An assessment procedure for glacial hazards in the Swiss Alps

Christian Huggel, Wilfried Haeberli, Andreas Kääb, Daniel Bieri, and Shaun Richardson

Abstract: Glacial hazards such as ice avalanches, glacial lake outburst floods, and debris flows have caused severe damage in populated mountain regions such as the Swiss Alps. Assessment of such hazards must consider basic glaciological, geomorphological, and hydraulic principles together with experience gained from previous events. An approach is presented here to assess the maximum event magnitude and probability of occurrence of glacial hazards. Analysis of magnitude is based on empirical relationships derived from published case histories from the Swiss Alps and other mountain regions. Probability of occurrence is difficult to estimate because of rapid changes in the nature of glacial systems, the low frequency of events, and the high complexity of the involved processes. Here, the probability is specified in qualitative and systematic terms based on indicators such as dam type, geometry, and freeboard height (for glacial lakes) and tendency of avalanche repetition, precursor events, and increased water supply to the glacier bed (for ice avalanche events). The assessment procedures are applied to a recent lake outburst with subsequent debris flow and to an ice avalanche in the Swiss Alps. The results yield reasonable event maxima that were not exceeded by actual events. The methods provide first-order assessments and may be applied in dynamic mountain environments where population and infrastructure growth require continuous evaluation of hazards.

Key words: glacial hazards, lake outburst, debris flow, ice avalanche, hazard assessment procedure, probability of occurrence.

Résumé : Des dangers glaciaires tels que des avalanches, des inondations par déversements de lacs glaciaires ont causé des dommages importants dans les régions montagneuses peuplées telles que les Alpes suisses. L'évaluation de tels dangers doit prendre en compte les principes de base de glaciologie, de géomorphologie, et d'hydraulique de même que de l'expérience obtenue par les événements antérieures. On présente ici une approche pour évaluer l'événement d'amplitude et de probabilité d'occurrence maximales d'événements de dangers glaciaires. L'analyse de l'amplitude est basée sur des relations empiriques dérivées d'histoires de cas publiées pour les Alpes Suisses et autres régions montagneuses. La probabilité d'occurrence est difficile à estimer à cause des changements rapides de la nature des systèmes glaciaires, de la faible fréquence des événements, et de la forte complexité des processus impliqués. Ici, la probabilité est spécifiée en termes qualitatifs et systématiques basés sur des indicateurs tels que le type de barrage, sa géométrie et sa hauteur de revanche (pour les lacs glaciaires), la tendance à la répétition d'avalanches, les événements précurseurs, et l'accroissement de l'alimentation en eau du lit des glaciers (pour les événements d'avalanches de glace). Les procédures d'évaluation sont appliquées à un récent déversement de lac avec écoulement de débris subséquent et à une avalanche de glace dans les Alpes suisses. Les méthodes fournissent des évaluations de premier ordre et peuvent être appliquées à des environnements montagneux dynamiques où l'accroissement des populations et des infrastructures requiert une évaluation continue des dangers.

Mots clés : dangers glaciaires, déversement de lac, écoulement de débris, avalanche de glace, procédure d'évaluation de risque, probabilité d'occurrence.

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Introduction

Glacial hazards from ice avalanches and glacial lake outbursts pose significant threats to people and infrastructure in high mountain regions. Assessments of such hazards are often hindered by an incomplete understanding of the processes involved, and the episodic and catastrophic nature of related events limits the application of physically based models. Instead, assessments are normally qualitative, or at best semiquantitative, based on simple glaciological,

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geomorphological, and hydraulic principles and from experience gained from previous events (Costa 1988; Costa and Schuster 1988; Haeberli et al. 1989; Dutto and Mortara 1992; Clague and Evans 1994). Studies have been performed on individual cases (e.g., Reynolds 1992; Margreth and Funk 1999; Haeberli et al. 2001), yet a lack of reference and materials can result in inconsistent assessments for similar conditions worldwide.

The Swiss Alps are especially affected by glacial hazards due to the close proximity of the population and infrastructure to glaciers. To address the issue, the Swiss Government has initiated programmes that have resulted in several studies of glacial hazards and related processes (Röthlisberger 1981, 1987; Haeberli 1983; Alean 1985a, 1985b; Haeberli et al. 1989, 1997; Margreth and Funk 1999; Kääb and Haeberli 2001; Huggel et al. 2002). Substantial experience in deriving and adapting basic relations for further hazard assessments has thus been gained (Huggel et al. 2000). Historic experience loses its local significance, however, as glacial environments evolve beyond historical and perhaps Holocene precedents (O'Connor and Costa 1993; Haeberli and Beniston 1998).

In this paper, two schemes for a first-order assessment of hazards from ice avalanches and glacial lake outbursts are proposed based on experience gained in the Swiss Alps. These assessment procedures integrate essential empirical relationships and provide reliable information on areas likely to be affected by glacial hazard processes. Emphasis is placed on the European Alps, but with reference to global examples to increase the potential applicability in other glacierized mountain regions. First, an outline of the characteristics of glacial hazards and the general method to perform a corresponding hazard assessment is given. Two assessment procedures are then presented for both glacial lake outbursts and ice avalanches, including a discussion of the involved processes and relationships used. Lastly, the applicability of the procedures by reference to two case studies in the Swiss Alps is demonstrated.

Glacial hazard characteristics

Definitions of hazard imply (*i*) the physical process involved, (*ii*) the magnitude of the event, and (or) (*iii*) the probability of occurrence (Ragozin 1994; Leroi 1996). Hazard can be defined as the magnitude multiplied by the probability of occurrence (Fell 1994). Probability of occurrence is usually derived from the frequency or recurrence period of an event (Van Steijn 1996; Zimmermann et al. 1997). Magnitude and frequency are generally related by a negative nonlinear relationship (Hungr 1997; Liu and Lei 2003), with the frequency of occurrence decreasing as the magnitude of the event increases.

Although true for most hydrologically driven hazards, this relationship implies that the physical system of the involved hazards remains unchanged. Glacial hazards fundamentally differ from hydrologically driven hazards in this respect, as the glacial system changes within time periods shorter than those needed to derive frequency characteristics. Hence, the application of a negative relationship between magnitude and frequency is limited for glacial hazards. In relation to frequency, a distinction can be made between events that occur

(*a*) only once (e.g., full-breach failure of moraine-dammed lakes), (*b*) for the first time (e.g., new formation and outburst of glacial lakes), and (*c*) repeatedly (e.g., ice-dammed lakes with drainage cycles, or ice fall). Frequency–magnitude relationships fail for hazards of types (*a*) and (*b*) due to missing data and experience. Hazards of type (*c*) with repeat cycles may have frequency–magnitude relationships, but these have not been established and applied. In consideration of the need for consistent assessment concepts for glacial hazards, the following approach is proposed.

Assessment of magnitude

Magnitude is viewed in terms of the probable maximum discharge (for lake outbursts), the probable maximum volume (for avalanches or debris flows), and the probable maximum travel distance. The consideration of event processes is implicit within the assessment of magnitude.

Probability of occurrence

Although determining the probability of occurrence is difficult for glacial hazards, for the purpose of practicality it is better to assign a probability, even if approximate and subjective, than not at all (Fell 1994). Decision-makers need a probability to plan, design, and construct mitigation measures. The method presented here allows a qualitative estimate of the probability of occurrence based on indicators described separately for glacial lake outbursts and ice avalanches.

Glacial floods and debris flows from lake outbursts

Overview of the assessment scheme

The assessment scheme for hazards from glacial lake outbursts follows the determination of lake volume, discharge, flow volume, and travel distance (Fig. 1). Supraglacial and proglacial lakes are recognized either by ground-based observation or by remote-sensing-based mapping. Subglacial and englacial water bodies cannot be directly observed, requiring historical experience to be taken into consideration in these cases. After the estimate of the lake volume, a distinction between ice-, moraine-, and bedrock-dammed lakes is made, which is essential for the outburst characteristics. Subsequent formation of a debris flow or a flood wave relates to flow volume, travel distance, and potential damage. Lastly, possible secondary effects and further assessment strategies (follow-up studies, monitoring) are considered. The estimates of various parameters are based on empirical equations and values referenced in the text or in Table 1.

Determination of lake volume

Techniques have been developed to detect and map glacial lakes using satellite images (Huggel et al. 2002). Topographic maps for derivation of lake area often do not represent the current situation and, hence, are generally less appropriate. The volume, V (in m^3), of a glacial lake can then be expressed as a function of the area A (in m^2) by using the empirical relationship from Huggel et al. (2002):

$$[1] \qquad V = 0.104A^{1.42} \qquad r^2 = 0.92$$

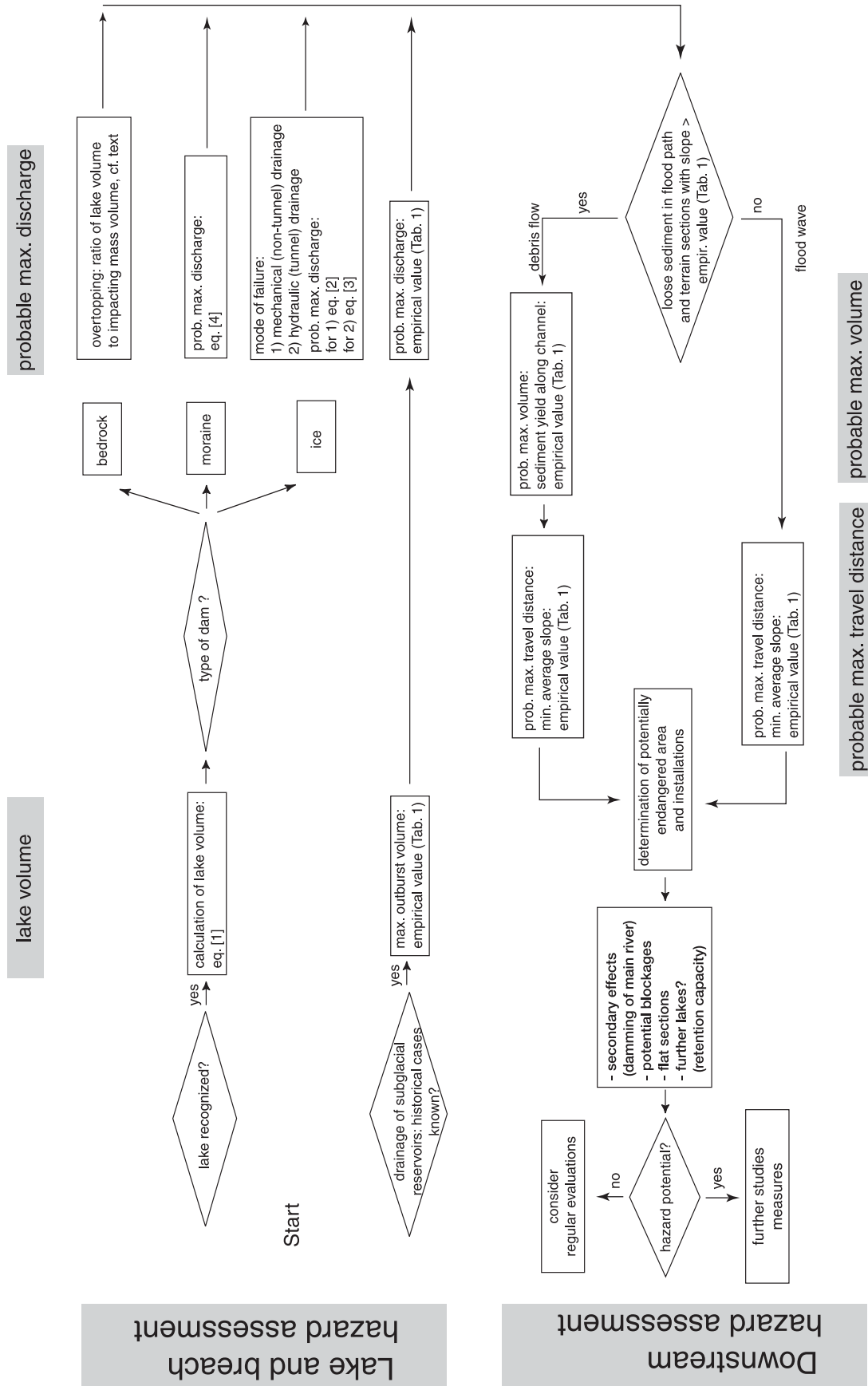**Fig. 1.** Assessment procedure for hazards related to glacial lake outbursts.

Table 1. Empirically based maximum values of different hazard processes for the European Alps (for references see text).

Process magnitude	Empirically based value	Confidence level
Max. starting volume, ice avalanche (ramp type)	5×10^6 m^3	Medium
Max. starting volume, ice avalanche (cliff type)	4×10^5 m^3	Medium
Max. outburst volume, subglacial water reservoir	3×10^6 m^3	Low
Max. discharge, subglacial water reservoir	2×10^2 m^3/s	Low
Max. travel distance, ice avalanche (min. average slope)	17° (0.31)	High
Max. travel distance, lake outburst flood (debris flow)	11° (0.20)	High
Max. travel distance, lake outburst flood (flood wave)	2–3°	Medium
Max. sediment yield along channel (debris flow, in large moraine bastions, per channel length unit)	750 m^3/m	Medium
Critical channel slope for erosion (debris flow)	8°	High

Note: Each value is related to a qualitative degree of confidence for assessing involved uncertainties. The confidence level indicated is based on the number of events from which the empirical values were derived.

Table 2. Comparison of measured and calculated lake volume for Himalayan glacial lakes. Calculation is based on eq. [1].

Lake	Measured area (m^2 × 10^6)	Volume (m^3 × 10^6) Calculated	Measured	Error (%)[a]	Reference
Raphstreng Tsho, Bhutan (1995)	1.380	54.408	66.83	23	Geological Survey of India 1995
Tsho Rolpa, Nepal (1994)	1.390	54.969	76.60	39	Mool et al. 2001
Thulagi, Nepal (1995)	0.760	23.323	31.80	36	Mool 1995
Imja, Nepal (1993)	0.600	16.673	28.00	68	Yamada 1993
Gelhaipuco, Nepal (1964)	0.548	14.659	25.45	74	Mool et al. 2001
Tam Pokhari, Nepal (1992)	0.470	11.787	21.25	80	Mool et al. 2001
Lower Barun, Nepal (1995)	0.780	24.200	28.00	16	Mool et al. 2001

[a]Calculated as the difference between measured and calculated values divided by the calculated value. Measured volumes are typically based on bathymetric surveys.

where the coefficient of correlation (r^2) is related to the original regression between area and mean depth. The relationship is based on data from glacial lakes in North America, South America, the Himalayas, Iceland, and the European Alps. Additional data compiled here for large Himalayan glacial lakes (for lake volumes of tens to over a hundred million cubic metres of water) suggest that the application of eq. [1] can result in an underestimation of the actual volume by 16%–80% in such cases (Table 2).

Determination of probable maximum discharge

The maximum discharge, Q_{max}, of a lake outburst strongly depends on the type of dam and drainage. The mechanically and hydraulically different mechanisms of lake drainage imply a fundamental distinction between ice-, moraine-, and bedrock-dammed lakes. Ice-dammed lakes that empty by progressive enlargement of subglacial channels have been found to produce smaller outburst floods for the same stored water volume than mechanical or sudden-break failures of ice dams and failures of moraine-dammed lakes (Haeberli 1983; Costa and Schuster 1988; Clague and Evans 1994). For a first-order assessment of the probable maximum discharge, Q_{max} (in m^3/s), of sudden breaks of ice dams, the application of Haeberli's (1983) empirical relationship is proposed:

[2] $Q_{max} = V/t$

where V is in m^3, and t is the drainage duration in seconds. For application in practice it is recommended to use $t = $

1000 s for maximum estimates, since values between 1000 and 2000 s were empirically found for events in the Swiss Alps (Haeberli 1983). Regarding subglacial drainage of ice-dammed lakes, Walder and Costa (1996) revised the relationship proposed by Clague and Mathews (1973) as follows:

[3] $Q_{max} = 46(V/10^6)^{0.66}$ $r^2 = 0.70$

where Q_{max} is in m^3/s, and V is in m^3 (parameters originally given in a dimensionless form; for error ranges see Walder and Costa 1996).

Outbursts from moraine-dammed lakes can be triggered by overtopping, piping and seepage, failure of the downstream slope, or a combination thereof (Evans 1986; Costa 1988; Costa and Schuster 1988; Clague and Evans 2000). The mechanics of breach formation are still not well understood, and quantitative data on observed outburst floods are scarce (Walder and O'Connor 1997). The complexity of the involved processes and the difficulties of determining the parameters in a physically sound way justify a simple method for a rapid assessment of probable maximum discharge (understood as a water–sediment mixture). According to Huggel et al. (2002),

[4] $Q_{max} = 2V/t$

where a triangular hydrograph is assumed, and $t = 1000$ s as for eq. [2]. The relationship approximately lies in the range

of the upper-bound 99% confidence interval of the regression from the dataset on moraine-dammed lake outbursts by Huggel et al. (2002).

Bedrock-dammed lakes may not fail but can trigger floods or debris flows. Mass movements such as snow or ice avalanches, landslides, debris flows, or rock falls reaching the lake can produce impact waves and overtopping of the dam, eventually resulting in a flood or debris flow. Glacial lakes are particularly susceptible to impact waves because of their steep shores and narrow lake geometries (Fritz 2002). The processes responsible for producing impact waves, run-up on the dam, and overtopping are complex and not completely understood (Vischer and Hager 1998). The formation and dimension of impact waves depend on depth and volume of the lake; volume, flow height, and velocity of the incoming mass movement; and the corresponding sliding surface slope. Walder et al. (2003) emphasized the significance of Froude number of the mass flow entering the lake and related rate of inflowing volume. The run-up height on the dam further depends on dam distance from the wave impact, impact angle with respect to reservoir axes, wave length and height, freeboard height, and slope of the dam. An ice cover of up to 0.5 m on the lake exerts only marginal influence on the wave and run-up height (Müller 1995), an interesting finding for assessment of glacial lakes in winter and spring. The ratio, H, of the volume of incoming mass to the lake volume is important for the estimation of the overtopping volume. Based on an analysis of case histories of landslide and avalanche impacts on lakes (Huber 1980; Müller 1995; Walder et al. 2003), the following ranges of H are defined: for H = 1:1 to 1:10, the lake may be emptied completely due to displacement of water; and for H = 1:10 to 1:100, water displacement or propagation (impact waves) may be involved, and a high probability of overtopping exists unless the freeboard is high relative to the wave size. Furthermore, the overtopping or outburst volume depends on the dam stability and potential failure.

Drainage of subglacial water bodies is treated separately because the assessment of such hazards poses special challenges. To date, no reliable method is available for detecting previously unknown reservoirs or predicting the timing of outbursts (Haeberli et al. 1989; Tweed and Russell 1999), though theoretical models on drainage initiation have been presented (e.g., Nye 1976; Fowler 1999; Anderson et al. 2003). Glaciers with sudden bursts of subglacial reservoirs do not seem to exhibit any common morphological or physical properties (Haeberli 1983). A trend towards repetitive events at the same glaciers has been observed, and floods can be associated with the termination of glacier surges (Björnsson 1998; Haeberli et al. 2002). Predictions of probable maximum outburst volume and peak discharge are based on reconstruction from past events in the Alps but are fraught with uncertainty; accordingly, corresponding extreme values are given in Table 1 (Haeberli 1983).

Determination of probable maximum volume

Outbursts from ice- or moraine-dammed lakes in mountainous environments commonly evolve into debris flows. Physically and numerically complex flow-behavior and routing analysis are out of the scope of a rapid hazard assess-

ment. The volumes and peak discharges of flows in glacierized terrain increase and decrease in correspondence with channel sections of erosion and deposition (O'Connor et al. 2001). Observations and theoretical considerations show that deposition generally starts from channel slopes of 8°, but occasionally occurs up to 14°, depending on discharge and channel geometry (Hungr et al. 1984; Jackson et al. 1989; Rickenmann and Zimmermann 1993; O'Connor et al. 2001). Erosion was found to be important where channel gradients exceeded 8° (O'Connor et al. 2001).

The probable maximum volume of a debris flow is estimated by the possibly entrained sediment volume along the channel length. In sections of extensive erosion such as in morainic deposits, the maximum eroded sediment volume per unit channel length has been found as several hundred cubic metres (Hungr et al. 1984; Haeberli et al. 1989; Rickenmann and Zimmermann 1993). More recently, values of up to 750 m^3/m have been observed in large alpine moraine-dam breaches (Huggel et al. 2002). Studies from North America suggest similar values of maximum cross sections in moraine cuts (O'Connor et al. 2001). Large moraine dams in the Himalayas and Andes, however, can show breach cross sections >2000 m^2 (e.g., Mool et al. 2001). Hungr et al. (1984) presented a categorization of channels into (*i*) bedrock, (*ii*) thin debris, and (*iii*) deep talus or moraine, and corresponding sediment yield rates. Channels in deep but not unstable talus have been found to show sediment yield rates of 10–30 m^3/m. Multiplication with corresponding erosional channel length yields a rough assessment of the maximum event magnitude. Application of an upper-bound estimate is reasonable, since errors and uncertainties due to local and regional differences in geology, topography, and hydrology of torrent catchments can be incorporated. Additional flow volume estimates can be derived from the consideration of the maximum sediment concentration in debris flows, which can reach up to about 50%–80% by volume in steep flow channels (Iverson 1997). Values of 50%–60% may be appropriate for average flow concentrations. An approximation of the flow volume is calculated by taking into account the volume of water stored in a lake (assuming a full lake draining scenario).

Determination of probable maximum travel distance

The probable maximum travel distance of a debris flow from a lake outburst is estimated using a relationship between peak discharge and travel distance. The travel distance is expressed as the average slope, describing the angle of the horizontal with a line from the starting point to the farthermost point of the deposition. In the Swiss Alps, a minimum average slope of 11° has been observed for debris flows from lake outbursts (Haeberli 1983; Huggel et al. 2002). Coarse periglacial debris flows in Switzerland not related to lake outbursts also show a minimum average slope of 11° (Rickenmann and Zimmermann 1993). Determination of minimum average slope α is done by using the data from Huggel et al. (2002), where α can be estimated in the bivariate plot of Q_{max} versus α (Fig. 3 in Huggel et al. 2002). The average slope thus derived can be used to delineate a debris-flow path to the farthermost point that might be affected (Rickenmann 1999). Lateral spreading behavior, for instance

Table 3. Indicators for deriving qualitative probability of occurrence for glacial lake outbursts.

Indicator	Attribute	Qualitative probability
Dam type	Ice	High
	Moraine	Medium to high
	Bedrock	Low
Ratio of freeboard to dam height	Low	High
	Medium	Medium
	High	Low
Ratio of dam width to height	Small, 0.1–0.2	High
	Medium, 0.2–0.5	Medium
	Large, >0.5	Low
Impact waves by ice or rock falls reaching the lake	Frequent, large volume	High
	Sporadic, medium volume	Medium
	Unlikely, small volume	Low
Extreme meteorological events (high temperature or precipitation)	Frequent	High
	Sporadic	Medium
	Unlikely	Low

on a debris fan, can thus not be assessed, and other models should be used (e.g., Iverson et al. 1998; Laigle and Marchi 2000; Huggel et al. 2003*a*).

Flood waves from lake outbursts (weight of sediment < weight of water) are assumed to form when little or no erodible material is present in the flow path and when the channel slope is less than the observed starting value of erosion (i.e., about 8°). Irrespective of the absolute amount of available loose sediment, however, flood waves can also be the dominant form if the relative amount of erodible sediment is small compared with the flood volume. This is particularly observed in floods involving millions of cubic metres of water in the Himalayas (Cenderelli and Wohl 2003) or in the Andes. Determination of the travel distance is less clear for commonly attenuating flood waves than for debris flows, which usually stop abruptly. Here, the maximum distance of potential damage is used, which has been empirically found to correspond to an average slope between 2° and 3° in the Swiss Alps (Haeberli 1983). In the Karakorum or in Bhutan, however, distances in excess of 200 km have been recorded (Hewitt 1982; Reynolds 2000).

For both debris flows and flood waves, processes along the flow channel may drastically change hazard magnitude and impact. For instance, temporary dams in the flow channel (e.g., by obstruction by wooden debris or flank failures) can suddenly fail and result in extreme peak discharges, possibly up to an order of magnitude larger than the "normal" debris flow or flood discharge (Armstrong 2003; Huggel et al. 2003*b*). Similarly, debris flows from tributary valleys damming the main valley river can cause blockages and result in repeated and extended flooding (e.g., Varuna valley 1987, Swiss Alps; Rickenmann and Zimmermann 1993).

Determination of probability of occurrence

Fell (1994) presented a number of ways to determine the probability of landsliding: (1) probabilistic analysis (Mostyn and Li 1993); (2) use of historic data (Morgan et al. 1992; Van Steijn 1996); (3) relationship to rainfall (Fell et al. 1991); and (4) use of geomorphological and geotechnical informa-

tion (Hungr et al. 1984). Approaches 1–3 cannot be applied for glacial lake outbursts due to a lack of frequency and historic data. The approach presented here uses geomorphological and geotechnical data and is more subjective than the other methods but allows a qualitative, or relative (within a study region), probability to be assigned.

The probability of a glacial lake outburst is a function of the basic susceptibility of the dam to fail and the potential for external trigger processes (Richardson and Reynolds 2000). Five key indicators are defined to which qualitative probabilities in the range of low, medium, and high can be assigned (Table 3). Each indicator is considered independently, and the scoring is based on the experience of the practitioner. Thus, the overall probability is not the mean of the individual indicators. Single indicators rated "high" (e.g., freeboard or dam geometry) may be sufficient to result in an overall high probability, irrespective of the rating of the other indicators.

The distinction between different dam types is fundamental for related process discrimination and associated probability determination. For moraine dams, freeboard and dam geometry (ratio of width to height) are crucial parameters, as they influence hydraulic gradients within the moraine (Clague and Evans 2000; Reynolds et al. 1998; Richardson and Reynolds 2000). Dams with high hydraulic gradients are more susceptible to collapses involving piping and slope failure. Impact waves from rock or ice falls, or debris flows, and extreme meteorological events, such as intense snow or ice melt due to high temperatures, or high precipitation, have been observed to be most effective trigger events for dam failure and lake outburst (Ames 1998; Richardson and Reynolds 2000; Clague and Evans 2000; Huggel et al. 2002). Determination of some of the indicators might require further statistical (e.g., meteorological), geomorphological (e.g., surface expression of buried ice), geophysical (e.g., internal composition), glaciological (e.g., glacier structures), or geotechnical (e.g., consolidation) analyses. The list of indicators provided here is not necessarily complete and can be extended in the future. Case studies in the corresponding section demonstrate this probability-based approach.

Fig. 2. Assessment procedure for hazards related to ice avalanches. MAAT, mean annual air temperature.
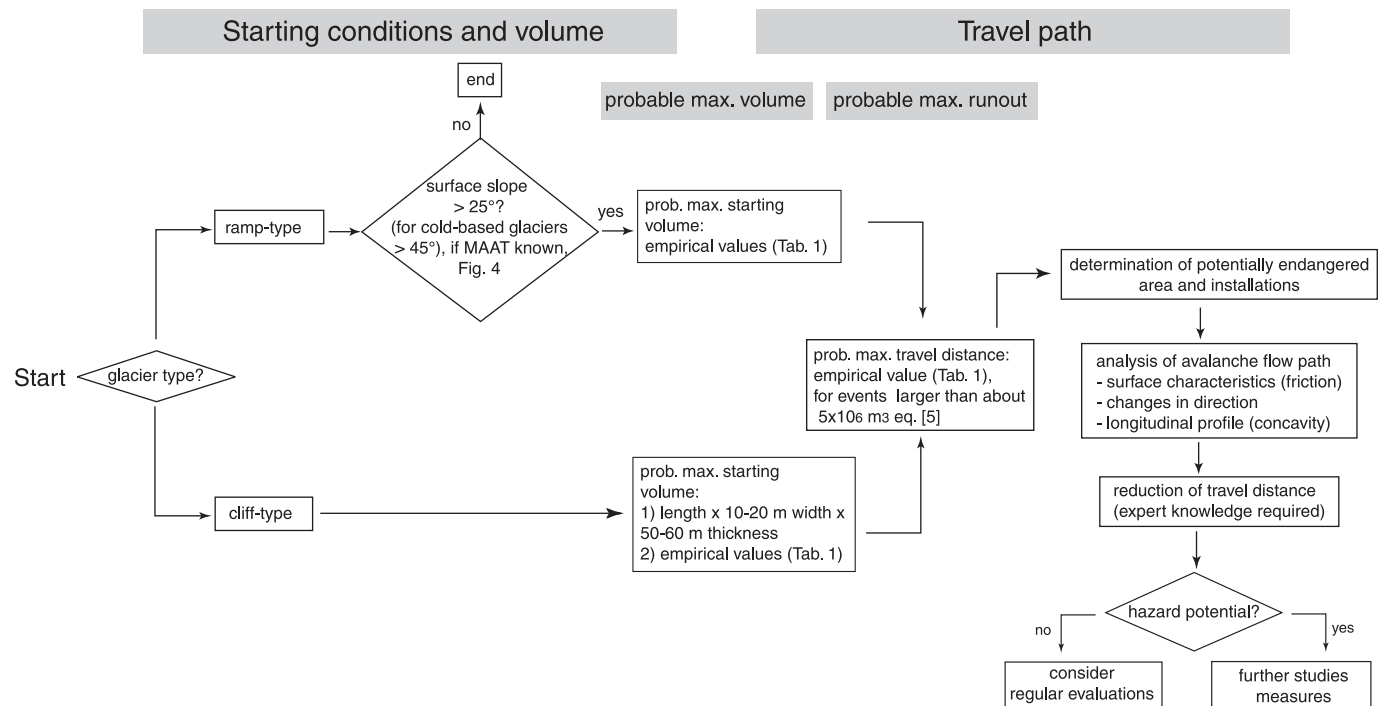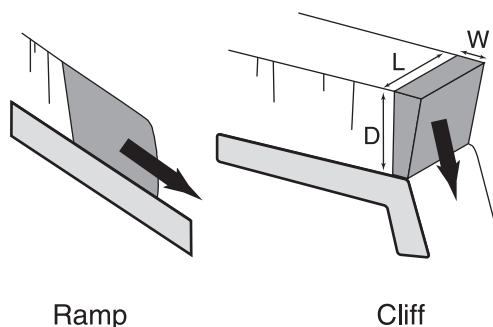

Fig. 3. Types of ice avalanche starting zones (modified from Alean 1985*a*). The parameters to determine the potential break-off volume for cliff-type glaciers include length (*L*), width (*W*), and thickness (*D*).

Ice avalanches

Overview of the assessment scheme

The assessment scheme is organized chronologically by the determination of glacier type and slope, avalanche volume, and travel distance. The estimates of the slope of critical stability and the different parameters are referenced in Fig. 2 and Table 1, respectively. The procedure to estimate the avalanche volume is distinguished depending on the glacier type. After determination of the travel distance, the geometry and morphology of the flow trajectory are analyzed in more detail to possibly adjust the first travel estimate and to eventually make recommendations for further actions.

Probable maximum volume

Comprehensive studies of ice avalanches are scarce, and understanding of the general process is limited. The data compilation and analysis of Alean (1985*a*) remains one of

the most pertinent works. In most cases, therefore, the assessment of ice avalanches from steep glaciers relies on empirical experience and topographic information.

The classification of ice avalanche starting zones into a ramp-type and a cliff-type has proven to be helpful for differentiation of hazardous situations (Fig. 3) (Haefeli 1966; Alean 1985*a*). Cliff-type glaciers are characterized by a marked break in slope of bedrock and (or) ice. Detachment relates to extending flow and crevasse formation rather than to the average slope of the glacier bed. The occurrence of ice avalanches from ramp-type glaciers involves instabilities at depth (ice–rock interface) and critical values for the inclination of the glacier bed (Alean 1985*a*). Stability conditions and critical slopes in such cases strongly depend on temperature conditions within and at the base of the glacier where the presence of meltwater causes a reduction in strength due to increased pore pressure and thus reduction in effective stress. Ice avalanches generally break off from small and steep glaciers and rarely from large valley-type glaciers (Alean 1985*a*). Such small and steep glaciers show a typical thickness of about 30–60 m. The comparably small thickness implies a more direct relation between the temperature of firn (compacted multiyear snow) and glacier bed than for large glaciers, and bed temperature can thus be reasonably well approximated by the firn temperature (Lüthi and Funk 1997; Haeberli et al. 1999). The mean annual air temperature (MAAT) can be used to estimate firn temperature where measurements are not available, although the firn temperature also depends on other parameters such as radiation flux, amount of penetrating and refreezing meltwater, or accumulation and ablation (e.g., Hooke et al. 1983; Suter et al. 2001; Suter and Hoelzle 2002). Given the MAAT (*T*), the critical slope β of the sliding surface can be derived from Fig. 4. The data suggest a power relation between *T* and β, which is reasonable in consideration of the similar power re-

Fig. 4. Relation between mean annual air temperature and critical slope for failure on ramp-type glaciers. Data on the corresponding ice avalanche events are from Alean (1985*a*) and this study. Mean annual air temperature (MAAT) is derived and extrapolated from meteorological stations at Bernina Hospiz, Grosser St. Bernhard, and Jungfraujoch, Switzerland. An approximate range of the existence of cold, polythermal, and temperate ice is indicated.
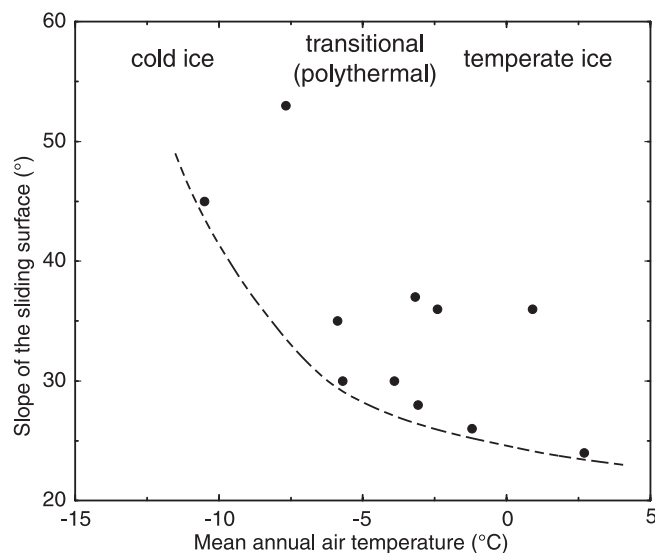
lations between temperature and ice deformation (Smith and Morland 1981; Paterson 1994) and between temperature and fracture of ice (Vaughan 1993; Haeberli et al. 1999; Davies et al. 2001). If the MAAT is unknown, an even cruder estimate may be helpful: cold-based glaciers produce ice avalanches from a minimum slope of the glacier bed of 45° and more, whereas temperate glaciers do so from a minimum inclination of 25° and more (Alean 1985*a*). For small and relatively thin glaciers, the slope of the glacier surface can be used as an approximation of the slope of the glacier bed.

Determination of the ice avalanche starting volume is difficult and uncertain. The volume actually breaking off depends on the stresses and related creep and deformation in the ice. General replication of ice mechanical conditions in steep glaciers has been achieved for specific cases (Haeberli et al. 1999) and can provide valuable indications for failure but is not practical within the present assessment procedure. Simple techniques such as deduction from crevasse patterns may apply in some cases but can be misleading in others (e.g., Allalin Glacier in the southern Swiss Alps, Röthlisberger and Kasser 1978; Alean 1985*a*; Kääb 2000). Here, it is proposed to derive the probable maximum starting volume of cliff-type glaciers from the cliff length, width (i.e., the distance between the potential break-off line behind the cliff front), and thickness. The length can be determined from accurate topographic maps, from remote sensing data, or in the field. The width can be estimated based on the assumption that cliff-type glaciers usually do not break off more than 10–20 m behind the ice front (Alean 1985*a*) (Fig. 3). The thickness may be estimated in the field or from high-resolution remote sensing data, or a thickness of 50–60 m may be assumed. Width and thickness describe typical conditions in the Swiss Alps. More data from other

glacierized mountains could strongly facilitate a general application.

A similar estimate of the probable maximum starting volume is often impossible for ramp-type glaciers. First estimates have therefore to rely on observed maximum volumes released (5 × 10^6 m^3, cf. Table 1). Extraordinarily large events outside the European Alps, however, have exceeded the volume indicated here by about one order of magnitude (e.g., the 2002 Kolka rock–ice avalanche in the Russian Caucasus, Kääb et al. 2003*a*).

Probable maximum travel distance

A simple one-parameter model approach is proposed for assessing the probable maximum travel distance of ice avalanches based on average avalanche slopes. Ice avalanches in the Alps do not show average slopes α below 17° (tan α = 0.31) (Alean 1985*a*). Travel distances only increase moderately with increasing avalanche volume, and no volume dependence seems to exist for smooth sliding surfaces (firn) (Alean 1985*b*), probably due to predominant basal friction. For first-order safety assessments, endangered areas and installations are delineated according to a 17° average slope. Many avalanche events do not cover the maximum distance thus calculated, however. The estimated travel distance may therefore be reduced by analyzing the flow path in more detail. The travel distance is significantly influenced by energy loss because of friction and due to possible changes in the flow direction. A strongly concave flow path, for example, leads to a reduction of the travel distance due to a higher flow velocity and thus larger frictional dissipation of kinetic energy (Alean 1985*b*). Topographic effects such as channeling may further influence the travel distance.

Rare cases of ice avalanches with average slopes smaller than 17° have occurred outside the European Alps involving extraordinarily large volumes and flow transformation into debris-laden flows (e.g., the 2002 Kolka rock–ice avalanche, Kääb et al. 2003*a*). The magnitude of such events is hardly predictable. For the small number of large ice avalanches known worldwide, volume versus average slope is plotted in Fig. 5. Regression analysis of the data from Fig. 5 gives the following equation:

[5] $\quad \tan \alpha = 1.111 - 0.118 \log(V) \quad r^2 = 0.84$

where α is the average slope, and *V* the volume of the ice avalanche in cubic metres. Equation [5] can thus be used to estimate the travel distance of large ice avalanches that exceed the volumes known from the Swiss Alps.

Entrainment processes along the flow path, in particular with regard to snow, should be considered, since they can significantly increase the volume, and thus the impact and travel distance, of ice avalanches. Possible secondary effects such as impact waves in lakes or damming of rivers by ice avalanche deposits are evaluated in the final step of the assessment (Vuichard and Zimmermann 1987; Clague and Evans 2000; Richardson and Reynolds 2000).

Probability of occurrence

In selected critical cases, challenging ground-based measurements (ice deformation rate) have been achieved for prediction of occurrence of ice avalanches (Flotron 1977; Iken 1977; Röthlisberger 1977; Lüthi and Funk 1997). For a more

Fig. 5. Regression (solid line) between average slope (tan α) and volume of large ice avalanches worldwide. The 95% confidence intervals are indicated (broken lines). Data are from Körner (1983), Alean (1985*a*), Slupetzky (2002), and this study.
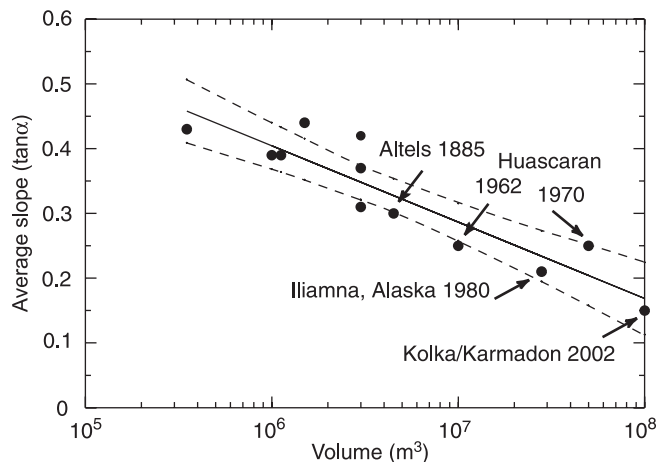
general application it may be useful to note that smaller ice-fall events from steep glacier fronts are usually more frequent than larger ice avalanches. A magnitude–frequency relationship may possibly apply, but ice avalanches are rare phenomena and there is insufficient information for analysis. A crude estimate of probability of occurrence based on four indicators is proposed.

First, a tendency of ice avalanche repetition at the same topographic position has been observed for ramp-type glaciers (Röthlisberger 1981; Alean 1985*a*; Funk and Minor 2001). Glacier advance and retreat and warming or cooling of firn may, however, alter the probability of occurrence. Second, ice avalanches from cliff-type glaciers have often been preceded by precursory smaller ice-fall events (Bieri 1996; Margreth and Funk 1999). Observations of rock-fall activity from steep glacierized zones should also be taken into consideration, since rock slope failures have repeatedly triggered large ice avalanches (Körner 1983; Kääb et al. 2003*a*). Hence, ice- or rock-fall activity and the knowledge of one or more former ice avalanches might be used as an indication of the probability of occurrence. Third, high input rates of rain or melt water to the glacier bed through the bedrock–glacier interface and crevasses may also increase the probability of failure (reduction of strength at the base, Röthlisberger 1987). Catchment size as an indicator of potential water input into the glacier may thus be taken into consideration. Lastly, crevasse patterns and their temporal evolution (if observations are available) can yield indications for failure processes (Kääb et al. 2000). In sum, the assessment of the probability of occurrence for ice avalanches must presently remain approximative and subjective, mainly due to the complex processes involved and the lack of understanding.

Case studies

Two case studies, a lake outburst and an ice avalanche, are selected for the application and evaluation of the assessment procedures. The choice of cases is motivated by assessment studies using methods similar to those presented here which

were performed prior to the events. The hazards were therefore realistically recognized, although appropriate mitigation measures were not taken because of political, economic, societal, and administrative difficulties.

Täsch lake outburst

Physiographic setting

The village of Täsch is situated in the upper Matter valley close to Zermatt (Valais, Switzerland). Above this village, Lake Weingarten (3060 m asl) lies in front of Weingarten Glacier at the toe of Alphubel (4206 m asl; Fig. 6). The lake is no longer in direct contact with the glacier and situated on a large Little Ice Age moraine deposit with a 700 m long slope of 30° on average, with sections of up to 36° (Fig. 7). The debris fans at Täschalp and Täsch are evidence of past debris-flow events, yet recreational structures and houses have been built on the Täschalp fan recently. After a steep gorge, the flow path eventually reaches the large debris fan on which the village of Täsch is located. For more details on the physical conditions and the event in general, see Huggel et al. (2003*c*).

Event

On 25 June 2001, a debris-flow event damaged considerable parts of the village of Täsch during a period without any significant precipitation. Damage to buildings and other installations amounted to about 12 million EUR (Hegg et al. 2002), and 150 people were evacuated (Fig. 8). During field inspections shortly after the event, the overflow channel of Lake Weingarten was found intact. However, a shoreline 0.4–0.5 m above the water level and erosion on the air side of the moraine that stopped 1–2 m before the lake were observed. Based on that and a lake area of 16 000 m^2, a lake overflow with an overtopping volume of 6000–8000 m^3 of water was assumed (Huggel et al. 2003*c*). Huggel et al. (2003*c*) further suggested the following outburst scenario: an elevated water level due to snow or ice jam at the overflow channel caused higher hydraulic gradients in the moraine dam and possible piping processes. Together with the (relatively moderate) flood after the rupture of the snow–ice jam, such progressive groundwater flow probably caused erosion to start at the air side of the moraine. Though a full moraine cut was not provoked by retrogressive erosion, the draining water was sufficient to initiate a debris flow.

From 25 000 to 40 000 m^3 of debris were eroded along the uppermost 1 km, with a maximum cross-sectional erosion of 30–50 m^2. Additional erosive force was added at the confluence with the torrent Rotbach (Fig. 6). At Täschalp, part of the entrained material was deposited and a bridge was destroyed. Lastly, at the fan apex of Täsch, the debris-flow front surged into a constructed channel. Since the channel was not designed for such sediment loads, it immediately became obstructed and the debris flow spread out onto the fan, causing the damage mentioned above (Fig. 8). The travel distance of the event was 5050 m, and the total volume of debris deposited in Täsch is estimated at 20 000 – 30 000 m^3.

Assessment procedure

The assessment procedure yielded the following findings: (*i*) lake volume V = 97 000 m^3 (eq. [1]) based on a lake area

Fig. 6. Situation at Lake Weingarten and Täsch. The debris flow from 25 June 2001, starting at the lake, and corresponding sections of erosion and deposition are delineated. (DEM25 c [copyright] 2004 swisstopo BA046420). Contours in metres.
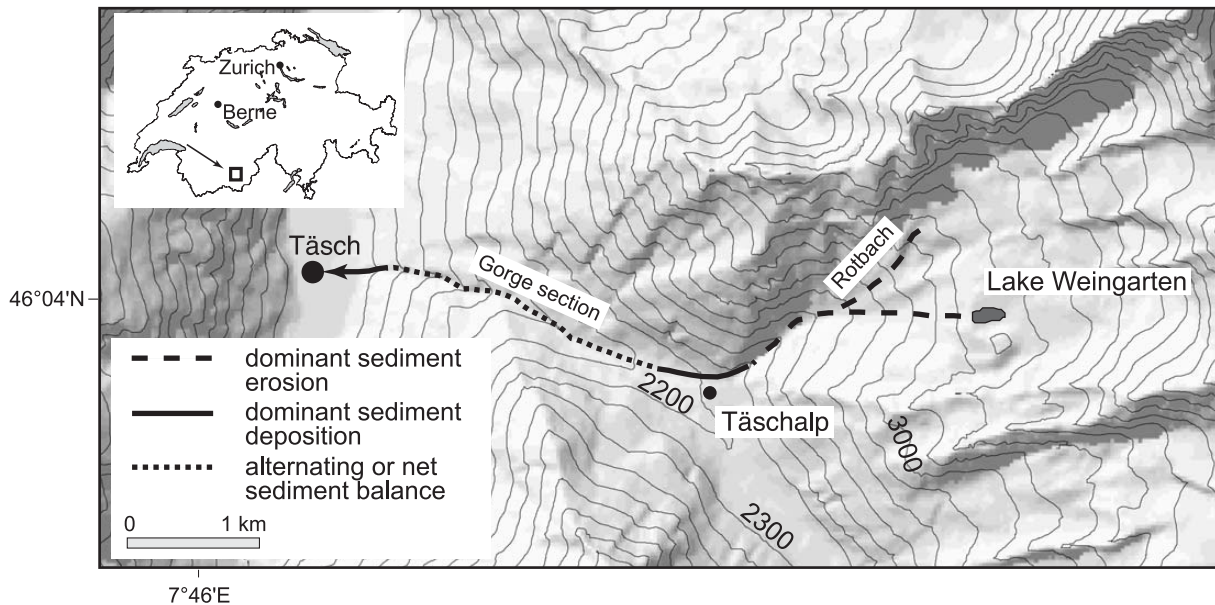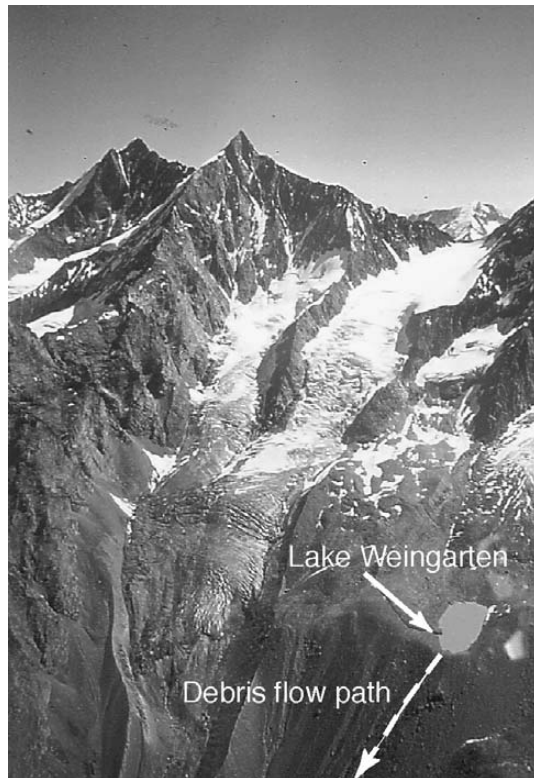

Fig. 7. Lake Weingarten with the large and steep moraine (indicated by the arrow) and the mountain peaks of Täschhorn and Dom in the background (photograph by W. Haeberli, July 1993).

Fig. 8. The village of Täsch a few days after the debris flow, which has mainly affected the left part of the settlement. The area of debris-flow deposits and related damage is shown by the broken line (photograph by A. Kääb, July 2001).


assuming a section of 500 m with an eroded sediment volume per channel length of 750 m^3/m (full breach in moraine dam) and a section of 800 m with 100 m^3/m (assuming a triangular-shaped channel cross section of 10 m depth and 20 m width); and (*vi*) probable maximum travel distance of the debris flow of ~7500–7700 m (vertical descent 1640 m, assuming an average slope value of approximately 11°).

These numbers are based on a scenario of a full dam breach. Secondary effects have to be considered in the lower gorge (blockage in particularly confined sections) and possibly at the confluence with the main river in Täsch (damming and subsequent flooding). The village of Täsch, only 4.8 km distance from the lake, is thus found retrospectively to be potentially endangered.

An estimate of the probability of occurrence of a lake outburst yields the following results (indicator and probability):

of 16 000 m^2 (derived from a 1998 Landsat thematic mapper satellite scene); (*ii*) moraine dam; (*iii*) probable maximum discharge Q_{max} = 194 m^3/s (eq. [4]), i.e., ~200 m^3/s; (*iv*) sediment abundantly available along the steep flow path (especially morainic material), thus formation of debris flow; (*v*) probable maximum volume of the debris flow of 455 000 m^3,

Fig. 9. Situation at Gutz Glacier. Ice avalanche runout areas (for Wätterlaui and Gutzlaui) are in dark grey as mapped before the 1996 event (1) and in light gray for the 5 September 1996 event (2). The road from Grindelwald to Grosse Scheidegg is shown as a broken line. Houses or alpine huts near or in the hazard zone are mapped (not in scale). (DEM25 c [copyright] 2004 swisstopo BA046420). Contours in metres.
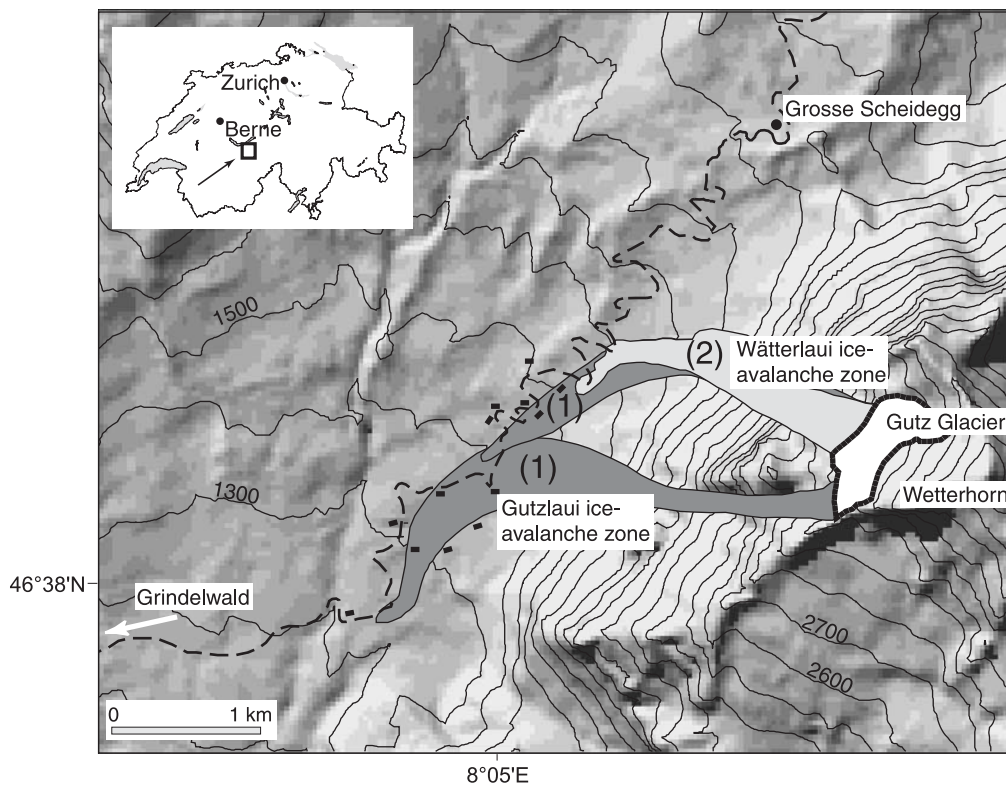
(*i*) moraine dam, medium to high probability; (*ii*) low (close to zero) ratio of freeboard to dam height, high probability; (*iii*) low ratio of dam width to dam height, high probability; (*iv*) sporadic impact waves, medium probability; (*v*) sporadic extreme meteorological events, medium probability. In consideration of the high rating of the most crucial indicators, namely freeboard and dam geometry, the overall probability of occurrence for an outburst of Lake Weingarten rates high.

Evaluation

The assessment procedure correctly identified the formation of the debris flow, yet it overestimated the actual volume and travel distance. This is because estimates of magnitude are based on a full dam breach, which was not the case for the 2001 event. Former studies on debris-flow hazards from Lake Weingarten – Rotbach derived a similar maximum volume estimate of 400 000 m^3 (M. Zimmermann, personal communication, 1999), again for a full breach scenario. The June 2001 debris flow can be considered a moderate event despite the severe damage in Täsch. Had a complete outburst of the lake occurred, with erosion of a large breach, the damage would certainly have been worse. Also on account of the partial drainage, the secondary effects downstream were less than might have been expected. Estimation of the probable maximum travel distance, in principle, predicts a runout beyond the confluence with the main receiving stream at Täsch. Had this occurred, there would have been the potential for secondary damming, upstream flooding, and a sudden dam breach with very high peak discharge. Critically, the 2001 debris flow did not exceed the maximum

estimates of volume and travel distance, a precondition for the validity of the approach.

The estimate of the probability of occurrence is an indication of the hazard found at Lake Weingarten. In fact, a high probability of occurrence together with the high potential magnitude results in a serious hazard for the downstream locations. Consequently, mitigation measures at the lake and at some downstream sections were started after the 2001 disaster (Huggel et al. 2003*c*).

Gutz Glacier ice avalanche

Physiographic setting

Gutz Glacier is situated on the northwest face of Wetterhorn (3701 m asl) close to Grindelwald (Bernese Alps, Switzerland; Fig. 9). This small cirque glacier terminates at the brink of a 1000 m drop over a 60° steep rock wall with a nearly vertical ice cliff of about 60 m height. Minor ice avalanche events from the "Wätterlaui" zone are frequent (several times per day in phases of activity; Bieri 1996) (Fig. 10) and part of the normal ablation mechanism of Gutz Glacier. The second ice avalanche zone ("Gutzlaui") does not show a clear ice cliff, and ice avalanche activity is much lower. In the past 100 years, several major ice avalanche events in the Wätterlaui have destroyed alpine huts and forested areas (Bieri 1996; Margreth and Funk 1999).

Event

On 5 September 1996, two major ice avalanches occurred at the Wätterlaui of Gutz Glacier. The first one at 3 p.m. had

Fig. 10. Ice avalanche from Gutz Glacier on 5 September 1996 (3 p.m.). The cliff of Gutz Glacier where ice broke off and the evolution of the avalanche over time are easily discerned. Deposits from previous smaller avalanche events are visible at the bottom of the photographs (photographs by E. Kalt).

an estimated volume of 80 000 – 100 000 m³ (Margreth and Funk 1999) and reached the road between Grindelwald and Grosse Scheidegg. Deposits of smaller ice avalanches from the previous days (Fig. 10) possibly reduced the friction and increased the travel distance. The second ice avalanche at 9 p.m. was of larger volume (120 000 – 130 000 m³) and covered the road at two locations (points 1605 and 1530 m asl) with a maximum ice deposit thickness of 4 m. Dust avalanche deposits covered approximately 35 000 m² (Margreth and Funk 1999). Three persons were injured due to the impact of the avalanche air pressure. Photogrammetric studies showed that 220 000 m³ of ice was lost from the front of Gutz Glacier between 26 July and 11 September 1996 (VAW 1997).

Assessment procedure

Gutz Glacier is a typical cliff-type glacier. The assessment procedure yielded the following findings: (*i*) probable maximum volume $V = 216\,000$ m³, estimated based on a thickness of 60 m, a length of 180 m, and a width of 20 m; (*ii*) probable maximum travel distance of 5.9 km, according to an average slope of 17°; endangered areas must be correspondingly delineated for several locations along the road between Grindelwald and Grosse Scheidegg, and a few inhabited houses were also considered to be potentially endangered.

The nearly 90° change in the direction of the avalanche path and the strongly concave longitudinal profile indicated that the travel distance could likely be less. Before the event, however, Bieri (1996) applied the reduction criteria of Alean (1985*a*) for the travel length and calculated a distance of 4.2 km (24°).

Two out of the four indicators proposed can be used for a rough estimate of the probability of occurrence. Several historic events from Gutz Glacier and smaller ice falls prior to the main event indicate a rather high probability of occur-

rence. Information on meltwater influence or crevasse pattern evolution was not available.

Evaluation

The volume was correctly estimated in comparison with the 1996 event. Furthermore, the 1996 event remained within the maximum limits delineated by the assessment. In winter, reduced friction on snow cover could increase the observed travel distance. After the 1996 ice avalanche, a detailed hazard mapping study was carried out by applying an adapted dynamic snow avalanche model (Swiss Federal Institute for Snow and Avalanche Research 1997; Margreth and Funk 1999). The travel distance was calculated as 200–300 m shorter in comparison with that calculated by Bieri (1996). A difficulty thereby encountered is the model's dependence of travel distance on the starting volume, a parameter that is difficult to assess in advance. Margreth and Funk (1999) also considered hazards from the powder part of the ice avalanche. In sum, the assessment performed could successfully retrodict the approximate effects of the ice avalanche. Determination of the starting volume (though correctly estimated in this case) and the probability of occurrence remains one of the major difficulties.

Discussion and perspectives

The assessment procedures presented organize and integrate empirical relationships and observations derived from analyses of past events to provide reasonable approximations of events of probable maximum magnitude from glacial lake outbursts and ice avalanches. The relationships yield probable event maxima and are thus designed to incorporate the large uncertainties inherent to the complex and strongly variable processes involved. Authorities concerned with planning and mitigation issues often need upper-bound estimates. Experts using the relationships proposed can estimate the uncertainties by indicated error ranges or from bivariate plots.

A first attempt was presented to derive a probability of occurrence to provide a consistent concept for assessment of glacial hazards in conjunction with estimates of magnitude. A few approaches for estimating probabilities of occurrence for mass-movement hazards have been presented recently, but few rigorous methods are available for debris-flow hazards (Rickenmann 1999). Swiss Government agencies, for instance, issued guidelines for the assessment of mass movement hazards following concepts developed for flood hazards (Lateltin 1997). Because of the specific nature of hazardous glacial processes, however, most of the concepts developed for other natural hazard types are not applicable for glacial hazards, and an approach based on qualitative indicators was therefore proposed. The approach is designed to fit into concepts for the delineation of hazard zones such as applied in Swiss practice (Lateltin 1997).

Two case studies have shown the beneficial aspects of the assessment procedures: rapid and reasonable hazard assessment based on little and easily obtainable information. Open questions and limitations of the approach might be related to the applicability outside the European Alps, in particular for very large events. Whereas the errors encountered for estimates of Himalayan lake volumes do not exert a primary effect on the related hazard, the approach to estimate the travel distance of lake outbursts needs more detailed investigations for conditions significantly different from those in the European Alps. Debris flows in the Swiss Alps are generally characterized by a high content of sediment and large grain size. In the Himalayas or the Andes, for instance, lake outbursts often involve a smaller relative amount of sediment and (or) much higher absolute amounts of water. The average slope of the flow path has then been observed to fall below values indicated here. Flow transformation from debris flows to hyperconcentrated flows has also been recognized to increase the travel distance (Pierson and Scott 1985). The relation used to estimate the average slope of the flow path (cf. Fig. 3 in Huggel et al. 2002) is rather insensitive to large differences in discharge (for $Q_{max} \geq 10$ m^3/s, approximately), and, consequently, the travel distance of major events does not need to be substantially greater than that for smaller events (cf. case study Täsch). Based on the available information, this relation has been valid for the European Alps so far, but more data would contribute much to increase the accuracy. For critical cases, more detailed results may be achieved by physically based models. Spring and Hutter (1981), Clarke (1982), and Tweed and Russell (1999) have presented approaches of catastrophic drainage of ice-dammed lakes, and Fread (1982, 1991), Faeh (1996), and Walder and O'Connor (1997) provided models for failure of natural (earthen) dams. Flow and runout characteristics of debris flows can be derived from numerical models including two-dimensional approaches (e.g., Iverson 1997; Bozhinskiy and Nazarov 2000; Gamma 2000; Laigle and Marchi 2000).

Applicability of estimates of starting volume for ice avalanches outside the European Alps depends on related glacier dimensions. Corresponding evaluation is hampered, however, by extremely scarce information on ice avalanches in most regions outside Europe. Process interactions and flow transformation often observed for major ice avalanche events can considerably enlarge the travel distance. Equation [5] provides an estimate of travel distance that is valid for such high-magnitude events.

Recently, empirical relationships such as presented here have been integrated into geographic information systems (GIS) and remote-sensing-based models to assess glacial hazards over large areas. Satellite imagery and terrain modeling were used to detect glacial lakes (Huggel et al. 2002; Wessels et al. 2002) and glacierized areas (Kieffer et al. 2000; Paul et al. 2002), from which the hazards from glacial lake outbursts, ice avalanches, and related process interactions were assessed by flow-routing models for the Swiss Alps (Huggel et al. 2003a, 2004; Salzmann et al. 2004). Such models based on empirical relationships presented in this study have also been applied for areas in the Andes (Huggel et al. 2003b) and the Himalayas (Kääb et al. 2003b). Results showed the large application potential but also confirmed that more data and research are needed for evaluation of the relationships in these areas.

Conclusions

This study presents procedures for first-order assessment of glacial hazards by evaluating the event magnitude, followed by estimating the probability of occurrence. Assessment of the event magnitude is based on empirical relationships, experience, and physical understanding. It sequentially includes estimates of lake volume, peak discharge, debris-flow volume, and travel distance for glacial lake outbursts and potential break-off volume and travel distance for ice avalanches. The processes involved in glacial hazards are highly complex and often inadequately understood. Hence, an attempt has been made to encompass the related uncertainties by probable maximum estimates of process magnitude. Probability of occurrence is estimated by qualitative indicators. Although reasonable results can thus be achieved for lake outbursts, probability of occurrence for ice avalanches is extremely difficult to derive and is fraught with uncertainties. The proposed set of indicators is open for further development, and it is hoped that it will stimulate discussions and further studies.

Acknowledgements

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