Charles University in Prague

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BACHELOR THESIS

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Prague, 2011

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Risk Analysis Methods of Natural Catastrophic Processes in High Mountain Areas

Metody rizikové analýzy přírodních katastrofických procesů ve velehorách

Bachelor thesis

Supervisor: Doc. RNDr. Bohumír Janský, CSc.

Prague, 2011

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In Prague, 25. 5. 2011

Zadání bakalářské práce

Název práce

Metody rizikové analýzy přírodních katastrofických procesů ve velehorách

Cíle práce

- vytvořit přehled metod a pracovních postupů, které se používají ve světové literatuře při analýze rozmanitých přírodních rizikových procesů

Použité pracovní metody, zájmové území, datové zdroje

- stěžejní částí práce je detailní literární rešerše světové i domácí literatury
- kandidátka se zaměří především na metody rizikové analýzy a rozpracuje je podle kategorií jednotlivých rizikových procesů
- kandidátka se speciálně zaměří na:
  - průvalová jezera ve světových velehorách, kde posoudí jednotlivé přístupy k modelování průtrží jejich hrází
  - procesy typu lahare (kamenné a bahenní proudy)

Datum zadání: 10.11.2010

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Podpis vedoucího práce: …………………………..

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Abstract

Glacial hazards such as ice or rock avalanches, debris flows, jökulhlaups or glacial lake outburst floods threaten lives and livelihoods of people. They may grow to unexpected magnitude, travel very long distances and afflict vast areas. To prevent loss of life and human installation damage, risk analyses need to be assessed for hazardous regions. There are various methods to gain information on slope stability, geology of moraine dam or loose debris availability. They can be divided into those used during terrain on-site research and methods of remote sensing. Based on processed data a risk analysis is created and mitigation measures are carried out if necessary.

Keywords

glacial hazards, moraine-dammed lake, risk analysis, outburst flood, high mountain areas, debris flow

Abstrakt

Glaciální rizika jako jsou laviny, kamenné a suťové proudy, výron vody z ledovce nebo povodeň z průvalového jezera ohrožují životy lidí i jejich obživu a majetek. Mohou se vyvinout do neočekávaných rozměrů a zasáhnout i vzdálená rozsáhlá území. Pro tyto regiony je nutné vypracovat rizikové analýzy, aby se zabránilo ztrátě života a škodě na majetku. Existují různé metody získávání informací o stabilitě svahu, vnitřním složení morénové hráze nebo dostupnosti uvolněné sutě. Lze je rozdělit na ty používané během terénního průzkumu a metody dálkového snímání. Na základě zpracovaných dat je vytvořena riziková analýza, z které případně vyplývá nutnost provést zmírňující opatření.

Klíčová slova

glaciální rizika, jezero hrazené morénou, riziková analýza, průval, vysokohorské oblasti, suťový proud

Contents

List of Figures

List of Tables

List of Abbreviations

GLOF – Glacial Lake Outburst Flood

NIR – Near Infra-Red

SWIR – Short Wave Infra-Red

TIR – Thermal Infra-Red

TM – Thematic Mapper

ASTER – Advanced Spaceborne Thermal Emission and Reflection radiometer

SPOT – Satellite Pour l'Observation de la Terre (satellite for observation of the Earth)

DEM – Digital Elevation Model

V-NIR – Visible to Near Infra-Red

LiDAR - Light Detection And Ranging

DTM – Digital Terrain Model

GIS – Geographic Information System

NDWI – Normalized Difference Water Index

GPS – Global Positioning system

GPR – Ground Penetrating Radar

SP – Spontaneous Polarization

ERT – Electrical Resistivity Tomography

1 Introduction

In high mountain areas all over the world natural catastrophic processes are often linked to glaciers and formations created by them. Glaciers have always posed a threat to people living within a relative proximity of glaciated valleys and mountain peaks and these were aware of the danger they are in. Nowadays human settlements and installations such as hydropower plants, infrastructure, teleferics and leisure amenities, sprawl to higher altitudes and thus increase the risk of potential catastrophe.

According to John M. Reynolds, any glacier or glacier-related feature or process that adversely affects human activities, directly or indirectly, can be regarded as a glacial hazard (Reynolds, 1992). Glacier fluctuations – surges and retreats, extreme meteorological events and climate warming, earthquakes and volcanic eruptions, these all may trigger any glacial hazard and cause serious damage over large areas. Ice or rock avalanches, debris flows, glacial lake outbursts and others may be so destructive due to low awareness of near-by living communities and local authorities, often uneasy foreseeability and the fact that one process can trigger another one. These chain processes are of much greater magnitude than expected. A minor ice avalanche that falls into a glacial lake produce a displacement wave which overflows a moraine dam and initiate its erosion, this leads to a dam failure and lake outburst, entrainment of loose sediment later changes flood to more dangerous debris flow (Figure 1). Therefore a chaining of such processes should always be taken into account when making a hazard assessment.

Unfortunately, most authorities are often not willing to react until such a disaster takes place in their town or territory and jeopardize lives and livelihoods of local inhabitants. Risk analysis is necessary for determination of zones that have high likelihood to be hit by potential hazard and those that are safe. Although such analysis is impeded by incomplete understanding of the processes involved and the episodic nature of related events, it is usually semi-quantitative and based on simple glaciological, geomorphological, hydraulic principles and experiences gained from previous events (Huggel et al., 2004a). However, conditions in glaciated high mountain regions around the world vary significantly (there are differences in seasonality, precipitation, morphology, geology, seismic activity etc.), that is why an assessment procedure must be applied to one specific region and result from experiences and event characteristics from this region. A method of risk analysis successfully used in the Swiss Alps (Huggel et al., 2004a) will not be suitable for Asian mountains of Tien Shan or Canadian Cordillera in British Columbia (McKillop and Clague, 2007). Applying an inadequate method could have immense impact on delineation of hazard zones and thus threaten safety of local inhabitants.

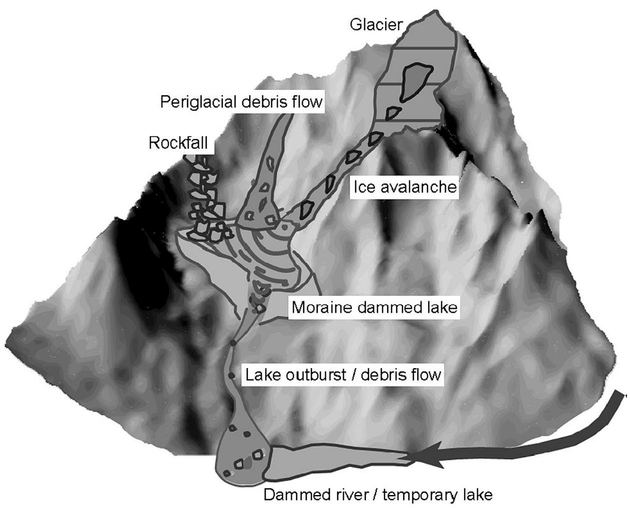

Fig. 1. Schematic overview showing potential interactions of hazardous processes.
Source: Huggel et al., 2004a.

In the first part of this thesis a review of glacier and glacier-related hazards with a focus on glacial lake outbursts will be presented. Glacier hazards involve the direct action of ice and/or snow, i.e. ice avalanches, glacier outburst floods or glacier surges. Glacier-related or indirect glacial hazards are a secondary consequence of a glacial process and include floods from outburst of moraine-dammed glacial lake or slowly evolving water resource problems as a result of glacier retreat and climate change (Richardson and Reynolds, 2000a). Even though these and other potential hazards are described in the following text individually, it should be emphasized that when making a risk analysis for a certain mountain area all potential triggers and possibly triggered processes must be considered as a whole.

Glacial lake outburst is one of the most dangerous and destructive glacial hazards with volumes of millions m^3 and surprisingly long travel distances (tens of km). Such a volume of water can easily entrain sediment downstream the breached lake and evolve into a debris flow. These two phenomena are very often connected since retreating glacier leaves behind vast amount of loose sediment on a valley-floor and upstream a glacial lake originates at a snout of the glacier (Figure 2). Peak discharges are therefore mainly influenced not only by the lake volume but also by sediment available in the flood path.

In the second part I would like to introduce the most important risk analysis methods and procedures. Hazard assessment for glaciated regions has become essential in the last decades as the number of those living within reach of ice avalanches or glacial lake outbursts rises. Monitoring of potentially dangerous glaciers and lakes has traditionally been based on field surveys but nowadays remote sensing turns out to be very helpful tool in identifying potential hazards especially in areas with limited access (Quincey et al., 2005). Estimates of potential glacier hazards can be summarized either verbally or graphically (i.e. in form of a map), depending on the certain situation (Haeberli et al., 1989). At the end of the second part a few assessment procedures for glacial hazards will be presented.

Fig. 2. Petrov Lake from the moraine dam towards the Petrov glacier.
(Photo M. Šobr; source: Janský et al., 2010)

2 Glacial hazards

Glacial hazards include lots of processes directly or indirectly linked to glaciers. They can be divided into groups based on a time scale during which such an event happens – minutes (ice/ rock avalanche), hours (glacial lake outburst flood), months-years (glacier surge) or decades (glacier fluctuation) (Richardson and Reynolds, 2000a). Another possibility is presented in Table 1, where glacial hazards are grouped into three main categories: mass movements, glacier-related floods and glacier length and volume changes (Quincey et al., 2005).

2.1 Locations

Glaciers are distributed not only in polar and temperate areas, but also in tropical zone and around the equator. However, not all of them covered up in this project since it concentrates on glaciers of high altitudes together with those where glacier-related processes may have negative impact on lives and livelihoods of people living within glacier proximity.

From European mountains it's only in the Alps (W. Haeberli, C. Huggel, S. D. Richardson, A. Kääb, N. F. Glasser and others) where studies are carried out mostly in Switzerland, less in Italy. The most significant potential hazards include ice avalanches, debris flows and moraine-dammed lake outbursts following glacier recession.

Moving eastwards, there are the Caucasus Mountains, an imaginary borderline between Europe and Asia, where mostly rock and ice avalanches and debris flows take place (A. Kääb, Desinov, L. V.)

The Tien Shan Mountains spread mostly in Kyrgyzstan where moraine- and ice-dammed lakes pose a threat to local people and jeopardize even the capital of this country – Bishkek (B. Janský, S. Yerokhin, C. Mayer, M. Dyurgerov, A. A. Grigoriev).

The highest mountain chain in the world – Himalayas and Karakoram, provides convenient conditions for developing potential hazards of high magnitude. Glacier-dammed lake outbursts associated with glacier surges or outburst floods from moraine-dammed lakes (GLOFs) are typical for this region with more than 8,000 m high peaks and steep slopes (J. M. Reynolds, S. D. Richardson, M. J. Hambrey, D. J. Quincey, D. I. Benn, K. J. Hewitt, M. Nakawo, S. R. Bajracharya, P. K. Mool and others).

New Zealand's glaciers in the Southern Alps such as Tasman Glacier and Franz Josef Glacier are studied by M. P. Kirkbride, C. R. Warren, B. Anderson, I. Owens or T. R. H. Davies. Another temperate glacier region on southern hemisphere is the Patagonia (Casassa, G., Rivera, A., N. F. Glasser, M. J, Hambrey, M. Aniya and others). There are many glaciers in the Ands south of 46° S fed by high precipitation from the Southern Westerlies – annual precipitation here can be 10,000 mm water equivalent, and as a result, the western glaciers are very dynamic (Bennett and Glasser, 2009).

A very closely observed glaciated region is the central part of South American Andes – Cordillera Blanca in Peru. Places of potential major ice or rock avalanches (as the one from Nevado Huascarán, May 1970, Lliboutry et al., 1977), moraine-dammed lake outbursts or debris flows are detected (B. Hubbard, E. Hegglin, J. M. Reynolds, M. Zapata, G. Plafker, G. E. Ericksen) and mitigation measures such as lake-level lowering, dam construction and creation of drainage tunnels are applied here.

Moving thousands of kilometers northward, there is a glaciated region of Cascade Range and Coast Mountains (J. J. Clague, S. G. Evans, O. Hungr, I. Blown, M. Church, J. A. Kershaw). Moraine-dammed lake outbursts in British Columbia have caused only minor damage so far but the likelihood that people or their installations will be impacted increases with further development (mining, forestry, hydro plants, tourism) and settlement of this region (McKillop and Clague, 2007).

Alaskan glaciers have high rates of snowfall and ablation which makes them some of the fastest advancing glaciers with velocities up to 500 m per year (Bennett and Glasser, 2009). Region of Alaska has also a distinctive concentration of surging glaciers such as Variegated Glacier and Black Rapids Glacier that have been studied to yield information on the cause of surge-type behaviour (Bennett and Glasser, 2009). Scientists concerned with this region are for example B. Kamb, C. F. Raymond, O. Eisen or N. F. Humphrey.

Table 1. Types of glacial hazards. Source: Quincey et al., 2005.

Hazard types		Description	Examples	References
Mass movements	Ice avalanche	Sudden mass movement of ice down slope. Starting areas classified as ramp- or cliff-type.	Mattmark, Switzerland, 1965. Eighty-eight dam construction workers killed.	Margreth and Funk, 1999
	Rock avalanche	High velocity (90–350 km/h) transport of fractured rock mass, often starting as a rock fall/slide on steep slopes. Triggered by freeze-thaw cycles (permafrost degradation), seismicity, or stress release following glacier retreat. Also known as sturzstrom.	Nevado Huascarán, Peru, 1962 and 1970. 18–23 000 killed in the 1970 event.	Lliboutry et al., 1977
			Kolka Glacier, Caucasus, Russia,2002. Avalanche from glacier headwall; over 120 people killed.	Kääb et al., 2003
	Debris flow	Typically a slurry of mixed grade soil and water. Commonly triggered by ice/rock avalanches and/or glacier/ glacial lake floods. In S. America known as aluviones. (sing. aluvión).	Nevado Salcantay, Peru, 1998. Failure of saturated proglacial sediments. Hydropower plant destroyed (cost $160 mil.).	Rickenmann, 1999
Glacier-related floods	Glacier outburst	Catastrophic discharge of water from the subglacial or englacial system. Often triggered by geothermal heating (jökulhlaup), opening of englacial channels at the start of ablation season or intense rainfall.	Grímsvötn jökulhlaup, Iceland, 1996. Peak discharges of 34 000 $m^3.s^{-1}$ reported. Damage to infrastructure.	Guðmundsson et al., 1995; Russell et al., 1997
			Mt Rainier, USA, frequent. Damaged infrastructure/ property	Walder and Dreidger,1995
	Glacial lake outburst flood (GLOF)	Catastrophic flood from the breaching of a moraine dam. Term used in Himalayan regions (synonymous French term débâcle).	Zyndan lake, Kyrgyzstan 2008	Narama et al., 2009; Janský et al., 2010
			Luggye Tsho, Bhutan, 26 casualties, 200 km runout.	Richardson and Reynolds, 2000a
	Ice -dammed lake outburst	Catastrophic flood from the failure of an ice dam. Often occurs periodically from the same lake.	Keyajir Lake, Xinjiang, China, every 1–4 years.	Zhang, 1992
			Ape Lake West, into Noeick river, Canada, 1984.	Jones et al., 1985
Glacier length and volume changes	Glacier fluctuations	Inundation of land by ice, or water resource shortages due to wasting of small glaciers.	Glacier Chacaltaya, Bolivia, contemporary glacier wastage.	Ramirez et al., 2001
	Glacier surge	Short-lived sudden increase in velocity, of an order of magnitude, often expressed as an advance.	Chiring Glacier, Karakoram, Pakistan.	Hewitt, 1998
			Ghiacciaio del Belvedere, Italian Alps, 2000–2002.	Haeberli et al., 2002

2.2 Types of glacial hazards

2.2.1 Ice avalanches

Ice avalanche is probably the most well known hazard in mountain areas. They occur when ice breaks off a steep glacier and under the influence of gravity it falls down-slope and gradually shatters into small pieces (Alean, 1985). Two main types of idealized starting zones can be identified (Salzmann et al., 2004):

- type 1 starting zones have a fairly large area of bedrock with a relatively constant slope;
- type 2 – the glacier develops a near-vertical cliff, typically 30-50 m high, from which ice breaks off when the cliff becomes too steep or even overhanging.

If runout distance of an ice avalanche is to be estimated, the volume of the falling ice must be known (Alean, 1985). These starting zones are usually called ramp-type and cliff-type, respectively (Figure 3). Ramp-type glacier is potentially hazardous when the surface slope exceeds 25°, or 45° for cold-based glaciers; concerning cliff-type glacier an ice break-off is always expected (Huggel et al., 2004a).

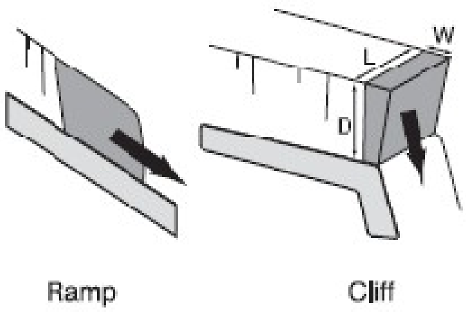

Fig. 3. Types of avalanche starting zones.
To determine the volume of potential break-off, width (W), length (L) and thickness of cliff-type glacier is needed. Source: Huggel et al., 2004a.

Runout distances of ice avalanches are usually short compared to those attained by glacier floods. However, in combination with rock falls or snow avalanches, it has the potential to cause especially far-reaching disasters, such as catastrophe of Huascaran (Cordillera Blanca) in 1970 with more than 18,000 casualties (Plafker and Ericksen,

1978) or Kolka-Karmadon (Russian Caucasus) in 2002 with 150 people killed (Kääb et al. 2003) (Salzmann et al., 2004).

2.2.2 Glacier outbursts

Glacier outburst is another type of glacial hazard described by Richardson and Reynolds (2000a). It refers to a rapid discharge of water under pressure from a glacier. Floodwaters can be released either subglacially where a pond of melting water formed near the base of the glacier or englacially through system of tunnels or vertical shafts called moulins inside the glacier. There are three recorded mechanisms by which water may burst from a glacier: the rupture of internal water pocket, the progressive enlargement of inner drainage channels or catastrophic glacier buoyancy with sub-glacial discharge. Devastating outbursts of invisible water pockets are quite rare although they can obviously occur in glaciers with various morphological characteristics. Extreme values of outburst volumes and peak discharges measured in the Alps are approximately 1-2 millions $m^3.s^{-1}$ and 100-200 $m^3.s^{-1}$, respectively (Haeberli et al., 1989).

When a geothermal activity triggers a glacier outburst, an Icelandic term *jökulhlaup* is used. Bennett and Glasser (2009) describe it as a wholly ice-derived catastrophic event that tends to produce high-magnitude, short-duration floods. The geothermal heat incite melting of ice at the base of the glacier and when the hydrostatic pressure of meltwater exceeds the constraining cryostatic pressure there is a burst through the ice. A prominent example is Grímsvötn, subglacial lake beneath Vatnajökull ice cap in Iceland. Here water builds up subglacially above a volcano and then drains within few hours through a 50 km long tunnel. The average volume of water discharge is 3-3.5 km^3. During the eruption of the volcano in 1996 a major jökulhlaup was generated with a peak discharge 45,000 $m^3.s^{-1}$. However, the term *jökulhlaup* can also be used simply as a synonym of a glacier flood.

2.2.3 *Debris flows, lahars*

When a sediment proportion in floodwaters increases to more than 20 % it becomes a hyperconcentrated flow, with more than 47 % of sediment it is a debris flow (Hyndman and Hyndman, 2009). If mud or clay dominates the solids choking the flowing mass, it is a mudflow; if volcanic material, it is called a lahar.

Active volcanoes are notorious for spawning lahars, especially during eruptions. Hyndman and Hyndman (2009) describe how the flow of hot ash and rocks rapidly mixed with melting ice and snow form dense slurry that collects more volcanic debris and even large boulders as it moves downslope. Even long after the last eruption the amount of ash on the volcano flanks provides enough material for catastrophic lahars which may be triggered by intense precipitation. Repeated lahar events were observed for example in Mexico from Iztaccíhuatl and Popocatépetl volcanoes (Schneider et al., 2008).

Debris flows are a widespread hazard most common in high mountain areas and along major active faults. Hyndman and Hyndman (2009) claim debris flows differ from stream flows in the amount of solid grains suspended in the flow. Since debris flow consists of coarse debris, rocks, water and fine-grained particles it can be twice the density than water. This allows picking up and carrying large boulders and moving at higher velocities than clear water. The water and grains move as a single viscous or plastic mass, with water and sediment moving together at the same velocity. Internal shear strength is high so shear is concentrated at the base and edges of the flow. The typical starting zone is on steep deep-seated slope with gradients of 25°-38° (Zimmermann, 1990). Debris flows often begin with heavy precipitation, rapid snow/ ice melting, sometimes the initial movement is a landslide. The most dangerous trigger is a flood from a glacier or glacial lake as the large volume of water is able to entrain huge amount of sediment. Values of eroded sediment volume per channel length unit (m) of up to 700 $m^3.m^{-1}$ have been recorded in alpine moraine-dam breaches (Huggel et al., 2004a; Haeberli et al., 1990). Quincey et al. (2005) claim that when the slope steepness decrease to 10 degrees debris flow thins and spreads out on a fan. Debris flow rapidly loose velocity if either the water or debris component is removed. Volume and destructive force of debris flow depends upon the initial starting volume, the runout slope gradient and the amount of erodible material along the runout route.

2.2.4 Glacier fluctuations

Glacier fluctuations are described in detail in Bennett and Glasser (2009) and include advances and retreats of a glacier snout with average speed of 3-300 m per year. This is called the "normal" mode of glacier flow. The second one is "fast" and refers to glacier surges which attain velocities 10-100 times greater than the common advance. However, the "fast" flow mode is limited by the amount of ice available in the accumulation zone. Once this ice has been exploited, the flow returns to "normal".

Haeberli et al. (1997) point out that glacier advances, although very slow compared to other processes in high mountains, can cause damage to man-made structures or lead to temporal damming of a stream and creation of an ice-dammed lake which constitute a menace to downstream settlements. Retreating of a glacier induces a potential hazard rather indirectly by stress redistribution within adjacent valley flanks which leads to slope instabilities and rock falls (Monte Rosa, Italian Alps; Fischer et al., 2006), by causing water resource problems for millions of people or by uncovering a significant volume of loose debris that is a source of debris flows for decades after the actual retreat. According to Bennett and Glasser (2009) glaciers are constantly responding to changes in climate as they influence their mass balance. If accumulation is greater than ablation, the balance is positive (either increased accumulation or reduction in ablation) and the glaciers grow, ice margin advances. Conversely, if ablation prevails it leads to thinning of the glacier and retreat of its margin. The authors conclude, however, that the link between climate, mass balance and glacier response is complex and may not be always so simple.

2.2.5 Glacial lakes

Types of glacial lakes can be distinguished according to the type of their dam to moraine-dammed, ice-dammed and dammed by a rock step (Huggel et al., 2004a). There are also more complex classifications of glacial lakes, for example the one by Janský et al. (2006). Those dammed by a rock step are considered the least dangerous because the belt of rocks is in most cases resistant to glacier erosional activities and water flows out the lake in the lowest point of the step (Janský et al., 2006).

Ice-dammed lakes (Figure 4) tend to occur where glaciers have advanced across drainage routes (Ding and Liu, 1992). These lakes can drain by flotation of the ice dam and subglacial discharge, by erosion of an overflow channel into the dam surface, by ice marginal drainage where the glacier dam meets valley side or by mechanical failure of the dam (Richardson and Reynolds, 2000a). An example of an ice dam rupture is the Hubbard Glacier in Alaska in 1986 – about 5.4 km^3 of water from Russel Fiord broke through the dam at peak discharge over 100,000 $m^3.s^{-1}$ (Mayo, 1989). On the other hand, Swiss glacier-dammed lake Gornersee drains subglacially almost every year within a few days (Huss et al., 2007)

Moraine-dammed lakes are the most closely observed due to their high hazard potential. In comparison with ice or bedrock damming, the morainic one is the least stable (Costa and Schuster, 1988). This type of glacial lake will be described in detail in the next section.

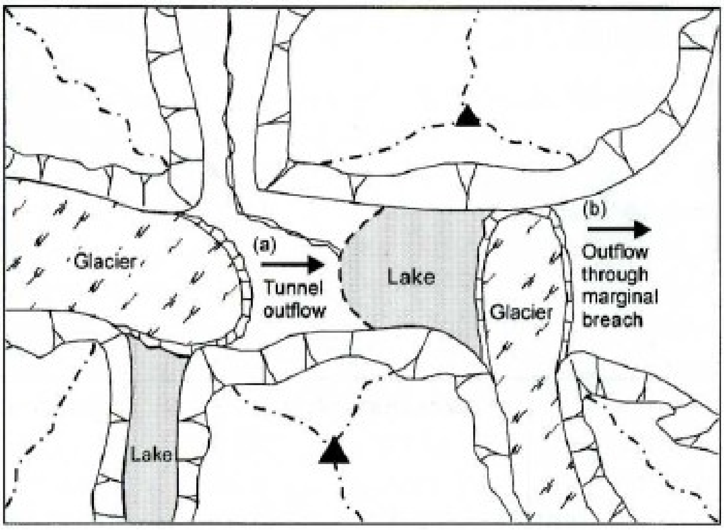

Fig. 4. Two styles of ice-dammed lakes and possible drainage.
Source: Richardson and Reynolds, 2000a.

2.3 Moraine-dammed lakes

Failure of a moraine dam is one of the most feared glacial hazards in high mountain areas because the water volume is often very large and the dam may be breached relatively quickly. Outburst floods from moraine-dammed lakes have been reported in many parts of the world – in the Alps (Huggel et al., 2002; Haeberli et al., 2001), in Himalayas and Karakoram (Richardson and Reynolds, 2000a; Reynolds, 1999; Hewitt, 1982; Mool, 1995), in Tien Shan (Mayer et al., 2008; Yerokhin, 2003), Andes (Carey, 2005; Harrison et al., 2006) and Coast and Rocky Mountains (Clague and Evans, 2000; Blown and Church, 1985). Many existing moraine-dammed lakes grow in size and their dams degrade and so the potential for high-magnitude outbursts increases (Bajracharya and Mool, 2009).

2.3.1 Formation and setting

Development of moraines usually dates back to the eighteenth and nineteenth century when cool climate (the "Little Ice Age") allowed glaciers to advance in some parts of the world (Grove, 1988). Since then retreating glaciers leave behind moraines which often serve as a dam. Richardson and Reynolds (2000a) allege that moraine-dammed lakes form either by meltwater collecting behind these moraines or by coalescence of supraglacial ponds to large lakes dammed by debris covered stagnant ice. The latter happens when long valley glaciers with low inclination are thinning but maintaining relatively stable terminus position. Some of the largest Himalayan lakes formed this way, for example Tsho Rolpa (3.2 km long) or Thulagi. Smaller lakes are associated with steeper glaciers where meltwater is drained to proglacial positions where it's prevented from further advancing by terminal moraine. Clague and Evans (2000) distinguish various settings of such lakes. Most of them occur in cirques or behind terminal moraines in upper reaches of narrow valleys. Less common setting is behind lateral moraines. Glacial lake can form in trunk valley where ice flowing out of tributary valley deposited the lateral moraine or in tributary valley dammed by lateral moraine of glacier in trunk valley. There are also recognized two types of lakes concerning their outflow: the first one has no surface overflow channels, the lake lies well below the rim of a dam (it has high freeboard) and the drainage is realized by seepage through the dam; the second one has an overflow channel across the glacial sediments (Costa and Schuster, 1988).

2.3.2 Structure of a moraine dam

Characteristics of morainic dams allege their stability and ability to withstand various disturbances from their surroundings. Clague and Evans (2000) claim that geometry of the dam is essential when assessing the likelihood of lake outburst. The dam may consist of one or more ridges separated by swales. The height of the dam together with its width is often combined into a width-to-height ratio that demonstrates the dam stability. In contrast to landslide dams, morainic dams have very steep flanks (about 40°) and are comparable to constructed dams (Figure 5). The higher and narrower the dam is, the bigger threat the lake poses. The height of most morainic dams are few tens of meters, however, some are more than 100 m high, thus the volume of water impounded by such moraine can be immense.

Dam material, as it's described in Clague and Evans (2000), is mostly poorly sorted and may contain fine sediments as well as large boulders. Some moraines consist largely (up to 80 %) of coarse, blocky and bouldery material whereas others are of silty and sandy diamiction and sandy gravel. Buried ice can constitute a substantial part of the moraine dam which are then called ice-cored. A discovery of an ice core within a moraine dam signifies another increase of potential hazard since the ice is progressively melting and thus destabilizing the dam. Thermokarst processes are demonstrated mostly by subsiding of moraine dam. Average rates of up to 3 m per year were measured for Imja Tsho, Nepal, and even higher for Tsho Rolpa (Richardson and Reynolds, 2000a).

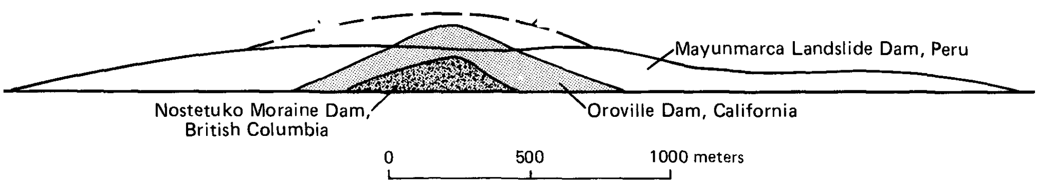

Fig. 5. Cross-section of landslide, constructed and moraine dam. Note the similar slope steepness of Nostetuko moraine dam and large constructed earth-filled Oroville dam in contrast to a landslide dam Mayunmarca in Peru. Source: Costa and Schuster, 1988.

2.3.3 *Triggering mechanisms*

Potentially dangerous moraine-dammed lakes require a trigger or more trigger mechanisms to initiate a flood (Richardson and Reynolds, 2000a). However, the exact mode of failure is not known for many lake outbursts. For example in Canadian Cordillera the cause of only two of the nine moraine-dam failures was determined with certainty (Clague and Evans, 2000). On the contrary there are many comprehensive studies of moraine dam failures, such as the one by Blown and Church (1985) who described the breach of Nostetuko Lake in British Columbia, Canada, or dam failure of Lugge Tsho, Bhutan Himalaya (Watanbe and Rothacher, 1996).

Over 53 % of documented outburst floods in the Himalayas in 20th century were triggered by displacement waves from ice avalanches from hanging or calving glaciers (Richardson and Reynolds, 2000a). A displacement wave can be also caused by a landslide or rock fall/ avalanche. In some cases large displacement waves (with heights of more than 10 m, Plafker and Eyzaguirre, 1979) are the primary source of the flood waters, in others the waves are smaller and do not displace much water. Nevertheless, they initiate incision of the moraine dam that can progressively lead to dam rupture as in the case of Queen Bess Lake (Clague and Evans, 2000).

Haeberli et al. (1989) mention that proglacial lakes can suddenly empty by retrogressive erosion of the spillway or by progressive groundwater flow – piping. These processes require a high water level (as for piping higher hydrostatic pressure is needed). Piping can gradually destabilize the dam so that even less exceptional event may initiate the failure. Moraines consisting of rather fine-grained material (silty and sandy diamicton, sandy gravel) can be more prone to piping than bouldery ones as groundwater may entrain silt and sand and carry them out of the moraine (Clague and Evans, 2000).

Another type of failure is overtopping and breaching caused by excessive runoff due to increased inflow during periods of rapid glacier retreat, jökulhlaup, rapid snowmelt or intense rainfall (Costa and Schuster, 1988). Lliboutry et al. (1977) confirmed significance of these climate-driven triggers as all precisely dated moraine-dam failures occurred during the rainy season (from October to April) in the Cordillera Blanca, Peru.

Moraine dams containing ice cores or interstitial ice are very prone to failure. The buried ice may melt if climate warms, causing the moraines to subside and eventually fail (Richardson and Reynolds, 2000b). Thaw flows and slumps can further weaken the moraines and Clague and Evans (2000) remark that melting ice core can also reduce the height of the freeboard and therefore amplify the risk of overtopping the dam by displacement waves. Ice-cores also provide potential pathways for lake water seepage through the moraine causing disturbed dam integrity (Richardson and Reynolds, 2000a).

Collapse of the moraine dam during an earthquake or inappropriate engineering works are last but not the least possible causes of failure. In addition, an earthquake may initiate settlement within the moraine or trigger an ice/ rock avalanche generating waves that overtop the dam (Clague and Evans, 2000).

2.3.4 Glacial lake outburst floods

This phenomenon often referred to as GLOFs is considered to be the most dangerous and devastating glacial hazard with strikingly long travel distances. Moraine-dammed lakes are prone to sudden failure as the stability of the dam and adjacent slopes is usually low. The probability of GLOFs occurrence has risen in many mountain areas due to the temperature increase and retreating of glaciers (Bajracharya and Mool, 2009). This catastrophic outburst from a moraine-dammed proglacial lake leaves behind a typical well developed alluvial fan – an evidence of former GLOFs. Bennett and Glasser (2009) claim that peak discharges were calculated as 60 times greater than seasonal floods from snow or glacier meltwater. Therefore these floods are immensely powerful and may erode and transport large quantities of sediment for long distances. In the Himalayas floods from glacial lakes may reach an incredible magnitude (because of the steep terrain and high differences in altitude) and in some cases even cross the borders to a neighboring country. Discharge rates of 30,000 $m^3.s^{-1}$ and runout distances of more than 200 km have been recorded in this region.

The size and style of a flood depends upon many factors, including the volume of water released from the lake, the height, width and structure of the dam, failure mechanism and downstream topography and sediment availability (Costa and Schuster, 1988). Clague and Evans (2000) conclude that failure of narrow high dams generates higher peak discharge than a low wide dam and moraine consisting mostly of sand and gravel tends to fail more rapidly than a dam of coarser and blocky material. Failure mechanism may also influence the flood size, for example, large displacement waves produce large-amplitude, low-duration floods and on the other hand slow incision commonly causes smaller peak discharges. As the initial burst through the moraine is often explosive, the flood can pick up large boulders weighing even 200 tons and carry them several hundred meters (Richardson and Reynolds, 2000a).

2.3.5 Cases of lake outbursts

Comprehensive documentation on GLOFs is still quite scarce (Bajracharya and Mool, 2009). Richardson and Reynolds (2000a) confirm that it is difficult to identify the trigger that caused the moraine dam breach and flood wave often destroys the recording instruments as it may reach amplitude of 2 m even 200 km downstream from the lake. However, the GLOF from Luggye Tsho in Bhutan in October 1994 is well documented, since a complete hydrograph from 100 km downstream of the flood source is available (Figure 6). It shows the 2-meter increase in water level of the stream within a very short period of time and then relatively slow decrease to normal state that lasted approximately 20 hours.

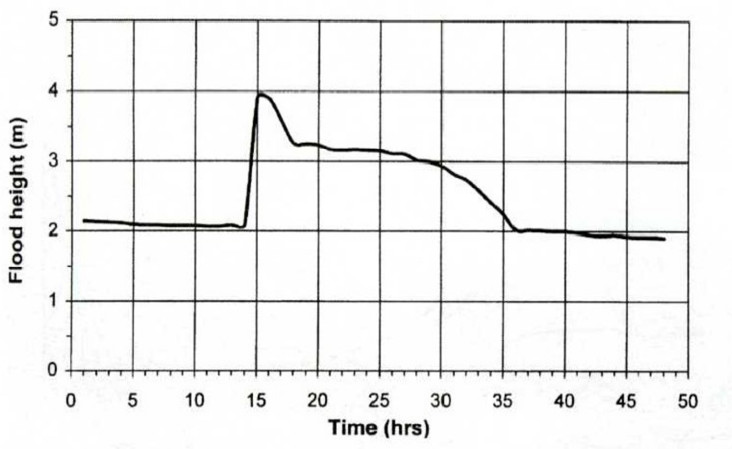

Fig. 6. Flood hydrograph for the GLOF from Luggye Tsho, Bhutan, in 1994.
Source: Richardson and Reynolds, 2000a.

Another example of a major glacial lake outburst flood is the 1985 flood from Dig Tsho located in Khumbu area, eastern Nepal, that was described by Vuichard and Zimmermann (1987). As a trigger mechanism a loosening of 150,000 m^3 of ice from a hanging Langmoche glacier was assessed. This ice mass plunged into the lake generating a displacement wave that overtopped the dam. The flood lasted for 4-6 hours, peak discharge of at least 1,600 $m^3.s^{-1}$ and total flood volume of 5 million m^3 of water were reported. The most significant impact of this GLOF was the complete destruction of a new hydropower station at Thamo, 30 houses, 14 bridges and heavily damaged trail network. The social, economic and environmental consequences were devastating – villagers even lost their subsistence when the forest and hectares of valuable arable land were hit by the flood. Even though Dig Tsho was stabilized, the 1985 surge eroded the river valley and the active scars threaten with landslides and further erosion. Bajracharya and Mool (2009) claim that at least one major GLOF occurs every 3-10 years in the Himalayas. However, with rising temperatures and more variability in the climate, the frequency of GLOF events is expected to increase markedly in the near future (Haeberli, 1990).

3 Risk analysis methods

Glacial hazards such as ice avalanches, debris flows or glacial lake outbursts have threatened people and their installations since human activities spread to higher altitudes. It is fairly impossible to fully suppress these natural processes and so ensure safety for locals. However, it is also highly improbable for people to stop utilizing and exploiting these high elevated regions all around the world. Therefore, risk analyses ought to be carried out for such hazardous regions to determine the potential danger and implement suitable mitigation measures.

There are various methods of identifying potential hazards, monitoring their development and estimating the probable magnitude of such event. Usage of particular methods and their combinations change over time with future bringing new possibilities and technologies. Comprehensive procedures for making assessment of potential glacial hazards have been developed focusing on a certain high-mountain region (e.g. Huggel et al., 2004; McKillop and Clague, 2007).

Optical remote sensing techniques have become essential for monitoring and assessment of potentially dangerous glaciers and glacial lakes. It is an increasingly important tool as high-quality sensor technologies are emerging and new analytical techniques are being developed (Quincey et al., 2005). However, remote sensing may not always be able to detect features with utter certainty and accuracy needed for any reasons, not speaking of those below the surface. Terrain research methods, observations and measurements constitute a significant and indispensable part of risk analysis that often provides scientists with key information on studied phenomenon.

3.1 Remote sensing

Remote sensing proved to be very helpful in identifying potential hazards especially in areas poorly accessible for physical or political reasons. Contactless monitoring of such places in high mountains may be carried out more frequently than terrain research which is often more expensive. There are two types of remote sensing: air-borne and space-borne.

Quincey et al. (2005) suggest selecting the most appropriate data source depending on the temporal, spectral and spatial characteristics of the observed hazard. Temporal resolution of imagery is the minimum time between two consecutive scanning of the same place on Earth. It relates to the rate at which a certain hazard develops. For example, glacier surges may develop during few days or weeks and therefore require regular and frequent monitoring, whereas formation of a glacial lake takes years or decades so yearly observations are sufficient. For long-term monitored hazards the length of data archive is very important as the tendency and future development may be estimated.

Spectral resolution of a sensor is a major determinant of usefulness for certain applications. Spectral regions provide information on surface characteristics that can hardly be detectable in visible radiation. Near-infrared regions (NIR; 0.7-1.3 μm) show specific snow and ice parameters, such as degree of snow metamorphosis, or information on water turbidity, which can be used to recognize different origins of meltwater. Shortwave-infrared data (SWIR; 1.3-3 μm) are often used for automatic delineation of glacierized areas. Thermal-infrared data (TIR; 3-14 μm) can be used to monitor variations in water temperature, which often signify the potential for lake development.

Spatial resolution should be always selected in relation to the phenomenon that is intended to observe. For preliminary assessments medium spatial resolution sensors (5-20 m) provide suitable imagery as they are able to cover large areas with their wide image swaths. Detailed investigations can be carried out using data from high spatial resolution sensors (up to 5 m) which allow distinguishing of fine structure and small-scale changes.

3.1.1 Space-borne remote sensing

Satellite sensors may yield information independently of the political, topographic or financial restrictions. Data of medium resolution cover up to tens of thousand square kilometers by one scene and are becoming well accessible, cheap (few EUR/ km^2 or much less) and a repeated cycle of few days is often possible (Kääb et al., 2005). Satellite imagery of high mountain regions began to be archived in the 1980´s so the longest periods of acquisition are almost three decades, which is important in monitoring long-term changes within glacierized areas (Quincey et al., 2005). Landsat TM (Thematic-Mapper) has a long period of acquisition and is valuable for providing seven spectral channels, however, its spatial resolution of 28.5 m predestinate it solely for usage in first-order assessments (Huggel et al., 2004b). There are also optical sensors of high spatial resolution such as Quickbird and IKONOS. These have spatial resolution in the range of 1 m which makes them suitable for examination of surface morphology in detail, e.g. moraine dams or glacier crevasses. Medium-resolution elevation data can be obtained using space-borne sensors (IKONOS, ASTER, SPOT-5) and on its basis digital elevation model (DEM) may be created (Quincey et al., 2005). Smooth topography allows measurements with vertical accuracy of 18 m, steep terrain may cause severe errors of hundreds of meters (Kääb et al., 2002).

3.1.2 Air-borne remote sensing

Aerial photography has longer tradition than space imagery so the archives offer successions convenient for comparison and trend-monitoring of glaciers or lake formation. Spatial resolution is very high but one scene covers usually few or few tens of square kilometers, which is incomparable to satellite sensors (Kääb et al., 2005). Processing of the photographs allow relatively accurate mapping of high mountain terrain within visible to near infrared (V-NIR) spectral region. Fine results in vertical measurements are attained with LiDAR (Light Detection and Ranging) which is described by Scheidl et al. (2008). LiDAR is a widely used technology to generate digital elevation information for e. g. examination of morphology of alluvial fans (Cavalli and Marchi, 2008), estimation of eroded and deposited material after debris flows (Scheidl et al., 2008) or generally for generating digital terrain model (DTM). Rapidly pulsing laser (up to 133,000 pulses per second) is the basic component of the whole system, which works on a principle of firing a laser from an aircraft and measuring the time that takes the pulse to be reflected from the Earth's surface back. Vertical accuracy of LiDAR can be as high as 0.1 m, even though it can decrease as the flying height of the aircraft or the slope of the terrain increases (Quincey et al., 2005).

3.1.3 Application on glacial hazard assessment

Remote sensing is used in glacierized regions for monitoring of horizontal and vertical displacements as they often signify a potential hazard development. Basic parameters used for remote sensing identification of potential hazards are summarized in Table 2. Also Kääb et al. (2005) present remote sensing aspects of recognition of various glacial processes that may be hazardous. Risk for breaching of a moraine dam can be evaluated by remote sensing in contrast to glacier outbursts from englacial or subglacial drainage systems. Moraine-dammed lakes are easily detectable, time series are particularly useful for assessing dynamics and estimating of future development. Recognition of moraine dam characteristics (dam geometry, deformation, settlement, surface material) requires high-resolution and high-precision techniques. Monitoring of associated glacier (its geometry, surface type, thickness changes, velocity etc.) is also important as it may help assessing of the proglacial lakes evolution.

Glacier surges as well as stable advance or retreat can be tracked by high-frequency remote sensing; mass changes from repeat DTMs. Surge-type glaciers can often be recognized from deformed, "looped" moraines. Possible source areas of ice avalanches are searched depending on occurrence of steep glaciers through combination of spectral data with DTM. Also areas of potential debris flows that may accompany glacier floods or lake outbursts can be detected by remote sensing. With sufficient spatial resolution it's possible to estimate the availability of loose debris in a potential flood path and its slope.

Table 2. Basic parameters used for remote sensing identification of potential hazards.
Source: S. K. Allen et al., 2009.

	Glacial lake floods	Debris flows	Ice avalanches
Surface characteristics	lakes on/ at the margins of a glacier expanding lake area steep moraine-dammed lakes	debris accumulations occurring within (recent) glacial zones	steep glacial ice
Critical slope gradient	sediment entrainment and hyperconcentration: 10°	flow initiation: 25-38° (Hungr et al., 1984; Rickenmann and Zimmermann, 1993)	temperate ice: 25° cold ice: 45° (Alean, 1985)
Maximum probable runout	clear water flood: may exceed 200 km and attain angle of reach < 3° GLOF triggered debris flow: angle of reach 11° (Huggel et al., 2002; McKillop and Clague, 2007)	angle of reach 11° (Rickenmann, 2005; Rickenmann and Zimmermann, 1993)	angle of reach 17° (Alean, 1985; Huggel et al., 2004a)

Huggel et al. (2002) distinguish three levels of hazard potential recognition (here specifically glacial lakes), starting at a rather general level covering large areas and then focusing progressively on smaller areas. The first level comprises detection of glacial lakes in the studied area. In the second level the hazard potential of detected lakes is assessed. Simple detection is supplemented by information about the related hazards and GIS (geographic information system) modeling based on satellite imagery and DEM (digital elevation model). Figure 7 represents a second level output showing potential places of initiation of debris flows, ice avalanches and glacial lake floods. The third level is concerned with detailed investigations of potentially dangerous lakes determined in the second level. Such investigations are carried out for each lake separately, applying very high resolution remote sensing data, geophysical studies and other field work.

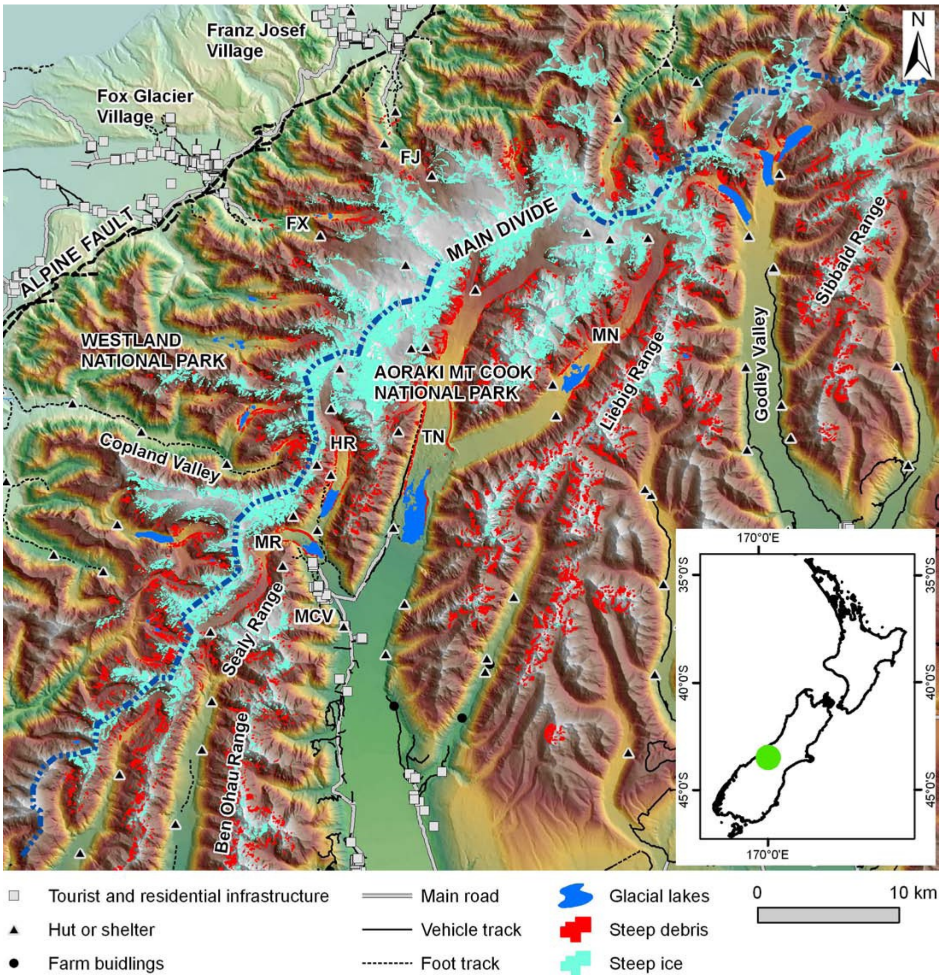

Figure 7. Map of Mount Cook region showing potential hazards. Ice avalanche (steep ice), debris flow (steep debris) and glacial lake outburst (glacial lakes). Source: S. K. Allen et al., 2009.

Although glacierized areas (Salzmann et al., 2004) and glacial lakes (Huggel et al., 2002) can be mapped automatically, several problems and inaccuracies may occur. Debris covered glacier snouts may be problematic as proglacial and supraglacial settings may have similar spectral response (Quincey et al., 2005). Casassa et al. (2002) demonstrated that fresh snow fall can cause a remarkable overestimation of a glacierized area and concluded that manual interpretation using stereo photography is still the most reliable technique for classifying glacierized areas.

Automatic detection of glacial lakes described by Huggel et al. (2002) is more effective even though problems may arise when self-shadowed areas are misclassified as lakes. Discriminating between water and other surface types is based on spectral reflectance differences. Water strongly absorbs in the near-infrared and middle-infrared wavelengths (i.e. 0.8-2.5 μm) and thus appears dark, whereas vegetation and soil have higher reflectance within these wavelengths and appear lighter. A normalized difference water index (NDWI) is used to enhance contrast between water and surrounding environment. Two spectral channels with maximum reflectance difference are used, a blue channel (maximum reflectance of water) and NIR channel (minimum reflectance of water), and they are compiled to this equation:

$$NDWI = \frac{B_{NIR} - B_{Blue}}{B_{NIR} + B_{Blue}}$$

where B is the spectral band (or channel).

NDWI values between -0.60 and -0.85 are typical for lake surfaces. Also other features relevant to the hazard assessment may be detected using various spectral channels. Vegetation, for example, is easily distinguishable due to its high reflectance in the NIR channel, and may yield information on dam stability and erosional activity of a moraine.

Remote sensing is very helpful concerning monitoring of surface features, however, it usually cannot aid in the identification of subsurface features (e.g. existence of subglacial lakes). Sometimes it is possible to identify them due to their surface expressions, such as thermokarst development, but this is not fully reliable (Quincey et al., 2005). Therefore, detailed investigations of subsurface features are carried out by various techniques during field works.

3.2 Terrain research

On-site measurements and observations are an integral part of the whole procedure of risk analysis; in some studies the data obtained during a terrain research are prevailing whereas in others data from remote sensing are more employed. There are various hydrological, geomorphological, geodetic and geophysical methods applied depending on the certain situation and the aim of the research. These methods often specify or confirm the not very precise information from remote sensing and they may yield crucial information on the subsurface geology.

3.2.1 Measurements and observations

Janský et al. (2008) described methods used during a terrain research of Petrov Lake and its moraine dam. Hydrological methods include bathymetric measurements realized with the aid of rubber dinghy and an echo-sounder with the accuracy for depths up to 50 m ranging from 10 to 30 cm (Figure 8). These measurements were systematically carried out on the lake and served to determination of the changes in depth and volume which have taken place during the past few years.

Next, physical and chemical parameters of lake water quality (temperature, dissolved oxygen, oxygen saturation, conductivity, salinity or pH) were measured down the vertical profiles. Hydrological measurements of all inflows and outflows should be done to calculate the lake water balance and fluctuations of water level. Climatic data, especially temperature and precipitation trends during the year, is also very important to monitor as the highest temperatures (and therefore ice/ snow melting) often occur together with increased rainfall which may raise lake water level and trigger its outburst (Figure 9). Meteorological stations installed in high mountain areas are often automated and send data in regular intervals directly to the researchers (Huss et al., 2007).

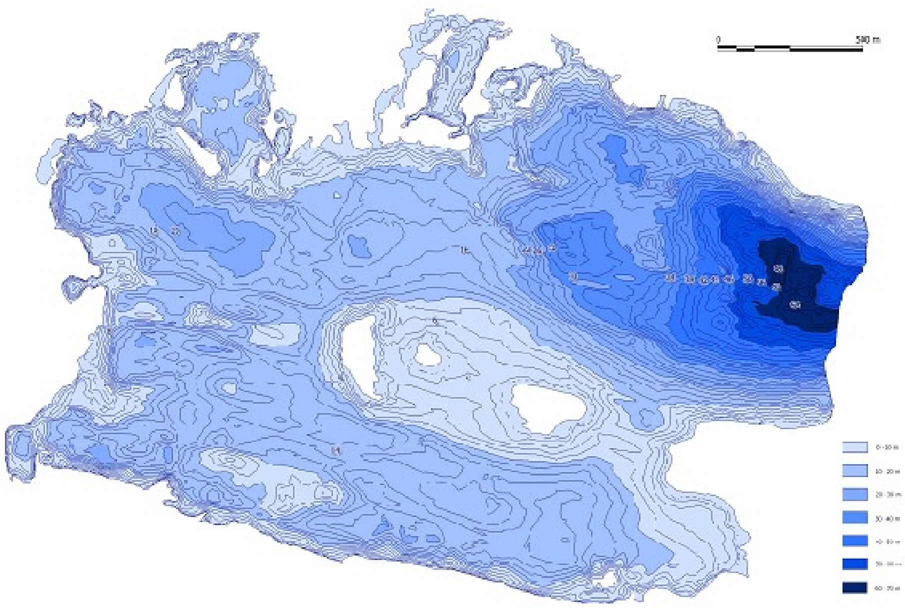

Fig. 8. Bathymetric map of Lake Petrov. Compiled from measurements undertaken in the years 2006 and 2009. Source: Černý et al., 2009.

Geomorphological methods include exploration of a dam structure, especially near the lake outflow as erosional processes may threaten the dam stability. Changes in morphology of the moraine dam should be monitored and compared with last investigation. If a glacier terminus is close to the lake, a survey of its margin is necessary, together with examination of crevasses and a rate of calving. Areas of subsidence are often closely monitored as they may be resulting from thermokarst processes and the dam may be destabilized. An accurate demarcation of a lake shoreline and glacier snout can be carried out either with total geodetic station (great accuracy but demanding and time consuming; not suitable for large lakes) or with GPS measurements (simple and fast but not so accurate; can be augmented by a satellite high resolution imagery).

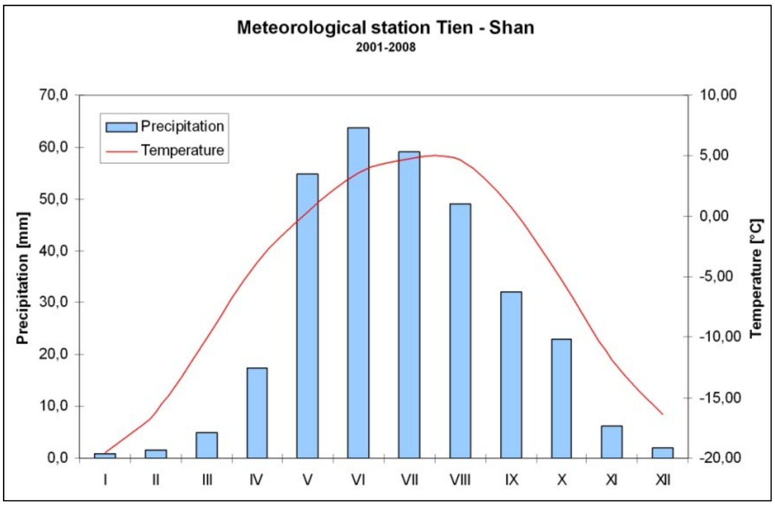

Fig. 9. Precipitation and temperature measured at the Tien Shan meteorological station 1930-2008.
Source: Černý et al., 2009.

3.2.2 *Geophysical methods*

Geophysical measurements can be very useful for a hazard assessment as they provide information on subsurface characteristics of a moraine dam. The aim of a survey is to reveal the existence of buried ice within the dam and to delineate the extent of the active zone (interstitial ice).

Černý et al. (2009) described geophysical methods used during the 2009 research of the Petrov Lake moraine dam. Ground-penetrating radar (GPR), spontaneous polarization (SP) and electrical resistivity tomography (ERT) are the main methods often applied to moraine investigation. Supplementary geophysical methods, including micro-gravimetry or monitoring of seismic activity, may also be helpful and yield additional data.

Ground-penetrating radar is a valuable technique for interpreting subsurface structure of a moraine and detecting frozen ground (Hinkel et al., 2001). It is often used in less stable part of a moraine where a stream flows from the lake as the incision may lead to breaching of a dam. GPR records reflections from boundaries between materials that have contrasting dielectric permitivity (ε) which is determined by ice/ water contents and characteristics of sediments.

The SP method can be used to identify leakage or percolation of water through the lake dam. It is predicted that leakages or intense melting of the dead ice within the moraine dam can be detected by the decrease in SP potentials. This method can also be used for monitoring changes in infiltration processes taking place near the lake outflow after its incision.

Pant and Reynolds (2000) used geoelectric methods as the means of delineating subsurface features with a high degree of spatial resolution. Especially useful is subsurface imaging or electrical resistivity tomography. As they mention, these methods are applicable within environmental, engineering, groundwater or geohazard investigations, so the study of glaciers, glacial lakes and natural dams is just one specific application. The valuable function is detection of frozen or melting ground, and areas of massive ice accumulation. To achieve the best possible results, the convenient condition for application of electrical resistivity (ER) method should be found. It is where the frozen material forms a large resistivity contrast with unfrozen material. The ERT method is often carried out at several transverse and longitudinal profiles and then a two-dimensional resistivity models for the measured data are generated (for example see Figure 10). It is assumed that the higher the ER values, the more ice content in the subsurface. Different ranges of electrical resistivity can be assigned to different types of material but they are approximate and may overlap with each other. However, there is no doubt in recognizing the dead ice distribution as it has exceptionally high resistivity to electric current flow (around 10^5 Ohm.m).

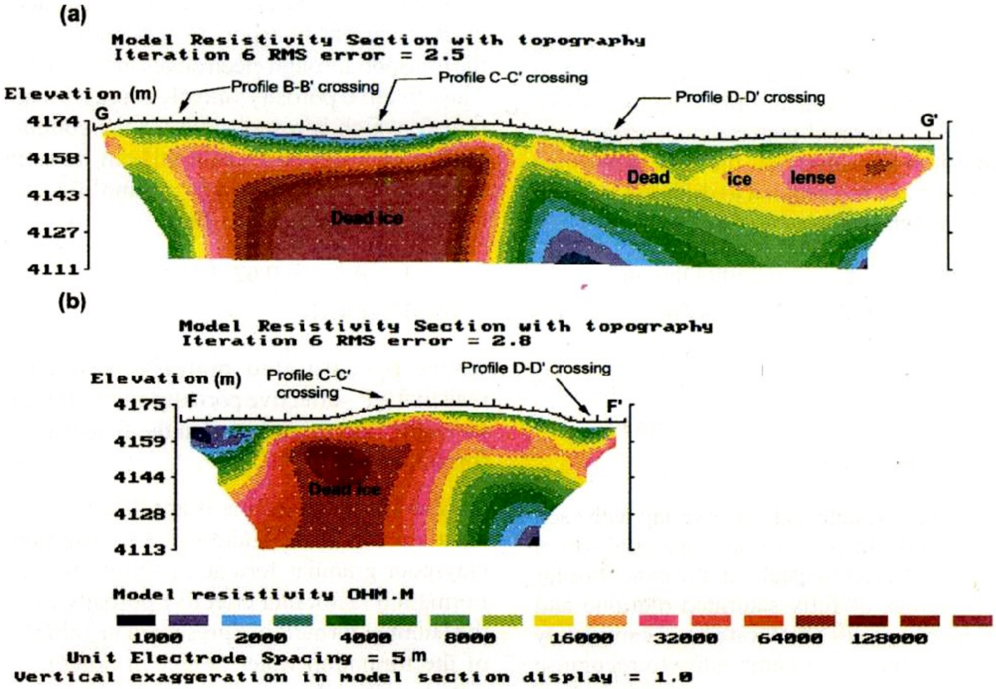

Fig. 10. Electrical images of profiles along the dam of the Thulagi Glacier Lake.
Source: Pant and Reynolds, 2000.

3.3 Procedures of hazard assessment

Different procedures of hazard assessment are applied for different high mountain areas around the world as the local conditions may vary significantly. Assessment procedures are mostly based on gained experience and historical cases within a certain region. I would like to present two methodologies both for first-order assessment of glacial lake outburst hazard. The first one was arranged by Christian Huggel, W. Haeberli, A. Kääb, D. Bieri and S. Richardson and is focused on glacial lakes in the Swiss Alps. The other one was compiled by R. J. McKillop and J. J. Clague and it concentrates on moraine-dammed lakes in the southern Coast Mountains, British Columbia.

3.3.1 Hazard assessment in the Swiss Alps

In this part a procedure by Huggel et al. (2004a) will be described as it represents a rapid and approximate hazard assessment based on simple glaciological, geomorphological and hydraulic principles and previous events experience. It integrates essential empirical relationships and aims to provide reliable information on potentially threatened areas. At first, an assessment of magnitude is carried out consisting of probable maximum discharge, volume and travel distance, then a qualitative estimate of the probability of occurrence based on several indicators is determined.

Lake volume calculation relates to the lake area measured from a satellite image and the following empirical relationship (Huggel et al., 2002) is used:

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

where V means the lake volume (m^3) and A is the lake area (m^2) and r^2 is the coefficient of correlation (related to the original regression between area and mean depth). Although this equation is based on data from American, Icelandic, European and Asian glacial lakes, it may seriously underestimate large Himalayan lakes (error of up to 80 %).

The maximum discharge of a lake outburst depends mainly on the type of a dam. Ice-dammed lakes that often empty by progressive enlargement of subglacial channels produce much smaller peak discharge than sudden rupture of the moraine dam, both storing the same volume of water (Costa and Schuster, 1988). For estimating the probable maximum discharge (Q_{max}) of sudden breaks of ice dams Haeberli's (1983) empirical relationship is proposed:

$$Q_{max} = \frac{V}{t}$$

where Q_{max} is in $m^3.s^{-1}$, V is in m^3 and t is the drainage duration in seconds. Since values between 1,000 s and 2,000 s were typical for events in the Swiss Alps, it is proposed to use t = 1,000 s to obtain maximum estimates. As to subglacial drainage of ice-dammed lakes, Huggel et al. (2004a) recommend relationship by Walder and Costa (1996):

$$Q_{max} = 46\left(\frac{V}{10^6}\right)^{0.66} \qquad\qquad r^2 = 0.70$$

where Q_{max} is in $m^3.s^{-1}$ and V is in m^3, r^2 is coefficient of correlation.

Outbursts from moraine-dammed lakes are influenced and may be triggered by various processes. In spite of the complexity of the breach mechanisms a simple method for rapid estimate of maximum probable discharge is offered by Huggel et al. (2002):

$$Q_{max} = \frac{2V}{t}$$

where as for previous equations the same units and t = 1,000 s are used.

Bedrock dams may not fail but a displacement wave produced by any mass movement can overtop the dam and cause floods or debris flows. The formation and dimension of the displacement waves depend on depth and volume of the lake, mass movement's volume, flow height, and velocity and the slope of an appropriate sliding surface. The run-up height of the wave on the dam further depends on distance between the place of material impact and the dam, impact angle, wave length and height, freeboard height and slope of the dam. An interesting fact is that ice cover of up to 0.5 m has only minor influence on the wave and run-up height (Müller, 1995). Walder et al. (2003) found out that if the volume of the incoming mass is up to 10 times smaller than the volume of the lake, it may be emptied completely due to displacement of water.

Drainage mechanism of subglacial water bodies is still not well understood as no reliable method for detecting previously unknown reservoirs and predicting the timing of their outburst is available. Predictions of probable maximum discharge and volume of the outburst are based on experience from past events in the Alps that are compiled in Table 3.

Table 3. Empirically based maximum values of different hazard processes for the European Alps. Source: Huggel et al., 2004a.

Process magnitude	Empirically based value	Confidence level
Max. outburst volume, subglacial water reservoir	3×10^6 m^3	Low
Max. discharge, subglacial water reservoir	2×10^2 m^3.s^{-1}	Low
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^{-1}	Medium
Critical channel slope for erosion (debris flow)	8°	High

Note: Each value is related to a qualitative level of confidence based on the number of events from which the empirical values were derived.

Outbursts from glacial lakes in mountainous regions often evolve into debris flows. The maximum probable volume of an outburst therefore depends upon amount of erodible material along the flow path. Erosion prevails where the channel slope exceeds 8° (see Table 3), deposition commonly starts at gradients below this threshold but there are exceptions depending on the discharge and channel geometry (Rickenmann an Zimmermann, 1993). The probable maximum volume can be estimated by volume of possibly entrained sediment per channel unit which can reach values of up to 750 $m^3.m^{-1}$ (Huggel et al., 2002). The first method presented in this study comprises of determination of the channel type, then its approximate sediment yield rates (e.g. channel in deep but stable talus has sediment yield rates of 10-30 $m^3.m^{-1}$) and finally multiplication with the length of erosional part of the channel. The second method is based on maximum sediment concentration in a debris flow which can be 50 to 80 % by volume (average concentration between 50 and 60 %) (Hyndman and Hyndman, 2009). Then an estimation of probable maximum volume is made taking into account the total water volume in the lake (assuming full lake draining).

The probable maximum travel distance of a debris flow from a lake outburst is expressed as the angle of the horizontal line with the line from the starting point to the farthest point of deposition (Huggel et al., 2004a). In the Swiss Alps the minimum angle for debris flows noticed was 11°. Debris flows do not develop from the lake outburst either if there is only little erodible material in the flow path or if the slope is less than 8° (starting value of erosion) or if the amount of erodible material is small compared to the flood volume. For flood waves (where sediment amounts less than 50 % by volume) the determination of maximum travel distance is less clear and usually corresponds to an angle of 2-3° in the Swiss Alps (Haeberli, 1983). However, processes along the flow channel may substantially change the magnitude and travel distance of the hazard. Debris flow, for example, may dam a river and cause blockages which can result in serious and often unexpected flooding.

Table 4. Indicators for deriving qualitative probability of occurrence for glacial lake outbursts.
Source: Huggel et al., 2004a.

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

To determine the probability of occurrence Huggel et al. present an approach using geomorphological and geotechnical data and yielding qualitative assessment of the probability. Five key indicators were chosen to which a qualitative probabilities ranging from low to medium and high can be assigned (Table 4). Authors warn that this approach is rather subjective and ought to be processed by an experienced practitioner. An important fact is that the overall probability is not the mean of the five indicators but a single one rated “high” may often result in the overall high probability. Dam type, freeboard height, dam geometry, frequency of impact waves on the lake and extreme meteorological events can all contribute to breaching of the dam. Moraine dams with small width-to-height ratio are prone to collapses (piping, slope failure), impact waves from mass movements may overtop the dam depending on the freeboard height and mass volume, and intensive melting and high precipitation may lead to increase in lake volume and thus to destabilization of the dam.

3.3.2 Hazard assessment in the Coast Mountains

Another procedure for making preliminary assessment of outburst flood hazard was compiled by R. J. McKillop and J. J. Clague (2007) and it focuses on the moraine-dammed lakes in southwestern British Columbia. They describe methods based solely on aerial photographs or satellite images for estimating outburst probability and four measures of outburst magnitude: peak discharge, maximum volume, maximum travel distance and maximum area of inundation. This procedure was applied to 174 moraine-dammed lakes larger than one hectare in the above mentioned region.

At first, the authors deal with distinction between outburst flood and debris flow. Outburst floods have high suspended and bed loads, negligible shear strength, exhibit turbulence and commonly occur in low-gradient broad valleys or where little sediment is available. Where channel downstream the moraine dam is sufficiently steep and enough sediment for entrainment is available, lake outbursts may transform into debris flows, which exhibit visco-plastic behavior and are mostly laminar. Debris flows travel at higher velocities than outburst floods and may transport large boulders over great distances (Pierson, 2005). Incorrect prediction of outburst development into a debris flow or remaining a flood can lead to unnecessary costly remediation or unexpected property damage and even loss of life. Therefore the authors assume that debris flows develop from outburst floods when there is enough loose sediment available and at least one reach of the channel is steeper than 10° (erosion is dominant when channel gradient exceeds this value; Hungr et al., 1984). For lakes in valleys with gradients less than 10° the procedure consists of an estimate of outburst probability whereas for those likely to generate a debris flow it involves in addition an estimation of outburst magnitude.

Peak discharge is the maximum instantaneous volume of water and sediment that passes a particular point in a channel (McKillop and Clague, 2007). In this procedure it is assumed that the outburst flood peak discharge is achieved within the moraine breach although it may be increased with entrainment of sediment downstream. Peak discharge depends on a variety of factors, such as lake water volume, the outburst initiating event, dam material and the rate at which the breach develops (Blown and Church, 1985). Firstly, it is necessary to calculate the lake volume which can be accurately measured just on site, but it reasonably correlates with lake area that can be measured remotely. Relation developed by O'Connor et al. (2001) is recommended to estimate moraine-dammed lake volume in the Coast Mountains, B.C.:

$$V = 3.114A + 0.0001685A^2$$

where V is lake volume (m^3), A is lake area (m^2). This equation was the most suitable as it is based only on moraine-dammed lakes which are situated on steep slopes and are generally very similar to those in the Coast Mountains. Several empirical relations were applied to drained lakes and the results compared with published approximations of the events to assess how precisely each predicts the peak discharge in the study area. Costa and Schuster's (1988) relation was chosen as suitable to predict peak flood discharge from moraine-dammed lakes in southwestern British Columbia:

$$Q_p = 0.00013(PE)^{0.60}$$

where Q_p is peak discharge ($m^3.s^{-1}$) and PE is potential energy of the lake water, which is product of dam height (m), lake volume (m^3) and the specific weight of water (9800 N/m^3).

Estimates of maximum volume of debris that will be delivered to the runout zone constitute an important part of hazard assessments. The total volume of debris is sum of breach volume and volume entrained within the channel. The authors recommend estimation of the volume of sediment likely to be eroded from the moraine dam that employs moraine width and height. The cross-sectional area of the breach may be parabolic or triangular, however, to facilitate the calculation the latter is assumed (Figure 11). Based on simple geometrical analysis, the following expression was derived:

$$V_b = W\left(\frac{H_d^2}{\tan\theta}\right)$$

where V_b is breach volume (m^3), W is moraine width (m), H_d is moraine height to lake surface and θ is the steepness of breach sidewalls (°). Angle of 35° for breach sidewalls is assumed for this study as it is consistent with most observed values in the study area (e.g. Nostetuko Lake, Blown and Church, 1985). Although this equation yields conservative values (especially for sharp-crested moraine dams) due to the assumption of breach being perfect triangular prism, accuracy of the estimates is sufficient.

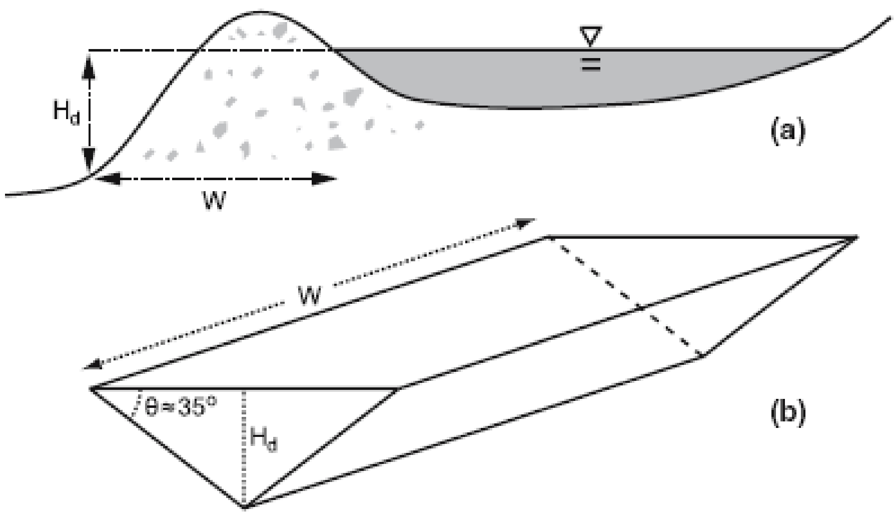

Fig. 11. Schematic diagram for estimation of moraine dam breach volume. (a) Cross-section. (b) Idealized moraine dam breach volume (triangular prizm). Source: McKillop and Clague, 2007.

The volume of sediment entrained within the channel may increase the total volume of debris by an order of magnitude (O'Connor et al., 2001). The authors slightly modified an approach by Hungr et al. (1984) to make it suitable for analysis based on remote sensing (Table 5). The approach discriminates five "channel debris yield rates" based on channel gradient (for simplicity an erosion-deposition threshold of 10° was set) and bed and bank material. Then it's necessary to determine the expected point of termination of the debris flow (see further) and divide the channel into homogenous reaches (minimum 400 m long) with respect to the characteristics that affect channel debris yield rate. The length and drainage area are measured and a channel debris yield rate is assigned, both for each reach. And lastly, the volume of sediment entrained within the reaches downstream of the moraine dam is calculated using following equation (Hungr et al., 1984):

$$V_r = \sum \left[A_i^{1/2} L_i e_i\right]$$

where V_r is the volume of sediment entrained within the reaches (m^3), A_i is the drainage area (km^2) bordering a reach i, L_i is the length of reach i (m), and e_i is the "channel erodibility coefficient" ($m^3.m^{-1}.km^{-1}$) for reach i. For simplification of the method, all debris entrained is deposited in a depositional reach (<10°) if there is any; therefore only debris from erosional reaches (>10°) upstream of the runout zone but not upstream of any depositional reach are entered into this equation (this holds for breach volume as well). Final calculation of probable maximum outburst-generated debris flow volume is simple:

$$V_m = V_b + V_r$$

where V_m is the maximum debris flow volume, V_b is the breach volume and V_r is the volume entrained within reaches, all in m^3.

Table 5. Channel debris yield rates. Source: McKillop and Clague, 2007.

Channel type	Average gradient (°)	Bed material	Side slopes	Channel debris yield rate (m3/(m km))
A	< 10	N/A	N/A	0
B	> 10	Non-erodible[a]	Non-erodible	0-5
C	> 10	Thin debris[b]	Mainly non-erodible	5-10
D	> 10	Thick sediments[c]	< 5 m high	10-15
E	> 10	Thick sediments	> 5 m high	15-30[d]

Notes:
[a] Bedrock or basal till.
[b] Discontiguous veneer of till, colluvium, alluvium, or lacustrine deposits (bedrock locally visible).
[c] Contiguous blanket of till, colluvium, alluvium, or lacustrine deposits (no bedrock visible).
[d] Yield rates for deeply incised channels can be up to 100 $m^3.m^{-1}.km^{-1}$) in special cases, e.g. an incision through a fresh slump.

Maximum travel distance of a debris flow is determined by the angle between the the source area and downstream limit of deposition. Based on documentation of debris flows in southwestern British Columbia a conservative value of 10° was established. However, the authors warn that inconsiderate usage of this value may lead to great overestimation of a debris flow travel distance and recommend taking into account increasing flow width and significant decrease in slope gradient of a channel.

In addition to above mentioned magnitude characteristics a maximum area of inundation can be estimated. For a rapid assessment of an area likely to be covered by debris the following equation by Griswold (2004) is recommended:

$$B_m = 20V^{2/3}$$

where B_m is the maximal area of inundation and V is debris flow volume.

Table 6. Regression coefficients required for estimating outburst probability.
Source: McKillop and Clague, 2007.

Variable	Category	Coefficient
Intercept	-	-7.1074 (α)
M_hw	-	9.4581 (β_1)
Ice_core_j:	Ice-free	1.2321 ($\beta_{Ice\text{-}free}$)
	Ice-cored	-1.2321 ($\beta_{Ice\text{-}cored}$)
Lk_area	-	0.0159 (β_2)
$Geology_k$:	Granitic	1.5764 ($\beta_{Granitic}$)
	Volcanic	3.1561 ($\beta_{Volcanic}$)
	Sedimentary	3.7742 ($\beta_{Sedimentary}$)
	Metamorphic	-8.4968 ($\beta_{Metamorphic}$)

Outburst probability is defined as the likelihood that a lake will drain, or partially drain, catastrophically within an unspecified period (McKillop and Clague, 2007). Determination of outburst probability is complicated by the fact that moraine-dammed lakes often drain catastrophically only once and that rarity of the events limit our understanding of triggering mechanisms. However, Fell (1994) claims that approximate and subjective estimation is better than no estimation. McKillop and Clague propose statistical model based on four variables: lake surface height-to-moraine dam width ratio (M_hw), presence of ice core in the moraine (Ice_core), lake area (Lk_area) and main rock type forming the moraine (Geology). Regression coefficients and categories of variables are presented in Table 6 and the outburst probability can be calculated using this equation:

$$P(outburst) = \{1 + exp - [\alpha + \beta_1(M\_hw) + \sum \beta_j(Ice\_core_j) + \beta_2(Lk\_area) + \sum \beta_k(Geology_k)]\}^{-1}$$

where α is the intercept, β_1, β_2, β_j, β_k are regression coefficients for *M_hw*, *Lk_area*, *Ice_core* and *Geology*, respectively. Lake area and width-to-height ratio measured values are directly put into the equation whereas for Ice_core and Geology values of 1 or 0 are given (1 for ice-cored, 0 for ice-free; 1 when the main rock type is one of the named, 0 for another rock type). Finally, the resulting probability is classified to one of the groups: very low (< 6 %), low (6-12 %), medium (12-18 %), high (18-24 %) and very high (> 24 %).

4 Discussion

In this part of the thesis I would like to draw attention to possible imperfections and inaccuracies of the above presented procedures. The main characteristic of such procedures is generalization. This means that equations used to calculate probable maximum volume, travel distance or area of inundation can hardly ever be utterly accurate. There is always certain percentage of error (difference between real and calculated values divided by the calculated value) and the limit of "acceptable" depends on subjective opinion of entrusted persons. However, generalization is necessary to examine large areas and make quick first-order estimations which is the main goal of hazard assessment procedures. Perfect accuracy is therefore not only impossible but also undesirable, as it would greatly decelerate the whole process.

Naturally, the more people, the more different opinions. Research teams have their own practices and apply their equations and sometimes it is very difficult to decide which one is more precise. For example, McKillop and Clague (2007) chose to use this equation $20V^{2/3}$ to calculate maximum area of inundation whereas Berti and Simoni (2007) prefer an equation $17V^{2/3}$. Priority is often given to the more conservative estimation especially when lives of people are in danger. However, excessive overestimation of an event may lead to unnecessary and costly mitigation measures which waste finances and attention needed for more serious cases.

The above presented procedures focus solely on physical part of such event. There are also assessments integrating both physical and socioeconomic factors. An assessment of vulnerability to glacial hazards was compiled by E. Hegglin and C. Huggel (2008) and it demonstrates this specific approach on a case study in Cordillera Blanca, Peru. Socioeconomic factors include preparedness (e.g. emergency plans, awareness, age and poverty of local population), prevention (urban planning) and response (capability to recover). This study aims to yield information on identification of protection deficit and tries to efficiently use limited data resources in the context of a developing country.

5 Conclusion

Development in glaciated high mountain areas around the world increases the probability of damage and loss of life. Risk analyses have therefore become necessary for hazard moderation and are applied across various regions. Air-borne and space-borne remote sensing has proved to be very helpful tool and with improving technologies it enables to gain very useful and accurate data. Nevertheless, terrain research still remains the indispensable part of the whole hazard assessment process.

Geoscientists seek to compose new methods that would be more objective and quantitative and fit to the specific region as precisely as possible. Glacial hazards are undoubtedly a serious problem which is obvious from rising number of concerned experts from different sectors. Physical geographer still has the principal role, however, other professions such as geologist, geophysicist or construction engineer have become and integral part of research teams. Nowadays, this problem has even greater extent. Impact of glacial hazards on population is the focus of attention of social geographers who increasingly intervene in this problem.

The aim of this thesis was to compile information on various types of glacial hazards and to present range of risk analysis methods. I think that I managed to fulfill it successfully. This thesis should serve as basis for case study which will be elaborated in the successive diploma thesis.

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