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Assessment of the hazard potential of ice avalanches using remote sensing and GIS-modelling

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Ice avalanches typically occur when a large mass of ice breaks off from steep glaciers. Since the reach of ice avalanches is usually low, their hazard potential is generally restricted to high mountain areas that are densely populated or frequently visited by tourists. However, far-reaching disasters are possible in combination with other processes such as rockfalls or snow avalanches. In addition, the hazard potential of ice avalanches is presently increasing as a consequence of climatic and socio-economic changes in mountain areas. Dealing with ice-avalanche hazards requires robust tools for systematic area-wide detection of hazard potentials. Corresponding techniques have not been developed so far. To bridge this methodological gap, a three-level downscaling approach was developed. This method chain is based on statistical parameters, geographic information system (GIS) modelling techniques and remote sensing. The procedure permits to perform a fast and systematic first-order mapping of potentially dangerous steep glaciers and their runout paths for an entire region. To validate the approach, a case study was carried out in the Bernese Alps, Switzerland. The results correspond well with local studies using dynamic avalanche models. Improvements can be obtained by expanding the method chain by including basic data of higher spatial resolution as satellite data and digital terrain models (DTM).

Keywords: *DTM, GIS-modelling, hazard potential, ice avalanche, remote sensing*

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Introduction

Ice avalanches typically occur when large masses of ice break off from a steep or hanging glacier (Alean 1984, 1985). In high-mountain areas with high relief energy, ice avalanches represent the normal ablation process of steep glaciers whose tongues do not reach down to areas with prevailing melting conditions. Fig. 1 shows an example for the starting, runout and deposit zone of an ice avalanche (Gutz Glacier, Bernese Alps, Switzerland). The locations of the sampling sites are shown in Fig. 2. Since the runout of ice avalanches is usually short compared to the distances attained, for instance, by glacier floods, the direct impact of any hazard is generally restricted to areas that are densely populated or frequently visited by tourists. However, in combination with rock falls, snow avalanches or lakes, ice avalanches have the potential to cause especially far-reaching disasters, such as the devastating catastrophes of Huascaran (Cordillera Blanca, western Peru) in 1970 (18,000 people killed; Patzelt 1983) or Kolka-Karmadon (Northern Osetia, Russian Caucasus) in 2002 (150 people killed; Kääb et al. 2003) showed. Such process combinations or chain reactions include:

- the triggering of especially large snow avalanches by ice avalanches in winter (Röthlisberger 1981, Giani et al. 2000)
- the combined break-off of rock and overlying steep glaciers (Giani et al. 2000, Haeberli et al. 2003)
- the transformation of ice avalanches into mud or debris flows due to friction melting (Kääb et al. 2003)
- lake outbursts triggered by impact waves from ice avalanches (Richardson & Reynolds 2000)

The potential impact from glacier hazards is currently increasing as a result of climatic and socio-economic changes. Glaciers are especially sensitive to changes in atmospheric conditions because of their proximity to melting conditions. Present atmospheric warming particularly affects terrestrial systems where surface and subsurface ice are involved. Changes in glacier and permafrost equilibrium are shifting beyond historically known conditions (Kääb et al. 2003, Kääb et al. in press). The melting-out of the iceman 'Oetzi' from the Schnalstal Glacier (at the border between Italy and Austria) is evidence that glaciers are currently approaching prehistorical conditions (Bonani 1994). Also, a number of recent historical glacier studies (e.g. Haeberli & Holzhauser 2003) show that glaciers reach conditions not documented for the past two millennia. As a result of these changes the hazard potential at specific places is changing. In some areas the hazard potential is increasing whereas in other areas it is decreasing. In consideration of this fact, the direct applicability of historical sources for hazard assessment is significantly reduced (Kääb et al. 2003, Zimmermann & Haeberli 1992, Evans & Clague 1994). Furthermore, the increasingly dense settlement and infrastructural development in the Alps, which is both extending and accelerating, leads to dangerous situations without historical precedence (Haeberli 1992). Human activity increasingly invades hazard-endangered zones.

The growing intensity of human activities combined with the acceleration of complex environmental changes in high mountain areas requires integrative and area-wide decision support, and the application of modern monitoring and modelling technology. To date, a number of specific studies on individual ice avalanche hazards have been performed, mainly based on recent catastrophes or imminent hazard situations (e.g. Röthlisberger 1981, Margreth & Funk 1999). Although tools for the scientific investigation of individual

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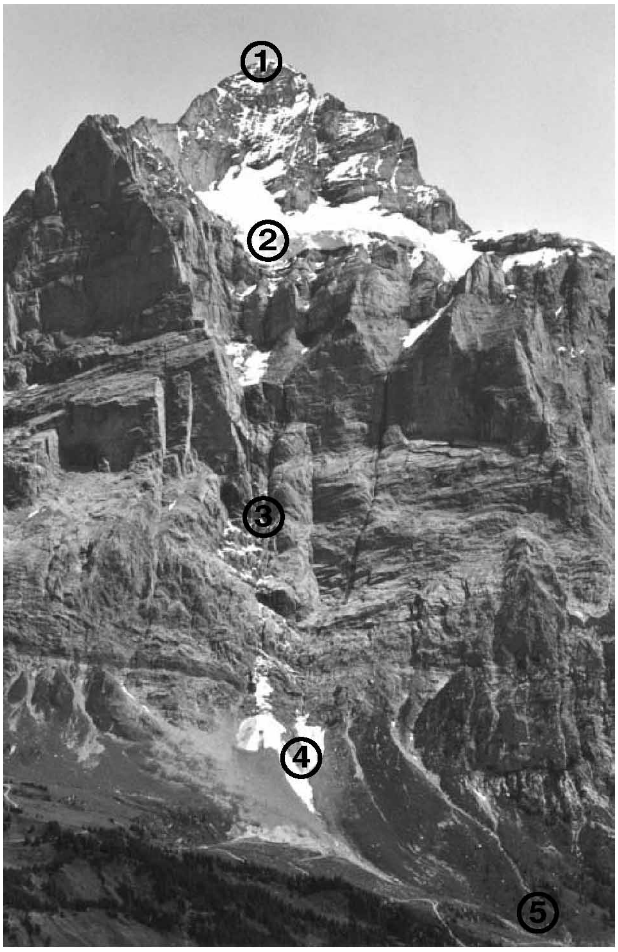

Fig. 1. Gutz Glacier (Bernese Alps, Switzerland), a typical situation of a cliff-type glacier. Wetterhorn (1), frontal cliff of Gutz Glacier (2), avalanche trajectory (3) with small deposits at the bottom of the rock wall (4), and the Grindelwald – Grosse Scheidegg road (5).

steep glaciers exist, a systematic approach for the area-wide detection of hazard potential from ice avalanches has not yet been developed. Such integrative detection is, however, a prerequisite for the efficient application of detailed analyses.

This contribution presents a sequence of techniques that tries to bridge the above-mentioned methodological gap. Based on statistical parameters, GIS and remote sensing work, the procedure makes it possible to perform a fast and systematic first-order mapping, i.e. a rough modelling able to provide a first estimation of potentially dangerous steep glaciers for an entire region (focused map scale *c.*1:25,000–1:50,000). It is not the aim of the proposed approach to deliver a detailed hazard map. Rather, we want to evaluate the application of robust statistical parameterizations combined with GIS and remote sensing techniques as a means of constructing hazard overview maps to serve as a basis for decision-making.

First, we introduce a multi-level approach for the detection of ice-avalanche hazard potentials. Then, case studies in the Bernese Alps are used to exemplify the methods. The subsequent section discusses, in particular, questions of accuracy, and in the prospects we outline some possible ways of improving the method chain.

Methods

The method chain presented here follows a three-level downscaling strategy of increasing resolution and accuracy for the data and methods applied, and of decreasing area covered (Fig. 3). Each level involves GIS and remote sensing techniques and applies empirical parameterizations. The first level aims at detecting and localising steep, potentially dangerous glaciers. The goal of the second level is to assess hazard zones that are potentially affected by ice avalanches. The third level is a detailed investigation of specific sites selected from level 2.

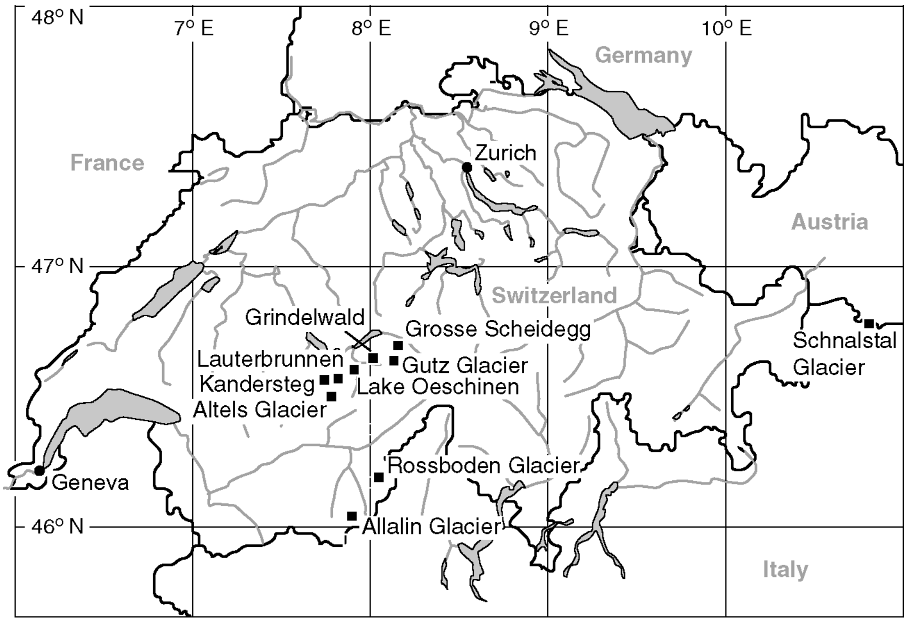

Fig. 2. Location map of the sampling sites.

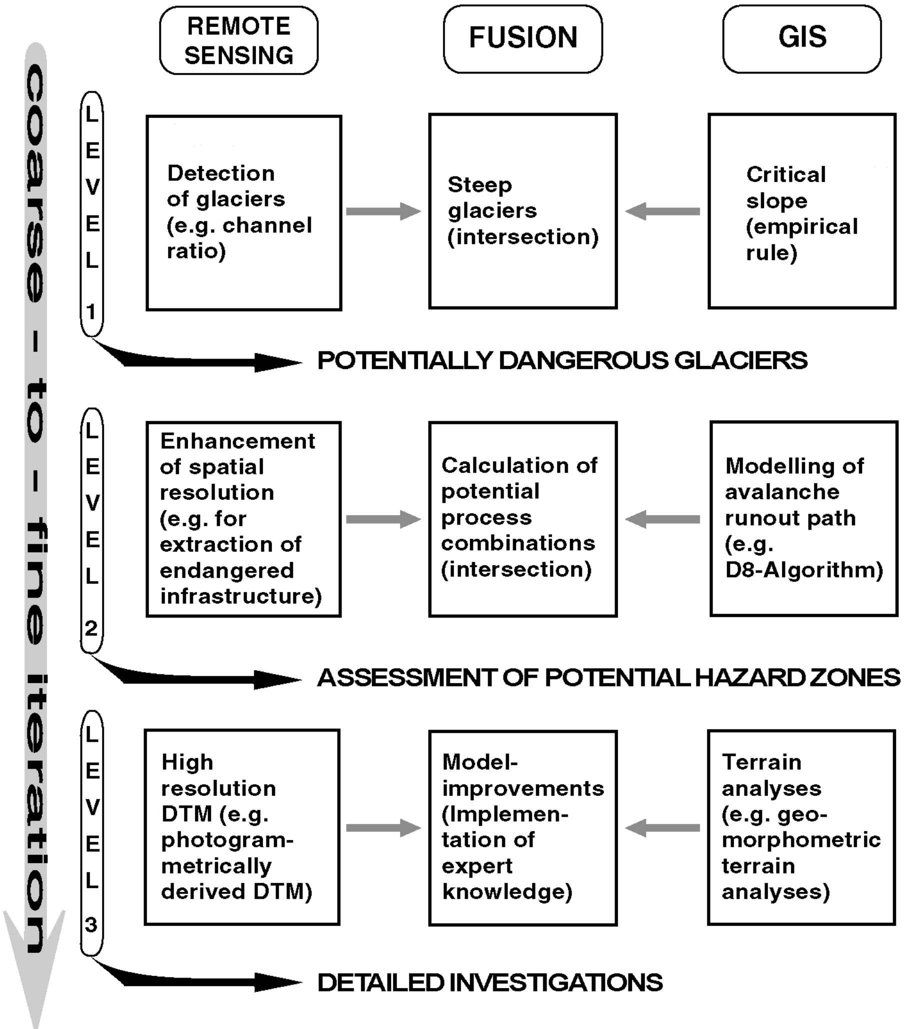

Fig. 3. Flowchart of the three-level downscaling strategy for detecting ice-avalanche hazard potentials. Some grid boxes give examples.

Statistical parameters of ice avalanches

In practice, the assessment of glacier-related hazards often has to be made on the basis of an incomplete understanding of the process by applying simple rules derived from basic knowledge and from experience gained from previous events (Costa 1988, Costa & Schuster 1988, Haeberli et al. 1989, Evans & Clague 1994, Kääb et al. 2000). The sporadic and catastrophic nature of such events limits the application of frequency-magnitude analyses, and the collection of anything more than basic parameters is often too difficult. Moreover, the chain reactions and disaster combinations mentioned in the introduction often require an integrative overview rather than detailed investigation of isolated processes.

The following statistical parameters relating to initial conditions and to the transit and deposition of ice avalanches were primarily derived from cases in the Swiss Alps studied by Alean (1984). Therefore, their application may principally be valid in the European Alps (Haeberli et al. 1989).

Avalanche-starting conditions depend on the type of failure. According to Alean (1984) and Haefeli (1966), ice break-off may result from two morphological types of potential ice avalanche starting zones: ramp-type and cliff-type glaciers (Fig. 4).

Ramp-type glaciers are situated on more-or-less uniformly sloped plains. The failure mechanism is due to the sliding or shearing of an ice mass on or near the bedrock after a reduction in adhesion. The occurrence of ramp-type ice avalanches suggests a dependency on the inclination of the glacier bed (Alean 1984, 1985). Observations (Alean 1984) show that the critical inclination of the glacier bed from which ice avalanches slide or break off increases with increasing altitude, possibly as a result of temperature conditions within and at the base of the glaciers. This dependency allows us to distinguish two sub-types of ramp-type glaciers: type A, which has a temperate bed, and type B, which has cold ice and is frozen to the bed. Ramp-type starting zones can release especially large volumes of ice. Volumes of over 1 million m^3 are possible (Alean 1985). Examples of ramp-type glaciers are the Allalin Glacier (Valais Alps) and the Altels Glacier (Bernese Alps).

Slope and basal ice temperature are primarily responsible for the disposition of ice avalanches. Cold glaciers produce

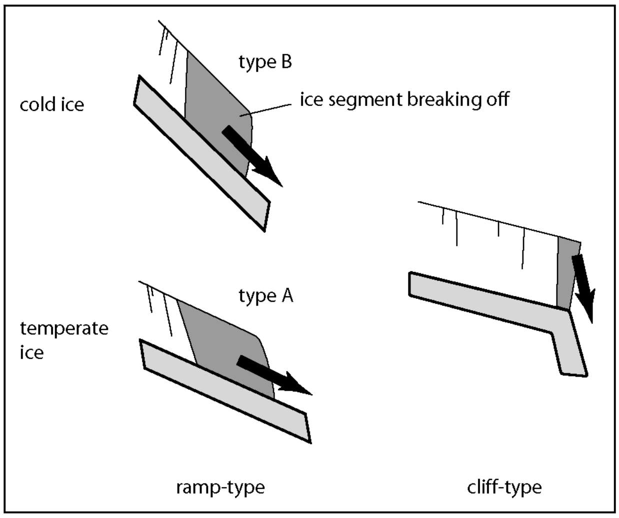

Fig. 4. Morphological typology of ice break-offs.

ice avalanches from a minimum bed slope of *c*.45°, while temperate glaciers do so from a minimum inclination of *c*.25° (empirical values; Alean 1985). Although cold glaciers tend to be more stable than temperate glaciers, it is reasonable to preselect the potential ice avalanche starting zones for a worst-case scenario, i.e. to consider all glaciers steeper than 25° as potentially dangerous.

Cliff-type starting zones lie at a point where a marked increase occurs in the slope of the terrain. The glacier develops a nearly vertical front. Break-off processes for this type are similar to dry-calving (Alean 1984). Due to the high tensile and shear stresses towards the steep front, the ice cracks into lamellas and seracs. No specific relationship exists between the frequency of ice avalanches and the inclination of the glacier bed or surface. Ice break-offs from cliff-type situations represent the natural ablation process for such glaciers. Therefore, only relatively small ice avalanches occur, usually well below 1 million m^3 (Alean 1984). Since the front of a cliff-type glacier is always steeper than 25°, these glaciers are automatically included in our analysis. An example of a cliff-type glacier is the Eiger west face (Bernese Alps).

The runout distances of (rock-) ice avalanches have reached up to 6 km in the European Alps (Rossboden Glacier, Valais; Alean 1985), with even higher values known in other mountain ranges (Caucasus; Kääb et al. 2003) (Andes; Patzelt 1983). For a first assessment based on these historically documented maximum runout distances, the area potentially affected by a major ice avalanche can roughly be defined as the area within such maximum reach (Haeberli et al. 1989).

Average slope of a mass fall event forms another common and useful approach for hazard assessment (Scheidegger 1973, Evans & Hungr 1993, Meissl 1998, Gamma 2000). The average slope describes the angle with the horizontal of a line from the top of the starting zone to the furthest point of deposition. Alean (1984) found a minimum average slope for ice avalanches of 31% in the Swiss Alps which seemed to be independent of an avalanche volume of up to 1 million m^3. This statistical parameter can also be used as a rough estimate for the runout distance in the Swiss Alps, supplementing and, usually, reducing the potential avalanche reach obtained from the 6 km approach.

Detection of steep glaciers (level 1)

Remote sensing techniques offer efficient methods for glacier mapping. The high value of Landsat Thematic Mapper (TM, 30 m × 30 m ground resolution) for glacier mapping has been demonstrated by several studies, and various algorithms have been developed (Hall et al. 1988, Rott & Markl 1989, Jacobs et al. 1997, Sidjak & Wheate 1999, Paul et al. 2002). Glaciated and ice-free areas can be distinguished by the variation in their spectral response from the bands TM4 (0.76–0.90 μm) to TM5 (1.55–1.75 μm) (Jacobs et al. 1997). The reflectance of deglaciated bedrock and vegetation increases from the TM4 to the TM5 spectral band. The opposite is valid for ice and water, where reflectance decreases significantly from TM4 to TM5. The reflectance of ice is estimated to be below 2% in the TM5 spectral band with respect to TM4 (Jacobs et al. 1997). Therefore, for automated glacier mapping, robust results can be achieved by the segmentation (threshold) of ratio images from TM4/TM5 using the raw digital numbers (DNs). This algorithm provides also sufficient results for areas containing cast shadow (Hall et al. 1987, Paul et al. 2002). Fig. 5A shows the result of this approach in the Bernese Alps. The glaciated area is well mapped. Only vegetation, rockwalls of lime and lakes cause detection errors. The robustness and the simple implementation of the method make it especially useful for the first-order assessment aimed at in our methodological level 1.

Several post-processing algorithms can enhance the glacier mask obtained from above band ratioing. The method of selection depends on the characteristics of the study site. We tried to tackle the difficulties of the aforementioned ratio approach in the spectral differentiation of vegetation and glacier as described by Rott & Markl (1989). Our results were substantially improved by using a segmentation in colour space with the condition that the digital number of the Hue component (of an Intensity Hue Saturation transformation) of the spectral bands 543 has to be higher than the threshold value of 42 (Fig. 5B). Paul et al. (2002) showed that in high mountain regions with glaciated environments a 3 × 3 median filter can further improve the quality of such classifications. In this way, isolated misclassified pixels situated outside the glacier mask and with a reflection within the corresponding spectral band, like parts of lakes or parts of rockwalls, were eliminated. Missing pixels within the glacier mask and with a reflection outside the corresponding spectral band such as, for example, debris-covered parts of a glacier, were added (Fig. 5C).

A slope map with a threshold of 25° can easily be generated from a DTM using standard GIS applications. The potentially dangerous glaciers can be identified by intersecting the glacier mask obtained above with this slope map.

In this study, we used the DTM ‘DHM25L1’ of the Swisstopo (Swiss Federal Office of Topography). It is a

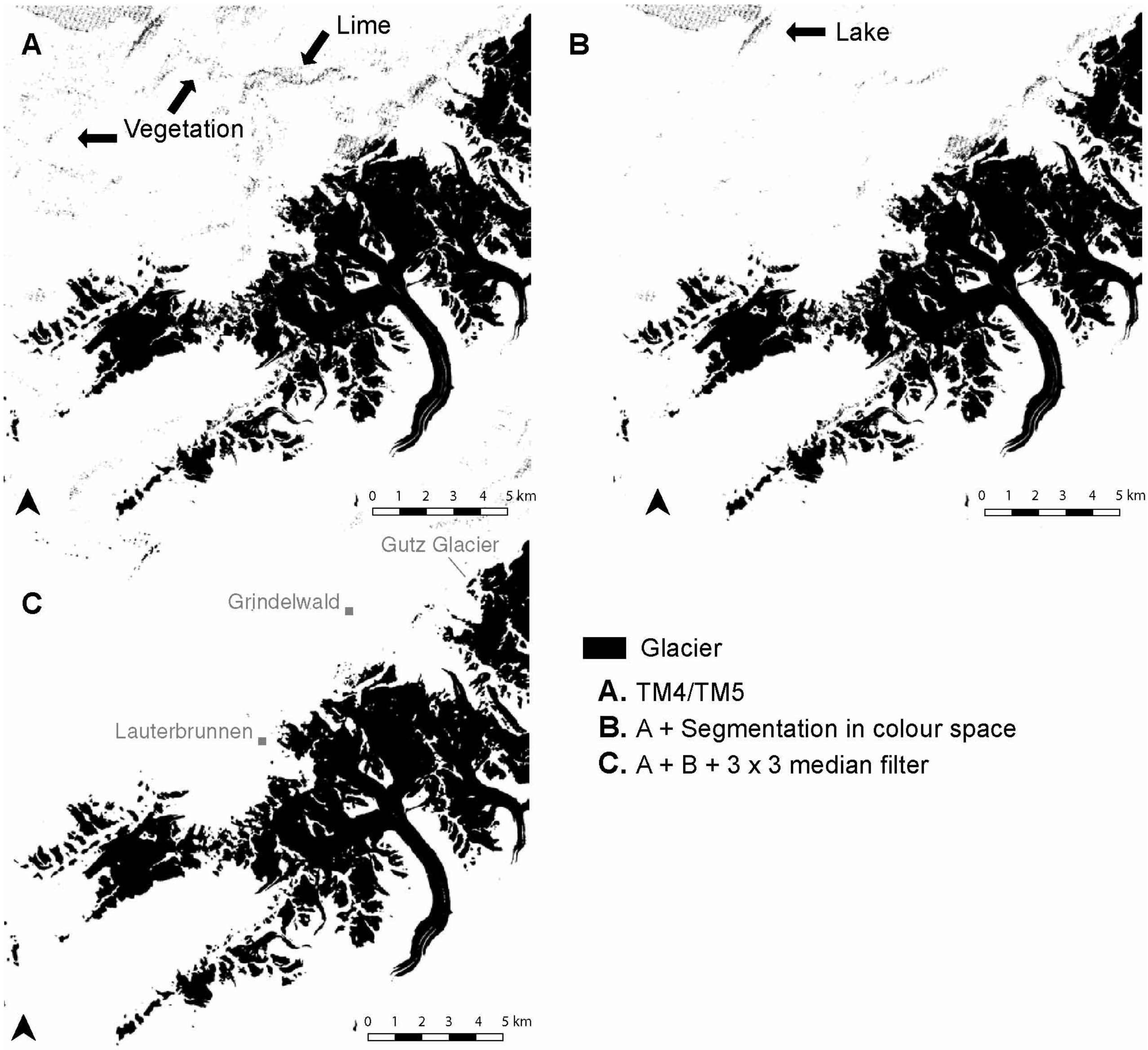

Fig. 5. Glacier mapping in the Bernese Alps (Switzerland) using Landsat Thematic Mapper data.

25 m-gridded DTM interpolated from contour lines on the Swiss topographic map series 1:25,000 and additional topographic points.

Assessment of potentially hazardous zones (level 2)

A first estimate of areas potentially affected by ice avalanches starting from steep glaciers can be derived from the statistical parameter of maximum runout distance. A GIS-based overlay of the potential maximum impact radius (6 km in the Swiss Alps) drawn around steep glaciers as obtained from methodological level 1 provides a first overview of areas which are potentially affected and unaffected. Obviously, drawing a 6-km radius around steep glaciers generally overestimates the actual endangered areas considerably, particularly because the process of downslope flow is not considered at this step. However, we consider such a first rough approach to be essential for building awareness during the hazard assessment and decision process. The events of Huascaran in particular and more recently of Kolka-Karmadon strongly suggest that such extraordinary case scenarios should be considered, at least in a first step.

A more detailed modelling of potential ice avalanche reach has to consider topographic constraints compared to the above rough-radius approach. For that purpose, we apply the average-slope approach combined with potential avalanche trajectories. These trajectories are modelled from a DTM for each steep glacier grid cell detected in level 1. As this task is similar to a general problem in hydrologic modelling, a number of methods are available. The approach we used here is also implemented in the ARC/INFO function 'Flowdirection' (Jenson & Domingue 1988, ESRI 1992), a frequently used software system. The fact that both the GIS and the algorithm used here are well established greatly eases the application and reproduction of the model. The method, designated D8 (eight possible directions), is a simple routing method for specifying flow directions to assign flow from each cell to one of its eight neighbours, either adjacent or diagonal, in the direction of the steepest descent (Huggel et al. 2003).

Topographic depressions are to be eliminated from the DTM before computing the trajectories (Tarboton et al. 1991). The resulting trajectories do not yet have any length limitation. Therefore, in a next step, the average slope concept is applied to the trajectory model as the criterion for the maximum runout distance to constrain the trajectories. The average slope concept is thereby defined as the slope of a line between the starting and the end point of an ice avalanche to the horizontal. For each cell potentially affected by the ice avalanche path, the ratio between the vertical drop and the horizontal distance along the curving flow path to the glacier is calculated. The modelled ice avalanche path is stopped when the average slope of 31% is reached. This implementation is achieved by using the ARC/INFO function 'Pathdistance' (ESRI 1992) which is actually designated for cost-accumulation applications of spread-modelling. Here, the function is used to calculate horizontal distance and vertical drop from each cell along the flow trajectory to the source zone (i.e. the failing glacier, cf. Salzmann 2002).

Detailed analyses (level 3)

The results obtained from level 2 facilitate the systematic identification of the hazard potential of ice avalanches. The interpretation of results and decisions regarding further steps require expert knowledge. From that perspective, levels 1 and 2 of our approach may be viewed as part of a decision-support system. A glacier hazard expert is able to modify the raw computed avalanche trajectories, avalanche reaches and endangered areas. In the same way, potential complex chain reactions have to be judged. Further steps in the decision-making process involve other scientists, locals and last, but not least, the authorities concerned. However, also on the technical level, methods for detailed analyses are available (level 3). Since such techniques have already been developed, we only give an overview.

Firstly, detailed remote sensing analyses are possible from high resolution aerial or satellite imagery (e.g. IKONOS, Quickbird, Eros). Photogrammetrically derived DTMs provide better resolution for trajectory modelling and help to assess the geometry of the glacier surface with respect to ice break-offs (Kääb et al. 2000). Repeated imagery even makes it possible to detect ice displacements (Kääb et al. 2000). High resolution imagery helps to assess the characteristics of potential avalanche trajectories (roughness, vegetation, installations, etc.). Secondly, dynamic avalanche models may be applied for selected sites (e.g. Margreth & Funk 1999). Lastly, sites found to have an especially high ice avalanche hazard potential may be subject to detailed ground-based and laboratory investigations. This includes the modelling of thermal conditions, the monitoring of ice lamella velocity (Haeberli & Röthlisberger 1976, Kääb et al. 2000), the monitoring of ice break-off activity (Iken 1977, Flotron 1978, Wegmann et al. 2003), glacier drillings and geophysical soundings, and numerical thermodynamic modelling (Wegmann et al. 2003).

Further methods for dealing with potential ice avalanche hazards range from planning and engineering measures to access restriction and the evacuation of people (Haeberli et al. in press).

Case studies in the Bernese Alps

Model demonstration and validation

To validate the proposed approach, the Gutz Glacier (Bernese Alps, Switzerland) (Fig. 1) was selected. This cliff-type glacier is situated on the north-west face of Wetterhorn, close to Grindelwald. It has two starting zones, known as 'Wätterlaui' and 'Gutzlaui' (Fig. 6). In the past 100 years, several major ice avalanches from the Gutz Glacier have been recorded, avalanches that have damaged huts, forest and animals. Minor ice avalanches are frequent (several times per day in active phases) and mostly without adverse consequences (Bieri 1996, Margreth & Funk 1999).

On 5 September 1996, two major ice avalanches occurred at the 'Wätterlaui' starting zone of the Gutz Glacier. The second, larger one, which had a volume of 170,000–190,000 m^3, reached the road between Grindelwald and Grosse Scheidegg, which is a regular bus route, and covered it for a length of 30 m with ice deposits as thick as 4 m. In addition, the powder avalanche deposits covered *c.*35 ha (Margreth & Funk 1999). Fortunately, only three people were injured as a result of the pressure waves produced by the powder avalanche (cf. Huggel et al. 2002b).

About half a year prior to this event, Bieri (1996) assessed the ice avalanche hazards from the Gutz Glacier by combining empirically-based methods with field analyses, but without using techniques such as GIS or remote sensing. Bieri's study (1996) concurs with the actual event of September 1996, thus enabling us to validate our modelling results.

Another basis for validation is provided by the detailed hazard mapping study of the Swiss Federal Institute for Snow and Avalanche Research (S. Margreth, unpublished data). They applied an adapted dynamic snow avalanche model. For the dense part of the ice avalanche, the model uses the Voellmy-Salm model (Salm et al. 1990), a one-dimensional rigid body model. For the powder part, the French model AVAER (Rapin 1995) is used to estimate the hazard zones of the Gutz Glacier (Margreth & Funk 1999). Fig. 6 shows that our topographically-based modelled runout paths match well with the dense part modelling of Margreth (S. Margreth, unpublished data). In addition, Fig. 6 illustrates a major problem when modelling ice avalanches: while the flow part

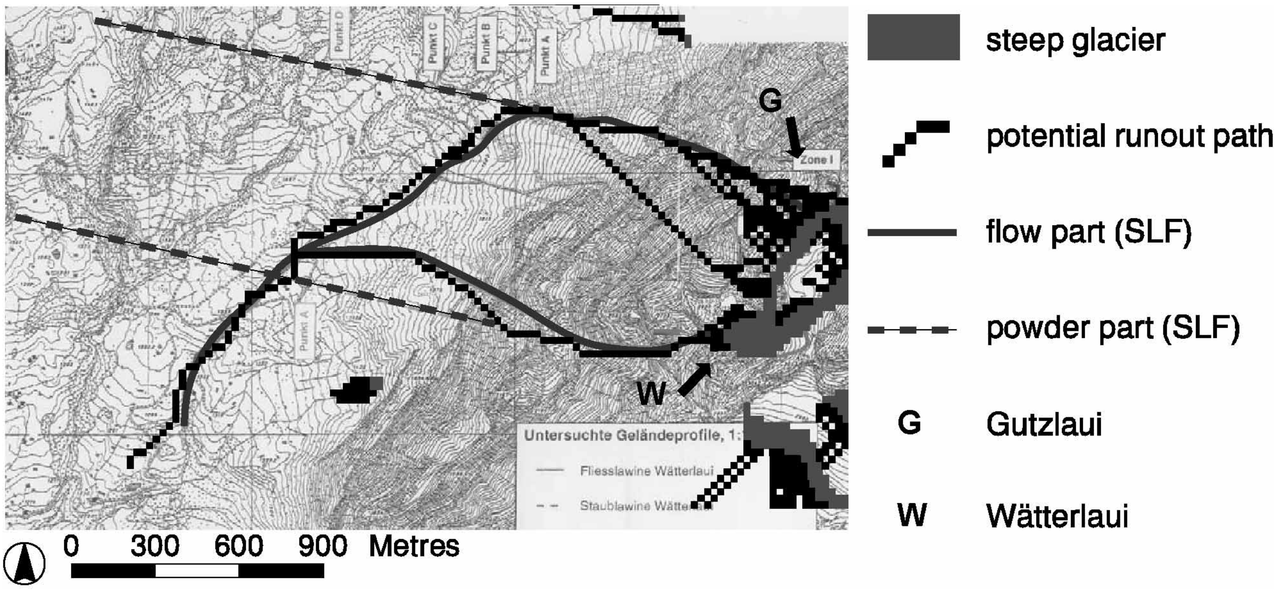

Fig. 6. Comparison of modelled runout paths (Gutz Glacier, Bernese Alps, Switzerland). The underlying hazard map was produced by the Swiss Federal Institute for Snow and Avalanche Research (SLF) (S. Margreth, unpublished data), and the overlays are modelled runout paths using the method proposed here.

of an ice avalanche is described quite accurately, the assessment of the potential impact of the powder part is rough or not even attempted.

Detection of possible process combinations

GIS-based intersections make it possible to calculate potential process combinations by combining computed runout paths with related objects (e.g. lakes, infrastructure). These objects can be extracted by delineating the objects from remote sensing data with enhanced spatial resolution (e.g. by a fusion of satellite data; Munechika et al. 1993), or if available from digital maps (as is the case in Switzerland). Using this method, it was possible to visualize the potential indirectly hazardous situation at Lake Oeschinen (Bernese Alps, Switzerland), a critical situation, which has been qualitatively known by the authorities for several years (Fig. 7). The lake is surrounded by glacier-covered mountains, and some of the glaciers have been classified as potentially dangerous. The runout paths of modelled ice avalanches make it possible to predict an impact on the lake. The possibility of large ice break-offs into Lake Oeschinen, which could produce a displacement wave and a debris flow

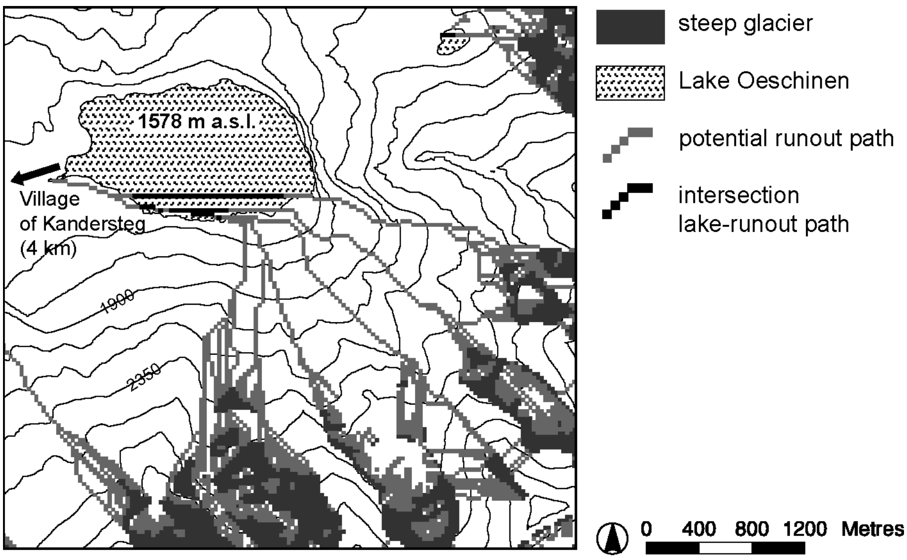

Fig. 7. Process combination of mountain hazards. Ice break-offs from a steep glacier into Lake Oeschinen, above the village Kandersteg (Bernese Alps), might produce a displacement wave and a subsequent debris flow.

that could possibly reach the village of Kandersteg can thus not be excluded.

Sensitivity studies

A sensitivity study was carried out to check the influence of the DTM quality on the modelling. For this purpose, the valley of Lauterbrunnental was selected as the study area because the topography in this valley is quite complex and very steep rock walls are found at the east side of the valley. The two different DTMs compared both have a spatial resolution of 25 m. The first of these is the 'DHM25L1', available at Swisstopo. This DTM has been interpolated from contour lines of the Swiss topographic map series 1:25,000 and additional topographic points. The elevation accuracy is in the order of 6–8 m for mountain areas. The second is a photogrammetrically derived DTM. This DTM was based on two scanned aerial photographs and was automatically derived using the digital photogrammetrical software SOCET SET from Leica-Helava-System (Kääb & Vollmer 2000). The two aerial photographs delivered by Swisstopo were taken on 15 August 1996. Both feature a resolution of 800 dpi (*c*.30 μm), a scale of *c*.1:20,000 and a ground resolution of *c*.0.5–1 m. The accuracy gained for the exterior orientation is 8 m RMS (Root Mean Square) in the horizontal and 5 m RMS in the vertical, which does not exactly reflect the accuracy potential of a photogrammetrically derived DTM. Due to extremely steep terrain within the selected subarea, the identification of precise Ground Control Points (GCPs) was difficult. Therefore, the accuracy of the DTM is somewhat reduced.

Fig. 8 shows three examples of how the quality of the DTM can affect the modelling of (potential) avalanche runout paths. Effects can be observed in the length of the runout paths or in the calculated trajectories. The results of steep glacier detection from the two DTMs are merged together into one layer in order to make the figure better readable. Nevertheless, we can recognize indirectly an effect where the starting points of the trajectories do not cover one another.

Discussion

The discussion is divided into three topics: base-data accuracy, statistical parameters and modelling. These are the main points to discuss on every level of the method chain. Therefore, the levels are not listed and discussed separately, but they are subsumed by the three mentioned topics.

Base-data accuracy

The resolution and accuracy of the base data (DTM and satellite imagery) are crucial factors in determining the quality of the final results. A spatial resolution of 25 m, as used here, is inherently a rough and generalized representation of the earth's surface. Also the interpolation procedure used in order to produce the DTM grid can have an influence on the accuracy. Furthermore, the slope calculation algorithm is varying according to different types of software (Jones 1998). Therefore, the pattern of a 25° slope map can be somewhat variable if using different types of software. Accordingly, the DTM accuracy influences the trajectory modelling too. When dealing with satellite data, the quality of the orthorectification is yet another relevant accuracy factor, especially in areas with a wide range of elevation differences, as found in high mountains. With the use of a 25 m DTM, an average accuracy for the orthorectification of approximately half a pixel (∼12 m) can be assumed for TM satellite images (Paul et al. 2002). In remote high mountain areas, such as the Himalayas, it can be less due to difficulties in finding suitable GCPs to orthorectify the satellite image. The limited accuracy of the database makes the application of more complex approaches questionable. Related models are only suitable for local studies with enhanced base data.

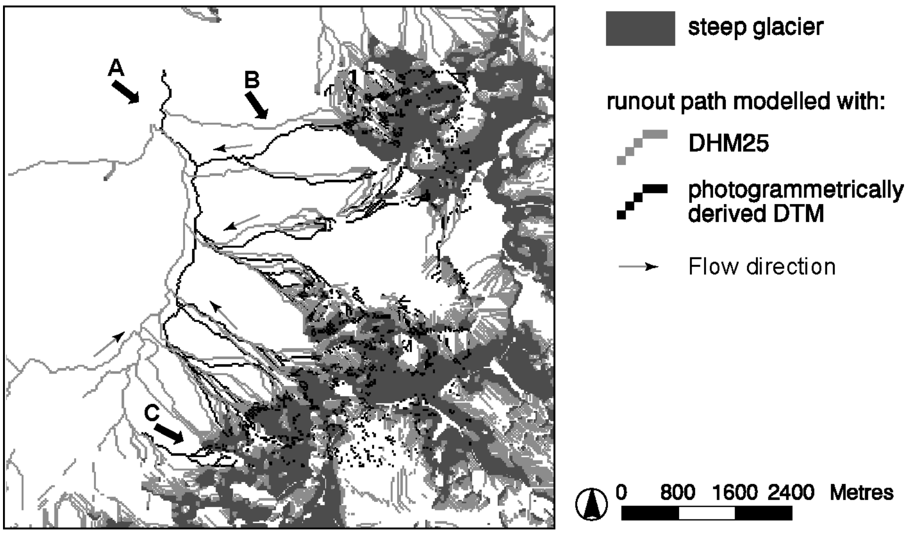

Fig. 8. Effects of the DTM quality (Lauterbrunnen, Bernese Alps, Switzerland). Examples: Arrow A marks the different modelled runout distances. Arrow B shows variable calculated trajectories. Arrow C shows differences in recognizing a potential starting zone.

Statistical parameters

Assessing potential glacier hazards requires the application of experience gained from previous events, combined with robust rules derived from glaciological theory (Haeberli et al. 1989). Both facets are included in statistical parameters. These, therefore, represent a suitable approach when dealing with glacier hazards at the focused scale; they often represent the only feasible way to assess hazards, due to a lack of basic data and an incomplete understanding of the processes involved.

The values for the parameters proposed here were primarily derived from cases in Switzerland (Alean 1984, 1985). In other parts of the Alps and in other (high) mountain regions of the world, such as the Himalayas or the Andes, these values can be exceeded. For instance, the ice avalanche from Glacier supérieur de Coolidge in Italy (Dutto et al. 1991) has demonstrated that small glaciers may become unstable on slopes which are less steep than 25°. The DHM25 is a surface elevation model. Therefore, the derivation of a glacier slope is based on the glacier surface slope and not on the glacier bed slope, which is actually the determining factor for sliding and shearing of a ramp-type glacier. For ice avalanches caused by break-offs of ice lamellae, which are the result of high tensile stress near the steep front, a surface elevation model is appropriate.

Like the critical slope, the statistical maximum runout distance of 6 km for rock/ice avalanches has also been exceeded in other mountain ranges (Kolka-Karmadon in 2002, Huascaran in 1970).

The proposed minimum average slope of 31% was reached on a smooth sliding surface (firn; Alean 1985). However, on rougher surfaces and less straight flow paths, energy loss due to internal and external friction and changes in flow direction significantly influence the runout distance. Energy loss is also possible through mass loss, for instance, when the runout path crosses crevasses or escarpments. Conversely, energy increase as a result of snow and debris erosion may extend the runout distance. Detailed terrain analyses can thus improve the prediction of runout paths by increasing and reducing, respectively, the average slope criterion according to the terrain characteristics of the flow path. There are some limitations too, regarding the validity of the DTMs applied. A thick snow cover in winter might change the topography. Topography depressions, for instance, can be filled by avalanche deposits or wind drift. Artificial or natural dams are not represented in a DTM. Both facets can influence the avalanche track and the runout distance.

Modelling

The main limitation in glacier mapping using the proposed method (TM4/TM5) concerns the detection of debris-covered glaciers. Since the slope of the debris-covered part of a glacier is usually low (cf. Maisch et al. 1999), it does not affect the goal of the level 1 of the method chain much (cf. Fig. 3). In contrast, one of the main strengths is the robust recognition of glaciers even in areas with cast shadow (cf. Paul et al. 2002).

To model the trajectories of an ice avalanche, we proposed the use of the ARC/INFO function 'Flowdirection', which was originally developed for hydrologic modelling. The application of this function takes the flowing dense part of an ice avalanche well into account, while the often more destructive and far reaching powder part is ignored (cf. Fig. 6). This is perhaps the most critical element in the procedure suggested. However, also with the adapted dynamic snow avalanche model mentioned above, used for instance by Margreth & Funk (1999) (cf. Fig. 6), estimating the suspension rate remains difficult. In future application, we will apply multiple-flow-direction approaches that may to some extent reduce the problem of the powder part ignored here.

As ice avalanches are especially dangerous in combination with other high mountain hazards we strongly recommend the investigation of further hazards that might develop from ice avalanches in methodological levels 1 and 2 (Huggel et al. 2004). Remote-sensing and GIS methods similar to those applied here exist for assessing the hazard potential of, for instance, glacier lakes or periglacial debris flows (Kääb et al. 2000, Huggel et al. 2002a, Maggioni & Gruber 2003).

Conclusion and prospects

The method chain presented in this article makes possible a fast and systematic first-order mapping of potentially dangerous steep glaciers for an entire region. This approach can be used as a support in decision making, and must be complimented by specific in-situ interpretation by experts.

The open character of the method chain allows the addition of extensions, facilitating expansion and improvement of the model. However, in accordance with the goal of this study to provide an approach with a wide practical application, the technical requirements and executive routines should not exceed the limitations of currently and commonly available software packages. To expand the method chain and to take into account the integrative facets of natural hazards, we suggest connecting the methods proposed here with related approaches for lake outbursts and debris flows (Huggel et al. 2003, 2004).

With regard to the modelling environment, there is probably more potential to improve the base data than the models. In the field of satellite imagery, the ASTER sensor (launched December 1999) onboard the satellite Terra could be noted. Since the spectral range and orbit are similar to those of Thematic Mapper, but the spatial resolution is higher (15 m compared to 30 m from TM), the detection of (steep) glaciers (cf. level 1) should be more precise. Furthermore, the ASTER sensor is able to produce stereopair images, which allows compiling of DTMs (similar to the procedure we mentioned for the aerial photographs) with a spatial resolution of *c.*30 m (Kääb 2002). Substantial progress is also being made in generating high resolution satellite data (e.g. IKONOS, Quickbird, Eros). For detailed analyses (cf. level 3), these imageries can be used as a substitute for aerial photographs (Kääb 2002).

Another interesting perspective in the field of worldwide digital terrain information is provided by the SRTM (Shuttle

Radar Topography Mission). In February 2000, during an 11-day mission, the SRTM radar system flew onboard the Space Shuttle Endeavour and gathered topographic data over approximately 80% of the land surfaces of the earth. The data gathered will be used to produce the most accurate and complete high-resolution digital topographic map of the earth's surface that has been compiled to date (Rabus et al. 2003). This development will make the model calculations proposed here applicable in many parts of the world.

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