Remote sensing based assessment of hazards from glacier lake outbursts: a case study in the Swiss Alps

Christian Huggel, Andreas Kääb, Wilfried Haeberli, Philippe Teysseire, and Frank Paul

Abstract: Glacier lakes are a common phenomenon in high mountain areas. Outbursts from glacier lakes have repeatedly caused the loss of human lives as well as severe damage to local infrastructure. In several high mountain ranges around the world, a grave uncertainty about the hazard potential of glacier lakes still exists, especially with respect to the effects of accelerating rates of glacier retreat as a consequence of atmospheric warming. Area-wide detection and modeling of glacier lake hazard potentials is, therefore, a major challenge. In this study, an approach integrating three scale levels allows for the progressive focus on critical glacier lakes. Remote sensing methods for application in glacier lake hazard assessment are presented, and include channel indexing, data fusion, and change detection. Each method matches the requirements of a certain scale level. For estimating potential disaster amplitudes, assessments must be made of maximum discharge and runout distance of outbursts floods and debris flows. Existing empirical relations are evaluated and complementary ones as derived from available data are proposed. Tests with observations from a recent outburst event from a moraine-dammed lake in the Swiss Alps show the basic applicability of the proposed techniques and the usefulness of empirical relations for first hazard assessments. In particular, the observed runout distance of the debris flow resulting from the outburst does not exceed the empirically estimated maximum runout distance. A list of decision criteria and related remote sensing techniques are discussed in conclusion. Such a list is an essential tool for evaluating the hazard potential of a lake. A systematic application of remote sensing based methods for glacier lake hazard assessment is recommended.

Key words: glacier lake outburst, hazard potential, remote sensing, empirical parameters.

Résumé : Les lacs glaciaires sont un phénomène courant dans les régions de hautes montagnes. La rupture des digues des lacs glaciaires ont causé à maintes reprises des pertes de vie de même que de lourds dommages aux infrastructures locales. Dans plusieurs chaînes de montagnes élevées dans le monde, il existe toujours une grande incertitude quant au potentiel de risques des lacs glaciaires, spécialement en rapport avec les effets de l'accélération des vitesses de retrait des glaciers résultant du réchauffement atmosphérique. La détection sur de grandes surfaces et la modélisation des potentiels de risques des lacs glaciaires présentent en conséquence des défis majeurs. Dans cette étude, une approche intégrant trois niveaux d'échelle permet de mettre l'accent progressivement sur les lacs glaciaires critiques. On présente les méthodes de détection à distance pour l'évaluation des risques dans le cas des lacs glaciaires, incluant l'indexation des canaux, la fusion des données et le changement de détection. Chaque méthode correspond aux exigences d'un certain niveau d'échelle. Pour évaluer les amplitudes de désastres potentiels, on doit faire les évaluations du débit maximum et de la distance de déposition des inondations et des coulées de débris dues aux ruptures de digues. On évalue les relations empiriques et on propose des relations complémentaires telles que dérivées des données disponibles. Des essais avec observations d'un récent événement de rupture de digue d'un lac endigué par une moraine dans les Alpes Suisses montrent l'applicabilité des techniques proposées et l'utilité des relations empiriques pour les premières évaluations de risques. Particulièrement, la longueur observée de la déposition de l'écoulement de débris résultant de la rupture de la digue ne dépasse pas la longueur maximale de déposition estimée de façon empirique. On discute en conclusion une liste de critères de décisions et de techniques de détection à distance. Une telle liste est un outil essentiel pour évaluer le risque potentiel d'un lac. On recommande l'application systématique de méthodes basées sur la détection à distance pour l'évaluation des risques des lacs glaciaires.

Mots clés : éclatement de la digue d'un lac glaciaire, potentiel de risque, détection à distance, paramètres empiriques.

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Introduction

Outburst floods from glacier lakes represent a serious hazard in many high mountain regions of the world. This study aims at evaluating methods for systematically detecting glacier lakes and assessing their hazard potential. It focuses especially on the applicability of these methods in remote regions (where most high mountains are) and on integrative hazard assessment over large areas, in both cases favouring the use of remote sensing technology. For reasons of data availability and field access, the method test was performed in the densely populated Swiss Alps.

The paper first describes the general three-level approach upon which the study is based. Then, in the methodological part, applicable remote sensing techniques are presented. Empirical relations are developed and adapted to complement these remote sensing techniques. A test study of a recent lake outburst in the southern Swiss Alps is presented for method testing. On the basis of the presented methods, a scheme of decision criteria for the evaluation of the hazard potential of a glacier lake is discussed.

Background

Outbursts from glacial and periglacial lakes can result in flood waves and often catastrophic debris flows where erodable debris reservoirs are present. The impact on human lives and infrastructure can be highly destructive and far-reaching. Glacial outburst floods can be produced by water reservoirs existing in front, or at the surface, base, or margins of glaciers (Haeberli 1983). During the strong glacier shrinkage of the 20th century, dangerous lakes developed in particular behind moraines which had been deposited by former glacier advances (predominantly from the Little Ice Age or earlier Holocene cold periods). Such moraine-dammed lakes show different characteristics in comparison to ice-dammed lakes, which often have seasonal cycles of filling and emptying (Blown and Church 1985). Moraine-dammed lakes usually do not form again after a complete catastrophic drainage.

Various studies have focused on glacial lake outbursts. In Peru, for example, the problem has been fully recognized since 1941, when an outburst flood destroyed the city of Huaráz killing 4500 people (Lliboutry et al. 1977). A considerable number of mitigation works have been carried out since (e.g., Ames 1998; Reynolds et al. 1998). In the Himalayas, retreating glaciers have prompted the evolution of large and rapidly growing lakes in glacial forefields with extremely high damage potential (Reynolds 1998; Yamada 1998). In the past decades, several lakes caused outburst floods affecting human lives and infrastructure (Vuichard and Zimmermann 1987; Yongjian and Jingshi 1992; Hanisch et al. 1996). Glacier lake outbursts were also studied in detail in North America, mainly in western Canada (Clague and Evans 1992; Mathews and Clague 1993; Clague and Evans 2000) as well as in Central Asia (Popov 1997).

In the Alps, and particularly in the Swiss Alps, the situation is different from the above regions because the lakes are generally smaller, and the infrastructure and settlements are situated much closer to the hazard sources. As a result, even small glacial and periglacial lakes have caused considerable damage (Haeberli 1980). As a result of a relatively high density and quality of documentation from historical sources and recent case studies in Switzerland, data on historical outburst catastrophes could be evaluated and compiled in a database forming a valuable background for empirical studies (Haeberli 1983; Huggel et al. 2000).

Most glacial lakes have not yet been identified or studied because of their remote locations. This is a problem of growing concern, particularly in large high mountain areas such as the Himalayas (Richardson and Reynolds 2000). Systematic inventories rarely exist, even in well-documented countries like Switzerland. The detection of glacial lakes is a crucial first step in the investigation of their hazard potential and in the prevention of sudden and unexpected catastrophes. The combination of remote sensing with geographic information systems (GIS) technologies offers strong advantages for first and at least qualitative hazard assessments of glacier lakes.

General approach

This study aims at developing and evaluating remote sensing based methods that enable the assessment of the hazard potential of glacier lakes. "Hazard potential" is used here as a qualitative or semi-quantitative term and refers to the predisposition of a glacier lake and its environment to produce outburst events. It is not intended to predict whether or when, for instance, a certain lake might break out, nor provide any information about the related risk, since this would require a detailed analysis of the expected damage of an outburst. The objective is to develop a decision chain through which glacier lakes can be detected and evaluated. If the hazard potential is then recognized to be critical (see the "Discussion" section for a set of related criteria) further and more detailed studies must be carried out. The strategy found to best meet these requirements starts at a rather general level covering large areas and then focuses progressively on smaller areas. Three different scale levels characterize the basic strategy of the study:

Level 1: The first level comprises the basic detection of glacier lakes over large areas. This potential for providing knowledge about the locations of many lakes and their high temporal variability makes space-borne remote sensing techniques a powerful tool.

Level 2: This level assesses the hazard potential of the lakes detected in Level 1. Simple detection in Level 1 must be complemented by information about the related hazards. Therefore, in Level 2, image analysis and GIS modeling based on multisource data such as satellite imagery and digital elevation models (DEM) are applied.

Level 3: This level is concerned with detailed investigations of lakes recognized through Levels 1 and 2 to have a significant hazard potential. Typically, such investigations are concerned with one specific lake and apply very high-resolution remote sensing data, geophysical studies, and other field work. Application of Level 3 is usually a prerequisite for carrying out on-site mitigation measures.

The typical spatial resolutions of remote sensing data for each scale level and possible sensor systems are specified in Table 1.

Table 1. Typical remote sensing ground resolutions for the scale levels.

Scale level	Ground resolution (m)	Sensor system
1	20–30	Landsat-TM
2	5–20	SPOT, IRS
3	1–5	IKONOS, aerial photography

Methods

Remote sensing for lake detection

The following techniques are based on optical panchromatic and multispectral remotely sensed data. A distinction is made between space-borne and air-borne remote sensing data (in this context satellite imagery and aerial photography, respectively). With regard to space-borne remote sensing data, there is a growing use of multiresolution and multispectral data. The techniques presented here refer to Landsat Thematic Mapper (TM) and Satellite Pour l'Observation de la Terre (SPOT) panchromatic data. Air-borne remote sensing data is processed by photogrammetric techniques.

The detection of glacial lakes using multispectral imagery involves discriminating between water and other surface types. Delineating surface water can be achieved using the spectral reflectance differences. Water strongly absorbs in the near- and middle-infrared wavelengths (0.8–2.5 μm). Vegetation and soil, in contrast, have higher reflectance in the near- and middle-infrared wavelengths, hence water bodies appear dark compared to their surroundings when using these wavelengths (Pietroniro and Leconte 2000).

When applying basic techniques of multispectral classification similar to those used for the normalized difference vegetation index, NDVI (Hardy and Burgan 1999), a normalized difference water index (NDWI) for lake detection was used (Huggel 1998). Applying the idea of two spectral channels with maximum reflectance difference for an object (i.e., water), a blue channel (maximum reflectance of water) and a near-infrared (NIR) channel (minimum reflectance of water) were chosen

$$[1] \qquad \mathrm{NDWI} = \frac{B_{\mathrm{NIR}} - B_{\mathrm{Blue}}}{B_{\mathrm{NIR}} + B_{\mathrm{Blue}}}$$

where B_i is the spectral band (or channel).

The following equation results when applying the NDWI to the spectral bands (TM1 and TM4) of Landsat-TM

$$[2] \qquad \mathrm{NDWI} = \frac{\mathrm{TM4} - \mathrm{TM1}}{\mathrm{TM4} + \mathrm{TM1}}$$

Typical NDWI values for lake surfaces range between –0.60 and –0.85. TM5 or TM7 could be used as alternatives to TM4, but the NDWI with TM4 has proven to be more capable of discriminating water from ice and snow, which is important in glacial environments. Theoretically, simple channel ratios (e.g., TM4/TM1) could work as well, but it was found that the NDWI showed an enhanced contrast between water and the surrounding environment. And it has the advantage of a normalized numerical range.

As a result of spectral reflection, self shadowed areas are misclassified as lakes. Integration of digital elevation data allows for rejection of these areas. With the reconstruction of the sun elevation angle and azimuth at the exact time of the satellite data acquisition, a cast shadow map was computed using a digital elevation model (DEM) of 25 m × 25 m ground resolution. The map was then overlaid on the NDWI image. It could thus be assured that only lakes appeared as black spots. Similar tests with a DEM of coarser horizontal resolution and poorer quality thereby indicated that the resolution and the accuracy of the elevations of the DEM are crucial to obtaining satisfactory results.

The fusion of Landsat-TM data with SPOT panchromatic data leads to enhancement of the ground resolution (10 m × 10 m compared to 30 m × 30 m with TM), but it is difficult to retain the spectral information of TM. Different fusion techniques were therefore investigated to combine the potential of both systems (e.g., Gross and Schott 1998; Pohl and van Genderen 1998; Hellwich 1999). The algorithm chosen in this study is based on a method proposed by Munechika et al. (1993) and takes into account the spectral sensitivity of the input channels. The spectral characteristics of the remote sensing data can thus be preserved better than in other fusion algorithms such as the IHS (intensity hue saturation) colour-space transformation (Pellemans et al. 1993). The improved spatial resolution together with the spectral information from TM after the fusion, allows for a more detailed analysis of the potential hazard sites. The inclusion of specific spectral channels (e.g., near-infrared) in the fusion process helps to enhance certain features relevant to the hazard assessment. Vegetation, for instance, is distinguishable from non-vegetated terrain due to its high reflectivity in the near-infrared and can provide important information regarding the stability and erosional activity of a moraine. Large debris deposits, which are in some cases visually detectable, can be mobilized during a lake outburst. Their assessment can thus be of help in estimating the potential debris flow volume. The clear visual detection of moraine dams can be difficult, even in Level 2- or 3-resolution images, as long as stereo viewing is not available. Successful detection also depends on the physical size (height, width) of the dam. The integration of high resolution DEMs (preferably 25 m × 25 m) can substantially aid in solving the problem because of their potential use for extraction of the geomorphometric object characteristics of moraine dams (e.g., slope, terrain curvature, etc., Schmidt and Dikau 1999).

Glacier lakes are part of the highly variable glacial and periglacial environment. The related hazard potentials can drastically change within years or even months. Change detection techniques are therefore integrated in the assessment of the hazard potential. Seasonal changes of glacier lakes are best assessed with remote sensing data with time intervals of a few months whereas long-term changes require a few years. The method proposed here for the detection of long-term glacier lake changes uses two co-registered Landsat-TM scenes from 1990 and 1998.

The best results in change detection analysis were achieved by the generation of a ratio image dividing the digital numbers (DN) from channel 5 from the first TM scene by those from channel 5 of the second TM scene. Objects and areas which were not subject to changes in the intervening time interval then appear in grey (ratio values near 1), whereas objects with marked changes are identified as black or white (ratio values << 1 or >> 1). Changes in glacier lakes, for example partial or total emptying due to outbursts, can clearly be distinguished as black areas in the ratio image, whereas glacier lakes that newly emerged appear in white. Lakes with no evident changes between the two satellite overpasses however, are reproduced in grey. An efficient change detection for glacier lakes over relatively large areas is thus facilitated.

Detailed investigations with air-borne remote sensing data usually require the use of photogrammetric techniques. Their application on glacier lakes is treated extensively in the literature (Kääb 2000; Haeberli et al. 2001) and not discussed in detail here. Of special interest are techniques which allow the reconstruction of 3D geometry and 3D change. DEM generation with a high accuracy in elevation can be performed by analytical photogrammetry using stereo aerial photography (Kääb 1996). Digital photogrammetric techniques enable less time-consuming and more dense, yet somewhat less reliable, height information to be obtained. Over rough terrains in high mountain areas in particular, difficulties can be caused by shadows and terrain distortions (Baltsavias et al. 1996). Nevertheless, these techniques can be applied for monitoring lake levels and changes in glacier thickness (important for ice-dammed lakes). In the case of moraine dams, the lake level in relation to the dam height determines the freeboard and thus relates to the risk of an upcoming outburst. Dam width and height can be deduced using standard photogrammetric procedures, and both have implications for the stability of the dam and its vulnerability to overtopping and erosion by displacement waves from ice or rock falls (see the "Discussion" section for further decision criteria of lake hazards). Determination of surface displacements (2D-movements) requires specific approaches. A digital procedure has recently been developed using high-precision orthoimages taken at different times (Kääb and Vollmer 2000). Block matching techniques (area-based digital correlation) then allow for measuring terrain displacements of selected locations. With the objective being to foresee potential trigger events of lake outbursts, debris and rock slope instabilities and ice movements in hanging glaciers can thus be observed continuously (Kääb et al. 2000).

It should be kept in mind that the photogrammetric techniques outlined above can only be reasonably applied for detailed studies of specific cases due to their high costs. Furthermore, the required aerial photography, in particular time series, are often not available for remote high mountain areas. Full exploitation of the potential of space-borne remote sensing data is therefore essential. With the recent launch of satellite systems with sensor capabilities not yet available to the public (e.g., IKONOS with 1 m × 1 m ground resolution), space-borne remote sensing might replace aerial photography in a number of applications.

Empirical models for outburst characteristics

Remote sensing techniques are suitable for the detection of phenomena related to glacier lake hazards. However, they are of limited use for modeling related processes. Empirical models are applied here to complement the results from remote sensing. The key parameters of these models are maximum discharge and runout distance of potential flood waves and debris flows from the outbursts considered.

Lake area can be extracted from remote sensing data. However, lake volume rather than area must be known to realistically estimate potential peak discharge for a possible outburst. There is no feasible way to directly derive this parameter from optical remote sensing data despite a number of efforts to perform mapping of surface water and depth measurements from satellite imagery (e.g., Benny and Dawson 1983). The reliability of these remote sensing based bathymetric studies depends on finding a significant relationship between water depth and reflected energy (Baban 1993). The water depth measurements commonly required to establish the relationship and the possibly large number of glacier lakes in poorly known high mountain areas make this approach unfeasible for our purposes, requiring that an empirical approach be chosen instead. Data on lake area, volume, and depth reported in the literature (Table 2) form the basis for the formulation of an empirical relationship between volume and area. Plots of volume against area usually show very high coefficients of determination (r^2) reflecting the dependency of volume on area. Since volumes are generally calculated by area and depth measurements, it is more reasonable to plot mean water depth against lake area (Fig. 1). The regression analysis between area (A) and mean depth (D), including a bias correction, yields the following equation

$$[3] \qquad D = 0.104A^{0.42} \qquad r^2 = 0.916$$

The lake volume (V) is then calculated as follows

$$[4] \qquad V = 0.104A^{1.42}$$

A similar expression was defined by the Canadian Inland Water Directorate for glacier-dammed lakes (cited in Evans 1986*a*):

$$[5] \qquad V = 0.035A^{1.5}$$

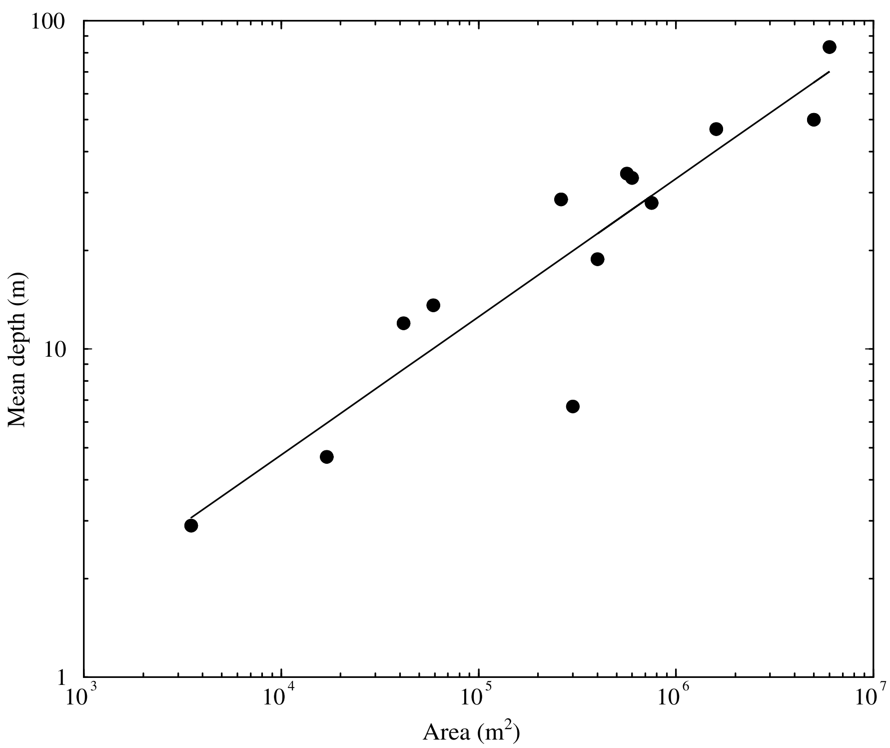
The comparison of the two expressions and the scatter in the regression, gives an impression of the uncertainty due to the high variability of lake geometry in nature.

The magnitude of a flood caused by the failure of a glacier or moraine dam is relevant for further hazard analyses. A variety of empirical equations based on documented outburst events has been proposed to estimate the maximum discharge (Q_{max}, Table 3). The variables in these equations are lake volume (V) (for ice dams) or potential energy (P_E) of the water reservoir. P_E is thereby expressed as the product of dam height, volume, and the specific weight of water (Costa and Schuster 1988). The large scatter in plots of Q_{max} versus volume or P_E reflects the diverse characteristics of individual dams and, as a consequence, the range of uncertainty introduced when estimates of maximum discharge based on the corresponding regression analyses are applied. The scatter also relates to the difficulty of directly measuring flood discharges. Accurate measurements are very difficult and values have often to be derived using indirect methods (Clague and Evans 1994). For moraine dam breaks, the equation proposed so far cannot be integrated in this study due to missing information about required dam heights that cannot be deduced from satellite remote sensing data (unless stereo images are available). Therefore, an empirical relation between peak discharge and reservoir volume had to be found. Such a relation cannot account for the complex physical, hydraulic, and hydrological processes involved in indi-

Table 2. Compiled data on glacier lake area and volume.

Lake	Area (m^2, $\times10^6$)	Volume (m^3, $\times10^6$)	Mean depth (m)	Type of lake	Reference
Ice Cave Lake	0.0035	0.01	2.9	Ice-dammed	Maag 1963
Gruben Lake 5	0.01	0.05	5.0	Thermokarst	Teysseire 1999
Crusoe-Baby Lake	0.017	0.08	4.7	Ice-dammed	Maag 1963
Gruben Lake 3	0.021	0.15	7.1	Ice-dammed	Kääb 1996
Gruben Lake 1	0.023	0.24	10.4	Moraine-dammed	Kääb 1996
MT' Lake	0.0416	0.5	12.0	Ice-dammed	Blown and Church 1985
Lac d'Arsine	0.059	0.8	13.6	Moraine-dammed	Vallon 1989
Nostetuko lake	0.2622	7.5	28.6	Moraine-dammed	Clague and Evans 1994
Between Lake	0.4	7.5	18.8	Ice-dammed	Maag 1963
Abmachimai Co	0.565	19.4	34.3	Moraine-dammed	Meon and Schwarz 1993
Gjanupsvatn	0.6	20	33.3	Ice-dammed	Costa and Schuster 1988
Quongzonk Co	0.753	21	27.9	Moraine-dammed	Meon and Schwarz 1993
Laguna Parón	1.6	75	46.9	Moraine-dammed	Lliboutry et al. 1977
Summit Lake	5.0	250	50.0	Ice-dammed	Mathews and Clague 1993
Phantom Lake	6.0	500	83.3	Ice-dammed	Maag 1963

Fig. 1. Regression between mean depth and area calculated for a set of ice- and moraine-dammed lakes (cf. Table 2).



vidual dam failures. Walder and O'Connor (1997) argue that the reservoir volume probably does not exert primary control on peak discharges. In the absence of complete understanding, as well as of the required parameters however, it may serve as a useful estimator of flood magnitude for initial hazard assessments. Such relations have also contributed to the investigation of the characteristics of different dam failure mechanisms, such as moraine, landslide, and ice dam failures (Costa and Schuster 1988).

The small sample of sufficiently documented failures from moraine dams constrains the regression analysis to a rather small database (Table 4). After bias correction the resulting equation is

$$[6] \qquad Q_{max} = 0.00077V^{1.017} \qquad r^2 = 0.94$$

The corresponding scatter plot of peak discharge (probably water–sediment mixtures in most cases) against volume includes four different empirical relations (Fig. 2). The relation given by Popov (1991) is based on outbursts in Zailisky Alatau, northern Tien Shan. It is similar to eq. [6] but predicts higher peak discharges for given volumes. Evans' (1986*b*) relation for data from man-made rock and earthfill dams would overestimate the peak discharge for smaller lake volumes. Nevertheless, the general similarity supports his suggestion that such dams breach in a similar manner to moraine dams. The relation of Haeberli (1983), (see Table 3),

Table 3. Selected published relations for lake volume and peak discharge.

Type of dam	Relation	Reference
Glacier, tunnel events	$Q_{max} = 75(V/10^6)^{0.67}$	Clague and Mathews 1973
	$Q_{max} = 46(V/10^6)^{0.66}$	Walder and Costa 1996
Glacier, nontunnel events	$Q_{max} = V/t_w$	Haeberli 1983*
	$Q_{max} = 1100(V/10^6)^{0.44}$	Walder and Costa 1996
Moraine	$Q_{max} = 0.00013P_E^{0.60}$	Costa and Schuster 1988†
	$Q_{max} = 0.0048V^{0.896}$	Popov 1991
Earth- and rock-fill	$Q_{max} = 0.72V^{0.53}$	Evans 1986*b*

*The relation is applied to events termed "sudden break". t_w is a time constant with an approximate range between 1000 and 2000 s.

†P_E is the potential energy of the reservoir (J) and defined as the product of dam height (m), volume (m^3), and the specific weight of water (9800 N/m^3).

Table 4. Compiled data on outbursts from moraine-dammed lakes.

Lake	Volume (m^3, $\times10^6$)	Max. discharge (m^3/s)	Reference
Moraine No. 13	0.0864	210	Costa and Schuster 1988
Gruben Lake 1	0.17	15	Teysseire 1999
Broken Top	0.189	71	Costa and Schuster 1988
M. Almatinka, Lake 2	0.22	350	Popov 1991
Sirwolte Lake	0.3	>70	This study; Teysseire 1999
Squaw Creek	0.333	297	Costa and Schuster 1988
Klattasine	1.7	1 000	Clague et al. 1985
Mingbo Valley	4.9	1 100	Watanabe et al. 1994
Nostetuko	6.5	11 000	Blown and Church 1985
Jancacurish	8.0	7 500	Lliboutry et al. 1977
Dig Tsho (Langmoche)	8.0	1 600	Watanabe et al. 1994
Zhangzhangbo Lake	19	15 920	Xu Daoming 1988

Fig. 2. Calculated regression (solid line) between peak discharge and water volume for moraine-dammed lakes (cf. Table 3), including similar relations published earlier.

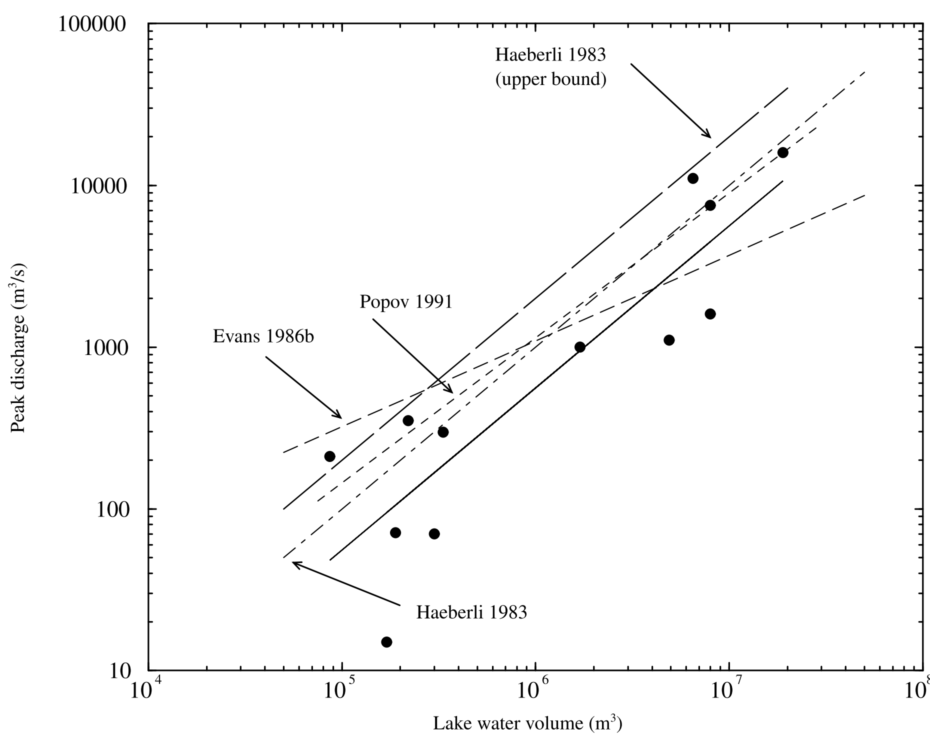
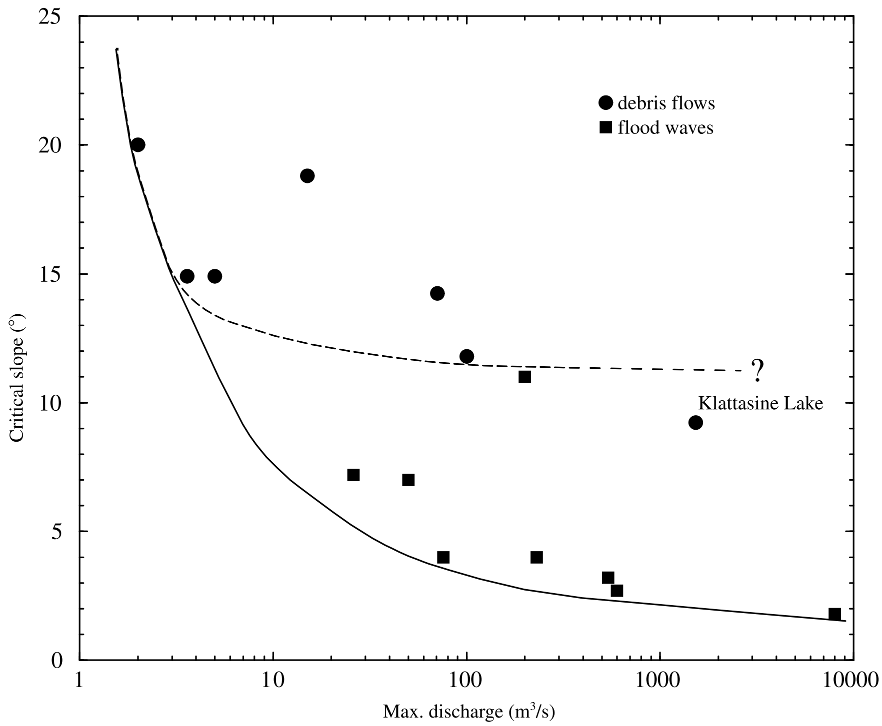


Fig. 3. Relation between peak discharge and overall slope of runout distance of lake outbursts with respect to flood waves and debris flows, based on data from the Alps. A single outburst event from Canada (Klattasine Lake) is marked.



originally derived from nontunnel glacier ice-dam outbursts ("sudden breaks"), accords quite well with the dataset on moraine dam failures. This leads to the suggestion that processes similar to sudden bursts (or mechanical failures) also occur in moraine dam failures

In Haeberli's relation, the lake volume is divided by a time constant of 1000 s. This value is based on experience from four outburst events in the Alps where 1000 s was found to be a characteristic value for the duration of the outburst (Haeberli 1983). The benefit of this relation lies in its simple and quick calculation of the peak discharge. In view of the large scatter in the data, such a simple approach seems no less appropriate than nonlinear relations. To obtain a worst-case estimate, Haeberli's original graph is shifted in a parallel manner in a log–log scale to envelop the dataset (Fig. 2)

[7] $$Q_{\max} = \frac{2V}{t}$$

where t is a time constant of 1000 s.

Before applying one of the relationships developed for peak discharges for glacier lake outbursts, it is crucial to identify the actual or most probable mode of failure. Moraine-dammed lakes have been found to produce larger outburst floods than glacier-dammed lakes for the same stored water volume or potential energy (Costa and Schuster 1988; Clague and Evans 1994) unless a mechanical failure (nontunnel drainage) of an ice dam is involved (Walder and Costa 1996). However, discriminating modes of failure in advance is not trivial in practice, which was well demonstrated by cases where a combination of tunnel and nontunnel (i.e., mechanical failure) drainage of ice dams occurred (Lago Argentino, Liss 1970; or Glaciar Grande del Nevado del Plomo, Fernández et al. 1990).

A rough estimate of the area potentially affected by the lake outburst should be part of the hazard assessment. In this study, a worst-case philosophy is followed for delineating the area which could be affected. The runout (travel) distance of an outburst flood is related to the amount of debris available to be mobilized. Outburst floods with a higher content of solid material form debris flows and stop abruptly, whereas flood waves with predominantly water attenuate. For a rough assessment of the maximum affected area, the peak discharge is used to estimate the overall slope of the outburst flood (the average slope between the starting and the end point of an outburst event). Figure 3 determines a critical slope (i.e., the overall slope corresponding to the worst-case outburst event) for a given peak discharge based on a set of data from the Alps. With a given elevation and location of the starting point (i.e., the glacier lake), the critical slope enables the determination of the maximum runout point and distance following the main flood path. It should be noted that in case of attenuating flood waves, the end point is defined as the maximum reach of damage in densely populated areas (Fig. 3).

The inclusion of a Canadian lake outburst (Klattasine Lake, Clague et al. 1985) into the dataset of the Alps indicates that for discharges in excess of 1000 m^3/s, the critical slope might be lower than the data from the Alps suggest.

Empirical models fit the requirements of initial hazard assessments fairly well as they are set up at the second scale level of the strategy outlined previously. More process-oriented models can be applied at the next scale. Such models exist for dam breaks (e.g., DAMBRK, Fread 1982) and for combined breach and flood wave – debris flow propagation processes (Faeh 1996). The input parameters needed for these models usually require detailed field studies.

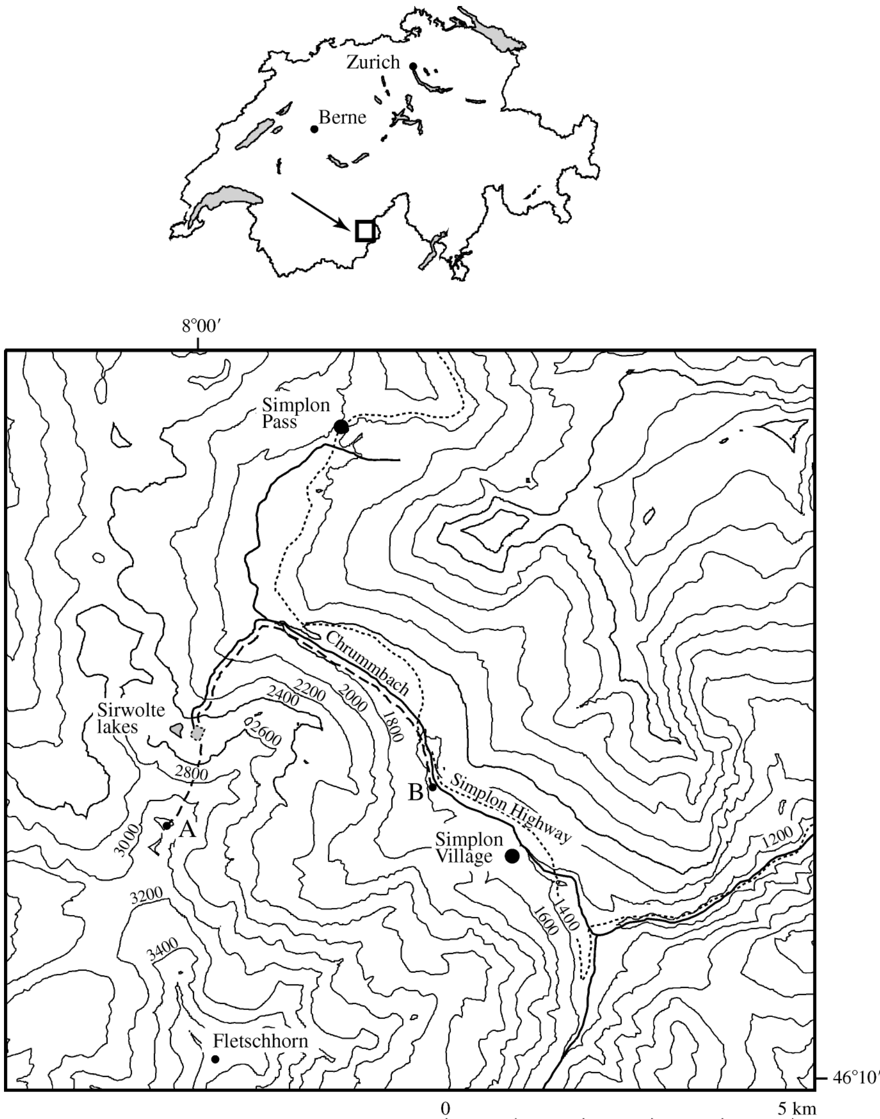


Fig. 4. Map of the Simplon Pass region, Switzerland, showing the location of the 1993 Sirwolte lake outburst. The location of the profile A–B (cf. Fig. 6) is indicated by a dashed line.

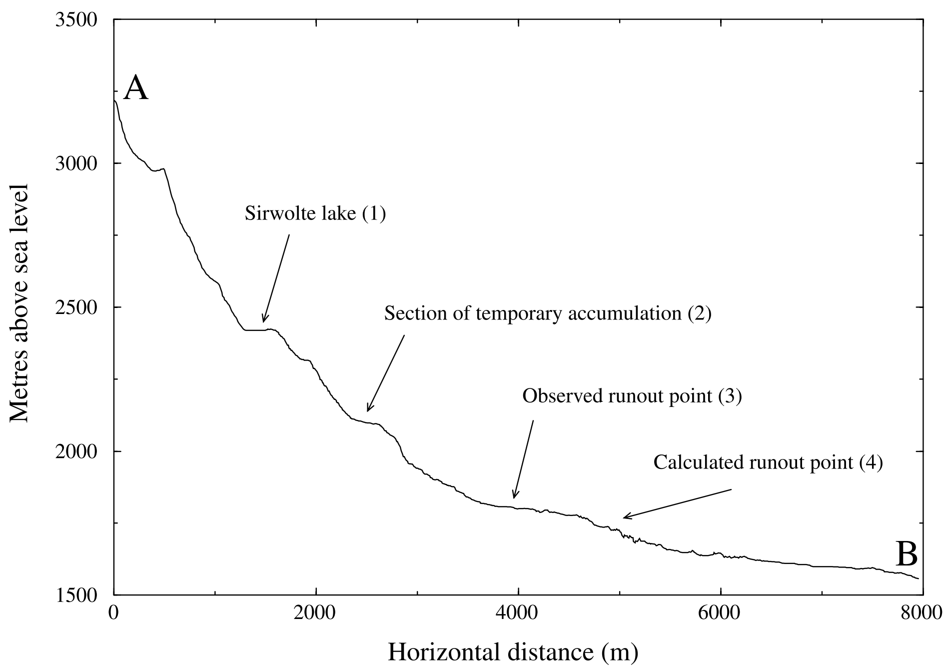
The Sirwolte test study

A lake outburst in the Swiss Alps in 1993 was selected to test some of the outlined remote sensing methods and to evaluate the applicability of the empirical relations. The test site is located in the southern Swiss Alps close to the summit of the Simplon Pass which connects Switzerland and Italy (Fig. 4). Two lakes in the Sirwolte area, situated at an elevation of 2420 m a.s.l. (eastern lake) and 2436 m a.s.l. (western lake), are fed by meltwaters from small glaciers and firn fields on the northern slope of the Fletschhorn massif (3993 m a.s.l.). Both lakes lie in a glacial cirque at the bottom of a steep rock wall with debris cones and are not in direct contact with a glacier. The western lake drains through an incision in the bedrock. The eastern lake (henceforth termed “Sirwolte lake”) was formerly dammed by a Little Ice Age moraine with a shallow overflow channel and broke out on 24 September 1993. It is worth noting that in a regional lake inventory and assessment prepared in 1992, the Sirwolte lake was already considered as hazardous (M. Fürholz, personal communication, 1992).

The failure of the moraine dam was probably caused by enhanced overflow from the lake during a period of heavy rainfall (Fig. 5). It is also possible that moraine failure occurred due to an overtopping wave generated by rockfall, debris flow, or due to piping. Still, no indication to confirm the latter hypotheses could be found. In view of the extraordinary rainfalls in that period which caused severe damage in several other places in the region (particularly in the city of Brig), a scenario of excess overflow (with overtopping) represents the most likely explanation. As a consequence, overflowing water provoked erosion on the outer slope of the moraine and possibly subsequent total breaching of the moraine. The dimensions of the breach are about 200 m in length and 150 000 m^3 in volume (Teysseire 1999). The maximum value for the eroded cross-sectional area is estimated at 900 m^2 with a mean along the breach of about 750 m^2. As an important follow-up to this event, the maximum average erosion value of 500 m^2, assumed so far for the Alps and based on several debris flow events (Haeberli et al. 1989), should thus be corrected. Melting from small

Fig. 5. General view of the moraine breach caused by the 1993 outburst. Location of the Sirwolte lake is indicated by arrow (numbering relates to Fig. 6. Photograph taken by Sonja Oswald 2000).

Fig. 6. Profile section A–B (cf. Fig. 4) showing observed and simulated runout distance of the 1993 lake outburst.

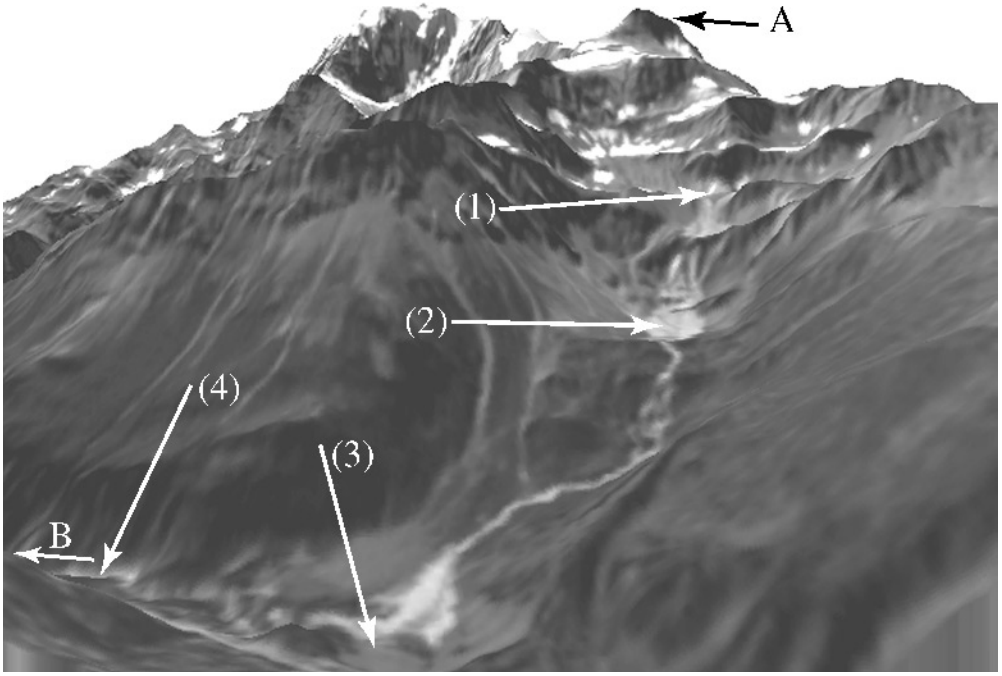


ice and perennial snow fields in the catchment area of the lake (1.15 km^2) did not seem to have played a significant role as a trigger factor for the outburst.

The debris flow generated by the mobilization of large amounts of loose morainic material swept over a steep rock cascade down to a less inclined section where part of the solid material accumulated. The flow then passed over another rock slope and finally spread out on a cone-like slope used as pasture where a hut was destroyed. The main river was just reached but most material accumulated on the cone so that no significant damming of the river occurred. The Simplon Pass road, an important highway located on the opposite valley side some 50 m above the main river bed, remained unaffected (Figs. 6 and 7).

The initial lake volume had been measured before the outburst using bathymetric methods and was determined to be 300 000 m^3 (Teysseire 1999). It is extremely difficult to realistically estimate the peak discharge of the outburst. In this case, it is based on the following considerations: the erosion processes during the breach formation were reconstructed using the sediment transport formula from Smart and Jaeggi (1983). Reports from eyewitnesses helped to calibrate the

Fig. 7. Simulated three-dimensional view of the Sirwolte lake area with Fletschhorn in the background, seen from Northwest and generated by merging a SPOT panchromatic image with a 25 m × 25 m digital elevation model (DHM25, Federal Office of Topography, Switzerland).



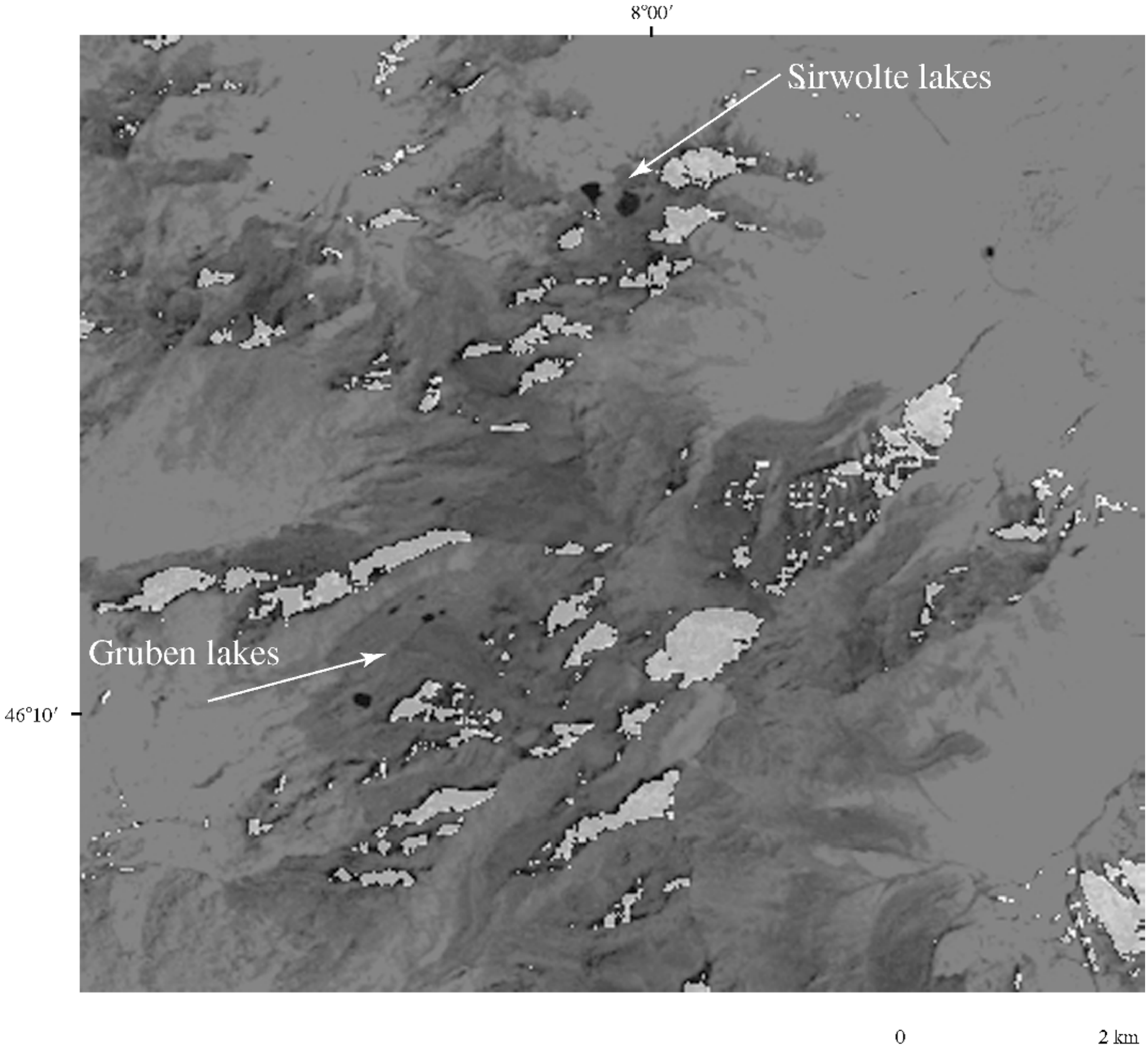
event duration. A gauge station in the main river, located 300 m below the confluence, was destroyed during the outburst event and could not be used for any measurements. At the Egga location, 6.5 km downstream from the Sirwolte lake, the peak discharge was estimated as 150 m^3/s reconstructing the cross-section using visible event traces. A peak discharge estimate for the same location, taking into account only the precipitation in the corresponding catchment (32 km^2), yielded about 80–115 m^3/s. The difference between these two values could approximately be assumed as the contribution from the lake outburst including attenuation effects (i.e., 35–70 m^3/s). However, since the debris flow stopped at the confluence with the main river, it can be assumed that this discharge contribution excludes the amount of debris transported by the debris flow. Based on all of these considerations, the maximum discharge of the outburst was first estimated as 50–90 m^3/s, which is probably a water-only estimate. When the size of the breach is taken into account, a peak discharge estimate of the water–sediment mixture should probably be in the range of a few hundred m^3/s. At the Gondo location, about 18 km downstream from the lake, the influence of the outburst was no longer clearly noticeable and amounted to only approximately 5% of the total flood discharge of the river.

Lake detection with NDWI was conducted using a Landsat-5 Thematic Mapper (TM) scene from 10 September 1990 with 30 m × 30 m ground resolution. Figure 8 shows the NDWI image including the Sirwolte and nearby Gruben areas, and the overlay of the shadow map for extraction of shadowed areas. For a test of the change detection procedure described in the “Methods” section, a Landsat-TM scene from 31 August 1998 was co-registered to, and merged with, the 1990 TM scene. Due to the outburst and emptying between 1990 and 1998, the eastern Sirwolte lake can clearly be distinguished as a black spot in the corresponding change detection image (Fig. 9). The western Sirwolte lake, where no changes took place, can barely be recognized, however. Further lake alterations can be detected in the Gruben area, some 5 km southwest, where mitigation constructions on lakes were carried out between 1990 and 1998 (Haeberli et al. 2001).

As input to eqs. [4] and [5] for calculation of the lake volume, the lake area was taken from the Landsat-TM image as 44 900 m^2. A comparison with an infrared aerial photograph (taken on 30 August 1991) revealed virtually the same area. Corresponding data could not be extracted from the SPOT-Pan image since it was recorded after the lake outburst. Former studies on a larger set of glacial lakes in the Swiss Alps indicated that there is a tendency to underestimate the lake area with decreasing ground resolution of the sensor system (Huggel 1998). Such scale–resolution problems represent common phenomena encountered in remote sensing (Cao and Siu-Ngan Lam 1997).

Equation [4] yields a lake volume of 420 000 m^3, and eq. [5] gives a volume of 333 000 m^3, hence the latter value came closer to the measured volume of 300 000 m^3. The integration of both volumes into further calculations gave a useful indication of the potential range of uncertainty. The maximum possible discharge obtained using eq. [6] for moraine dam failures was 400 m^3/s or 320 m^3/s, respectively, for the two volumes. Compared with the reconstructed peak discharge of the water–sediment mixture (i.e., a few hundred m^3/s), the result of eq. [6] gives a realistic value. The critical slope was derived from Fig. 3. No quantitative estimate of the amount of unconsolidated debris in the flow path could be made on the basis of the available remote sensing data. But in view of the large amount of loose morainic ma-

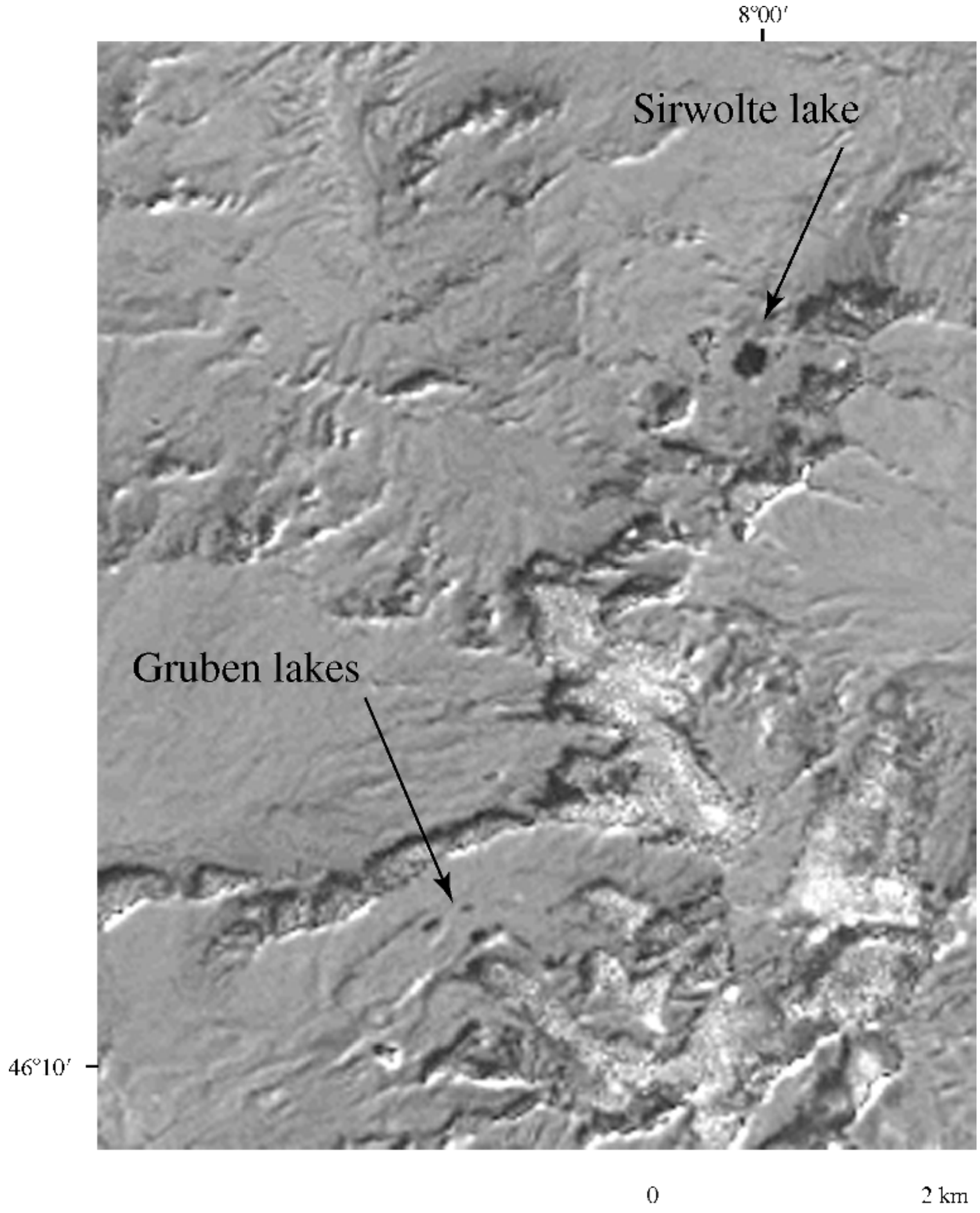
Fig. 8. NDWI for lake detection image based on a 1990 Landsat-TM image overlaid by a shadow map (pixels in light grey). Areas indicated by arrows are discussed in the text.



terial, it was assumed that a debris flow and not a flood wave would form. The critical slope for the runout path was thus estimated as 11.3–11.5° for the two discharge scenarios. As can be seen here, critical slope estimates for outburst-related debris flows based on Fig. 3 are relatively insensitive to maximum discharges when values of about 50 m^3/s are exceeded.

The corresponding runout distance can be determined using georeferenced satellite and DEM information or with the aid of topographic maps. In the present case, the debris flow caused by the outburst was expected not to overrun the 1735 m a.s.l. point (Fig. 6). The range of deviation of the runout distance is about ±100 m (horizontal distance). The 1993 outburst showed that the debris flow actually just stopped at the confluence with the main river Chrummbach at 1805 m a.s.l., some 880 m before point 1735 m a.s.l. The primary goal of the maximum runout approach (i.e., the calculated runout distance must not be shorter than the observed one) was achieved. The applied overall slope approach did not take into account any topographic or hydrologic irregularities, in particular the confluence with the main river, which has a major effect on the behavior of the debris flow (deposition of debris material, possibly damming of the main river). The difference between the estimated and the observed runout distance can therefore be reduced by a closer examination of the flood path. In this case, the high-resolution SPOT- Pan image and the fused image (Landsat-TM with SPOT-Pan) in combination with the DEM data were used. Generation of a 3-D model with arbitrary setting of viewing angles and height (Fig. 7) revealed one section of reduced inclination (Fig. 7,

Fig. 9. Change detection image generated by channel ratio of two Landsat-TM images (1990 and 1998, using TM5). Areas which were subject to changes between 1990 and 1998 appear in black or white. Areas of interest are indicated by arrows.



arrow (2)) which would probably attenuate the outburst flow, simultaneously with the accumulation of debris material. Debris flows with temporary accumulation sections tend to have reduced runout distances.

Discussion

The methods proposed here are intended to enable systematic hazard assessments over large areas of glacier lakes in remote high mountain regions. The kind and combination of criteria used to assess hazard potentials according to different scale levels vary from case to case. In the following discussion, a distinction is made between decision criteria that are part of the predisposition (including the lakes and the dams) and those related to trigger mechanisms and to the down-valley section of the lake.

Lake area and volume are of primary importance since they define the amount of water available for an outburst. Georeferenced satellite data in combination with eq. [4] for volume estimates are applied at this early stage. The rate of growth of the lake indicates possible developments of the hazard situation. Field investigations tend to provide information at a specific point in time and therefore, might underestimate the speed of evolution. Change detection techniques based on satellite image time series are especially useful in such cases. The process of determining whether a lake is dammed by ice, moraine, or bedrock can be supported by multispectral satellite imagery (Table 5). In special cases, discrimination between moraine and rock dams can be difficult and might require field verification. Dams with small width–height ratios and little freeboard between the lake surface and the top of the dam are more vulnerable

Table 5. Decision criteria for evaluation of a glacier lake's hazard potential (scale levels are with increasing focus from Level 1 to Level 3).

Decision criteria	Scale level	Applicable techniques and data
Lake		
Lake area and (or) size	1	NDWI, georeferenced satellite images
Rate of lake growth	1–2	Change detection; satellite image time series
Contact with glacier	1	Multispectral (MS) satellite image classification
Surrounding geometry	2	Geomorphometric DEM analysis
Advancing and (or) retreating glacier	2–3	Visual analysis (type of glacier tongue); glacier parametrization
Dam		
Dam type (bedrock, moraine, ice)	2–3	High-resolution MS satellite data classification; aerial photography; field study
Dam stability	3	Geophysical field studies; vegetation image indices
Width and (or) height ratio of dam	2–3	Stereo satellite imagery and photogrammetric techniques
Freeboard	3	Stereo satellite imagery and photogrammetric techniques
Evidence of outbursts and (or) breaches	2	High-resolution satellite imagery
Melting ice cores	3	Change detection; surface changes (photogrammetry)
Trigger mechanisms		
Steep glaciers and (or) icefall	2–3	High-resolution MS satellite data; surface deformation (photogrammetry); DEM analysis
Rockfall	2–3	Visual recognition of deposited boulders (photo interpretation; field survey)
Snow avalanche	2	MS satellite data; DEM (steep snow fields)
Calving activity	2–3	High-resolution MS satellite data (visual recognition of drifting ice blocks; steep glacier tongues)
Landslide	3	Photogrammetric surface deformation measurement
Interconnected lakes	1–2–3	NDWI; high-resolution satellite imagery; field studies (drainage system study)
Catchment area (precipitation and meltwater input)	2	Hydrological DEM analysis
Down-valley flood path		
Amount of loose material	2–3	Panchromatic and MS satellite data classification; field study
Topography	2–3	DEM analysis; visualization techniques

to overtopping and erosion by excess overflow or displacement waves due to snow–ice avalanches, rockfall, or calving. Therefore, photogrammetric 3D techniques (or possibly Level 2- or 3-resolution stereo satellite imagery) are necessary to derive information on the dam's dimension. Melting ice cores in a dam can seriously reduce the freeboard and the stability of the dam. Photogrammetric change detection methods are a tool to measure settlements (Haeberli et al. 2001). Glacier fluctuations that are also detectable by remote sensing techniques significantly influence the development of a glacier lake. Potential glacier development can be estimated from basic glaciological parameters (e.g., Haeberli and Hoelzle 1995) which can be derived from remotely sensed data.

Although the precise time of a (sudden) outburst event cannot be predicted based on remote sensing alone, it is possible to use such techniques to check for potential trigger mechanisms. Displacement waves from ice or snow avalanches, rockfall, or calving glaciers are able to provoke lake outbursts (Grabs and Hanisch 1993; Clague and Evans 1994; Vuichard and Zimmermann 1987). Steep glaciers are best detected by means of Level 2-resolution multispectral satellite images combined with slope information from DEMs (Table 4). Drifting ice blocks on the lake surface, well recognizable in satellite data, indicate calving activity. Detecting rockfall hazard is much more difficult or even beyond the capabilities of remote sensing technology unless very clear indications such as large deposits of boulders are visible. Interconnected glacier lakes can trigger chain reactions producing outburst floods into lower lakes (Haeberli 1980). Recognition of drainage paths between lakes connected thus is, therefore, an important task involving methods on all three scale levels, i.e., from lake detection to field observations, depending on the characteristics of the drainage system (peri-, supra-, or sub-glacial).

Lake outbursts can also be triggered by progressive processes. Precipitation events or high runoff input from snow–ice melting can lead to enhanced overflow and erosion of the spillway and of the dam. The potential for such runoff processes can be evaluated by hydrological DEM analysis of the catchment area of the lake. The study of the down-valley section of the potential flow path is of importance for estimating the characteristics and effects of the outburst flood (Table 4). Remote sensing can contribute to the discovery of narrow passages such as gorges (temporary blockages) or potentially endangered settlements in the flood path. Detection and determination of debris deposits in the flow path on the basis of remote sensing data may be possible only in a general qualitative way. Estimating the probability of the flood transforming into a debris flow can thus be complicated. In general, these complexities make it difficult to formulate deterministic models and suggest the application of models based on empirical data (Clague and Evans 2000).

In the present study, remote sensing techniques are widely used for deriving basic information on glacier lake hazard potentials. The authors believe that the ability of space-borne sensor systems to regularly monitor potentially hazardous glacier lakes is of increasing importance in the context of environmental and climatic change, particularly affecting high mountain and glacial environments. Such monitoring is crucial since global warming shifts glacial and periglacial hazard zones into ranges where historical analogues do not exist. Thus, the usefulness and validity of traditional hazard assessment based on historical experience may soon be on the decline.

Conclusions

Based on the proposed methods, it is concluded that glacier lakes can be detected in remote sensing data. Characteristics of the lake and the dam, and the potential for trigger mechanisms of lake outbursts can be evaluated using specific techniques on different scale levels. Empirical relations allow an estimate of a potential outburst flood hazard. If the evaluation process indicates a serious hazard potential, a more rigorous study with field work is usually required. In view of the hazard potential of glacier lakes in many high mountain regions, a systematic application of such remote sensing based methods is recommended.

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