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Impacts from climate change related hazards in high-mountain areas: A review of assessment techniques

Christian Huggel[1]

Abstract

Climate change has a particularly strong impact in high-mountain regions, as rapidly shrinking glaciers demonstrate in a clear manner. These drastic geomorphic changes have important implications with respect to natural hazards. The aim of this paper is to document the possible processes and consequences of such hazards, and to demonstrate how modern remote sensing and modeling techniques can be used for rapid assessment of potentially endangered areas.

Three case studies are presented from the European Alps, the Andes and the Caucasus. They refer to hazards associated with glacial lake formation and growth, and possible related lake outbursts, as well as massive mass movement processes due to destabilization of large glacierized mountain walls.

Due to the remoteness and difficult access in most high-mountain regions, satellite remote sensing is a highly appropriate tool for monitoring purposes in these areas. We outline here the range of currently available satellite sensor data and show how it can be used to identify potential hazard sources. Based on the detected critical areas, we use mass movement propagation models embedded in Geographic Information Systems (GIS) to approximately delineate endangered areas. Such remote sensing and modeling based first-order hazard assessments are an important tool for further detailed studies, for land use planning, and for prevention and mitigation measures.

Introduction

Natural hazards from glacial and periglacial environments frequently affect populated high mountain regions. Hundreds or even thousands of lives can be lost in catastrophes related to glaciers. For glacial hazards, annual economic loss is estimated to be in the order of 100 million EUR worldwide (Kääb *et al*., 2005). Hazards having their source in glacial and periglacial areas represent a major risk to life and property in densely populated high mountain areas such as the European Alps. A continuing trend of long-term atmospheric warming since the end of the Little Ice Age and increasing human activities in mountain areas are two important components which govern the risk posed by such hazards.

The glacial and periglacial environment is very sensitive to atmospheric warming, and thus quickly affected by melt conditions, as evidenced in the rapid strong retreat of mountain glaciers currently occurring. In fact, in the 2001 IPCC report, mountain glaciers were declared among the best natural indicators of atmospheric warming. In the European Alps, for instance, glacier extent has receded to the minimum of the last few thousand years (Haeberli *et al*., 2002). Significant glacier recession can influence the development of related hazards. For example, potentially unstable glacial lakes often form in glacier forefields dammed by frontal moraines. Concerned with the such risk, UNESCO recently issued a strong warning regarding lake outburst hazards in the Himalayas. Despite inconsistencies in the recording of natural historical hazards, it seems that there has been an increase over the past decades in the frequency of lake outburst events in the Himalayas (Richardson and Reynolds, 2000). Steep slopes of unconsolidated debris no longer covered

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by glaciers are a potential cause of debris flows. New ice break-off zones on glaciers may evolve while others may cease to be active. Atmospheric warming also affects permafrost distribution. The active layer zone may become deeper, and rockfall activity may increase or evolve at locations where it was not previously known to occur. Lateral rockwalls can be destabilized by glacier retreat due to the stress changes induced. In general, climate change may bring about a shift of the hazard sources. It is difficult to ascertain whether the frequency and/or magnitude of events have actually increased. However, events with no historical precedence do already occur and must also be faced in the future.

In the last few decades, human settlements and activities have greatly increased in high mountain regions such as the European Alps. Infrastructure has been expanded into areas which had not been developed previously. Hence, there was a parallel increase in damage potential and vulnerability of mountain communities giving rise, in turn, to a growing conflict with natural processes. Expensive protective structures have had to be built to reduce the risk. Spatial conflicts between human settlements and interests, and hazardous natural processes are very acute and strongly driven by economic, social and political factors.

In this paper we first want to demonstrate with three case studies possible consequences in terms of processes and hazards that are directly related to climatically-driven change. Then, we outline the capabilities of current satellite remote sensing systems to identify and monitor potentially hazardous areas based on a range of methods. Finally, we present a model for rapid assessment to map endangered areas and make reference to applications in the field of disaster management and response.

Currently experienced phenomena and related disasters

In recent years, a number of the aforementioned phenomena related (e.g. glacial lake outbursts) to climatic change have been observed in different high-mountain regions of the world. Some have caused significant natural disasters. In the following sections we present selected cases which we regard to be a characteristic response of high-mountain, and particularly glacial and periglacial, environments, to further atmospheric warming.

Glacial lakes in Perú

Glaciers of the Cordillera Blanca in Perú have been strongly affected by recent climatic changes and have rapidly retreated (Kaser, 1999). In the course of glacier recession, glacial lakes have been growing or new ones have formed over the last years and decades (Silverio and Jacquet, 2003). Many of these lakes represent a potential hazard to the communities in the Rio Santa valley because of the risk of lake outbursts (Carey, 2005).

In fact, the Cordillera Blanca has been repeatedly affected by glacial disasters in the past. Some of the largest glacial lake outbursts and catastrophes ever documented roared down the río Santa valley in the Cordillera Blanca in the 20th century. In 1941 the glacial lake Palcacocha, dammed by a gigantic moraine (figure 1), suddenly burst through and triggered a flood which destroyed about one third of the city of Huaráz more than 20 Km away and killed about 6.000 people (Reynolds, 1992). After the 1941 Palcacocha catastrophe, various mitigation measures such as lake level lowering, dam construction or artificial drainage tunnels were undertaken chiefly financed by the hydro-power company ElectroPerú and its subsidiary in Huaráz, Hidrandina S.A. However, the mitigation activities have decreased in recent years due to a lack of resources, political changes and the privatization of ElectroPerú. The prevailing hazards are characterized by a low probability of occurrence but high potential magnitude as is typical for glacial hazards (Huggel *et al*., 2004a). Due to constant glacier retreat, Lake Palcacocha has regained size in recent years and now is filled with 3,7 million m^3 of water. A recent incident at Palcacocha caused deep concern and confusion in the 100.000+ people of Huaráz. In March 2003, one of the steep moraine slopes confining the lake failed and generated an impact wave in the lake. The wave destroyed one of the constructed overflow dams and generated a small flood. Huaráz was affected by an increased sediment load in the river causing severe fresh water problems for one week. A concurrent NASA report was released regarding the threat of an ice avalanche falling into Lake Palcacocha thereby producing an outburst flood which could badly affect Huaráz (Steitz and Buis, 2003). This provoked great worry and even panic among people in Huaráz, and eventually considerable economic loss. The NASA report turned out to be a severe misinterpretation (Vilimek et al., 2005) but the incident demonstrated the vulnerability of the region not only to natural disasters but also to failed risk communication (Huggel *et al*., 2007).

Figure 1. The glacial lake Palcacocha in the Cordillera Blanca, Perú, dammed by a massive moraine bastion. The moraine breach from the 1941 lake outburst is to the lower right. In the background Pucaranra mountain (6.156 m.a.s.l.) (photo: E. Hegglin, 2005).

Trift glacier, Swiss Alps

In recent years, Trift glacier in the Central Swiss Alps has become a particularly instructive example of rapid glacier retreat, associated lake formation and hazards. Until the late 1990's the glacier tongue was in contact with the bedrock barrier confining the glacier. The tongue was located in a sediment-filled overdeepened trough and connected to the rest of the glacier by an ice fall. Rapid recession made the glacier lose the contact to the bedrock barrier and the first water bodies began to form around 1998 (Raymond *et al*., 2003). Ongoing climate-related glacier shrinkage, and self-accelerating processes related to glacier calving, caused an extraordinary decay of the Trift glacier terminus along with the formation of a constantly growing lake. This lake currently has a volume of several million m^3. Further ice decay and lake growth will leave the ice fall debuttressed, and ice avalanches into the lake could be a consequence. Such avalanches would cause impact waves in the lake, possibly resulting in a lake outburst flood. The physical conditions (i.e. mainly the bedrock barrier) make the possibility of full and sudden lake failure unlikely but downstream structures could nevertheless be seriously affected by smaller potential floods. In addition to the growing hazards, the glacier retreat and lake formation made the track to a frequently visited alpine hut inaccessible and a hanging bridge had to be built instead (figure 2).

Figure 2. The rapidly retreating tongue of Trift glacier in the Swiss Alps with the growing lake which represents a potential danger for the downstream areas. A hanging bridge had to be built because the traditional alpine route is no longer accessible due to lake formation (photo: KWO, 2005).

Ice-rock avalanche Caucasus

The third case described here is the 2002 ice-rock avalanche disaster in the Russian Caucasus. Its occurrence is only partly related to current climatic changes in high mountains but the initial slope instability that caused the avalanche is clearly indicative of processes in steep and glacierized mountain walls we will likely have to face in the future.

In the evening of September 20, 2002, a large rock/ice avalanche took place on the northern slope of the Kazbek massif, North Ossetia, Russian Caucasus (Kotlyakov et al., 2004; Haeberli *et al*., 2004). The avalanche started as a slope failure on the NNE face of Dzhimarai-khokh (4.780 m.a.s.l.) below the summit and involved massive volumes of rock and ice (from hanging glaciers). The slide impacted Kolka glacier which was entrained to a major extent (Huggel *et al*., 2005). The rock/ice avalanche which then formed had a volume of about 100 x 106 m^3 and traveled down the Genaldon valley for 19 Km before being stopped at the entrance of the Karmadon gorge (figure 3). A mudflow continued downvalley for another 15 Km and stopped 4 Km short of the town of Gisel. Both the avalanche and the mudflow were completely devastating, caused the death of about 120 people and destroyed important traffic routes, residential buildings and other infrastructure. The ice dam which was formed by the ice/debris deposits at Karmadon dammed several marginal lakes of up to 5 million m^3 of water. Potential floods from these lakes were an imminent threat to the downstream areas after the disaster (Haeberli *et al*., 2004).

A similar event entraining virtually a complete valley-type glacier has not been documented previously and has, therefore, important implications for worldwide glacial hazard assessments (Huggel *et al*., 2005). The catastrophic erosion of an entire valley-type glacier creates an impression of “the un-thinkable becoming reality”.

In the context of shrinking surface ice and degrading permafrost the initial slope failure processes in the Dzhimarai-khokh NNE wall are important because they are highly relevant to other similar glacio-topographic conditions.

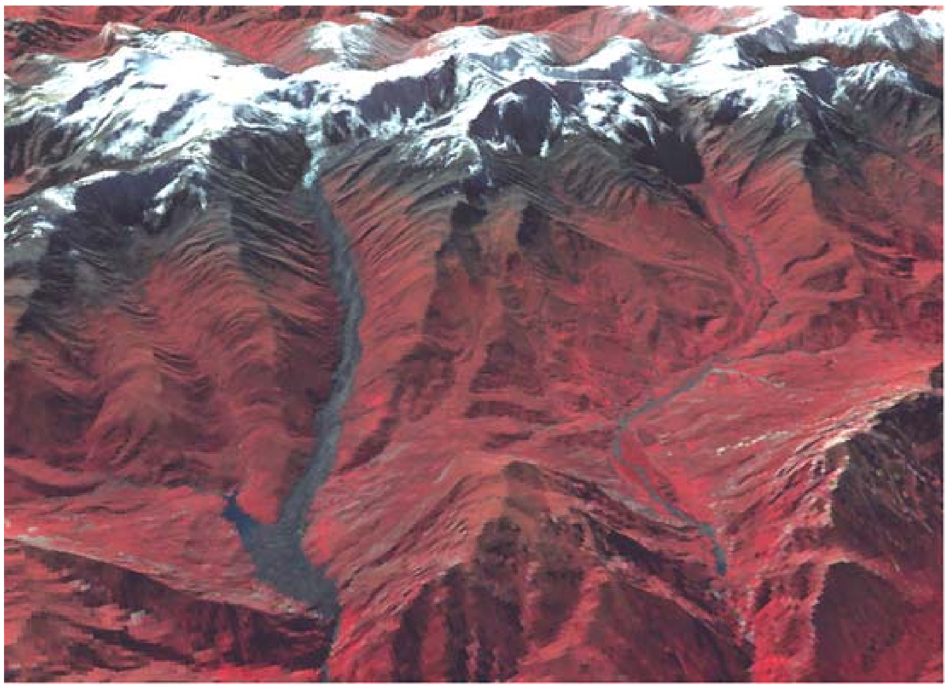

Figure 3. The Kolka-Karmadon ice-rock avalanche path along the Genaldon valley with the ice dam at Karmadon. A 3D view generated from ASTER satellite imagery and thereof derived digital elevation model (image processing: K. Schmutz).

In fact, thermal conditions affecting ice and water within rock fissures have probably played a major role. Bedrock stability in cold mountain areas can be especially low in warm or degrading permafrost (Davies *et al*., 2001; Gruber *et al*., 2004). Based on data from a former weather station near Karmadon, a mean annual air temperature (MAAT) of -6 ± 2 °C at the lower and -11 ± 3 °C at the upper end of the detachment zone are estimated (Haeberli *et al*., 2003). Bedrock surface temperatures in the detachment zone may thus be estimated at about -5 to - 10 °C, indicating bedrock conditions of cold permafrost. The thermal conditions, however, are complicated by the existence of hanging glaciers in the Dzhimarai-khokh NNE wall. Such steep ice bodies can induce significant thermal anomalies to the underlying bedrock since latent heat dissipation from percolating and refreezing meltwater at the firn surface often involves phase equilibrium temperature at the ice/bedrock interface behind the frozen ice front (Haeberli *et al*., 1997). Hence, it is reasonable to assume that the Dzhimarai-khokh failure zone was in a complex condition of relatively cold/thick permafrost combined with warm or unfrozen parts. This can involve meltwater flow in steeply inclined and heterogeneously permeable material and favor high and variable water pressures. Such conditions at critical equilibrium are sensitive to disturbances. Long-term atmospheric warming with its influence on surface and subsurface ice, as well as short-term seasonal variations in precipitation, have likely essentially contributed to the slope failure in the geologically and structurally unfavorable situation of the Dzhimarai-khokh NNE face (Haeberli *et al*., 2003).

The massive failure of a large glacierized wall in the Caucasus may be an example of how such high-mountain walls can be destabilized in the context of atmospheric warming. Similar conditions can be found in many other regions. For instance, in the European Alps, development of slope instabilities in the Monte Rosa east face over the past few years are being monitored with increasing concern (Kääb *et al*., 2004). In August 2005, the slope instabilities culminated in one of the largest Alpine ice avalanches during the past 100 years.

Monitoring techniques

The rapid changes in glacierized high-mountain regions induced by climatic change makes regular observations a critical prerequisite for early detection of possibly hazardous processes. Most high-mountain areas are remote, physically difficult to access and sometimes involved in political and military conflicts such as in the Caucasus or in the Kashmir region. Remote sensing based techniques therefore represent important tools for monitoring in such areas. Satellite sensors have experienced a rapid technical development in the last decades and currently provide information at spatially and temporally high resolution. High cost effectiveness in comparison to on-site studies are a further strong advantage. Figure 4 provides an overview of currently important optical satellite sensors with their spatial resolution in relation to their temporal resolution and cost of acquisition.

In the following sections a variety of techniques are presented that demonstrate how satellite imagery can be used to monitor and identify potentially hazardous phenomena in glacial and periglacial areas.

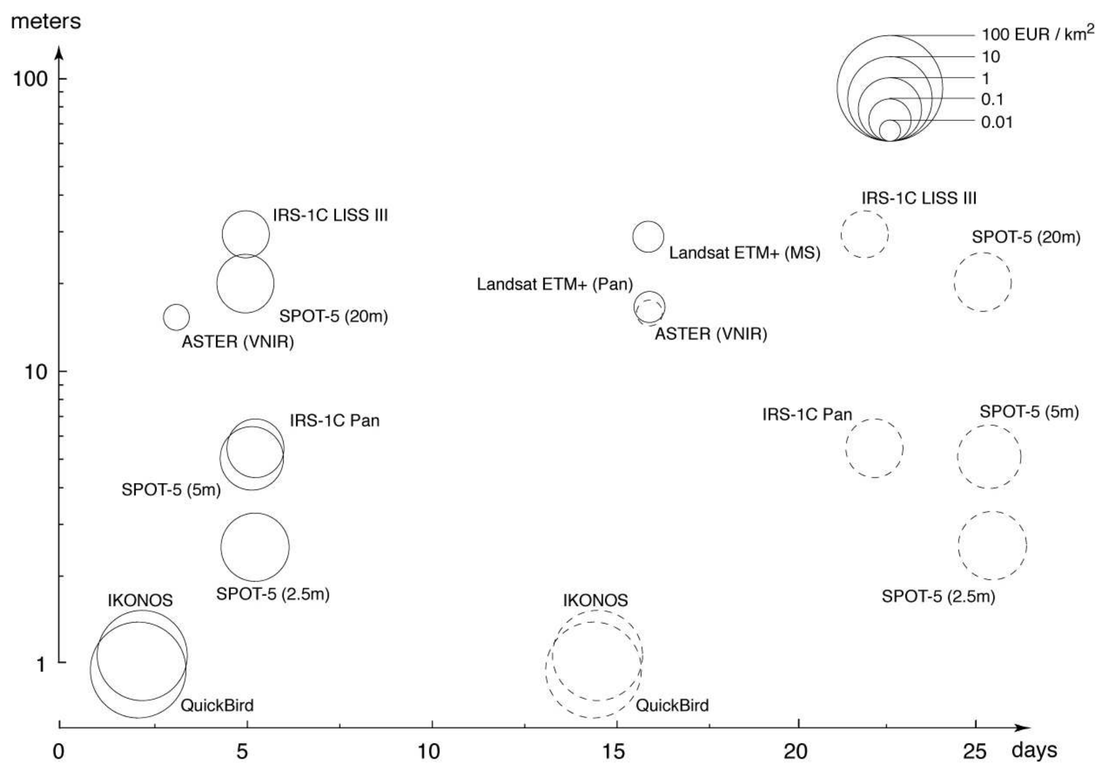

Figure 4. Overview of available optical satellite sensors for use in monitoring of mountain areas in terms of revisit periods (dashed circles indicate regular revisit cycles, solid cycles refer to special sensor programming requests), spatial resolution and acquisition cost (may be subject to changes) (data partly from Kramer, 2002).

Detection and monitoring of ice avalanche prone glaciers

Monitoring and identification of glacier areas can be achieved using multispectral satellite imagery. Several studies have used the Landsat-TM sensor and shown that an algorithm applying the ratio of TM band 4 and 5 provides robust results for mapping of glacierized areas (Hall *et al*. 1988, Paul *et al*. 2002). Automated glacier mapping is enabled by segmentation (thresholding) of the TM4/TM5 ratio image (Paul et al. 2002). Several image processing steps result in a reasonably accurate identification of glacier areas (Huggel et al., 2004b). The occurrence of ice avalanches on steep glaciers with topographic characteristics of a ramp suggests a dependency on the inclination of the glacier bed. Temperature conditions within and at the base of the glacier are also important. Accordingly, the critical bed slope of avalanching glaciers has been observed to increase with increasing altitude (Huggel *et al*., 2004a). In the European Alps, temperate glaciers have been found to produce ice ava-lanches from a minimum slope of about 25º, and cold-based glaciers from about 45º (Alean 1985). Climatic change, i.e., atmospheric warming and/or intense liquid precipitation, may cause higher amounts of water at the base of the glacier, and thus unfavorable stress changes, and possibly failure. The critical bed slope indicated here therefore needs reassessment in the future. On glacier-capped volcanoes, for instance, it has been recently found that glaciers fail at lower slopes than the above temperature-slope relationship suggests (Caplan-Auerbach and Huggel, in press).

For identification of the potentially avalanche prone glaciers, the glacier map is combined with a digitial elevation model (DEM) to extract those areas with slopes steeper than 25º. DEMs should be at sufficiently high spatial resolution to provide a realistic picture. The Landsat-TM resolution (i.e. 30 m) may be regarded as a minimum.

Detection and monitoring of glacial lakes

Glacier lakes are part of the highly variable glacial and periglacial environment. As demonstrated with the aforementioned case studies, a hazard potential can be developing over years, but dangerous developments can also occur within months or even shorter (cf. the Monte Rosa case in 2002/2003, Tamburini *et al*., 2003). In remote high-mountain areas, satellite data is therefore an essential tool to monitor the changes. A simple and straight-forward method to identify glacial lakes was proposed by Huggel *et al*. (2002). According to this study, a Normalized Difference Water Index (NDWI) using multispectral satellite imagery provides the discrimination of water and non-water surfaces. When applied to Landsat-TM, the NDWI can be defined as:

$$\mathrm{NDWI} = \frac{\mathrm{TM4} - \mathrm{TM1}}{\mathrm{TM4} + \mathrm{TM1}}$$

With TMi indicating the respective Landsat-TM band.

Mis-classifications resulting from pixels in shadow can be eliminated by computing a cast-shadow mask using a 25 m DEM to simulate the sun position at the time of satellite overpass. Since the method is automatic, it allows the detection of glacial lakes over large areas along with the surface area of each lake. For the hazard potential of a glacial lake, the lake volume, rather than the surface area, is a determinant factor. The lake volume can be derived from an empirical relationship between mean lake depth h and lake area A (Huggel *et al*., 2002):

$$h = 0{,}104 \times A^{0{,}42} \qquad r^2 = 0{,}92$$

The coefficient of correlation is relatively high but the natural variability of lake depth is large and volume estimates must therefore remain approximative. Remote sensing data and digital terrain modeling was also used to further evaluate the hazard potential of glacial lakes, using a set of criteria consisting of important parameters such as lake size, lake and dam geometry, or dam type (Huggel *et al*. 2002, 2004a). Peak discharge, that would result from a lake outburst, can be estimated empirically based on the lake volume (e.g. Walder and Costa, 1996; Huggel *et al*., 2002).

Detection of potentially unstable debris slopes

Debris flows with potentially devastating consequences for downstream areas often originate on steep slopes with unconsolidated sediment. In periglacial areas, such sediment typically results from glacial erosion and deposition processes. Glacier retreat accelerated by climatic change exposes large sediment reservoirs. Thus, in the context of climate-change impacts in high-mountain regions, new areas will become sources for debris flows that are not part of our the historical experience.

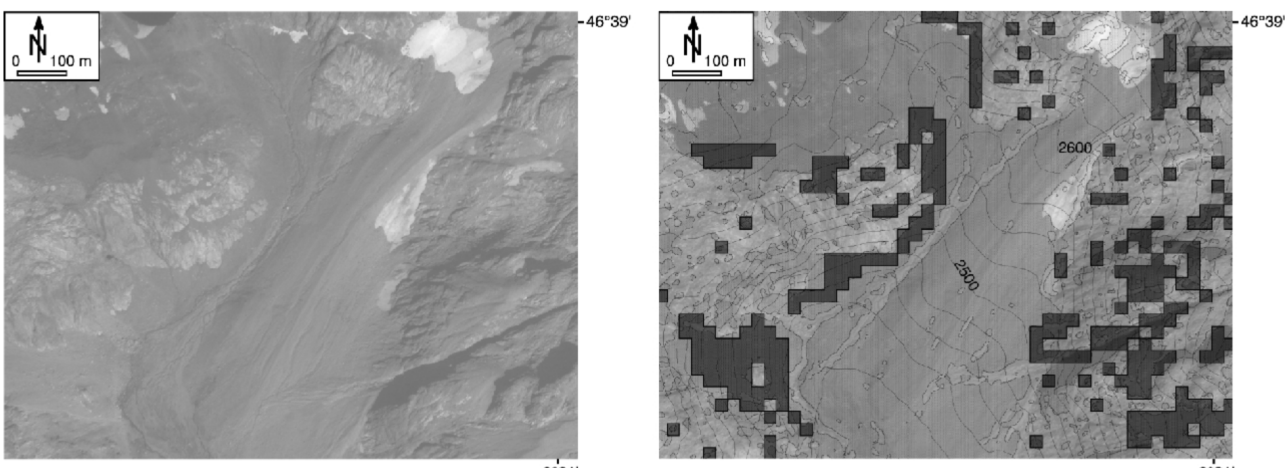

Figure 5. Detection of potentially unstable debris slopes using IKONOS 1 m resolution images, texture and digital terrain modeling. Grid cells in dark grey indicate areas which may be subject to destabilization (example from the Grimsel region, Swiss Alps).

Here, we describe a technique to detect such large and potentially unstable debris reservoirs based on high-resolution satellite images. A main problem for achieving the detection is the difficult distinction of rock and debris due to their spectral similarity. Therefore, classification algorithms considering spectral information only are unlikely to yield satisfactory results (Paul *et al*., 2004). It has been found that the spatial resolution played a crucial role in the distinction between rock and debris material: debris accumulations show a uniform surface structure in contrast to exposed bedrock as a function of spatial resolution. Such uniform structures are not recognized by satellite sensors with spatial resolution of 20 to 30 m, and spatial

resolution is thus a limiting factor. The method described here uses IKONOS data but could also be applied with QuickBird imagery or aerial photos (Huggel *et al*., 2004b).
An edge detection filter was found to be able to detect the structural uniformity of debris accumulations, and to discriminate them from the irregular structure of bedrock. The filter calculates the average of the grey value difference between the central pixel and each of its surrounding neighbors, and assigns the value to the central pixel. More uniform areas have smaller grey value differences and are thus assigned lower values. The number of neighbors is defined by a moving window of specified dimensions. Appropriate window size basically depends on the scale of the structure to be detected. Here, best results were obtained by a 11 x 11 window. The resulting grey value image was then segmented into debris and bedrock according to a threshold value of 47. A 5 x 5 median filter was finally applied to smooth the classification and avoid small isolated pixel. Rickenmann and Zimmermann (1993) found that debris flows originating in large and steep debris reservoirs such as talus or scree slopes have typical starting slope inclinations between 27º and 38º. For detection of potential debris flow initiation zones, areas with a slope range between 27º and 38º (using a 25 m-gridded DEM) were therefore selected from the previously classified debris accumulation areas (figure 5).

Mass movement modeling

The remote sensing and DEM modeling based methods described in the previous section provide the ability to detect and map surface areas of glacier, water and unconsolidated sediment in high-mountain environments that have the potential to suffer failures and induce gravity-driven mass movements such as avalanches and sediment-laden flows. It is important to assess the possibly severe consequences of such mass movements in terms of areas potentially affected. A variety of mass movement models have been developed in recent years for such a purpose. Here, we describe a GIS-based model that is able to integrate the information extracted from remote sensing data and yields a measure of probability that a certain zone is affected by a given mass movement. The model MSF (modified single flow direction model) was originally developed for lake outburst floods (Huggel *et al*., 2003) but has also been applied to ice and rock avalanche processes (Huggel *et al*., 2004b; Noetzli *et al*., 2006). Inputs to the model are the initial failure zones (steep glaciers, lakes, unstable sediment slopes) as derived from the remote sensing methods and a DEM.

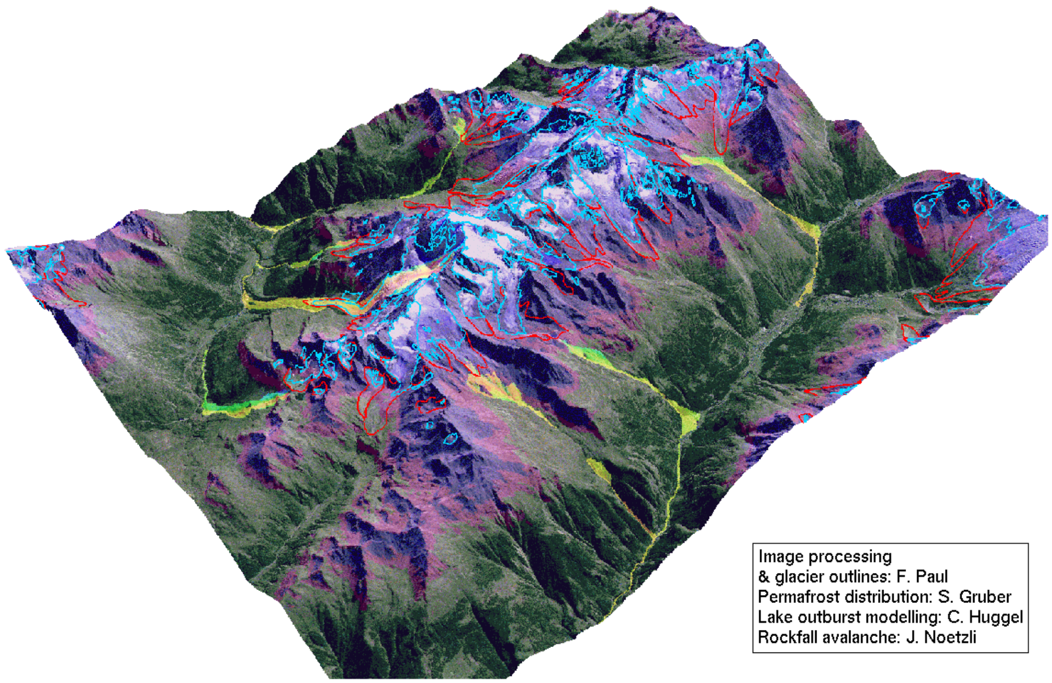

Figure 6. 3D model of current and historic glacier extent (red lines: 1850, blue lines: 1973 extents), modelled permafrost distribution (in magenta) and modeling of lake outbursts/debris flows and rock-ice avalanches in the Saas valley – Simplon region, southern Swiss Alps.

The basic idea is to propagate flow from the source location downstream until a certain empirically defined point of runout is reached. The algorithm is based on a single flow direction approach with an important modification to allow diversion from the steepest descent direction. A function was integrated that enabled flow diversion of up to 45º from the steepest descent direction (Huggel *et al*. 2003). A linear function defines that the more the flow diverts from the steepest descent direction the greater is the resistance. Flow resistance is then related to a probability function which basically de-fines that the more flow resistance has to be overcome to reach a point, the less likely is it affected by the flow (Huggel *et al*. 2003). The model is thus capable of simulating the different characteristics of debris flows or avalanches in confined channel sections (with largely limited spread due to converging flow) and on relatively flat or convex terrain (e.g., debris fans; with greater spread due to more diverging flow), and to provide corresponding probabilities.

The model is stopped when an arbitrarily defined ratio of drop height H to horizontal runout length L is reached. The H/L ratio is usually defined based on empirical information for the corresponding type of mass movement. For example, a maximum runout approach could be applied for debris flows in the Swiss Alps with H/L = 0,19 or for ice avalanches with H/L = 0,31 (Huggel *et al*., 2004a, b). The applied H/L ratio determines the extent of potential damage of a mass movement, and consequently the value has to be evaluated in detail for each situation. Figure 6 provides a 3D-model of a regional application of the MSF model for lake outburst and rock-ice avalanche processes in the southern Swiss Alps.

Disaster management and response

The fundamental objective of the methods presented so far is the early detection and prevention of hazards due to avalanches and sediment-laden flows in high mountains. The improved capabilities of recently launched satellite sensors, however, also make them suitable for disaster applications, their use being mainly for disaster management and response. The application and potential of high-resolution satellite sensors is briefly outlined below.

High resolution satellites such as IKONOS or QuickBird are currently the only satellite sensors actually suitable for a sound evaluation of damages from mass movements or floods. The spatial resolution of the sensor is therefore a critical factor. In a study of the Caucasus avalanche disaster, damage assessment with QuickBird images was possible down to individual buildings. The satellite images were best used to evaluate the number of inundated or destroyed buildings. Precise damage characteristics of single buildings, however, could not be recognized with QuickBird images. Minor or major traffic routes affected could also be designated.

In emergency situations, time is of critical importance. The minimum of ca. 60 hours for rapid data delivery with QuickBird can result in an essential delay depending on the type of disaster. New satellite constellations are being planned which are dedicated particularly to disaster management/response and have data delivery times of a few hours (Kerle and Oppenheimer, 2002). In fact, the overall cost of a disaster often depends on how quickly the event is responded to, and how efficiently response activities are managed. This requires a synoptic overview of the affected area. Satellite images of 15 - 30 m resolution do not completely fulfill these needs. QuickBird images do have the capabilities for emergency applications, for example, assessment of critical lifelines such as roads, telecommunications or power supplies.

Conclusions

Climate change has a pronounced impact in high-mountain regions. In glacierized areas, the rapid retreat of glaciers is an unambiguously clear signal. These drastic changes on the earth surface, and partly also sub-surface, have important implications with respect to natural hazards. The case studies presented in this paper have demonstrated the potentially severe consequences of hazards originating in glacial and periglacial environments.

Due to the remoteness and difficult physical access of most high-mountain areas, satellite remote sensing is an appropriate tool to identify and monitor the ongoing changes. A variety of satellite sensors with different capabilities in terms of ground resolution or revisit periods are currently available. We have presented here several methods to identify potential hazard sources using different satellite data products. Avalanche and debris flow propagation models imbedded in GIS subsequently allow an approximate delineation of areas endangered. Such remote sensing and model based first-order hazard assessments are an important tool for further detailed studies, for land-use planning, and for prevention and mitigation measures.

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