GLACIER FLOODS

S. Zgraggen-Oswald, W. Haeberli, A. Kääb

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1. Introduction

In comparison to other glacial hazards, glacier floods represent the highest and far-reaching glacial risk, i.e. the risk with the highest potential of disasters and damages. Glacier floods are triggered by the outburst of water reservoirs in, on, underneath and at the margin of glaciers. These floods are commonly much larger than storm induced floods and can appear anytime. Due to the unpredictable nature of glacier flood triggering, exact forecasting of an event is almost impossible.
The peak discharge of glacier floods can be larger than storm induced floods. Consequently they are potentially more devastating in their downstream effects. They dramatically reshape stream channels and pose a hazard to human settlements and infrastructure.

2. Process

2.1 Water Reservoirs

Lakes, as hazardous water reservoirs, mostly emerge slowly (exception: lakes dammed by surges or ice avalanches). Lakes can develop in the glacier forefield (proglacial), at the glacier bed (subglacial), in regions with buried ice, permafrost, thermokarst (periglacial), and in and on the glacier itself (englacial as water pockets and supraglacial). The lakes are dammed by ice, debris and/or rock.

2.2 Outburst Mechanisms:

The mechanically and hydraulically different mechanisms of lake drainage imply a distinction between ice- and moraine- dammed lakes.

Ice Dams

1. Mechanical Breaching (sudden outburst)

The dams consist of ice debris or ice blocks from previous ice avalanches, surges, ice falls and result in temporal blockage of the runoff. Similar effects can originate from snow drift/avalanche dams.
As shown in Fig.1, the **discharge** typically rises and recedes rapidly. Characteristically the drainage is short-lived and only lasts a few minutes. In some cases the breaching is preceded by a runoff interruption.

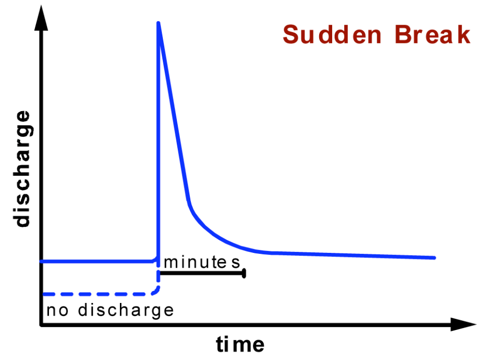


Fig. 1: Schematic hydrograph of mechanical breaching of ice dams, (Haeberli 1983)

2. Overflow

In cases of high water levels, flood waves, high melt water input or changes in lake or dam geometry can lead to an overtopping of the dam. As a result water overflowing the ice dam erodes a breach into the dam. This phenomena is mostly observed for cold glaciers.

3. Progressive Breaching (hydraulic break)

There are two phenomena that can lead to progressive breaching of ice dams:

- **progressive extension of ice channels** as a result of ice dam flotation
- **progressive groundwater flow on the glacier bed:** occurs rather seldom and can only develop in narrow ice dams with high hydraulic gradient

As the hydrograph below shows, the runoff increases progressivelly within hours up to days. Prior to the peak discharge the water often shows a colouring due to increased fine sediment load.
The failure mechanism of the ice dam is explained by the hydrostatic flotation hypothesis (Thorarinsson 1953).

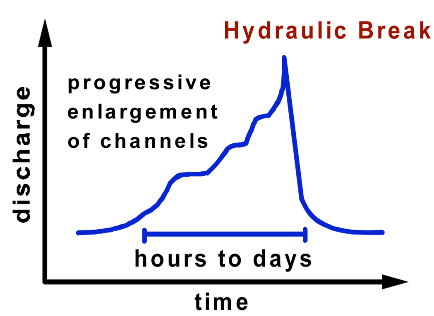


Fig. 2: Schematic hydrograph of progressive breaching of ice dams (Haeberli 1983)

Moraine Dams

Breaching of moraine dams involves piping (progressive groundwater flow) within the till, retrogressive incision and slides on steep slopes (instabilities). Moraine dams generally fail by overtopping and incision.

1. Overtopping (retrogressive incision)

In the case of overtopping, water spilling over the dam crest erodes a channel along the downstream face of the dam. The dam crest is eroded and breached by the escaping water, and the head of the breach channel retreats upstream. Due to both fluvial erosion and mass failure the breach channel enlarges (Ralston, 1987).

2. Piping (progressive groundwater flow)

Piping failure can occur with lake level short of overtopping the dam. Water percolating through the dam at a sufficiently large hydraulic gradient carries away sediment, creating "pipes" that first appear at the downstream face of the dam. As pipes enlarge and erode headward, water spilling from the pipes flows down the downstream face of the dam and erodes a channel. Eventually the dam crest above the pipe collapses and is carried away by the flow, leaving a breach (MacDonaldand Langridge-Monopolis, 1984).
Unlike the other outburst mechanisms, piping does not require an external trigger event.

3. Instabilities

Many moraine dams are susceptible to failure because they are steep-sided and consist of cohesionless sediments and have a high porosity/ cavity from dead ice remains or frozen ground. In cases of saturation the moraine stability decreases and slides can occur.

3. Triggering

Events such as heavy rainstorms, ice and snow avalanches, calving, rockslides and rockfall, debris flows or an influx of water caused by sudden drainage of an upstream lake can generate impact waves that trigger lake outbursts. As a result especially small lakes can drain completely.

Cases	Frequency	Magnitude
usual	decades	from several 10'000 up to millions of m^3
extreme	$\geq$ centuries	many millions of m^3

4. Data Acquisition, Mapping and Monitoring

For detection and mapping of the hazard potential of glacier lakes remote sensing, photogrammetry, GIS-modelling as well as field observations are used. Applied techniques include multitemporal analysis of air- and space-imagery, compilation of digital terrain models, surface displacements.

Targets are:

- recognition of lake formations (morphologic situation)
- mutations of the lake and water surface (*freeboard*, retention capacity)
- development and evolution of ice dams
- stability of dam (height-width -ratio, saturation, material)
- settlement of the dam (*Permafrost* degradation, dead ice)
- analysis of transition and deposition area of floods resp. debris flows (peak discharge, erosion capacity, minimal overall slope of debris flows 19 Grad)
- Water pockets can not be recognised there is a general residual risk.

Attention:
Water pockets can not be recognised and remain as a general residual risk.
Lakes that drained due to breakage of ice dams, often refill after some time again. The difficulty is to recognise such dangerous lakes during the state of emptiness.

5. Estimation Models

5.1 Lake Volume

Owing to the often extreme magnitude and catastrophic nature of glacier lake-outburst floods, peak discharge and runout distance are the only parameters that can be estimated. Direct measurements and further quantitative assessments are severely limited.

The volume for both ice- and moraine- dammed lakes is estimated with the empirical formula:

$$V = 0.1m * A^{1.4} \qquad \text{Eq. 1}$$

A= area in m^2, m = meters

To satisfy statistical standards, the relation should be based on a statistical analysis between mean depth and area (Huggel and others, 2002).

5.2 Ice Dams

Mechanical Breaching (sudden outburst)

The drainage of a sudden outbursts can last only a few minutes. The peak discharge is estimated with the empirically found term:

$$Q_{max}(\text{sudden break}) \approx \frac{V_w}{t_w} \qquad \text{Eq.2}$$

Qmax = peak discharge [m^3/s], Vw = outburst volume (mostly the dammed water volume), tw = empirical time constant (medium period of the flood wave, worst case approx. 1000 sec)

Progressive Breaching (hydraulic break)

Most of the ice dam breaks are of hydraulic nature. This outburst mechanism occurs in solid ice and with large water volumes. The runoff increases progressive within hours up to days. With the term:

$$Q_{max} = 46\left(\frac{V}{10^6}\right)^{0.66} \qquad \text{Eq.3}$$

Qmax = peak discharge [m^3/s], V = outburst volume [m^3] (mostly the dammed water volume) (Walder and Costa, 1996)

5.3 Moraine Dams

Predicting the peak discharge of moraine dammed lakes, is quite difficult. It depends on the outburst water volume, on the rate and extent of the breach growth, to a lesser degree to the shape of the breach and the basin hypsometry. Further the formation of debris flows has to be accounted. In consideration of the difficulties to overcome these aspects a very simple "worst-case" method has been developed. The maximum discharge can be expressed as:

Type of dam	**Relation**	**Reference**
Moraine	$Q_{max} = 2V/t$ [1)]	Huggel et all. [1)]
	$Q_{max} = 0.00013\ P_E^{\ 0.60}$	Costa and Schuster 1988 [2)]
	$Q_{max} = 0.0048\ V^{0.896}$	Popov 1991
Earth- and rockfill	$Q_{max} = 0.72\ V^{0.53}$	Evans 1986

[1)] worst-case estimation, t = time constant normally 1000s
[2)] 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 (9800N/m^3)

Floods from moraine-dammed lakes have higher peak discharges than floods from glacier-dammed lakes.
Actually the peak discharge is rather regulated by the rate and the extent of breach growth, than by the initial water volume or depth. These parameters can, however, hardly be estimated.
Further difficulties are resulting debris flows, which can feature volumes of 3-4 times the initial water volume.

Piping potential

To estimate the piping potential the hydraulic gradient **i** has to be analysed. In general it is described as:

$$i = \frac{\Delta h}{\Delta s} \qquad \text{Eq. 4}$$

h = water potential, s = distance

Water flows from the higher to the lower water potential. At a critical gradient $\mathbf{i_c}$ the danger of progressive groundwater flow occurs.

$$i_c = \frac{\rho - 1}{1 + n_0} \qquad \text{Eq. 5}$$

ρ = specific weight ratio of the sediment and water (~ 2.7), n_0= porosity (0.1-0.3)
In general high gradients (above 1) are necessary to induce piping.

Slope stability

In non-consolidated materials, the *factor of safety* (F) for slides is as followed defined:

$$F = \frac{\left(1 - \frac{m \rho_w}{\rho_s}\right) \tan \phi}{\tan \beta} \qquad \text{Eq. 6}$$

β = inclination of the failure plane, ϕ = internal friction angle of till (≈30°), ρ_w = water density, ρ_s = sediment density, **m** = ratio of the thickness of saturated material above the failure plane and the depth of the failure plane (complete saturation: m=1)

As the equation indicates, steep slope angles and an internal failure plane are necessary to initiate slides.

Erosion potential
The erosion potential for relative small outbreaks (< 10^6 m^3) can be estimated with the term:

$$E \approx s_e * 500m^2$$ Eq. 7

s_e = flow distance in erodable material

The erosion depth mostly stays under 10-20 m, since the creek is mostly paved with boulders. To tear open the pavement a critical depth of discharge is necessary:

$$h_c = 0.15 \frac{d_m}{J}$$ Eq. 8

d_m = magisterial grain size, J = inclination of the water channel

Empirically-based maximum values of different hazard processes

Maximum hazard-related process magnitudes	empirically-based values
max. ice avalanche starting volume (ramp- type)	$5x10^6$ m^3
max. ice avalanche starting volume (edge- type)	$4x10^5$ m^3
max. outburst volume, subglacial water reservoirs	$3x10^6$ m^3
max. discharge, subglacial water reservoirs	1-$2x10^2$ m^3/s
max. ice avalanche runout (min. average slope)	17º (31%)
max. lake outburst flood runout (debris flow)	11°
max. lake outburst flood runout (flood wave)	2-3°
max. sediment yield along channel (debris flow, in large moraine bastions, per channel length unit)	700 m^2
critical channel slope for erosion (debris flow)	8°

6. Combinations and Interactions of Hazards

Ice and or Rock Avalanches
Due to their nature, glacier floods hold a great potential of being triggered by ice avalanches and/or rock avalanche.

Debris Flow
The floodwaters of glacier floods may mobilise large amounts of sediment as they travel down steep valleys, producing highly mobile debris flows. Such flows have larger discharges and greater destructive impacts than the floods from which they form. Resulting debris flow can feature volumes of 3-4 times the initial flood water volume.

Succeeding Floods
Downstream debris flows, initiated by glacier floods, may dam the main waters of a valley. A lake can form and at some point breach the debris dam with a succeeding flood.

Slope Instabilities
Lake outbursts can destabilize valley flanks by undercutting (land slides potential).

7. Long term Effects

Mass balance, thermal and the hydraulic regime of a glacier are modified by climate impacts. As a result **glaciers retreat or advance** and alter the water reservoir. Consequently the **disposition of glacier floods changes**.
During periods of advance or stagnation some glaciers build large lateral and end moraines. Lakes may form behind these moraines in times of glacier retreat.
Warming from the late 1800s until about 1940 and again from 1965 to today destabilised moraine dams with interstitial ice or ice cores. The warming also forced glaciers to retreat and permafrost to degrade, prompting ice avalanches, landslides, and lake outbursts that have destroyed moraine dams.

8. Integral Risk Recognition and Assessment

Due to large losses, granting of concessions and questions about environmental compatibility, a demand of integral risk recognition and assessment occurred. Suggestions on adequate hazard assessments have to be made on the basis of over-all surveys (see integral ice avalanche hazard assessment scheme).
Due to incomplete understanding of the different processes but increasing demand for realistic approaches, assessment of glacier- and permafrost-related hazards in practice often relies on empirical relations. Since there is no data basis available in most cases, first evaluations are often established on simplest models and empirical estimation procedures, regarding starting, transition and deposition area.

The goals of a risk analysis are to:
• get an overview of the situation
• set priorities
• develop monitoring concepts
• clarify the responsibilities
• consider the level of risk acceptance (are the measures adequate?)

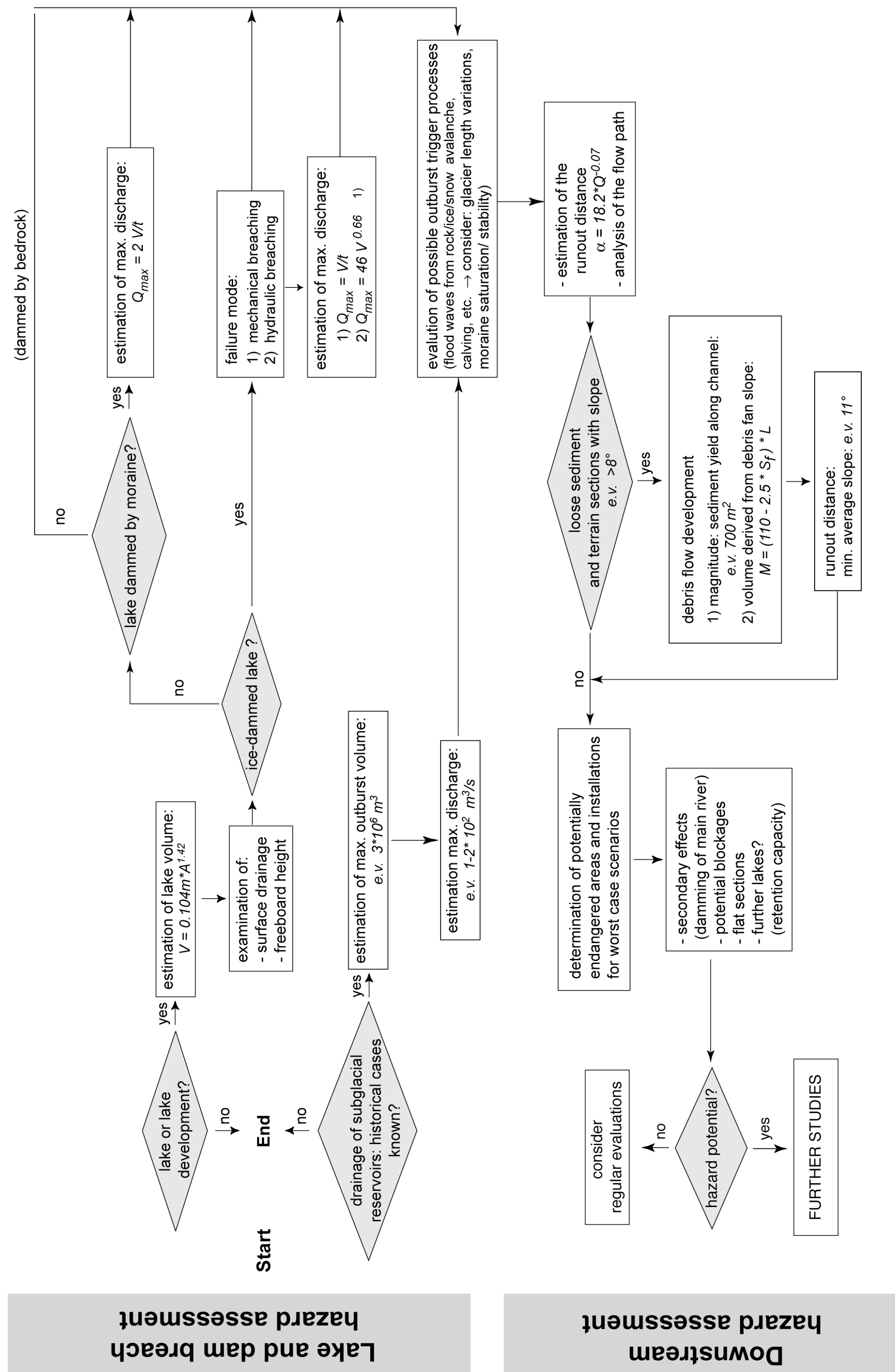
In practice it is reasonable to examine the situation by processes and to start with the glacier length variations.

8.1 Assessment (current and future glacier stage)

Glacial floods often represent the crucial root-risk. Outbursts of water pockets and sudden blocking of glacial runoff seldom lead to large damage. In return they are unpredictable and can occur in principle everywhere.
Often water reservoirs do not exist anymore after an outburst. But there is a high potential of regeneration.

To estimate the risk of glacier lakes the following points should be inspected:

- morphological situation
- development tendency
- possible outbreak mechanisms
- stability of dam (height-width -ratio, saturation, material, settlement due to permafrost degradation or dead ice)
- water level (*retention* capacity by the occurrence of flood waves or heavy rainfall)
- estimation of the peak discharge
- erosion capacity
- dispersion processes (flood waves, *debris flows*)
- risk and damage range (*overall slope*)
- regeneration of at the time being of water reservoirs
- unusual signs (example: turbid water □ some kind of erosion or piping takes place)



α = overall slope
e.v. : empirical value
1) in 10^6 m^3

Integral glacier floods hazard assessment scheme

9. Protection Measures

It is of great importance to balance reasons for possible measures from case to case in terms of feasibility and proportionality.
Mitigation of the impacts of glacier floods requires hazard and vulnerability assessments and the implementation of risk management policies and strategies including public awareness campaigns, planning and development regulations, and construction codes and standards. The hazard problems are often caused by mismanagement including unwise land-use practices. Land-use zoning, in partnership with professional inspections and proper design, can alleviate many of the problems associated with glacial hazards.

9.1 Passive measures:

- avoidance of dangerous zones (development regulations in terms of land use zonings)
- forecasting and warning systems
- public education and awareness

9.2 Active measures:

constructive measures and safety constructions:

at the glacier: - build a debris dam (change of the permeability in the ice dam)
- run-off regulation (keep glacier length variations in mind)

below the dam: - retention basin
- till gatherer
- water channel constructions

early warnings and organized evacuation

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