initial avalanche and all stages of the outburst flood were modelled with RAMMS, the propagation of the impact wave and spillover off the lake was modelled with IBER (see Appendix 2 for details on these models).Following the general approach outlined in Section 3.2, scenarios are required for the initiation of the process chain, which in the case of Lake 513, consisted of small (high probability), medium (medium probability), and large (low probability) scenarios for the initial ice/rock avalanche. For the remainder of the process chain, the next stage of the modelling is initiated based on the output from the previous stage (Figure 16). Firstly, the input data for IBER modelling of the impact wave propagation and spillover was a hydrograph estimated from the volume and density of the avalanche simulated by RAMMS. Secondly, the flood hydrograph produced by IBER then served as input to the RAMMS modelling of the downstream flow, with model parameters tuned and adjusted to capture transformations in flow rheology along the path.

Once the entire process chain is simulated for all three scenarios, flow intensities can be classified, hazard levels assigned according to the intensity – probability matrix, and a combined model-based hazard map produced (Figure 17). For the case of Lake 513, this model-derived hazard map was generalised following fieldwork, and the classification scheme modified to ensure consistency with the local administrative system. This illustrates how a general assessment framework may be modified and optimized for local implementation, and reinforces that model-based results on their own are an insufficient basis for planning response and mitigation strategies.

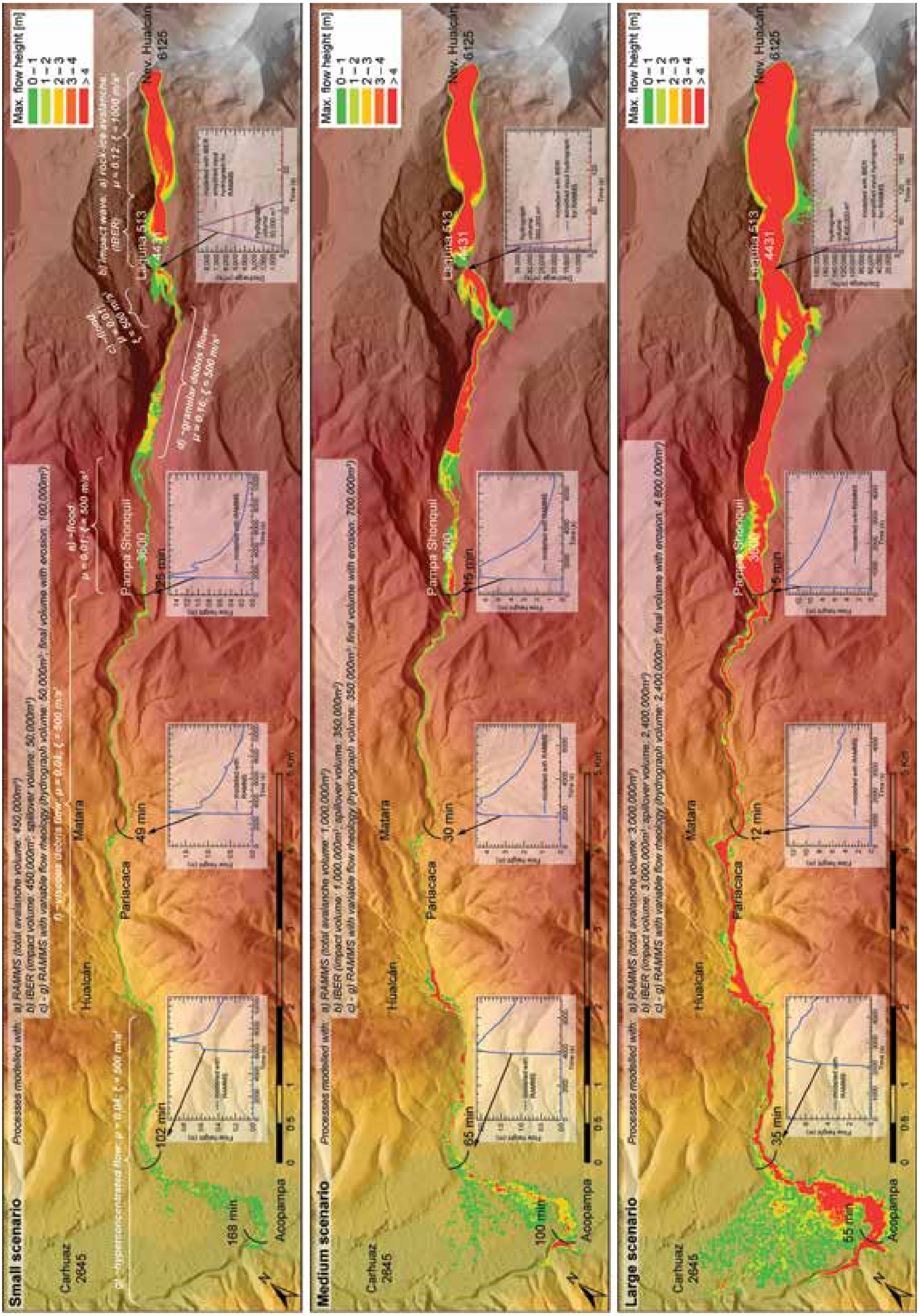

Small scenario
Medium scenario
Large scenario
Max. flow height [m]
0 – 1
1 – 2
2 – 3
3 – 4
> 4
Nev. Hualcán
6125
Laguna 513
4431
Pampa Shonquil
Pariacaca
Hualcán
Matara
Carhuaz
2645
Acopampa
188 min
102 min
49 min
26 min
100 min
65 min
30 min
15 min
55 min
35 min
12 min

Figure 16

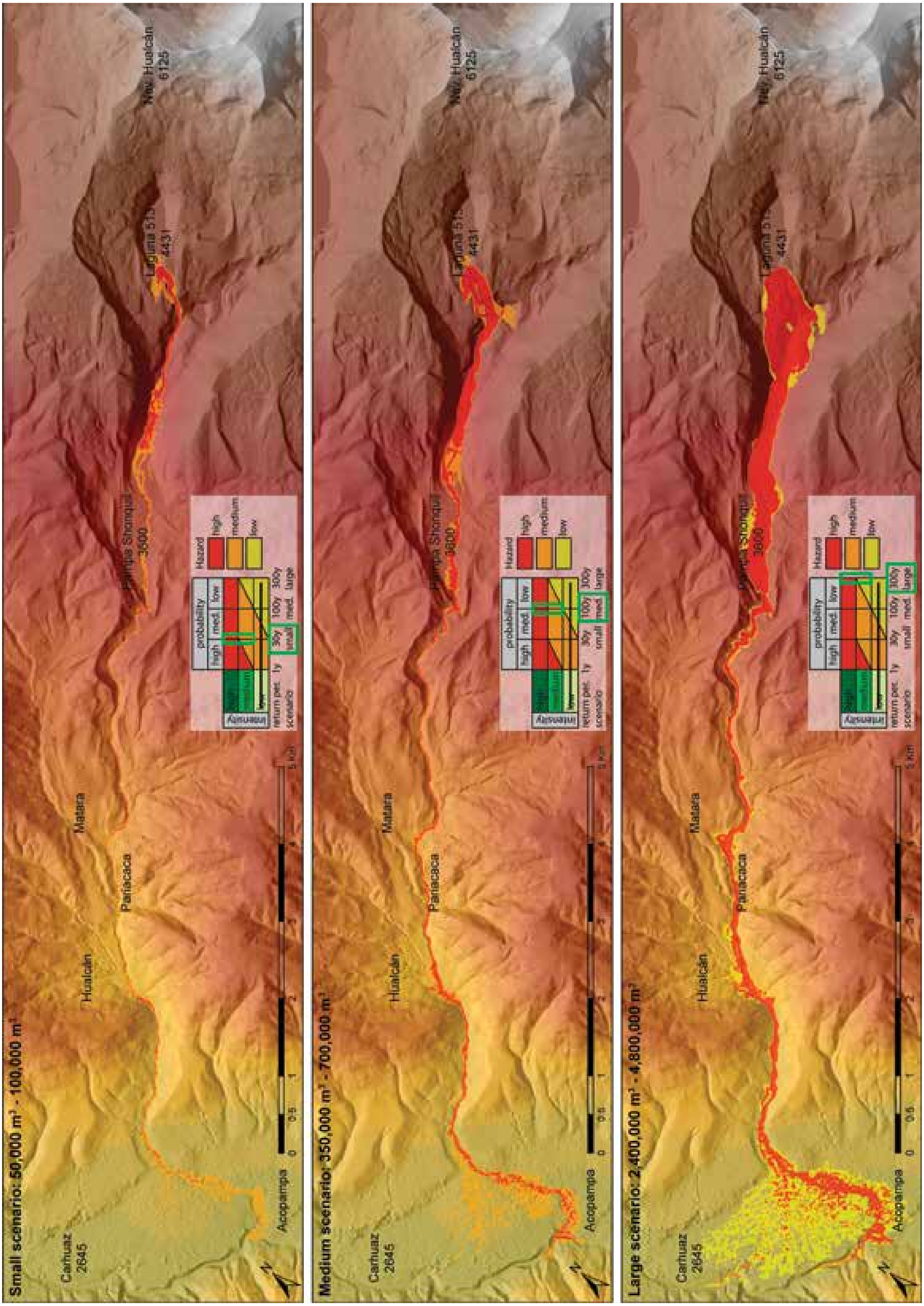

Small scenario: 50,000 m³ - 100,000 m³
Medium scenario: 350,000 m³ - 700,000 m³
Large scenario: 2,400,000 m³ - 4,800,000 m³
Carhuaz
2645
Acopampa
Hualcán
Pariacaca
Matara
Pampa Shonquil
3600
Laguna 513
4431
Nev. Hualcán
6125
probability
high
med.
low
intensity
return per.
1y
30y
100y
300y
scenario
small
med.
large
Hazard
high
medium
low
5 km

Figure 17

Figure 17

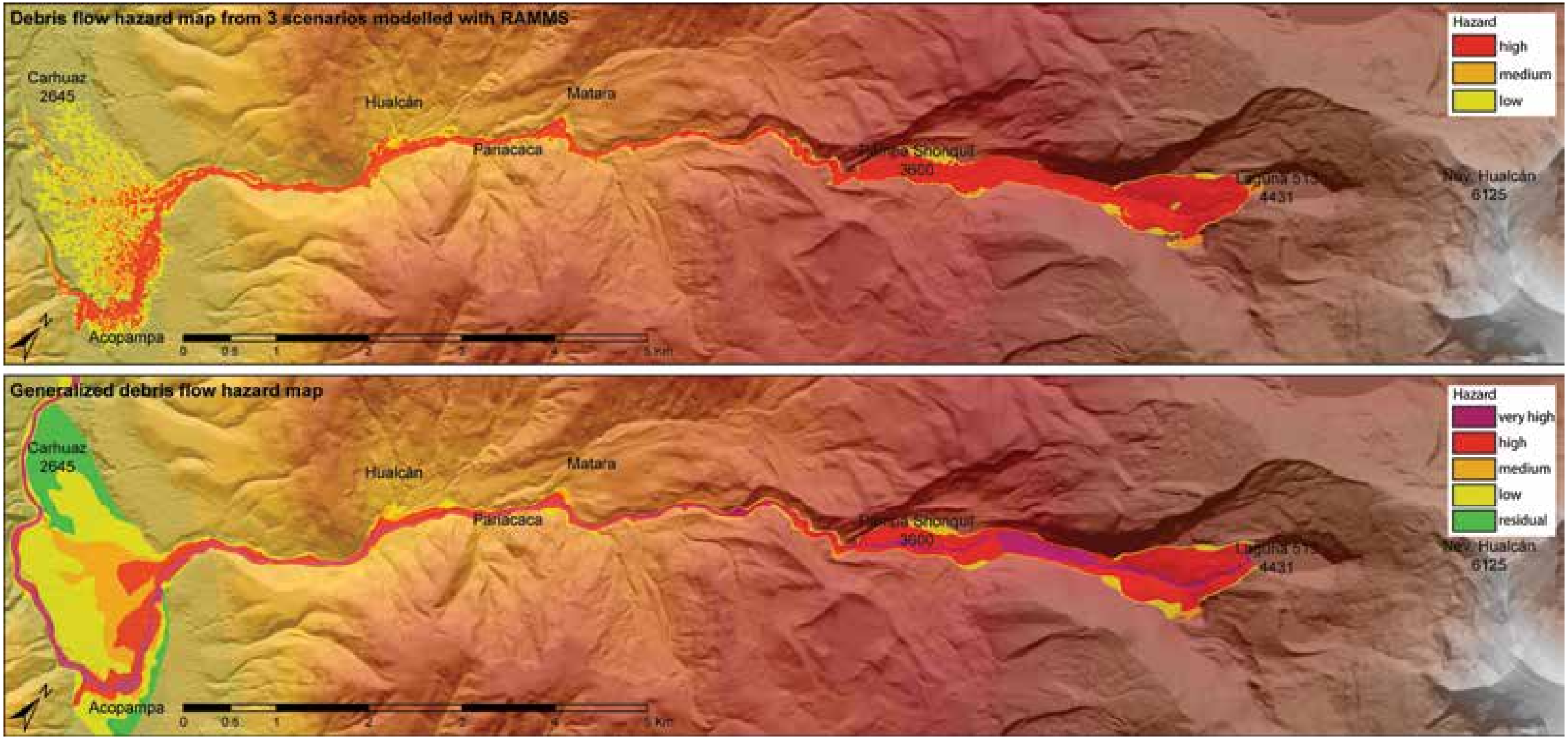


Figure 16. Numerical modeling results (RAMMS) of three scenarios (small, medium, large) of potential mass movement process chains involving a GLOF from Lake 513, Peru. For clarity, IBER modelling of the impact wave propagation and spillover of the lake is not shown. The flow durations are indicated along each flow path for the three scenarios.

Figure 17: Hazard classification for the 3 scenarios, based on modelled flow intensity and probability. Flow intensity was classified from a combination of modeled flow heights (Figure 16) and velocities (not shown). The model-based hazard map was further generalized and revised according to fieldwork and in-line with the needs and expectations of local authorities.

APPENDIX 1 GUIDANCE TABLES FOR SUSCEPTIBILITY AND STABILITY ASSESSMENT

Guidance tables are provided below for susceptibility and stability assessment (see Section 2 for further details). Factors may be relevant for conditioning (Con.), triggering (Trig.), and/or the magnitude (Mag.) of any event. For many factors, relationships with susceptibility or stability are not straightforward, and the expert must apply judgement across a range of attributes to determine whether conditions are favourable (low susceptibility) or unfavourable (high susceptibility). The tables are ordered by process type. However, the expert should give special attention and awareness to the possibility for process interactions and potential compound events, such as ice or rock avalanches triggering an outburst flood, or a rock avalanche deposit remobilizing as a more mobile debris flow or debris flood event (see also Part 1, section 2.2, and Part 2, section 3.4).

Table A1: Rock Avalanche

Susceptibility factors for Rock Avalanches	Relevance			Key Attributes	Susceptibility		Assessment methods	Assessment scale
	Con.	Trig.	Mag.		Lower	Higher		
Atmospheric								
Temperature	+	+		Mean temperature	No trend	Strong trend	Station-based or gridded climate analyses	Basin
				Intensity and frequency of extreme temperatures	Low	High	Station-based or gridded climate analyses	Basin
Precipitation		+		Intensity and frequency of extreme precipitation events.	Low	High	Station-based or gridded climate analyses	Basin
Cryospheric								
Permafrost conditions	+		+	State of permafrost, distribution and persistence within bedrock slopes. Depth of active layer and unstable mass.	No permafrost or cold permafrost	Warm (thawing) permafrost	Model-based (indirect) Geophysical (semi-direct)	Regional to basin. Site specific.
Glacier conditions	+		+	Retreat (thinning) from within or below rock slope.	No retreat	Significant retreat	Remote sensing, field studies, anecdotal evidence	Regional to basin
Geotechnical and geomorphic								
Rock mass quality	+		+	Lithological characteristics Degree of weathering	Favorable	Unfavorable	Geological mapping (remote sensing or field)	Basin to site specific
Condition of discontinuities	+			Degree of weathering, aperture, filling (e.g. breccia or gouge), seepage	Favorable	Unfavorable	Geological mapping (remote sensing or field)	Basin to site specific
Geometry of discontinuities	+		+	Dip, orientation, spacing, persistence	Favorable	Unfavorable	Geological mapping (remote sensing or field)	Basin to site specific
Condition of slope	+			Overhanging, convexities, irregularities	Favorable	Unfavorable	Geological mapping (remote sensing or field)	Basin to site specific
Slope angle	+			Topographic slope angle. Critical range or threshold angle established from local inventories.	Low slope angle	Steep slope angle	Geological mapping (remote sensing or field)	Basin to site specific
Slope height	+		+	Relative relief of the face or slope	Small	Large	Geological mapping (remote sensing or field)	Basin to site specific
Seismicity	+	+		Potential magnitude & frequency, ground acceleration	Low potential	High potential	Geological mapping & modelling.	Regional
Rockfall evident	+	+	+	Frequency and magnitude of past activity	Not evident	Frequent and increasing activity	Geological mapping (remote sensing or field)	Basin to site specific

Table A2: Ice Avalanche

Susceptibility factors for Ice Avalanches	Relevance			Key Attributes	Susceptibility		Assessment methods	Assessment scale
	Con.	Trig.	Mag.		Lower	Higher		
Atmospheric								
Temperature	+	+		Mean temperature	No trend	Strong trend	Station-based or gridded climate analyses	Basin
				Intensity and frequency of extreme temperatures	Low	High	Station-based or gridded climate analyses	Basin
Precipitation		+		Intensity and frequency of extreme precipitation events.	Low	High	Station-based or gridded climate analyses	Basin
Cryospheric								
Thermal conditions	+			Cold, polythermal or temperate glacier. Distribution and persistence of permafrost. Thermal anomalies due to hanging glaciers.	Expert judgement of implications for failure mechanisms and processes.		Model-based (indirect) Geophysical (semi-direct) Boreholes (direct)	Regional to basin. Site specific.
Glacier conditions	+		+	Cliff or ramp type situation.	Expert judgement of implications for frequency/ magnitude.		Remote sensing	Regional to basin
Crevasse density and orientation	+			Formation of cracks across glacier. Size and depth of crevasses.	Not evident	Large and widespread	Remote sensing	Basin to site specific
Bed topography				Steep slope angle and sudden breaks in topography. Convex slopes. Lack of frontal abutment.	Favorable	Unfavorable	Inferred or modelled from surface topography. Geophysical survey.	Regional to basin. Site specific.
Glacial hydrology	+	+		Distributed subglacial drainage system for ramp-type failures. Evidence of increased water pressure and or blockages (critical for polythermal glaciers), such as pooling at surface or sudden changes in discharge for large catastrophic failures.	Favorable	Unfavorable	Remote sensing, hydrological modelling, and field studies.	Basin to site specific.
Glacier velocity	+			Increase in surface velocity, particularly below crevasse zones.	No change	Rapid increase	Remote sensing, field studies	Basin to site specific
Glacier geometric change	+			Thickening towards base of hanging glacier. Thickening of valley glacier tongue as evidence for surging.	No change	Large thickening	Remote sensing	Basin to site specific
Glacier length change	+			Retreating or advancing towards steeper topography, and/or new thermal regimes.	Favorable	Unfavorable	Remote sensing, field studies, anecdotal evidence	Regional to basin
Ice avalanches evident	+	+	+	Frequency and magnitude of instabilities, including serac fall.	Not evident	Frequent and increasing activity	Remote sensing, field studies, anecdotal evidence.	Basin to site specific
Geotechnical and geomorphic								
Underlying bedrock stability	+	+	+	See rock avalanche susceptibility assessment	Unstable	Stable	Geological mapping (remote sensing or field)	Basin to site specific
Seismicity	+	+		Potential magnitude & frequency, ground acceleration	Low potential	High potential	Geological mapping (remote sensing or field)	Basin to site specific

Table A3: Glacial Lake Outburst Flood

Susceptibility factors for GLOFS	Relevance			Key Attributes	Susceptibility		Assessment methods	Assessment scale
	Con.	Trig.	Mag.		Lower	Higher		
Atmospheric								
Temperature	+	+		Mean temperature	No trend	Strong trend	Station-based or gridded climate analyses	Basin
				Intensity and frequency of extreme temperatures	Low	High		
Precipitation	+	+		Intensity and frequency of extreme precipitation events.	Low	High	Station-based or gridded climate analyses	Basin
Cryospheric								
Permafrost conditions	+			State of permafrost, distribution and persistence within lake dam area and bedrock surrounding slopes	No permafrost or cold permafrost	Warm (thawing) permafrost in dam area and/or surrounding debris or bedrock slopes	Model-based (indirect)	Regional to basin. Site specific.
Glacier retreat and downwasting	+		+	Enlargement of proglacial lakes, enhanced supraglacial lake formation, dam removal or subsidence	No retreat, lake expansion, or dam subsidence	Significant retreat, lake expansion, or dam subsidence	Geophysical (semi-direct)	Regional to basin
Advancing glacier (incl. surging)	+			Formation of ice-dammed lakes	No change evident	Advance and damming evident	Remote sensing	Regional to basin
Ice avalanche potential	+		+	See ice avalanche susceptibility assessment	Lower	Higher	Remote sensing	Basin to site specific
Calving potential	+		+	Width of glacier calving front, activity, crevasse density	Not evident	Large and frequent	See ice avalanche susceptibility assessment	Basin to site specific
Lake size	+		+	Area or volume	Smaller	Larger	Remote sensing, modelling of bed topography, field studies	Regional to site specific
Lake bathymetry	+		+	Influence on dam hydraulics, influence on displacement wave propagation and run-up	Favorable	Unfavorable	Field studies (sonar measurements)	Site specific
Sub- Supra- or englacial drainage	+	+		Connectivity of the lake to the glacial hydrological system	Not connected	Well connected	Field studies and modelling	Site specific
Geotechnical and geomorphic								
a) Dam characteristics								
Type	+		+	Bedrock, moraine, ice	Bedrock	Ice, (ice-cored moraine)	Geophysical (semi-direct)	Regional to basin
Ice-cored moraine	+			Thickness, persistence, and condition (linked to permafrost)	Absent	Large and thawing	Remote sensing	Site specific
Dam width to height ratio	+		+	Width across the dam crest relative to the dam height	Larger	Smaller	Remote sensing	Basin to site specific
Freeboard to dam height ratio	+		+	Elevation difference between lake surface and lowest point of moraine.	Larger	Smaller	See ice avalanche susceptibility assessment	Basin to site specific
Lithology	+		+	Coarseness of moraine material, presence of fine-grained material, volcanic material etc.	Coarse material predominant	Fine-grained or volcanic material predominant	Remote sensing, modelling of bed topography, field studies	Site specific
Downstream slope	+			Mean slope on downstream side of lake dam.	More gentle	Steeper	Field studies (sonar measurements)	Basin to site specific
Vegetation	+			Density and type of vegetation (grass, shrubs, trees).	Widespread	Absent	Field studies and modelling	Basin to site specific
b) Catchment topography and hydrology								
Catchment area	+			Total size of drainage area upstream of catchment, proportion glaciated/ non-glaciated	Smaller	Larger	DTM analysis	Regional to basin
Mean slope	+			Steepness of catchment area	More gentle	Steeper	DTM analysis	Regional to basin
Drainage density	+			Density of the stream network in catchment area	Lower	Higher	DTM analysis	Regional to basin
Stream order	+			Presence of large fluvial streams, facilitating rapid drainage into lake	No or low order only	Large high order streams evident	Remote sensing, DTM analysis	Regional to basin
Upstream lakes	+			Presence and susceptibility of upstream lakes.	Absent	Several lakes	Remote sensing	Regional to basin
c) Geotechnical stability								
Rock avalanche potential	+		+	See rock avalanche susceptibility assessment	Lower	Higher	See rock avalanche susceptibility assessment	
Moraine instabilities	+		+	Potential for landslides from moraine slopes into the lake	No steep moraine slopes adjacent to lake	Steep, unstable moraine slopes adjacent to lake.	Dtm analysis, remote sensing, field work, geophysical investigations	Basin to site specific
Seismicity	+			Potential magnitude & frequency, ground acceleration	Lower	Higher	Geological mapping & modelling	Regional

Table A4: Debris Flow

Susceptibility factors for Debris Flows	Relevance			Key Attributes	Susceptibility		Assessment methods	Assessment scale
	Con.	Trig.	Mag.		Lower	Higher		
Atmospheric								
Temperature	+	+		Mean temperature	No trend	Strong trend	Station-based or gridded climate analyses	Basin
				Intensity and frequency of extreme temperatures	Low	High	Station-based or gridded climate analyses	Basin
Precipitation		+	+	Intensity and frequency of extreme precipitation events.	Low	High	Station-based or gridded climate analyses	Basin
Cryospheric								
Permafrost conditions	+		+	Cold, polythermal or temperate glacier. Distribution and persistence of permafrost. Thermal anomalies due to hanging glaciers.	Favorable	Unfavorable	Model-based (indirect)	Regional to basin. Site specific.
Glacier conditions	+			Cliff or ramp type situation.	No retreat	Significant retreat	Geophysical (semi-direct)	Regional to basin
Snow cover	+	+		Formation of cracks across glacier. Size and depth of crevasses.	Absent	Widespread	Remote sensing, field studies, anecdotal evidence	Basin to site specific
Frost-weathering	+			Steep slope angle and sudden breaks in topography. Convex slopes. Lack of frontal abutment.	Low intensity	High intensity	Remote sensing and field studies.	Regional to basin. Site specific.
Geotechnical and geomorphic								
Stability of headwall	+		+	See rock avalanche susceptibility assessment	Unstable	Stable	See rock avalanche susceptibility assessment	Basin to site specific
Sediment characteristics	+		+	Particle size distribution, permeability, shear strength.	Favorable	Unfavorable	Inferred from geological mapping or directly measured in field	Basin to site specific
Slope angle	+		+	Slope angle sufficient for initiation, but not too steep that debris cannot accumulate. Critical angle depends on other factors.	Low slope angle	Critical range of 20 - 45°.	Geomorphological mapping (remote sensing or field)	Basin to site specific
Slope geometry	+		+	Break in slope – upper convex slope (source) with lower gradient concave slope below (accumulation), e.g., contact zone between rock wall and talus slope.	Distinct break not evident	Distinct break evident	Geomorphological mapping (remote sensing or field)	Basin to site specific
Sediment reservoir typology	+		+	Active reservoirs (talus slope, sediment filled drainage channels) mostly supply-limited, relict reservoirs (morianes, fluvial terraces) most supply-unlimited. Rock glaciers may be both.	Expert judgement of implications for frequency/ magnitude.		Geomorphological mapping (remote sensing or field)	Basin to site specific
Slope size	+		+	Area and depth of accumulation.	Small	Large	Geomorphological mapping (remote sensing or field)	Basin to site specific
Vegetation cover	+		+	Continuous, sporadic or absent.	Absent	Widespread	Geomorphological mapping (remote sensing or field)	Basin to site specific
Seismicity	+	+		Potential magnitude & frequency	Low potential	High potential	Geological mapping & modelling.	Basin to site specific
Debris flow activity	+		+	Frequency and magnitude of past activity	Not evident	Frequent and increasing activity	Remote sensing, field studies, anecdotal evidence.	Basin to site specific

Table A5: On-site Permafrost Hazards

Susceptibility factors for Ice Avalanches	Relevance			Key Attributes	Susceptibility		Assessment methods	Assessment scale
	Con.	Trig.	Mag.		Lower	Higher		
Atmospheric								
Temperature	+			Mean temperature	No trend	Strong trend	Station-based or gridded climate analyses	Site Specific
				Intensity and frequency of extreme temperatures	Low	High	Station-based or gridded climate analyses	Site Specific
Precipitation		+		Intensity and frequency of extreme precipitation events.	Low	High	Station-based or gridded climate analyses	Site Specific
Cryospheric								
Permafrost conditions	+	+	+	State of permafrost, distribution and persistence within bedrock slopes. Depth of active layer and unstable mass. Influence on mechanical, thermal and hydrological regime.	Favorable	Unfavorable	Model-based (indirect) Geophysical (semi-direct) Drilling (direct)	Site Specific
Glacier conditions	+	+	+	Retreat (thinning) from within or below site. Influence on mechanical, thermal and hydrological regime.	No retreat	Significant retreat	Remote sensing, field studies, anecdotal evidence	Site Specific
Geotechnical and geomorphic								
Mechanical conditions of perennially frozen fissured rock mass	+	+	+	Permafrost degradation affects on (i) friction/ fracture along rock-rock contacts, (ii) friction/ fracture along rock-ice contacts, (iii) deformation of ice in fractures (iv) deformation of frozen infill material	Favorable	Unfavorable	(i) mechanical laboratory testing of frozen materials (ii) LiDAR, SAR and remote sensing change detection (iii) geophysical recon-naissance of geotechnically relevant parameters (iv) mechanical modelling	Site Specific
Sediment characteristics	+		+	Mechanical behavior as controlled by (i) stress conditions (e.g. downhill forces/loading) (ii) proportional ice and debris (impurity) content (iii) ice temperature (iv) water content in the ice (v) water and heat supply to the ice body	Favorable	Unfavorable	(i) mechanical laboratory testing of frozen materials (ii) LiDAR, SAR and remote sensing change detection (iii) geophysical recon-naissance of geotechnically relevant parameters (iv) mechanical modelling	Site Specific
Slope angle	+		+	Rapidly changing hydrostatic and cryostatic conditions due to perched groundwater above permafrost and ice segregation processes.	Favorable	Unfavorable	Hydrogeological mapping, measuring and modelling	Site Specific
Slope geometry	+		+	Rock glacier creep, solifluction, subsidence, glofs, rock-ice avalanches, debris flows: see also tables 2 – 5.	Favorable	Unfavorable	Geomorphological mapping: see also tables 2 – 5.	Site Specific

APPENDIX 2 LISTING OF MODELLING TOOLS FOR HAZARD ASSESSMENT

Name	Process(es)	Required data	Output(s)	Price	Environment	Availability	Reference
RAMMS	Modules for debris flows, snow avalanches, rockfall. Also used ice- & rock-avalanches	DEM, Voellmy-friction parameters (2), initial volume (e.g. landslide) or hydrograph	Flow properties: e.g. depth, velocity, pressure	ca. USD 2500 / yr (different durations, discount for educational licences)	Stand-alone software (IDL)	ramms.slf.ch	Christen, M. and 11 others. 2012. Integral hazard management using a unified software environment: numerical simulation tool "RAMMS" for gravitational natural hazards. In: Koboltschnig, G. et al. (eds.) 12th Congress INTERPRAEVENT, Grenoble, France. Vol. 1. 77-86.
MSF	"Debris flows	DEM starting zone	Probability of affection	Free	AML ArcGIS toolbox Phython (Arcpy)	Contact the authors	Huggel, C., Kääb, A., Haeberli, W. and Krummenacher, B. 2003. Regional-scale GIS-models for assessment of hazards from glacier lake outbursts: evaluation and application in the Swiss Alps. Natural Hazards and Earth System Sciences 3 : 647–662.
FLO-2D	Mudflows	DEM, friction parameters, input hydrograph	Flow properties: e.g. depth, velocity	Flo-2D Basic (free) FLO-2D Pro USD 995.	Stand-alone software	flo-2d.com	O'Brien, J.S., Julien, P.Y. and Fullerton, W.T. 1993. Two-dimensional water flood and mudflow simulation, J. Hydraul. Eng., 119, 244– 261.
BASEMENT	"Flood flow	"DEM	Depth, velocity	Free	Stand-alone software	basement.ethz.ch	Vetsch D., and 16 others. 2006-2017. BASEMENT – Basic Simulation Environment for Computation of Environmental Flow and Natural Hazard Simulation. Version 2.7., Zurich, VAW.
Titan2D	Breach formation in moraine dams"	Topography, roughness data, flow information	Flow properties: e.g. depth, velocity, pressure	Free	Open-source software	sourceforge.net/projects/titan2d/	E. B. Pitman, C. Nichita, A. Patra, A. C. Bauer and M. Bursik, A. 2003. Numerical Study of Granular Flows on Erodible Surfaces, Discrete and Continuous Dynamical Systems - B3 (4).
IBER	Wave propagation	Bathimetry, hydrograph of impacting mass movement	Turbulent free surface unsteady flow	Free (registration needed)	Stand-alone software	iberaula.es	Bladé, E., Cea, L., Corestein, G., Escolano, E., Puertas, J., Vázquez-Cendón, M. E., Dolz, J., and Coll, A. 2014. Iber: herramienta de simulación numérica del flujo en ríos. Revista Internacional de Métodos numéricos para Cálculo y Diseño en Ingeniería, 30, 1–10.
r.avaflow	Two-phase flows, avalanches, debris flows, etc.	DEM, friction parameters, initial conditions	Flow properties: e.g. depth, velocity, pressure	Free (in evelopment, still experimental)	Open-source,stand-alone version available	www.avaflow.org/software.html	Mergili, M., Benedikt, M., and Pudasaini, S.P. 2017. r.avaflow - The open source GIS simulation model for granular avalanches and debris flows. r.avaflow distributions.
LAHARZ	Rock avalanches, debris flows	Topography, volume scenarios	Inundation areas	Free	ArcMap	pubs.usgs.gov/of/2014/1073/	Schilling, S.P. 2014. Laharz_py—GIS tools for automated mapping of lahar inundation hazard zones: U.S. Geological Survey Open-File Report 2014-1073, 78 p., https://dx.doi.org/10.3133/ofr20141073.
Rockyfor3D	Rockfall (point-mass model with probabalistic predictions)	Raster maps for topography, rock & soil properties, etc.	Rockfall trajectory (height, energy, runout, etc.)	Free	Stand-alone software	ecorisq.org/ecorisq-tools	Dorren, L.K.A. 2012. Rockyfor3D (v5.1) revealed - Transparent description of the complete 3D rockfall model. ecorisQ paper (www.ecorisq.org): 31 p.
RAMMS Rockfall	Rockfall (true 3D rock rotation mechanics)	Rock shape, size, topography, starting conditions	Rockfall trajectory (height, energy, runout, etc.)	ca. USD 2500 / yr (different durations, discount for educational licences)	Stand-alone software	ramms.slf.ch	Christen, M. and 11 others. 2012. Integral hazard management using a unified software environment: numerical simulation tool "RAMMS" for gravitational natural hazards. In: Koboltschnig, G. et al. (eds.) 12th Congress INTERPRAEVENT, Grenoble, France. Vol. 1. 77-86.

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