Kääb A., Reynolds J.M and Haeberli W. (in press): Glacier and permafrost hazards in high mountains.
In: *Global Change and Mountain Regions – A State of Knowledge Overview*. The Mountain Research Initiative. Kluwer.

Glacier and Permafrost Hazards in High Mountains

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Keywords: *Climate change, Debris flow, Flood, Glacier, Ice avalanche, Permafrost*

1. Glacier and permafrost related hazards

Glacier- and permafrost-related hazards represent a continuous threat to human lives and infrastructure in high mountain regions. Related disasters can kill hundreds or even thousands of people at once and cause damage with a global sum on the order of 10^8 EURO annually. Glacier and permafrost hazards in high mountains include:

- outbursts of glacier lakes, causing floods and debris flows,
- ice break-offs and subsequent ice avalanches from steep glaciers,
- stable and unstable glacier length variations,
- destabilisation of frozen or unfrozen debris slopes,
- destabilisation of rock walls, and
- combinations or chain reactions of these processes.

Generally, glacier floods represent the glacial risk with the highest potential for disaster and damages (up to 3 km^3 flood volume, and, in exceptional cases, up to 40,000 m^3/s runoff and over 1,200 km run-out distances). Glacier floods occur in most glacierised mountains of the world and are triggered by the outburst of water reservoirs in, on, underneath and at the margins of glaciers. Most reservoir types develop slowly and can be identified at the surface, a precondition that favours the application of remote sensing techniques for monitoring glacial and periglacial lakes. Floods from ice-dammed lakes and proglacial moraine-dammed lakes, in particular, represent a severe and sometimes recurring danger. Thus, various studies have focused on these glacier lakes, which occur in many mountain ranges of the world (Fig. 1; e.g. Richardson and Reynolds 2000a).

Compared to the distances covered by glacier floods, ice avalanches often affect much smaller areas. Corresponding disasters are generally restricted to densely populated high-mountain regions. However, in combination with other glacier hazards, ice avalanches have the potential for far-reaching disasters. In zones with high seismic activity and geothermal heat flow, the risk of major ice break-offs is greatly increased, as was demonstrated dramatically by one of the most destructive glacier catastrophes, the Huascarán disaster in 1970, with a loss of over 18,000 lives (Plafker *et al.* 1971). Also, the extraordinary 20 September 2002 rock/ice avalanche at Kolka/Karmadon (Caucasus), a combination of rock and ice destabilisation killing over 100 people, drastically underlines the devastating potential of ice avalanches (Fig. 2; Kääb *et al*. 2003).

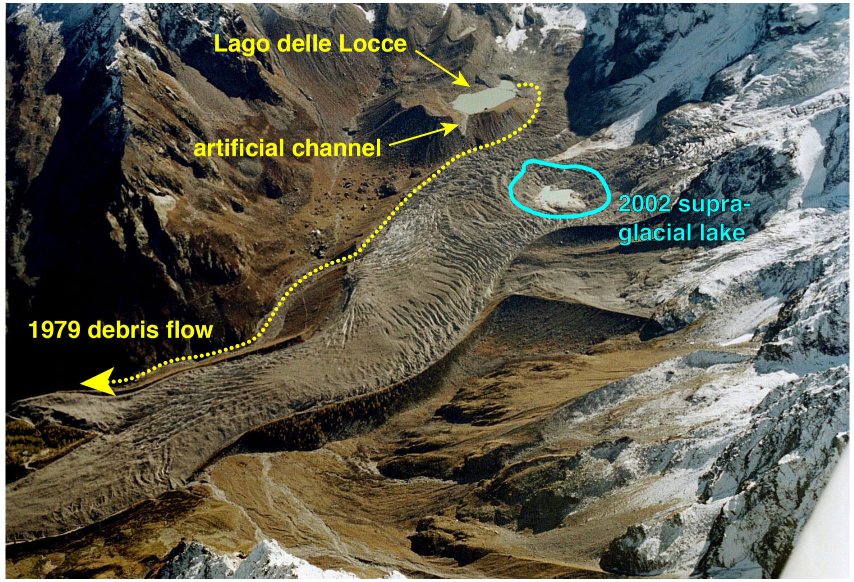

Figure 1: Belvedere Glacier, Monte Rosa massive, Italian Alps, as seen on 13 October 2002. In 1979, an outburst flood from the Lago delle Locce breached the lateral moraines of Belvedere Glacier and caused a severe debris flow, which among other things destroyed a chair lift. To prevent further lake outbursts, the lake level was lowered and controlled by an artificial channel. In summer 2001, the glacier started an untypical surge-type movement with glacier speeds increased be one order of magnitude compared to previous decades. As a consequence, the glacier became heavily crevassed and its tongue advanced over the Little Ice Age moraines, destroying forest and tourism infrastructure. In spring 2002, a so-called supraglacial lake of 3 million m^3 developed on the glacier, which became a severe flood risk for the village of Macugnaga within a couple of weeks. The Italian Civil Defense Department and the scientists involved initiated emergency actions. These included continuous lake level monitoring, evacuation of certain parts of the village of Macugnaga, an automatic alarm system, the installation of pumps and detailed scientific investigations. From summer to autumn 2002 the lake lowered naturally. (Haeberli *et al*. 2002; Kääb *et al*. 2003) (Photo: Christine Rothenbühler).

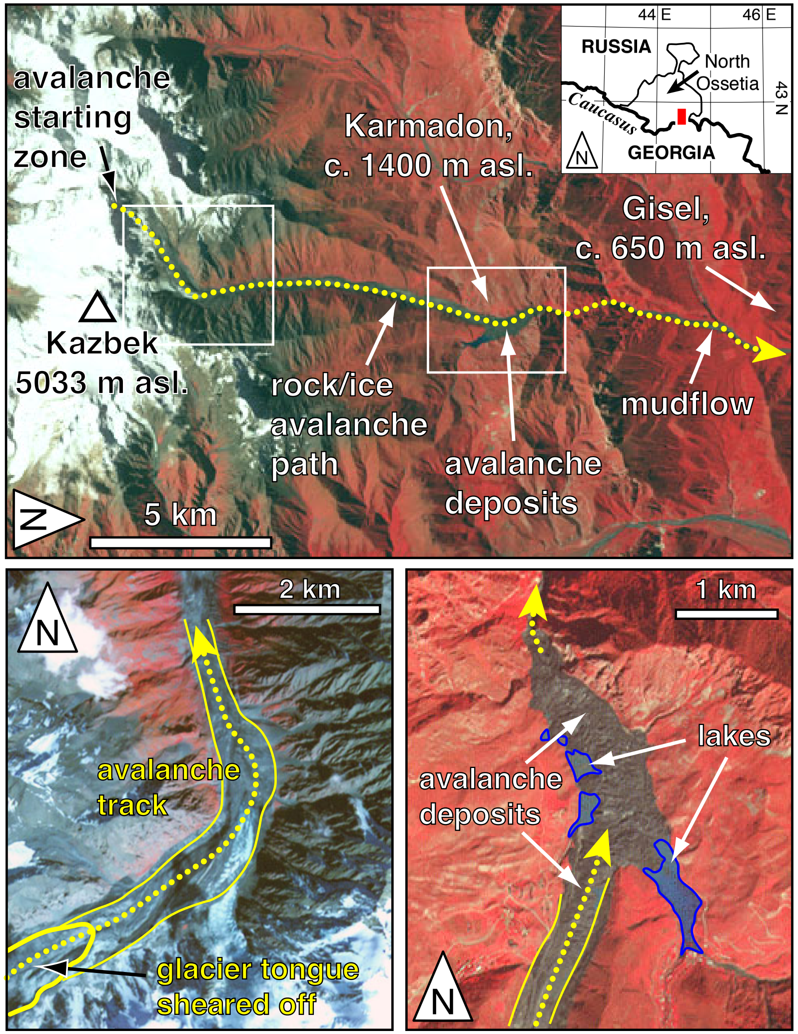

Figure 2: ASTER false color satellite image of 6 October 2002, showing traces and deposits of the 20 September 2002 Kolka-Karmadon rock/ice avalanche that killed over 120 people. The red rectangle in the inset indicates the location of the satellite image. The two white rectangles mark areas that are displayed in more detail in the small pictures. A rock/ice avalanche of several million m^3 started on the north face of the Dzimarai-khokh in the Kazbek massive. Its impact sheared off the entire tongue of Kolka glacier. The subsequent 80 million m^3 avalanche destroyed parts of the village Karmadon before it was stopped by the narrowing valley flanks of the Karmadon gorge. A devastating mudflow was triggered by the rock/ice avalanche and continued 15 km further down-valley but did not reach the village of Gisel. The rivers entering the gorge were progressively dammed by the avalanche deposits and formed huge unstable lakes. (Kääb *et al.* 2003).

Advancing and retreating glaciers can pose a direct risk to mountain infrastructures. From a global point of view, the prediction of glacier length variations is complicated by the fact that glaciers can vary in a continuous (stable) or unstable way (i.e., glacier surges; e.g. Haeberli *et al*. 2002). Surging glaciers are able to rapidly destroy installations or induce other hazards, such as ice- and rock-falls. They can temporarily dam lakes, which, when these dams fail, produce some of the largest known outburst floods. Within the last 100 years, for example, a large ice dam in the Upper Indus Basin in Pakistan failed, resulting in the total drainage of 3 km^3 of stored water within 48 hrs.

A widespread risk in high mountains is related to accumulations of loose sediments on steep slopes, which represent potential sources of debris flows (Zimmermann and Haeberli 1992). Such debris accumulations can occur in the form of moraines, moraine dams, or steep valley flanks uncovered by retreating glaciers. In other words, they are strongly connected to glacier development. Another important factor in this context is permafrost, which influences the stability and hydrology of debris slopes (see Harris, this volume). Whilst the trigger mechanisms of these frequently unexpected debris flows often remain unclear (e.g. melting dead ice, permafrost-hydrology interactions) and are therefore difficult to predict in individual cases, the respective hazard potential seems to be connected to the presence of permafrost and its changes. The instability of rock slopes can also be connected to glacier variations. Glacier retreat leads to stress redistribution within adjacent valley flanks, which can cause mass movements such as rock-slides (Kääb 2002). For example, late-glacial ice retreat was associated with a large number of landslides and these events have also been observed during the present glacier retreat since the end of the Little Ice Age. Changes in the thermal regime of cold rock walls and related effects on rock stability (Davies et *al.* 2001) are still poorly understood processes but are of increasing concern in view of recent catastrophes (Giani *et al*. 2001).

Glacier floods, ice avalanches and glacier length variations, represent relevant hazard potentials in high mountains on an individual basis. However, combinations and interactions between these or other hazard types are of similar or even greater importance. In fact, many of the largest known glacier catastrophes are characterised by hazard combinations and/or process chains. For instance, if ice and/or rock avalanches enter natural or artificial (i.e. reservoir) lakes, they are able to trigger flood waves and, as a consequence, can lead to overflowing and breaching of natural (or artificial) dams with corresponding flood and debris flow disasters. Ice avalanches are a special risk in the winter season when the run-out distance increases considerably due to strongly reduced friction on snow. In addition, ice avalanches are able to trigger large snow avalanches, thereby greatly enhancing the avalanche volume (Alean 1985). Of much more importance than the direct impact of glacier length variations is the indirect risk of triggering glacier floods and ice avalanches (e.g. Grove 1987). Advancing glaciers are able to dam rivers and create lakes. Many known glacier floods have their origin in such ice-dammed lakes (e.g. Bruce *et al.* 1987). On the other hand, retreating glaciers often leave behind moraine-dammed lakes. These moraines can be breached resulting in floods and also represent an important sediment source for debris flows (e.g. Haeberli, 1983). Glaciers retreating or advancing over a topographic break in slope have a greatly increased risk of ice breaking off their tongue (cf. the 1965 catastrophe of Allalin Glacier, Swiss Alps). Shock waves related to ice- and rock-fall impacts are able to destabilise glaciers and other high mountain terrain.

While the above interactions represent trigger-chains that influence hazard situations on short timescales, many environmental changes in glacial environments can impact the hazard potential on longer timescales of decades or centuries. For example, retreating glaciers may destabilise steep slopes and cause mass movements, or uncover steep debris reservoirs that are sources of periglacial debris flows for decades or centuries after the actual retreat (Zimmermann and Haeberli 1992; Haeberli *et al*. 1997; Kääb 2000). Such system interactions in high mountains clearly show the urgent need for integrated hazard assessments to account for a variety of relevant processes and their linkages on different timescales.

2. Climate change, human activities and related shifts of hazard zones

Mountain regions are particularly sensitive to climate change. Changes in glaciers, snow and permafrost and corresponding impacts on natural hazards in high-mountain systems could, in fact, be among the most directly visible signals of global warming and may seriously affect human activities (Haeberli and Beniston 1998). For example, in the Himalayas in Nepal and Bhutan, glacier lake outburst floods occurred at a frequency of roughly one flood per decade in the 1950s; this rate has since increased to one flood every three years in the 1990s and it is anticipated that event frequency could further increase to one significant glacier outburst flood each year by 2010 (Richardson and Reynolds 2000a). It is predicted that both the number and size of glacial lakes will increase as climate changes. Coupled with increasing rural development and investments in infrastructure, particularly in hydropower, the vulnerability of mountain communities to outburst floods is growing rapidly. Furthermore, for those rivers fed largely by ice melt, reduction in glacier volumes will have a particularly strong impact on dry-season river flows, and on the provision of downstream water for hydropower, irrigation and potable water supplies. In some regions, most noticeably in Pakistan, climate change will increase environmental, economic and social vulnerability for tens of millions of people. Whilst catastrophic floods (too much water too quickly) are a very palpable hazard, so too are “soft” hazards, such as reduced glacier water during the dry season. Consequently, hazards in high mountains must be considered in relation to water resource management and cannot be seen in isolation. As an example, in Peru, hazards associated with high altitude glacial lakes are being mitigated, using methods that control the lake water volume and ensure safe water reservoirs.

Marked changes in glacier extent due to climate change may be accompanied by both the formation and disappearance of ice- and moraine-dammed lakes, and steep hanging glaciers may become less stable. On the other hand, steep glacier tongues with their present-day potential for large ice avalanches could disappear. Re-vegetation of deglaciated terrain is slow and leaves morainic deposits unprotected against erosion over extensive time periods of several decades and more. On steep slopes, freshly exposed or thawing non-consolidated sediments can become unstable, resulting in debris flows and landslides of varying magnitudes. Once one event has occurred in a particular valley, the remaining slopes may become destabilised even further. The risk of secondary damming of rivers by debris flows also needs to be considered. In places of pronounced glacier retreat, changes in stress distribution and surface conditions of rock walls in deeply cut glacier troughs could induce large mass instabilities. The general tendency is towards a shifting of hazard zones with considerable changes in the processes involved and a widespread decrease in the stability of high-mountain slopes. Special measures are needed to ensure the structural stability and durability of installations for tourism, transportation and telecommunication in permafrost areas. Similarly, detailed hazard assessments must be undertaken routinely and regularly to avoid damage to hydropower installations due to the impact of glacier-derived floods, which can cost many tens of millions of Euros. If, in fact, environmental conditions in high-mountain regions were to evolve beyond the range of Holocene and historical variability, hazard assessments may become increasingly difficult because estimates of hazard potential based on empirical data from the past (historical documents, statistics, geomorphological evidence) will not be directly applicable under new conditions.

3. Modern methods of hazard assessment

Historical data on glacier and permafrost hazards can be used to test spatial models based on new earth observation and geo-informatics techniques. Such modern methodologies provide powerful tools to assist hazard assessments in complex mountain systems, which are experiencing increasing change and divergence from equilibrium conditions.

The assessment of glacier and permafost hazards requires systematic and integrative approaches. Presently, the most successful strategy is based on the combination of remote sensing, modelling with Geographical Information Systems (GIS), geophysical soundings and other local field surveys (Richardson and Reynolds 2000b). These methods are best structured in a downscaling approach from area-wide first-order assessments for systematically detecting hazard potentials (i.e., the domain of space-borne remote sensing and GIS-techniques) to detailed ground-based or air-borne local investigations in high-risk areas (i.e. the domain of geophysics, surveying, and air-borne and close-range remote sensing).

Air- and space-borne optical and microwave data can be applied to automatically classify glaciers, lakes, debris and other terrain types relevant to glacier and permafrost hazards (Kääb *et al*. 2002). Furthermore, some of this data can be used to derive digital terrain models (DTM), an invaluable prerequisite for analysing hazard potential in high-mountains and for related GIS-modelling (Huggel *et al*. 2002; Kääb 2002). Even ice flow and terrain displacements can be measured with high accuracy from repeated remote sensing data (Kääb 2002). With these methods, the terrain cover, geometry and dynamics of an area can be fully investigated without direct access. This can be especially beneficial in mountain areas where the potential sources of glacial hazards lie in geopolitically unstable regions (e.g. Kashmir, Afghanistan) but where the principal impact zones lie significantly downstream. Remote sensing can also be of great use in assessing glacial hazards across international borders where glaciers in an inaccessible part of a country extend their impact into a neighbouring country (e.g. China into Bhutan, India and Nepal).

A further step towards an integrative hazard assessment consists in the application of GIS and other numerical models for simulating processes that are too complex or undetectable by remote monitoring. Glacier lake outburst floods, ice avalanches or debris flows can be modelled with a GIS (e.g. Huggel *et al*. 2002). Also, permafrost distribution, approximate ground-, firn- and ice-temperatures, or various other terrain parameters that have an impact on natural hazards can be computed. Especially the fusion of remote sensing results with numerical process models provides a promising base for the assessment of hazard potentials (e.g. Huggel *et al* 2002)

A more detailed analysis of the hazard sources detected by remote sensing often involves ground-based methods. Geophysical investigations, employing electrical resistivity tomography and ground penetrating radar (Reynolds 1997), in particular, have been used to develop three-dimensional maps of geological structures and have provided information on instability zones such as buried ice bodies within moraine dams, which could lead to breaches in the dam if the ice were to melt (Richardson and Reynolds 2000b; Pant and Reynolds 2000). Furthermore, the use of geophysical methods can provide information about the prevalent physical processes behind glacial and periglacial hazards and can lead to a better understanding of the behaviour of natural dams and their potential to fail. Terrestrial surveying, using laser ranging or Global Positioning Systems (GPS), is needed for accurate mapping and detection of terrain dynamics with high spatial and temporal resolution.

While many glacial and periglacial hazards may develop into major potential hazards, if left unchecked, there are many examples in the Alps, in Nepal, Bhutan and especially Peru, where lakes with high hazard potential have been re-mediated very successfully (Fig. 3; e.g. Reynolds *et al*. 1998; Haeberli *et al*. 2001). The remote monitoring of changes in glacial lakes is crucial in order to help prioritise which lakes should be re-mediated first and when it would be most expedient.

Figure 3: The nearly completed spillway at Tsho Rolpa (4,500 m), Rolwaling Himal, Nepal, in 2000. The lake level was lowered successfully by 3.5 m following construction of the new spillway and sluice gates. It took from April 1999 to July 2000 to complete the works at a cost of ca $3 million. Heavy machinery had to be flown to the site in bits and reconstructed at site. Glacier ice is still present within the moraine dam (right-hand side of picture). Although the glacial hazard has been reduced significantly, it has been recommended that the lake level should be drawn down at least a further 11.5 m to ensure an adequate Factor of Safety for the 150-m high moraine dam. (Photograph © Reynolds Geo-Sciences Ltd, 2000).

4. The near future and its challenges

Glacierized mountain areas would be among the most heavily affected parts of the world in the event of accelerated future warming. Due to the complex interactions of the different variables of the energy balance in such areas, potential future changes can only be estimated very roughly. Empirical methods and energy balance considerations indicate that a large fraction (about one-third to one-half) of the presently existing mountain glacier mass on earth could disappear over the next 100 years with anticipated atmospheric changes. With an associated upward shift of the equilibrium line by some 200 to 300 meters, yearly thickness losses of 1 to 2 meters would have to be expected for temperate glaciers, and many low-latitude mountain ranges would lose major parts of their glacier cover within decades (see section III in this volume). The consequences would include changes in hazard situations, but also in the water cycle and in landscape evolution.

Under such circumstances, the concept of sustainable development in the highest belts of cold mountain areas becomes questionable, because large-scale climatic forcing would by far outweigh any local environmental influences. The main challenge would, in fact, be to adapt to high and accelerating rates of environmental change (Haeberli and Beniston 1998). Empirical knowledge would have to be increasingly replaced by improved process understanding, especially concerning runoff formation and slope stability. Robust numerical models would have to help with the design of hazard mitigation measures at high altitudes. The intensive research on glacier hazards carried out in Switzerland during the past decades (e.g. Haeberli *et al*. 2001) can illustrate possibilities and limitations of hazard assessments and mitigation.

The above-mentioned recent catastrophes clearly demonstrate the key issues with respect to assessing and mitigating glacier and permafrost hazards:

- The large potential for hazard assessment based on remote sensing and numerical modelling has to be fully exploited, and knowledge has to be transferred to affected regions in the second and third world;
- Scientifically objective criteria need to be developed to assess the hazard potential of glacial lakes and other glacial and periglacial hazards;
- Scientists should work towards a greater transfer of information and improved communication between the scientific and political communities to raise the awareness and willingness of the responsible authorities to use the available information and knowledge basis on glacial and periglacial hazards;
- The impacts of environmental change on hazard potential need to be continually monitored and a rapid transfer of this information is critical for the successful mitigation of hazards in highly sensitive high-mountain environments.

The sudden and unexpected surge-type flow acceleration and advance of Ghiacciaio del Belvedere (Italian Alps; Haeberli *et al*. 2002; Kääb *et al.* 2003) and the Kolka/Karmadon rock/ice avalanche (Caucasus), which has been without precedent (Kääb *et al.* 2003), clearly shows that future surprises cannot be excluded. The learning process must continue and an open exchange of knowledge and experience must guarantee high-quality research on glacier and permafrost hazards and their mitigation in high mountain ranges of the world.

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