ICE AVALANCHES

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1. Introduction

Ice fall emerges, when ice breaks of a glacier. It occurs in form of ice avalanches and calving. Ice avalanches mostly affect much smaller areas than glacier floods. Due to the lower reach of ice avalanches, corresponding disasters are generally restricted to densely populated high mountain regions (especially the Alps). However, in combination with other glacier hazards, ice avalanches have the potential for far-reaching disasters. In zones with high seismic activity or enhanced geothermal heat flow, the risk of major ice break offs is increased. example: Huascarán

2. Process

2.1 Starting Area

With respect to the **glacier-bed geometry**, it is possible to distinguish 2 morphological types of starting areas:

Ramp: The starting area is situated on a steep and uniform slope, on which the ice slides or shears. The instability affects primarily the base of the hanging glacier (basal sliding and shearing).
example: Altels

Edge: In this case the starting area lies at a marked break of the slope angle. Due to strong tensile stresses the ice cracks in form of unstable seracs.
example: Moench

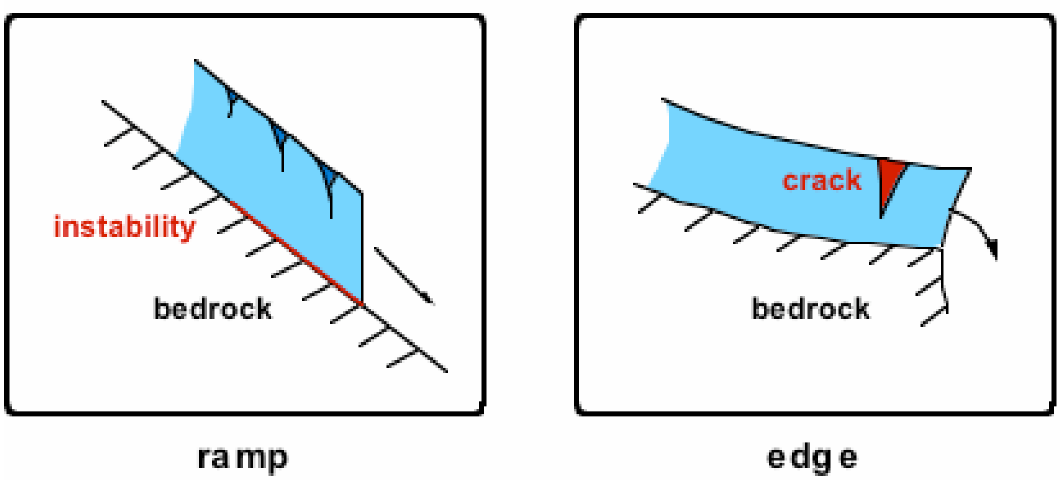

Fig. 1: Ice avalanche starting zones: ramp-type and edge-type (modified after Alean 1984)

2.2 Transition and Deposition Area

Ice avalanches show similar shattering and friction characteristics like landslides. The flow and pressure rates are comparable with snow avalanches and small ice volumes slide and role like rock fall on snow. If the deposition area happens to be a snow covered area or a lake, the resulting chain reactions can be very serious.

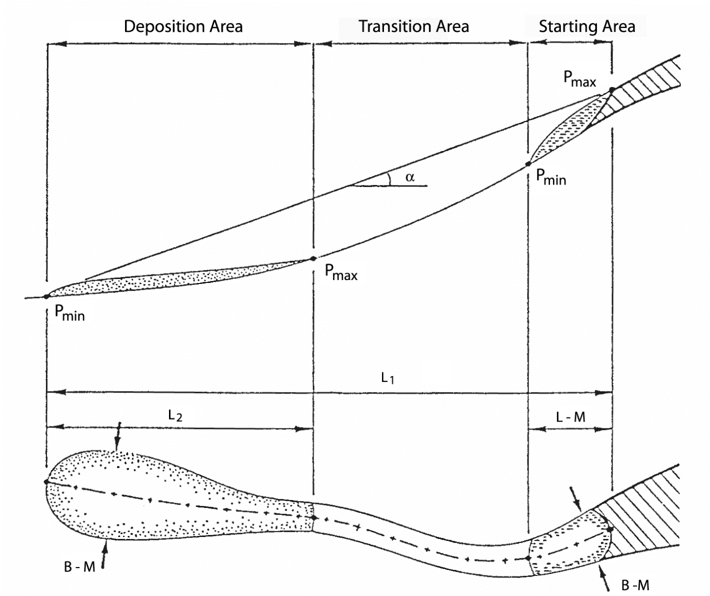

Fig. 2: Starting Area, Transition Area, Deposition Area and important parameters of an ice avalanche, (Source: Alean 1984)

3. Triggering

Because of its complexity, there is still little knowledge about how ice avalanches initiate from internal processes. They occur on both, temperate and cold glaciers. Ice avalanches are the dominant ablation process for cold high-altitude hanging glaciers.
Avalanches from glaciers in edge situations have a tendency to replicate. Cold glaciers produce ice avalanches during all day times and seasons. Temperate and polythermal glaciers rather break off in times of superior melting like summer and autumn months.
Further, external impacts like earthquakes and rock avalanches can trigger ice avalanches.
example: Huascarán

Large break offs have heavy impacts on their surrounding. Small break offs get dangerous in interaction with other hazards (chain reactions).

3.1 Magnitude & Frequency

	Frequency	**Magnitude**
small break offs	daily (ablation effect)	a few m^3
large break offs	can range from decades to centuries	thousands to millions of m^3

4. Data acquisition, Mapping and Monitoring

For the detection and mapping of potential risky disposition of hazards remote sensing, photogrammetry, GIS-modelling as well as field observations are used. The monitoring of a possible risk is done with remote sensing or geodesy.

4.1 Monitoring

Monitoring of recognised ice avalanche is done indirectly by analyzing crevasse situations , glacier geometry and accelerating ice movement. Therefore repeated ground-, air- and space-borne imagery as well as geodetic measurements are used.

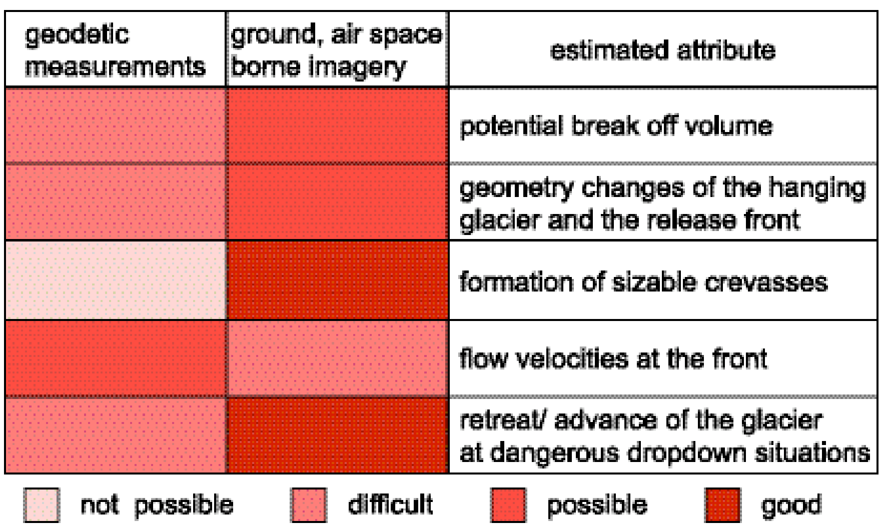

Fig. 3: Usability of data acquisition and monitoring methods in comparison

The following attributes can be estimated:

- potential break off volume
- geometry changes of the hanging glacier and the release front
- formation of sizeable crevasses
- flow velocities at the front
- retreat resp. advance of the glacier at dangerous dropdown situations

Since forecasting of break off events is based upon high-frequency velocity measurements, the velocity measurements are done with geodesy.

4.2 Mapping

Due to glacier tilt and shadows, it is common that the visibility of steep glaciers on aerial views and satellite images is bad.
Often glaciers are snow-covered, which complicates the detection of crevasses.

5. Estimation Models

5.1 Starting Area

The disposition of ice avalanches is set by the slope angle and the basal ice temperature. Temperate glaciers show a critical ramp slope of 25° and cold glaciers of 45° (empirical values). The difference is due to the increasing adhesion with decreasing ice temperature and loss of basal sliding.
Because small glaciers sometime feature smaller slope values, the target values are to be treated with care. Furthermore, in nature glaciers also exists as polythermal forms and correspondingly intermediate critical angles.

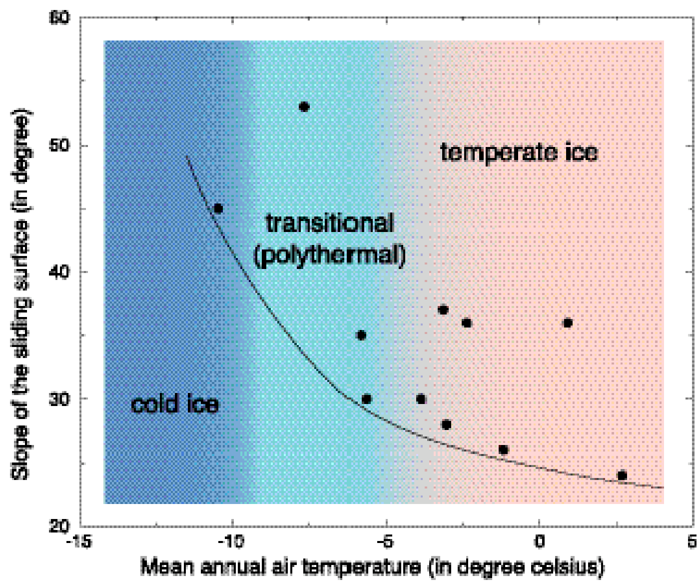

Fig. 4: Relation between mean annual temperature and slope of the sliding glacier surface (Huggel et. al. 2002)

Most break off volumes of ice avalanches in edge situations are well bellow 1 million m3, whereas in ramp situations volumes exceeding 1 million m3 are possible.

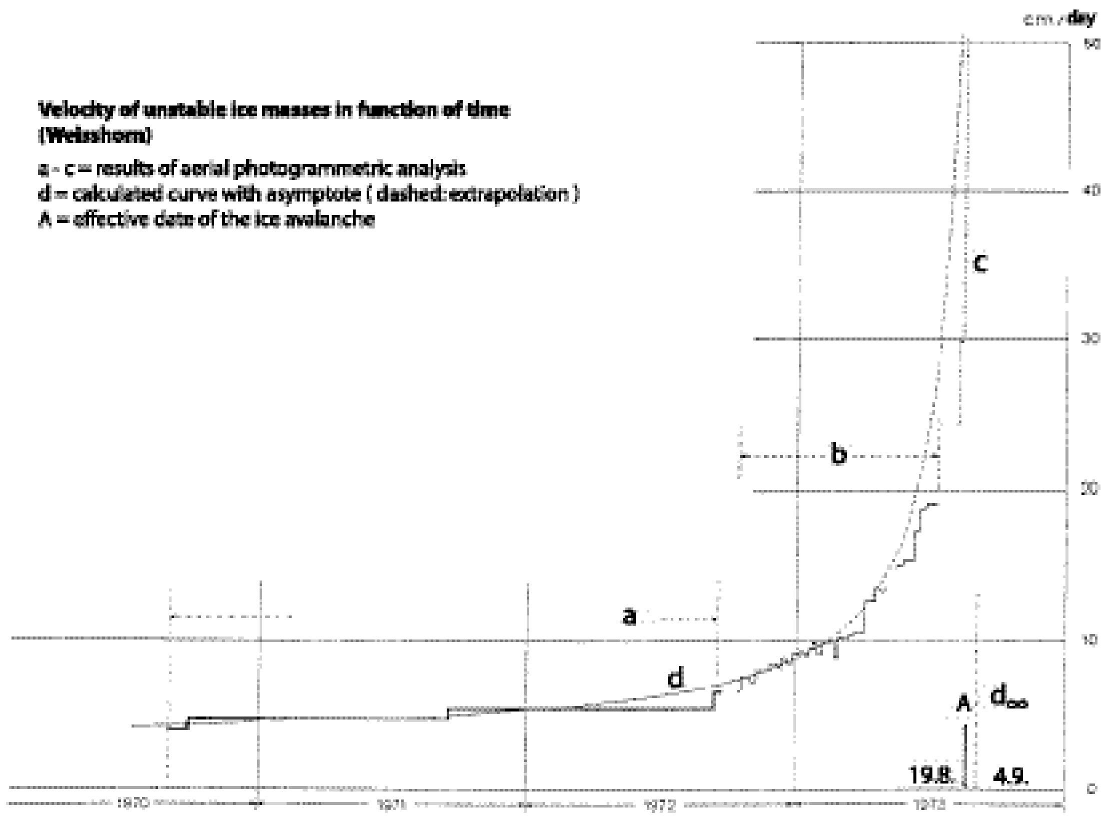

Fig. 5: Velocity of unstable ice masses in function of time, Weisshorn, Swiss Alps, (Röthlisberger 1981)

Flow acceleration before break off tends to follow a hyperbolic form. Travel speeds of ice avalanches are high and can reach 400 km/h and more. Due to higher flow depth and velocities, large break off volumes feature greater runout distances and smaller overall slopes than minor ice avalanches.
The velocity of the unstable ice masse before breaking off can be estimated with the empirical formula.

$$v = v_0 + \frac{a}{t \quad \square t}$$ **Eq. 1**

v = flow velocity, t = time, v_0 and a = constants to be calibrated

5.2 Transition and Deposition Area

During an avalanche event, the ice is successively shattered. Thereby, a substantial amount of ice powder is produced. For most parts, ice avalanches are accompanied by enormous shock waves, which often harm more than the avalanche itself.
In the Alps the maximum reach amounts up to 6 km, but in most cases it is less than 5 km. The minimal overall slope equals 31% (13°).
As a rough rule of thumb the runout distance (s) equals three times the height of fall (h):

$s = 3 * h$ **Eq. 2**

The runout distance increases in winter due to strongly reduced friction on, and mobilisation of, snow. (Weisshorn)
For the characterization of the fall process and the pathway 1- and 2-parameter (geology) models are used (see snow avalanches).

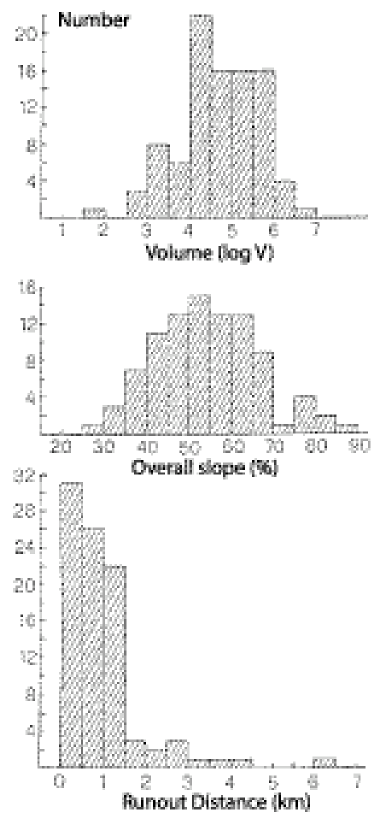

Fig. 6: Frequency distribution of volume, overall slope and runout distance of parameterised ice avalanches in the Alps
(Alean 1984)

6. Combinations and Interactions of Hazards

Although rather small areas are directly affected by the risk of ice avalanches, the indirect consequences can nevertheless be disastrous.

Process	Chain Reaction
Glacier Floods / Debris Flows	Ice avalanche → into a natural or artificial lake → triggering of a flood wave → breaching of the natural or artificial dam → flood and/or debris flow disaster (Tsho Rolpa)
Snow Avalanches	Ice Avalanche → triggering of a snow avalanche → increase of the avalanche volume and the runout distance (Weisshorn)
Rock Avalanches	Combination of rock and ice avalanches → increase of the avalanche volume, density and flow speed (Huascarán)

7. Long term Effects

Long-term effects influence the disposition for ice avalanches. Climate changes modify the mass balance, the thermal and the hydraulic regime of a glacier. As a result the glacier may retreat or advance and/or change its stability.
If a glacier retreats into a edge or ramp situation the potential ice avalanche risk will rise. In the opposite case the risk will decrease.
Changes in the geometry as well as in the thermal and hydraulic regime can reduce the stability of a hanging glacier, due to increasing temperature.
example: Altels

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.

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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?)

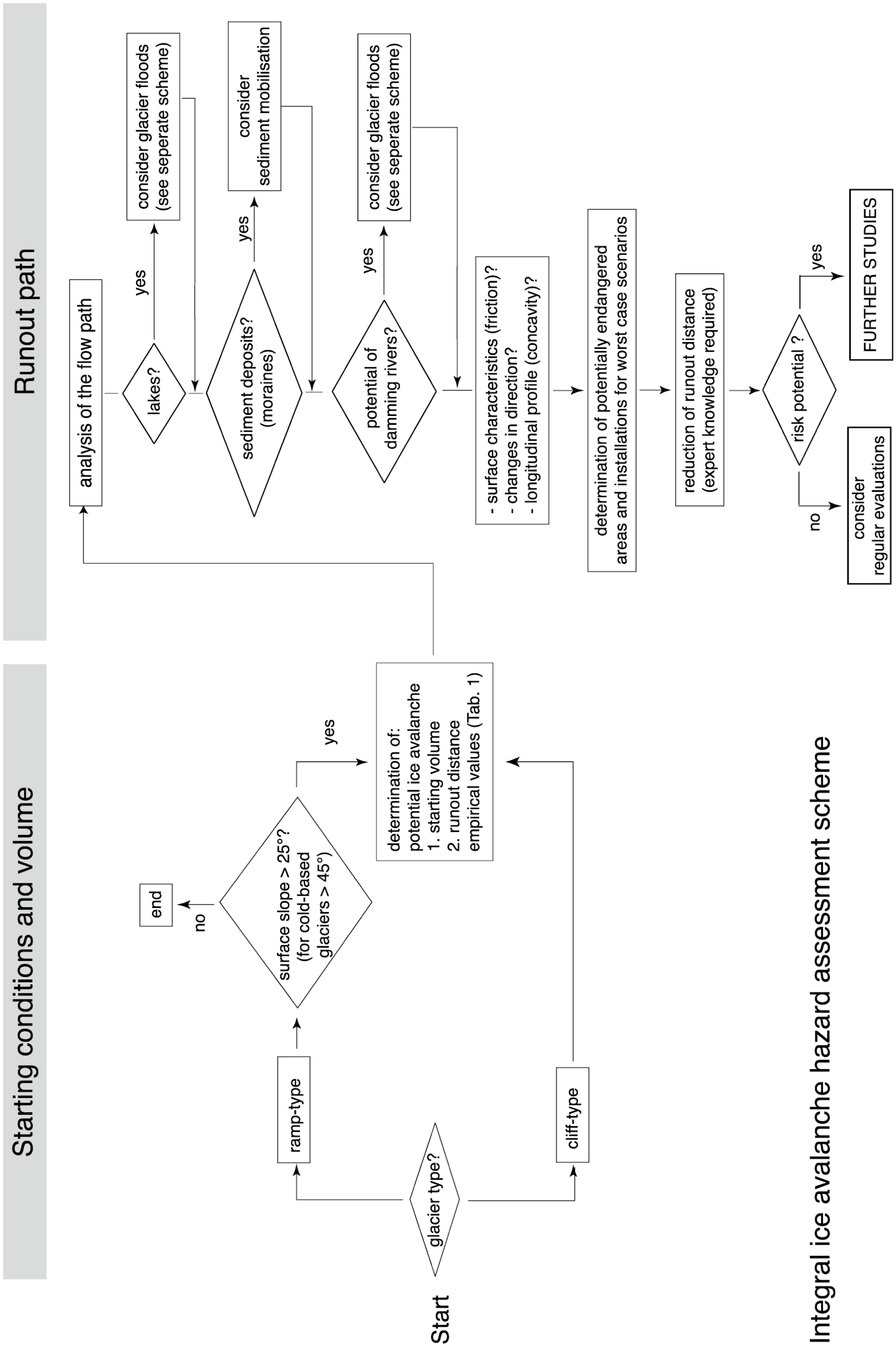
In practice it is reasonable to examine the situation by processes and to start with the glacier length variations.

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°

8.1 Assessment (current and future glacier stage)

Risk	Questioning	Survey Target
Primary risks	Where are suitable break off conditions?	edges, ramps, ice temperature
	What is the possible break off volume?	dimension of unstable ice
	What is the runout distance?	overall slope (d_{max}=3*h) (caution: shock waves !!)
Secondary risks	Can ice avalanches be triggered?	snow covered steep slopes
	Is there a risk of initiating flood waves?	natural and artificial lakes
	Can the damming of rivers or creeks occur?	rivers and creeks



Integral ice avalanche hazard assessment scheme

9. Protection Measures

The detection and localisation of potential risk situations is relative simple for experts. Ratings for worst case scenarios can be easily estimated with simple method. Whereas in only very rare cases, combined with a huge effort, a time prediction can be done.
It is important to balance reasons for possible measures from case to case in terms of feasibility and proportionality.
Mitigation of the impacts of glacial hazards 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

in general: avoidance of the endangered zone (estimated with the overall slope)

long term: hazard mapping and zoning

short term: evacuation in times of acute endangerment (requires a suited monitoring and the possibility of prognosing the hazard, which is often obnoxious because the danger is not even visible)

risk reduction: shortening the duration of stay or closure of the endangered zones examples: ski slopes, hiking trails, access roads, consideration of the risk acceptance and public education (danger signs)

9.2 Active Measures

long term protection constructions in the fall path:
- deflection dams
- drainage or draw down of artificial and natural lakes
- dimensioning of reservoir freeboards
- avoidance of impounding rivers by relocation of waste-pipes

short term interactions at the glacier:
- artificial release of ice masses (is only reasonable with small ice masses)

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