Glacial Hazards

Risk Assessment and Mitigation

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Topics

- Terminology: Hazards. Risks. Mitigation.
- *Global ice and exposure to hazards*
- *Types of glacial hazards*
- *Hazard Assessment: Mapping and Modelling*
- *Monitoring and risk mitigation*

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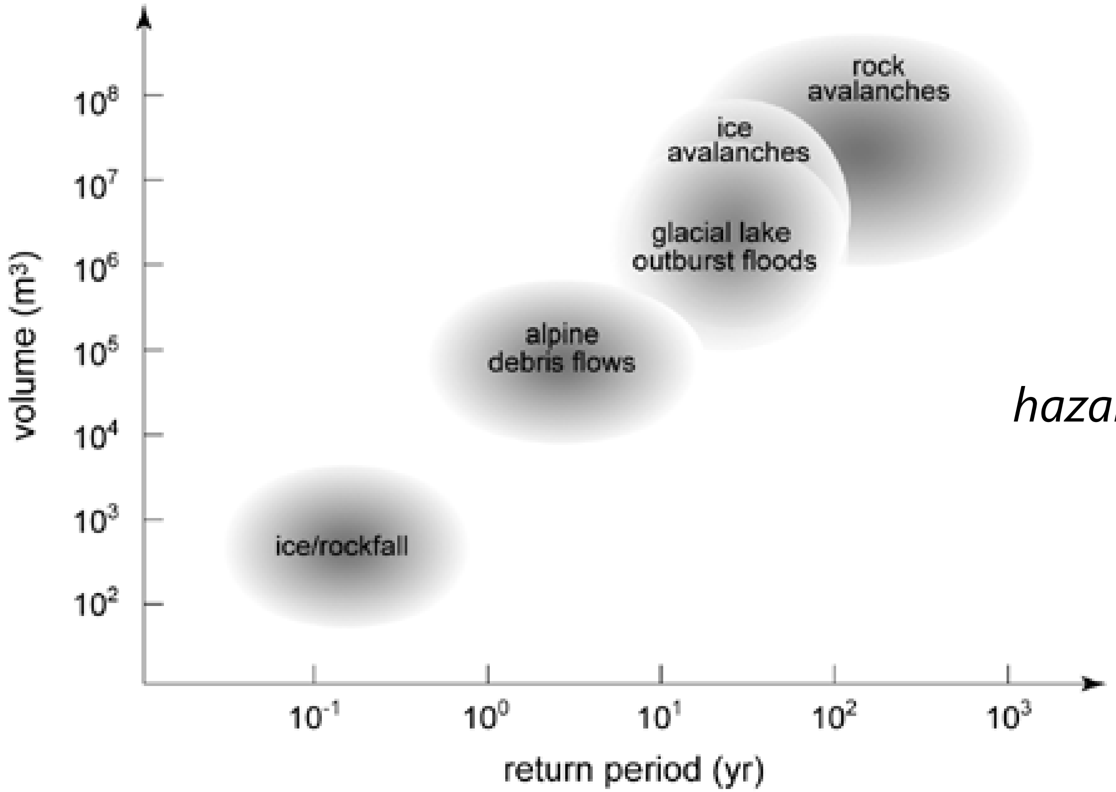
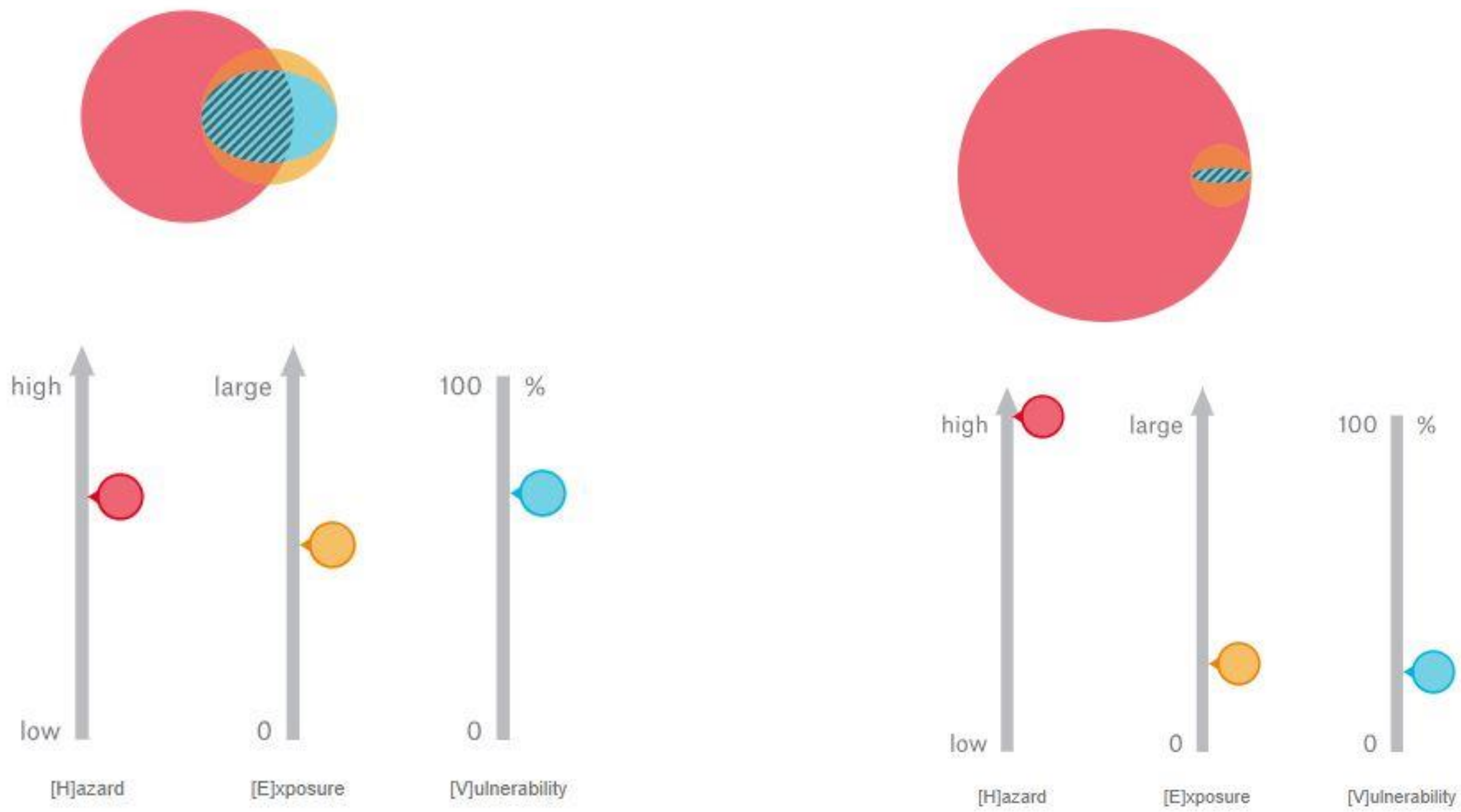
Return periods vs. volumes



hazard = f(probability, intensity)

Geology Today, Volume: 28, Issue: 3, Pages: 98-104, First published: 25 May 2012, DOI: (10.1111/j.1365-2451.2012.00836.x)

risk = hazard * exposure * vulnerability [* insurance penetration]



MunichRe

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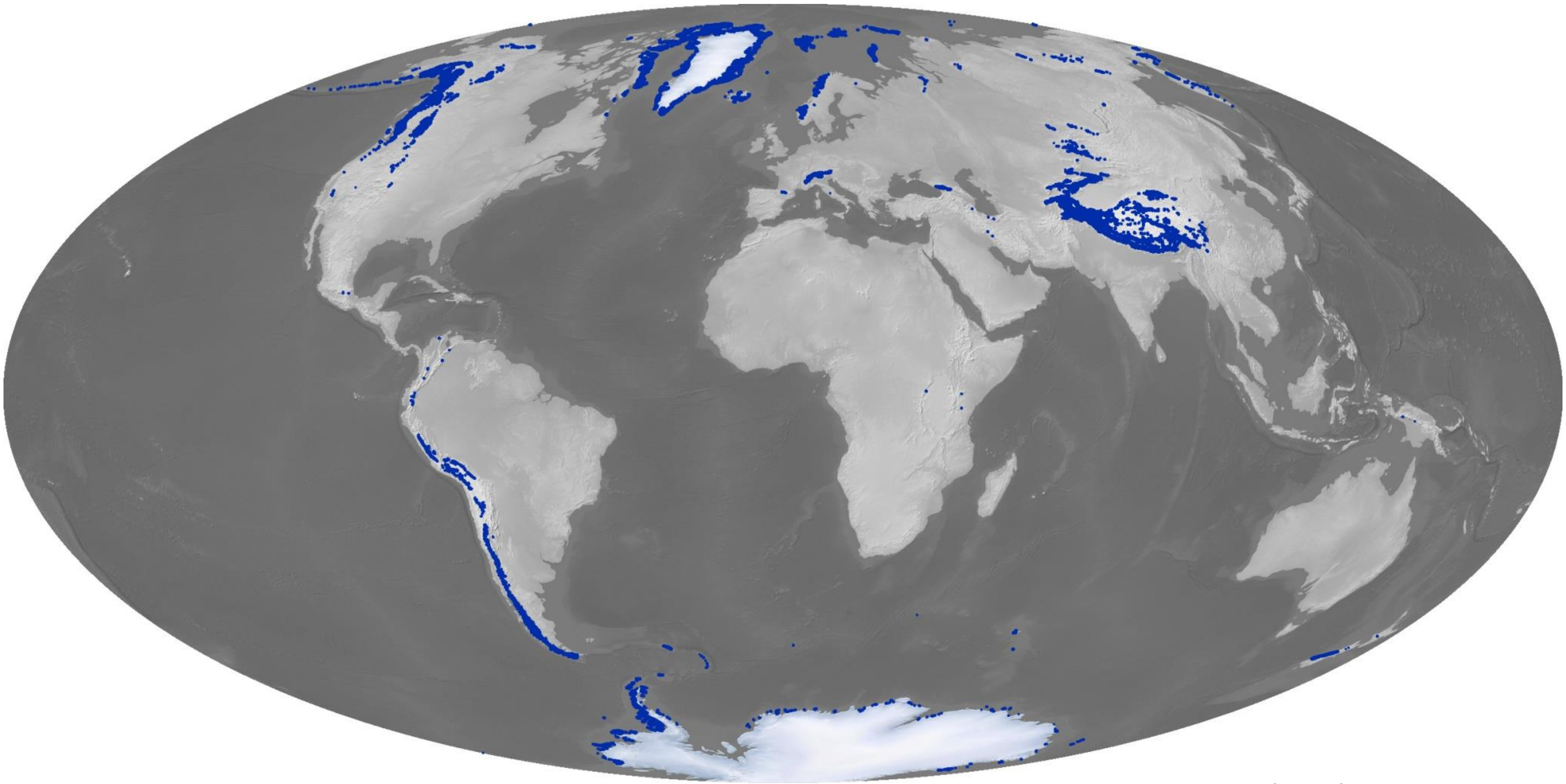
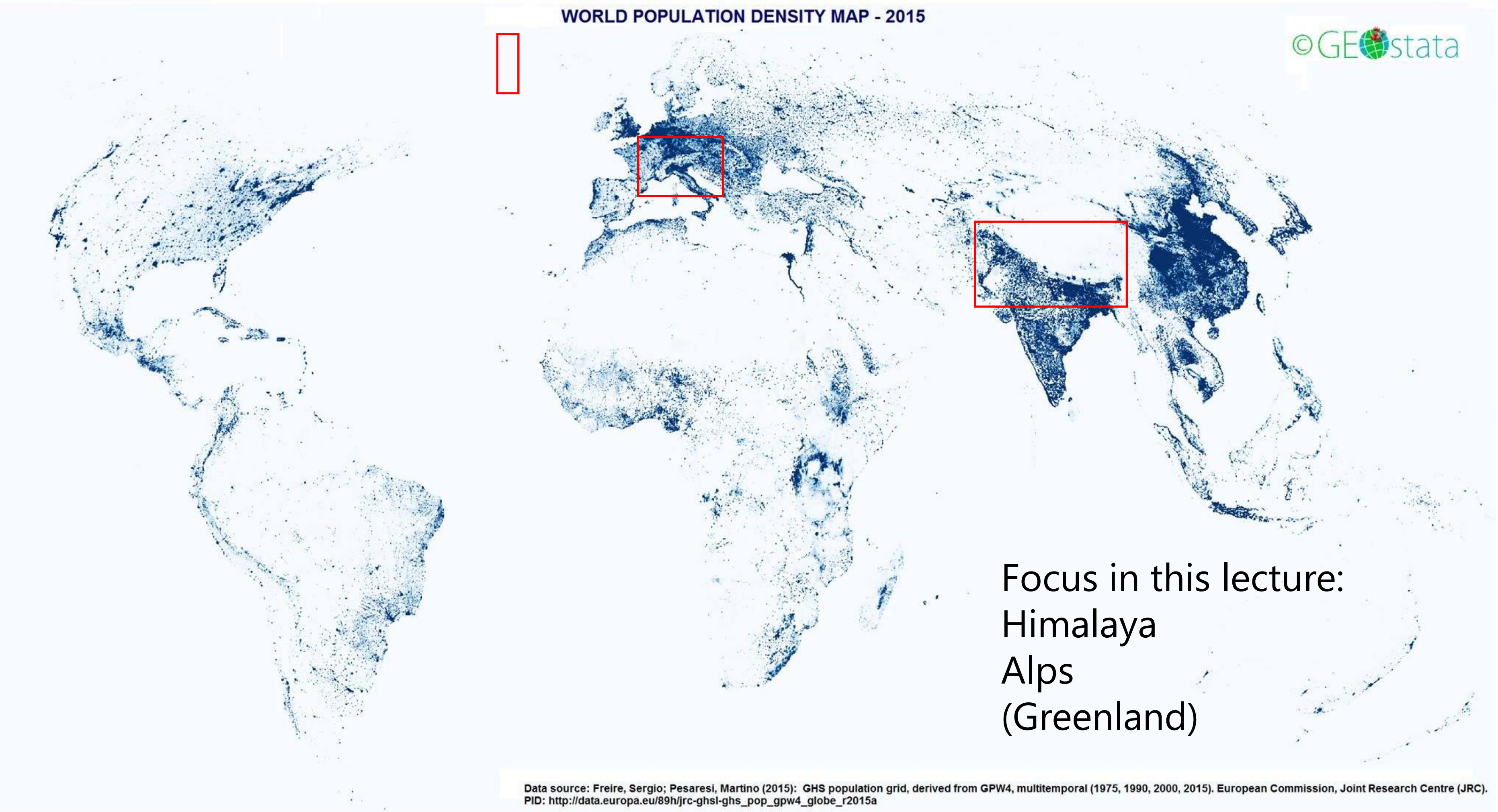
Glaciers Globally

Total Area:
RGI: 734 933 km^2
WGI: 747 688 km^2



R. Simmon, NASA; based on RGI4 (2013)



Focus in this lecture:
Himalaya
Alps
(Greenland)

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Glacier related hazards

- glacier lake outburst floods (+ resulting events)
- ice break offs (+ resulting events) / collapsing glaciers
- glacier length variations
- destabilization of frozen soils/slopes

Kaab et al., 2005

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Glacier Lake Outburst Floods (1)

British Columbia
Canada

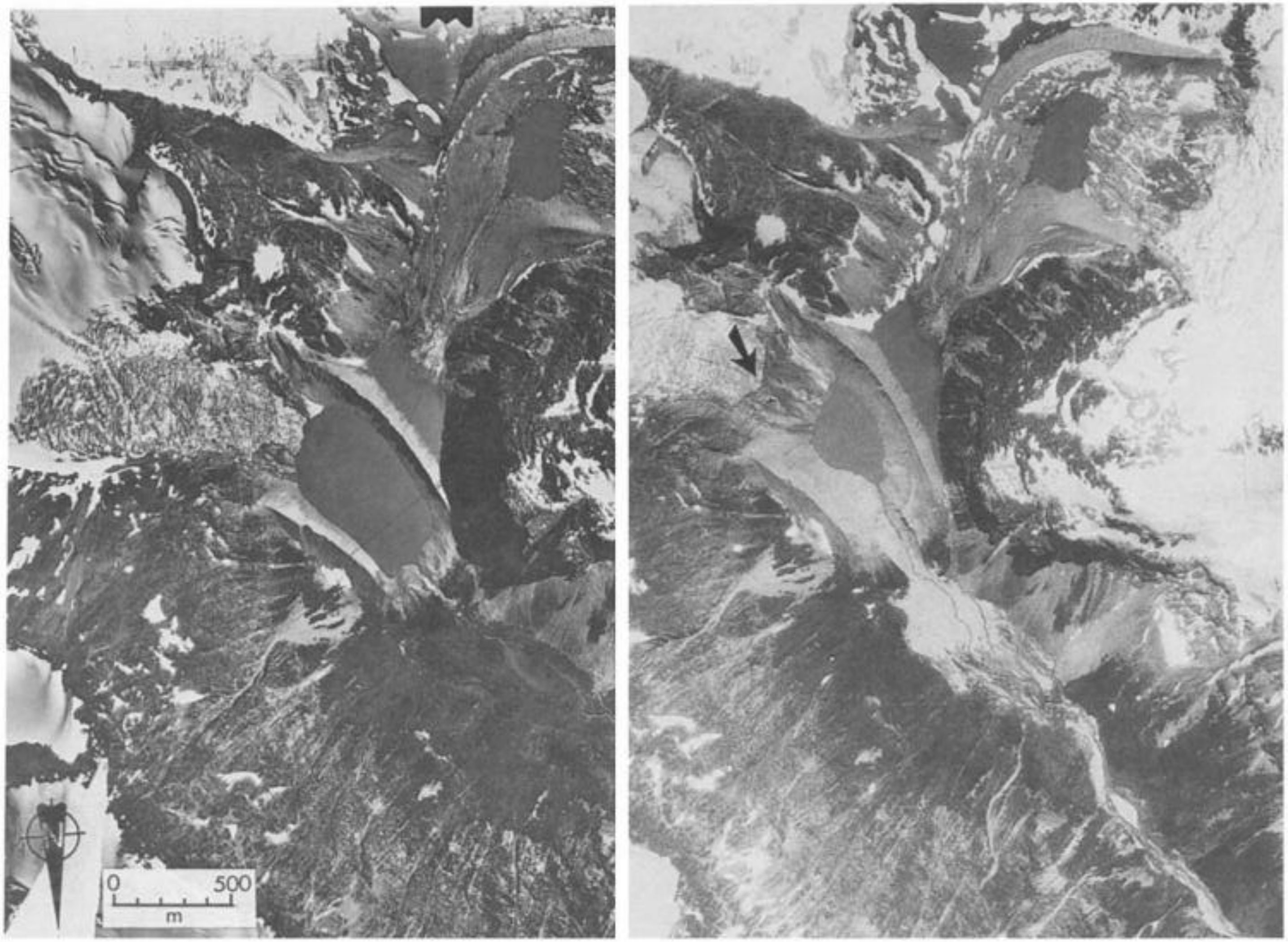
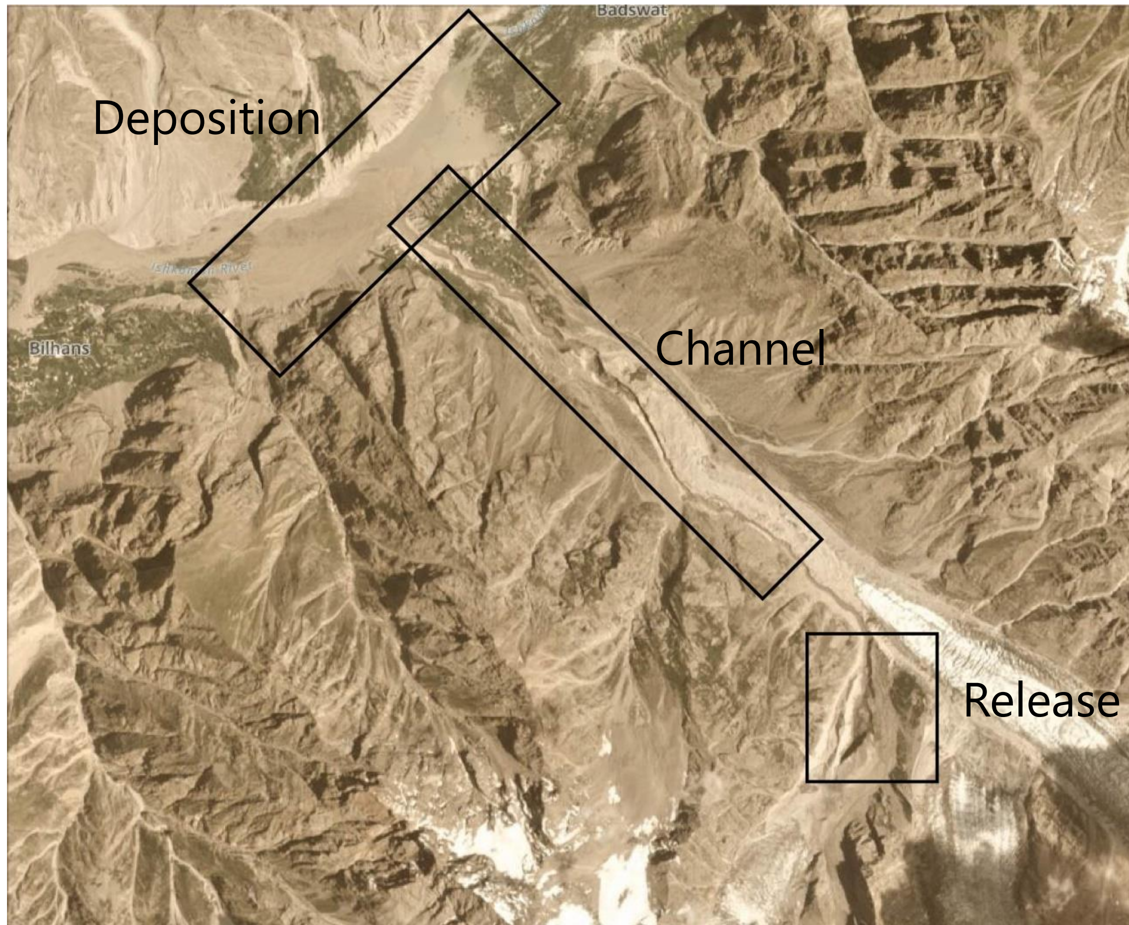


Fig. 12. Aerial photographs of Nostetuko Lake before (left, BC79069-190) and after (right, BC86048-147) the outburst flood of July 19, 1983. Failure occurred when toe of Cumberland Glacier (arrow) collapsed into the lake and generated waves that overtopped the moraine.

Glacier Lake Outburst Floods (2)



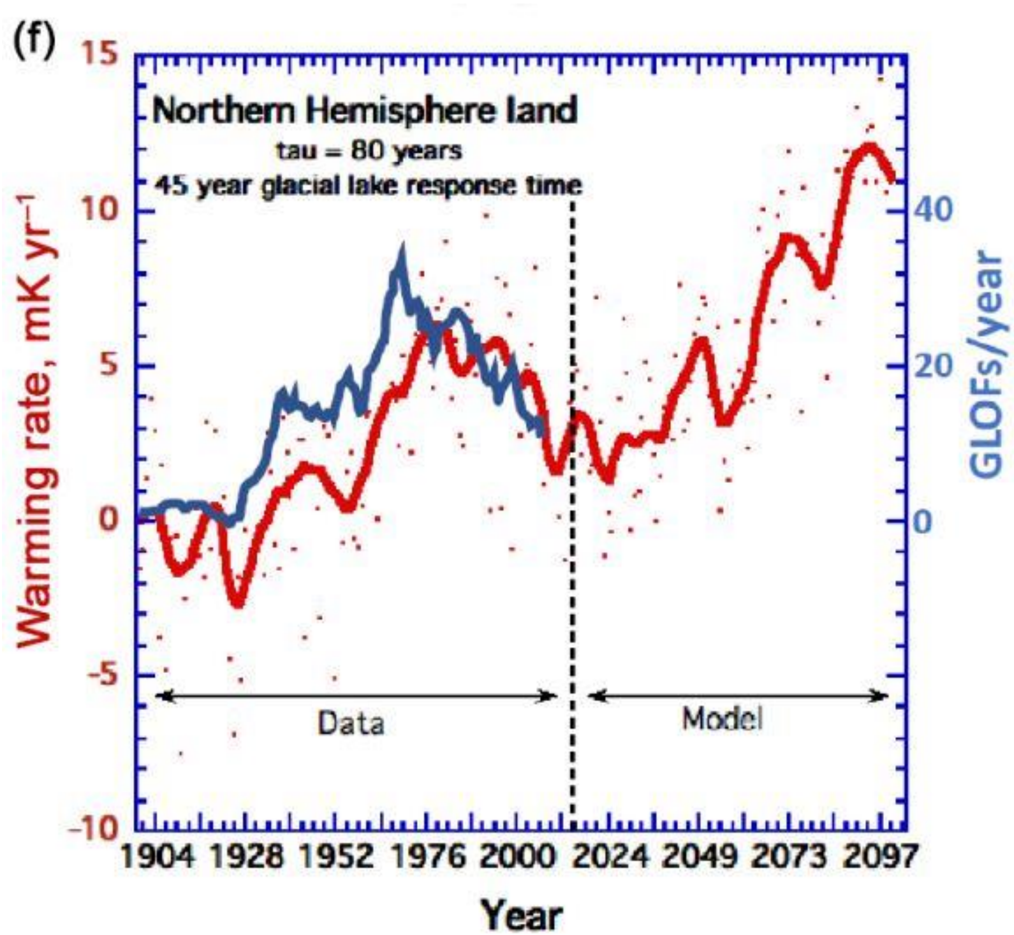
Helicopter Image/Pakistan Army; Sat image Planet

Glacier Lake Outburst Floods - *Causes*

- Mass movement into the terminal lake causing overtopping (destabilizing glacier/rock slopes)
- Failure of a moraine dam (melting of ice cored moraine)
- Surging glaciers damming a river (surges/melt season)
- Failure of an internal lake (internal melt)

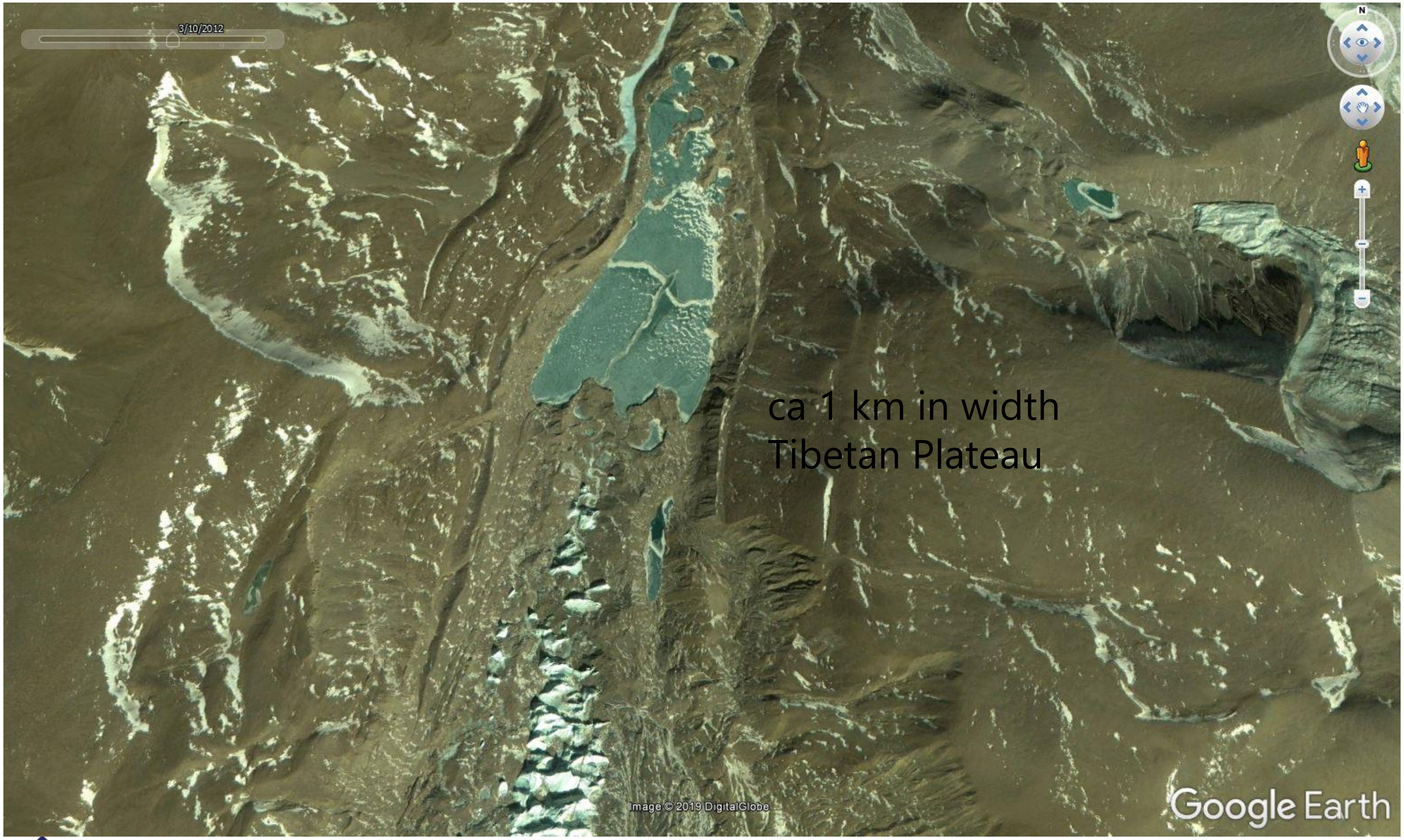
Glacier Lake Outburst Floods - *Causes*

- Link to climate change?
  - Seems very plausible and some indications
  - Difficult to proof with very little data
  - Data bias towards more observations in recent years



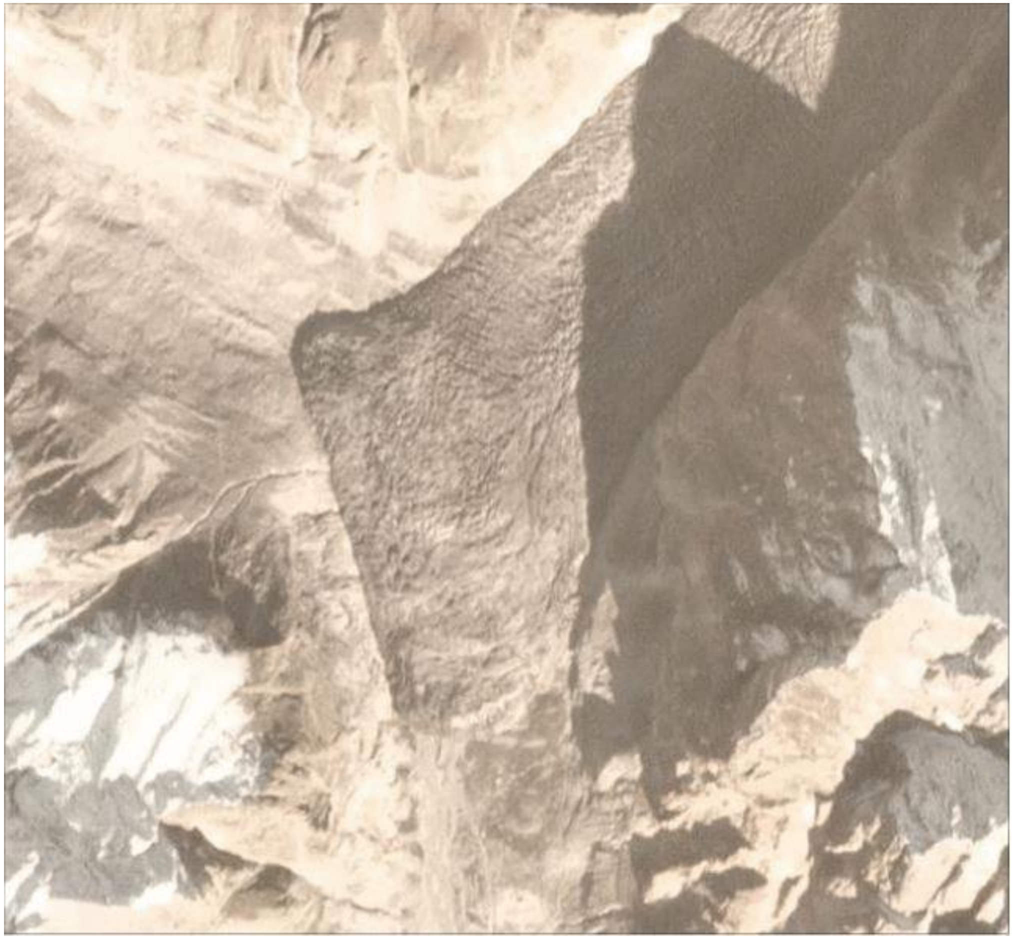
Harrison et al., 2018

Growth of terminal lakes (2012)



Growth of terminal lakes (2017)

Surging glaciers



- Rapidly advancing glaciers block rivers
- Potentially hazardous lakes
- Interference with water supply
- Karakoram, Svalbard, Andes, Alaska

Glacier Lake Outburst Floods - *Results*

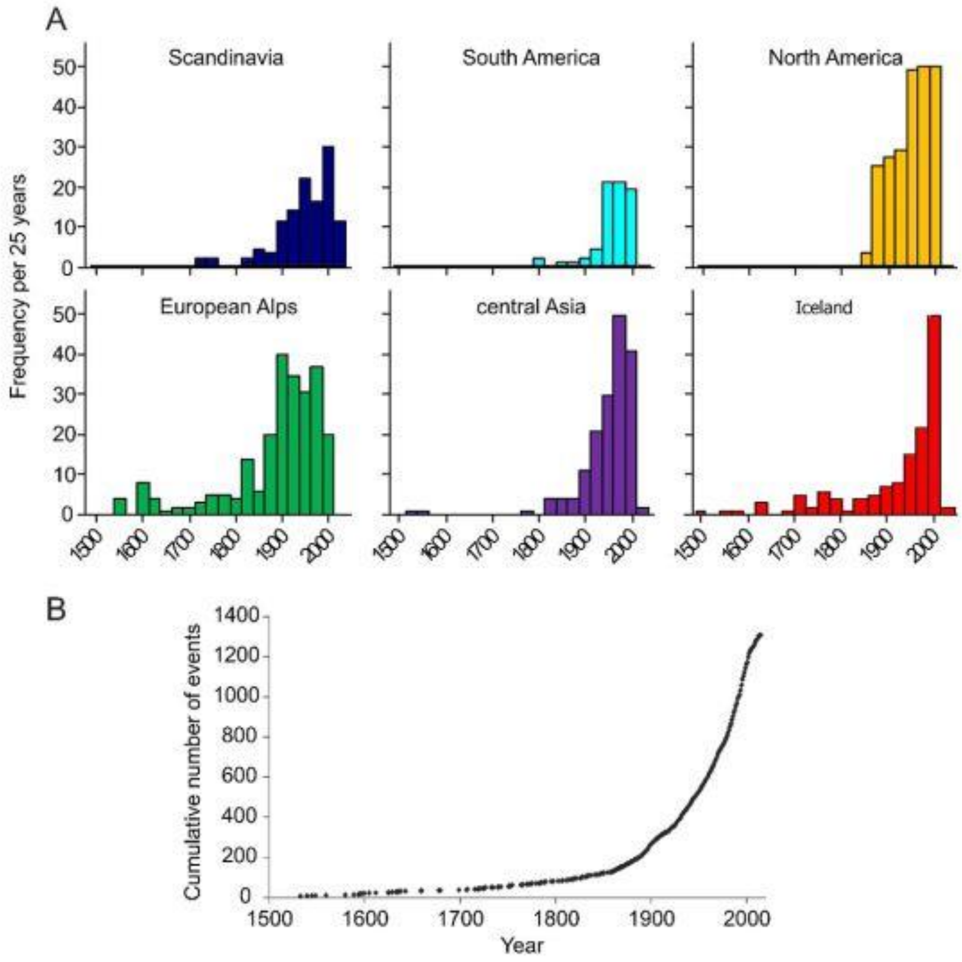


Fig. 3. Number of glacier outburst floods per 25 years by major region (A) and as a global cumulative total (B). Note that for clarity the x-axis is limited to displaying records from the last 500 years.

- ca 1500 GLOFs since 1500
- ca 15 000 deaths
- Trend? Observation bias?

- https://www.youtube.com/watch?v=e83ONiIzyK8&list=PLD585D2210775E1CD

Carrivick and Tweed, 2016

Glacier Lake Outburst Floods - *Results*

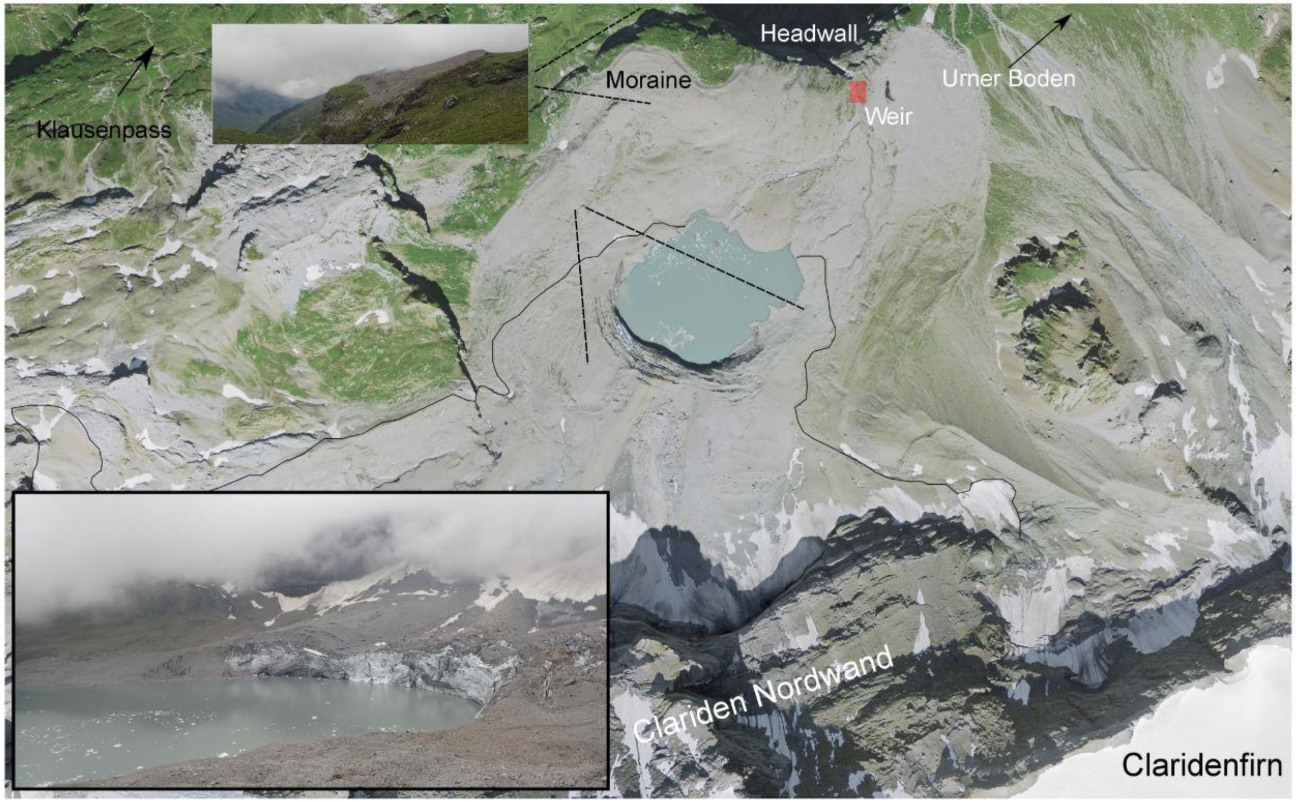


Figure 1: Griesseeli in an orthophoto from 2013 (main frame, swisstopo). The calving front as well as the frontal moraine of the glacier are shown in insets taken in August 2016 by the authors.

Steiner et al, 2016

- Relatively small lake in Switzerland
- Rapid growth due to glacier retreat
- Potential threat from ice break offs into the lake
- Huge damage potential due to expensive hydropower plant below

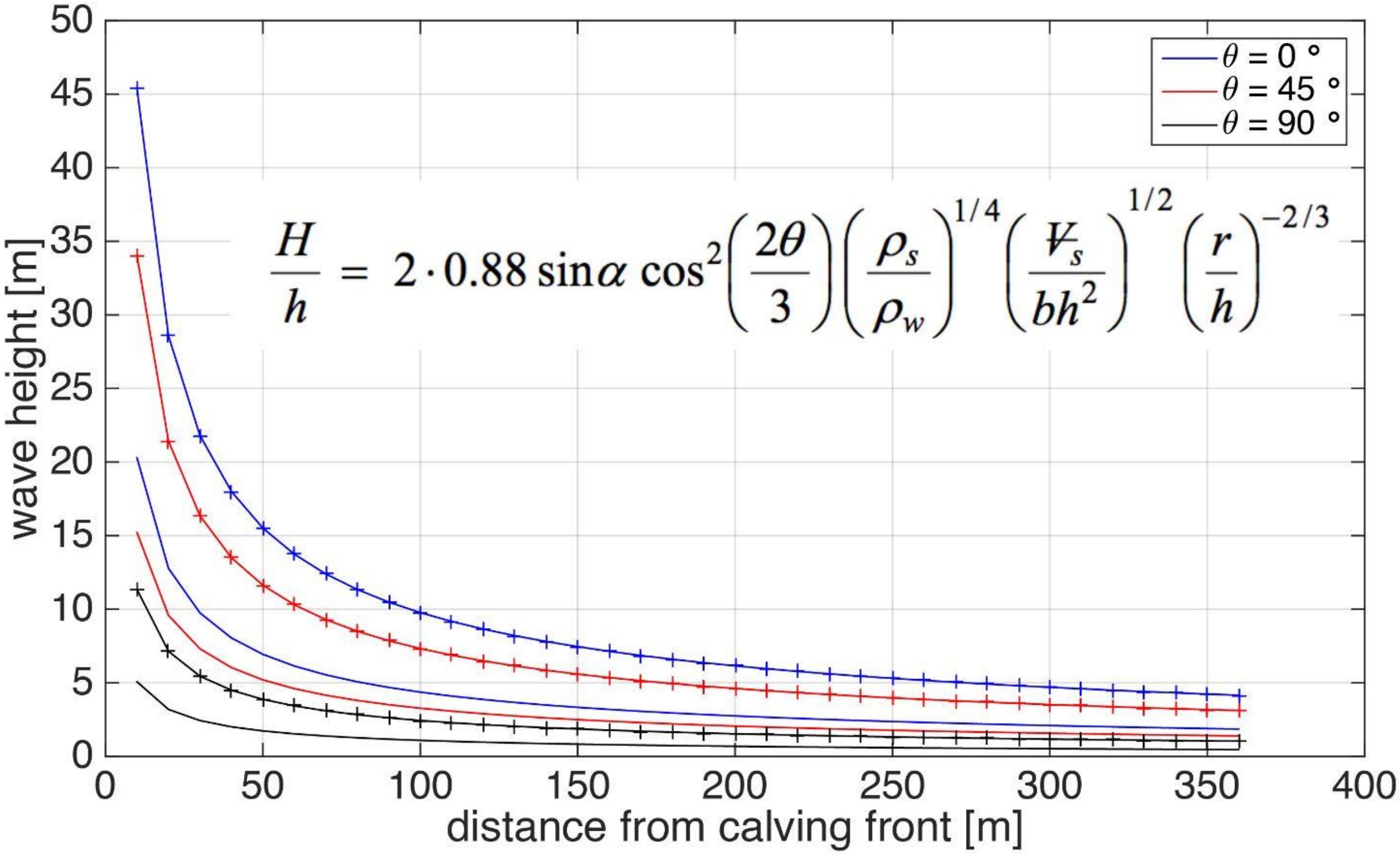
Impact waves

- Possible precursor of outburst flood
- Multi-hazard problem (landslide/avalanche + waves + dam failure + flood)
- Part of dam risk assessment in mountainous areas (wave run up height included in 'freeboard')

Figure 11: Schematic sketch showing a typical glacial lake outburst chain resulting from an initial mass movement (from, Worni et al., 2014). (1) A mass movement (ice, rock or debris) enters a lake, producing (2) a displacement wave that (3) overtops and (4) incises and erodes the dam area. (5) A flood then travels downstream where (6) populated areas and infrastructure are exposed. Note that displacement waves can be catastrophic with or without erosion of the dam area, and as such, can threaten also apparently stable bedrock dammed lakes.

Allen et al., 2017, GAPHAZ

Impact waves



Steiner et al, 2016

Glacier Lake Outburst Floods - *Results*

- Downstream flood hazard
- Large deposits of sediments (permanent damage to agriculture)

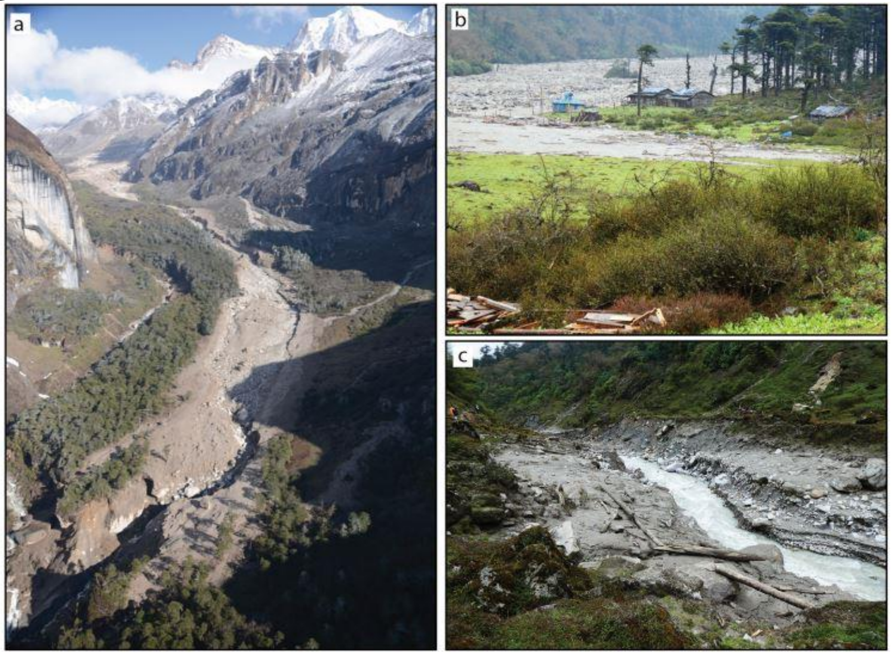


Fig. 13 **a** The flood path from the air. **b** The destruction at Yangle Kharka, where four buildings were destroyed. **c** The narrowed flood channel below Yangle Kharka

Byers et al., 2018

Glacier related hazards

- glacier lake outburst floods (+ resulting events)
- ice break offs (+ resulting events) / collapsing glaciers
- glacier length variations
- destabilization of frozen soils/slopes

Ice break offs + collapsing glaciers

- Increasingly dangerous with receding glacierettes/hanging glaciers
- Added danger in seismically active regions

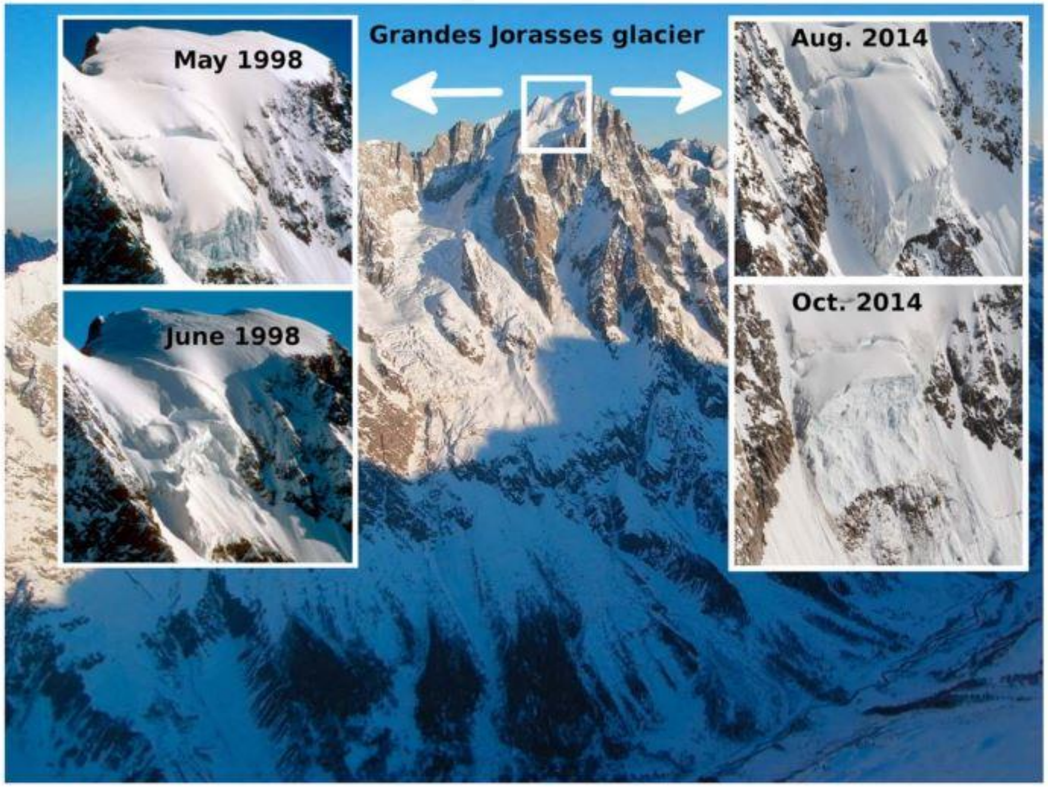


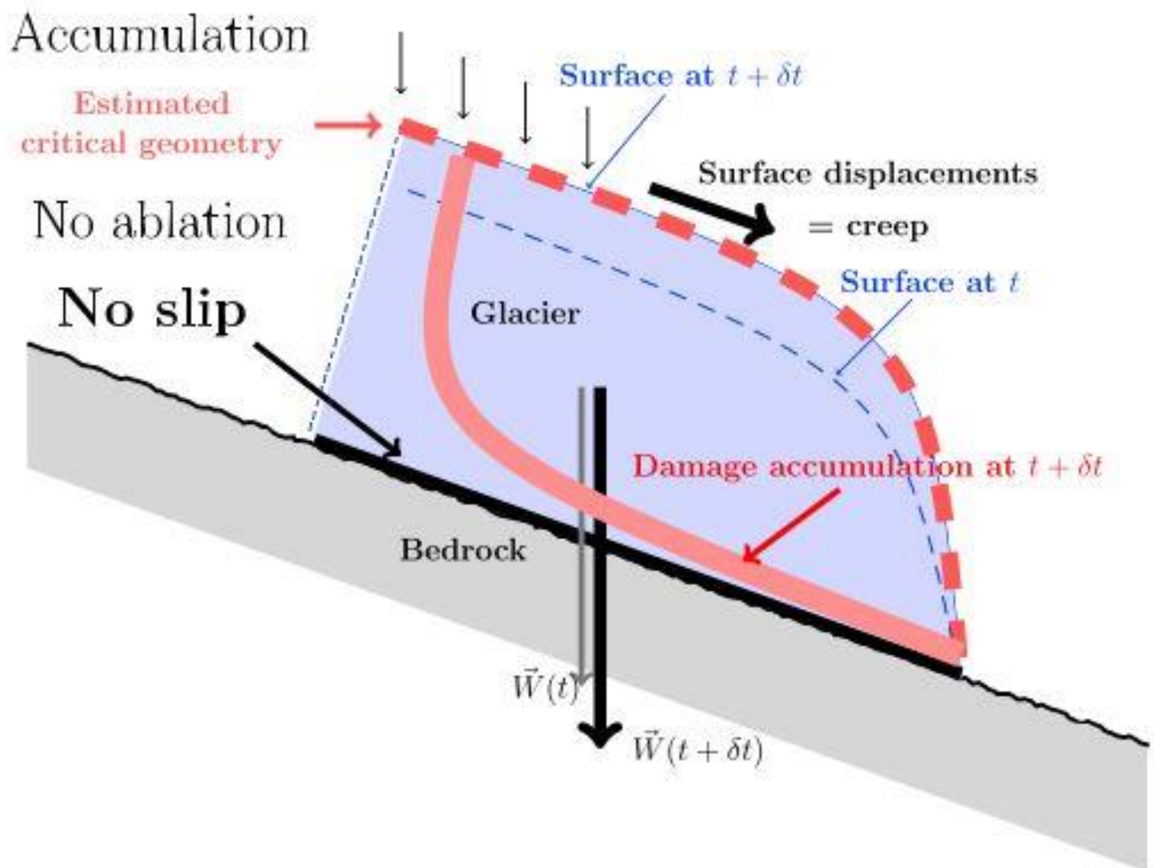
Figure 7. South side of the Grandes Jorasses and the Italian Val Ferret. (left inset) Evolution of the hanging glacier from May to June 1998. (right inset) Evolution of the hanging glacier from August to October 2014.

Faillettaz et al., 2015

Ice break offs + collapsing glaciers

Causes – *cold based; damage propagation*

- 3 glacier types
  - cold based
  - warm based
  - polythermal



Faillettaz et al., 2015

Causes –
transition from cold to warm based

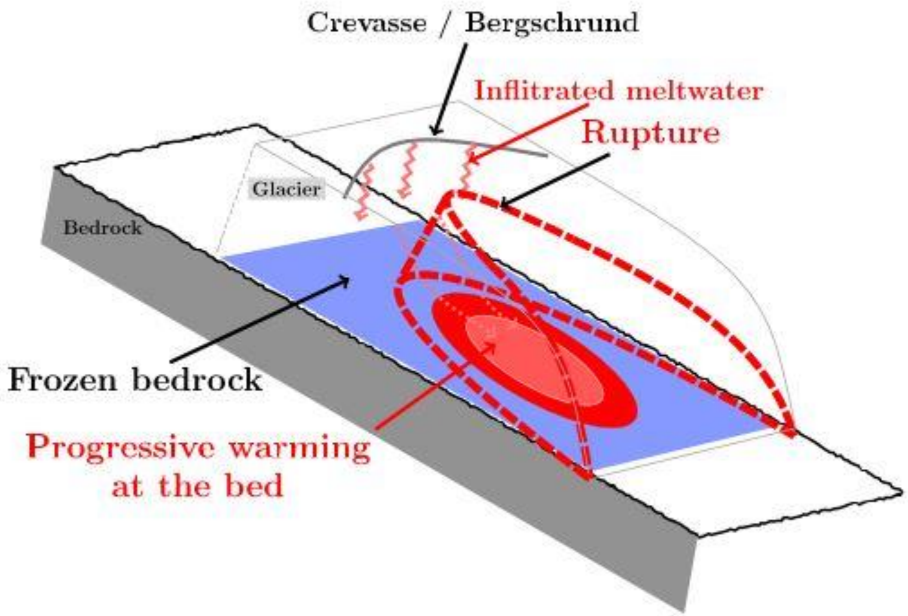


Figure 12. Schematic evolution of the instability initiated by a rapid localized warming at the ice-bedrock interface.

Faillettaz et al., 2015

Causes – *warm based; hydraulic slip*

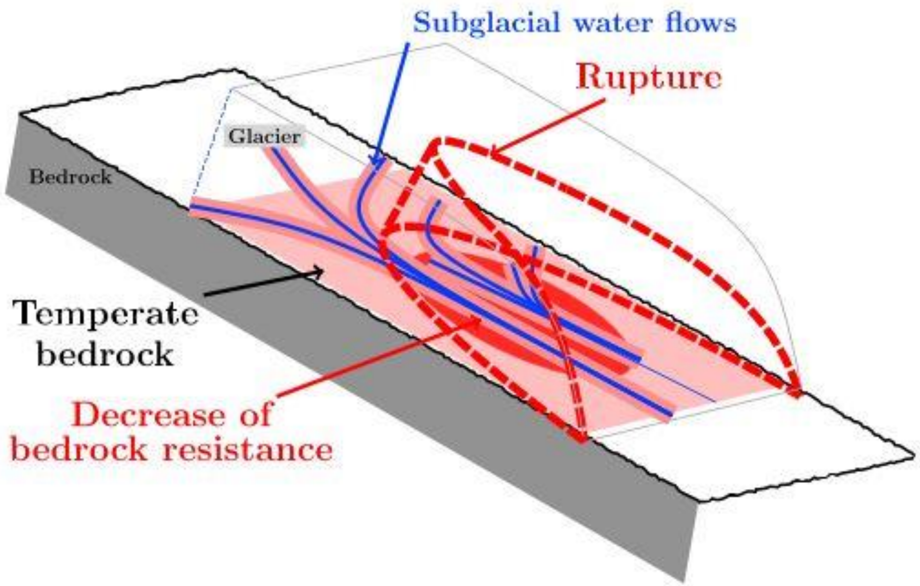


Figure 16. Schematic evolution of the instability for the case of a balanced glacier with a decreasing basal resistance due to increasing subglacial water pressure.

Faillettaz et al., 2015

Results – accidents in remote locations (Switzerland)

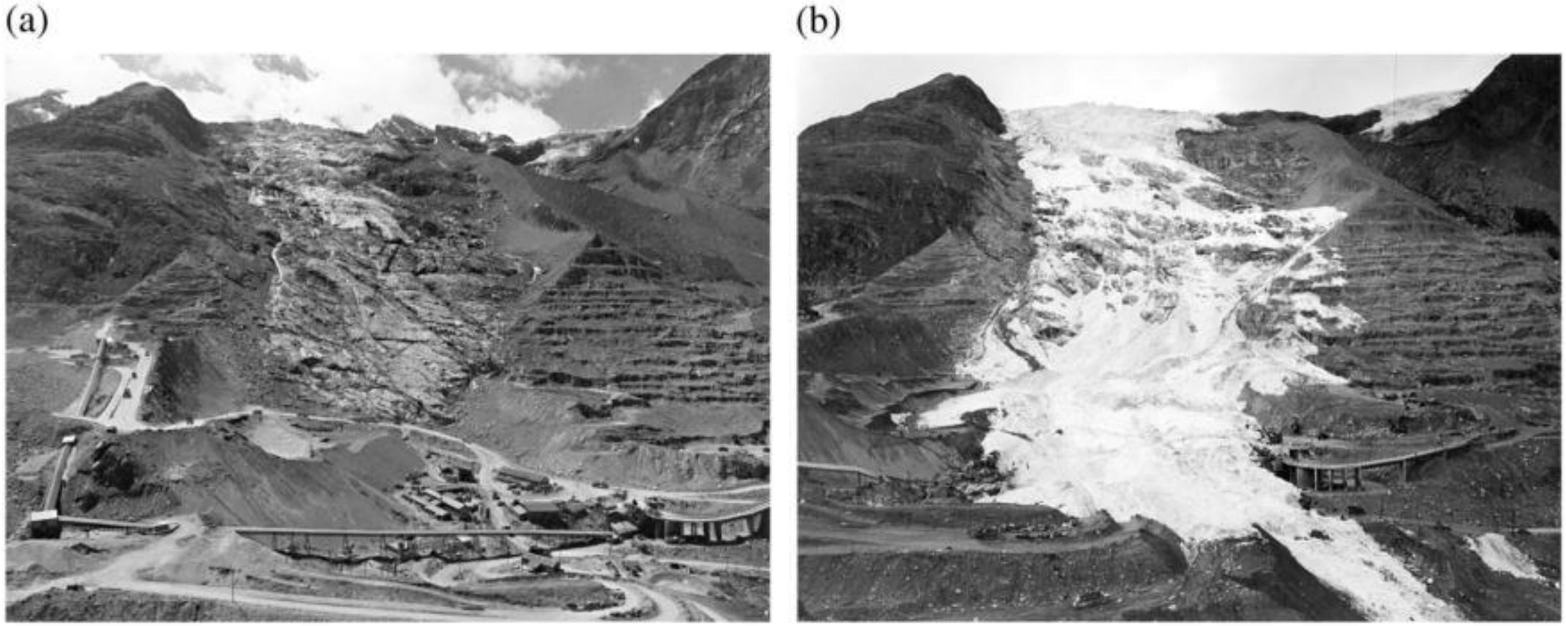


Figure 13. The Mattmark disaster: 2×10^6 m^3 of ice broke off on 30 August 1965 (archive VAW).

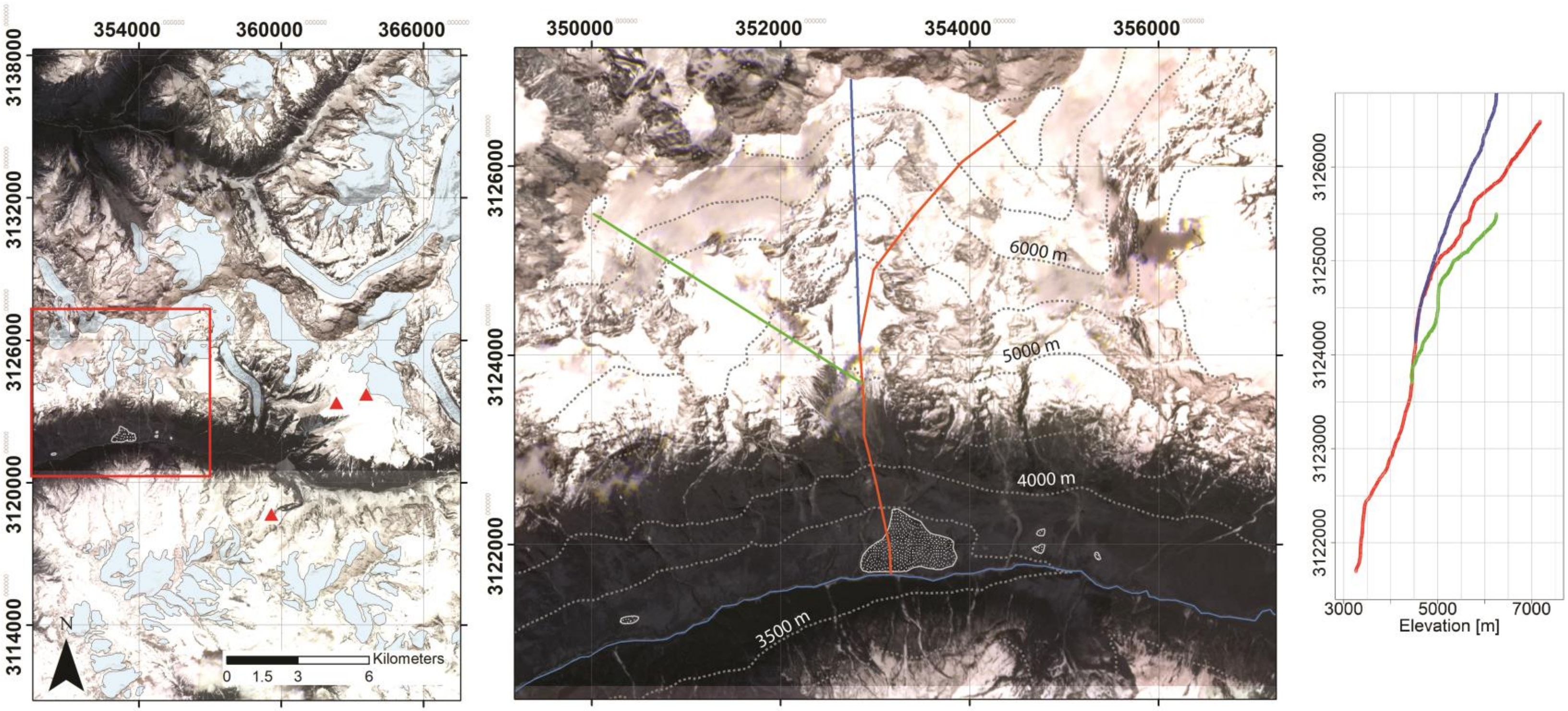
Faillettaz et al., 2015

Results – co-seismic events

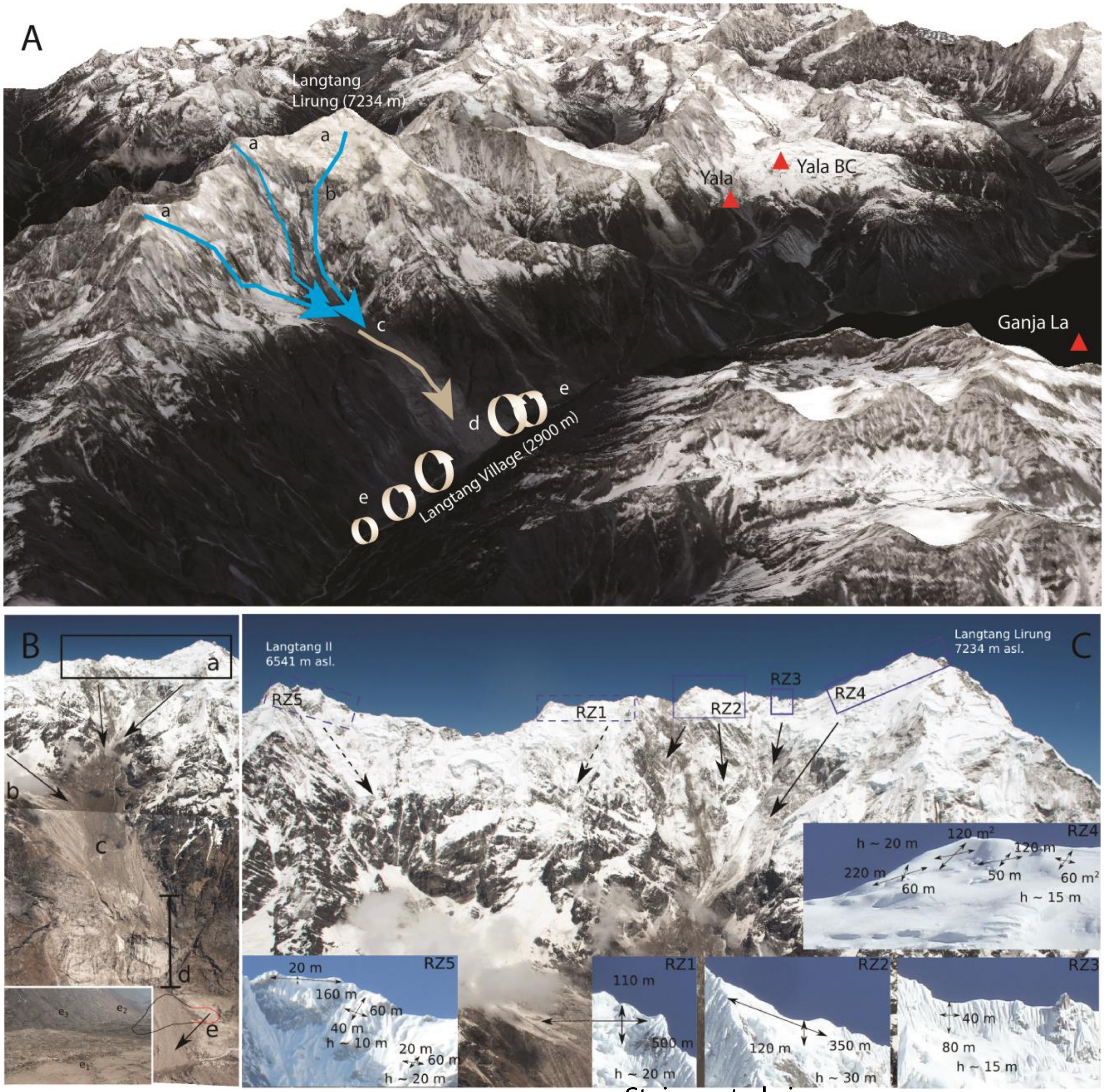
- Gorkha earthquake 2015 in Nepal
- >4000 co-seismic landslides
- Ice-break offs that caused deposits of up to 100 m depth
- Multi-hazard (ice break off + avalanche + debris flow)

Kargel et al., 2016

Results – co-seismic events

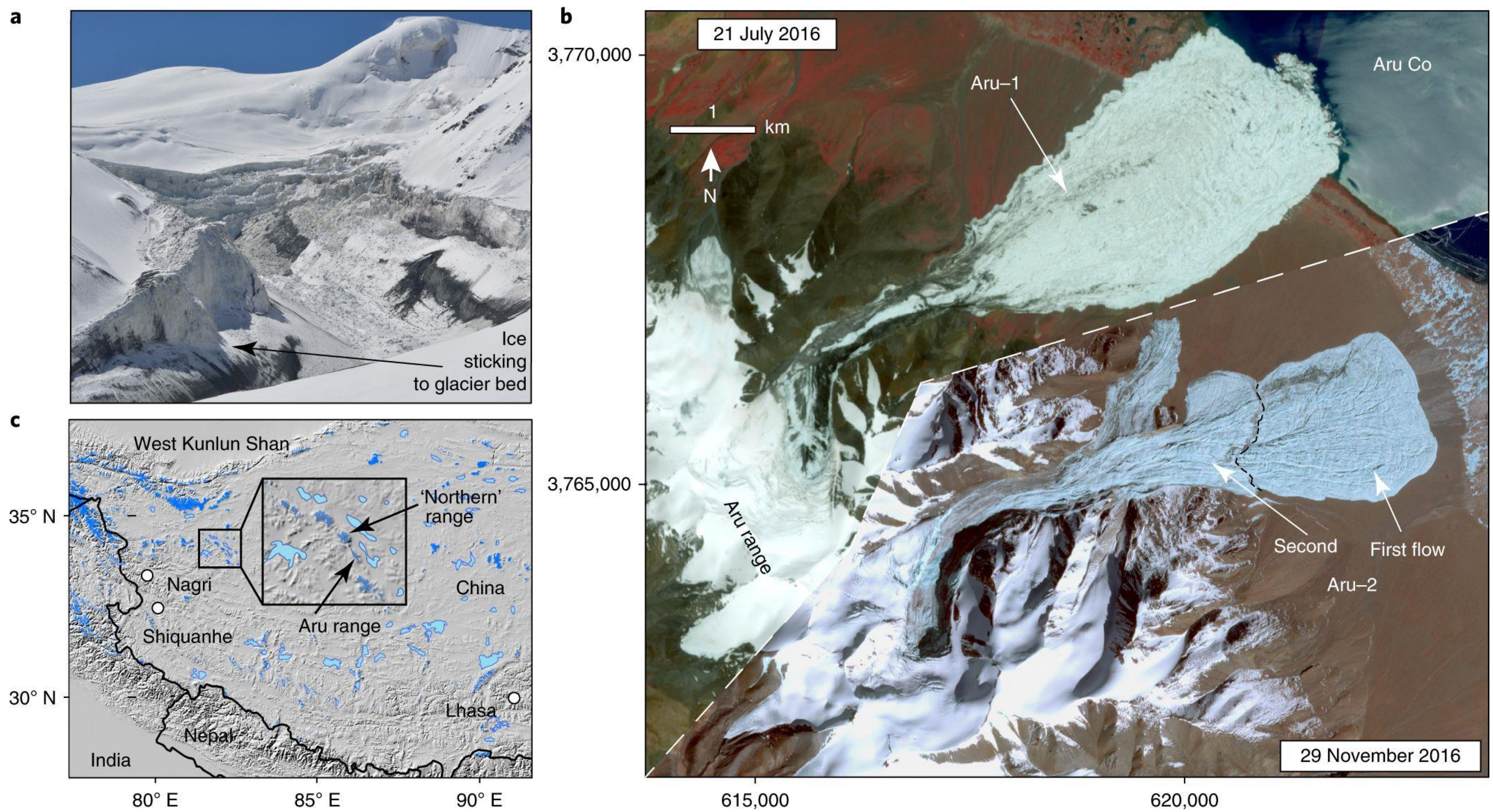


Steiner et al., in prep.



Steiner et al., in prep.

Results – Internal glacier collapse

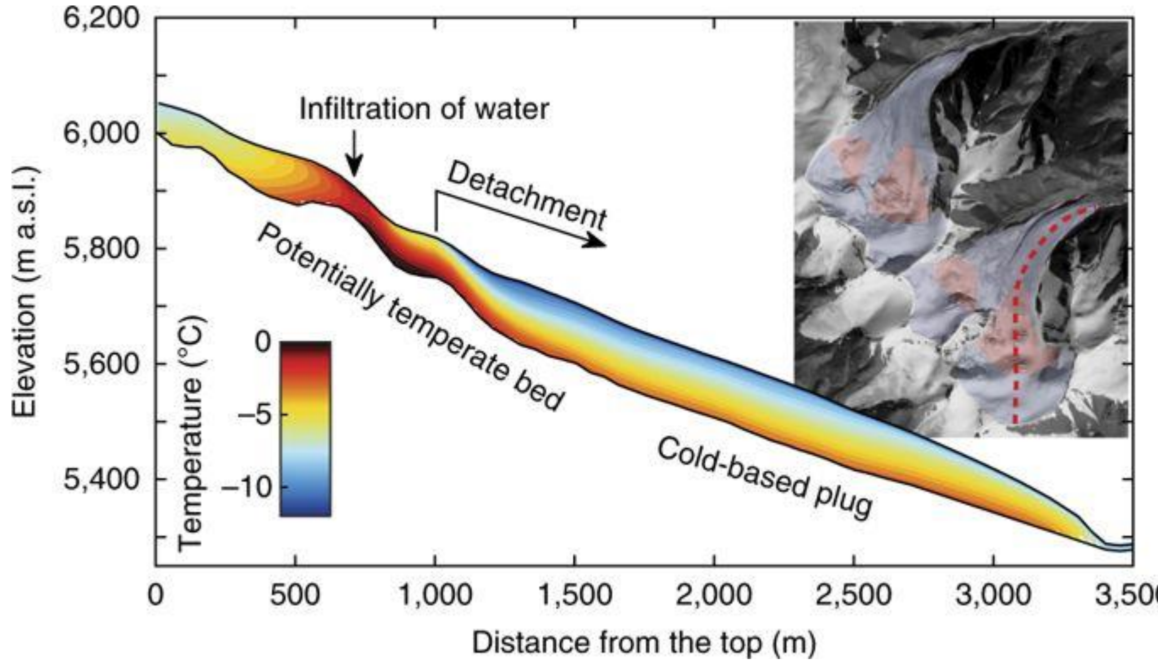


Kaab et al., 2018

- Regional temperature increase leads to internal ‘melt lakes’
- Once pressure becomes too high and ice instable, the glacier ‘fails’
- So far singular events (2) but with catastrophic consequences (>125 deaths in Russia during the Kolka slide in 2002)

Kaab et al., 2018

Gilbert et al., 2018



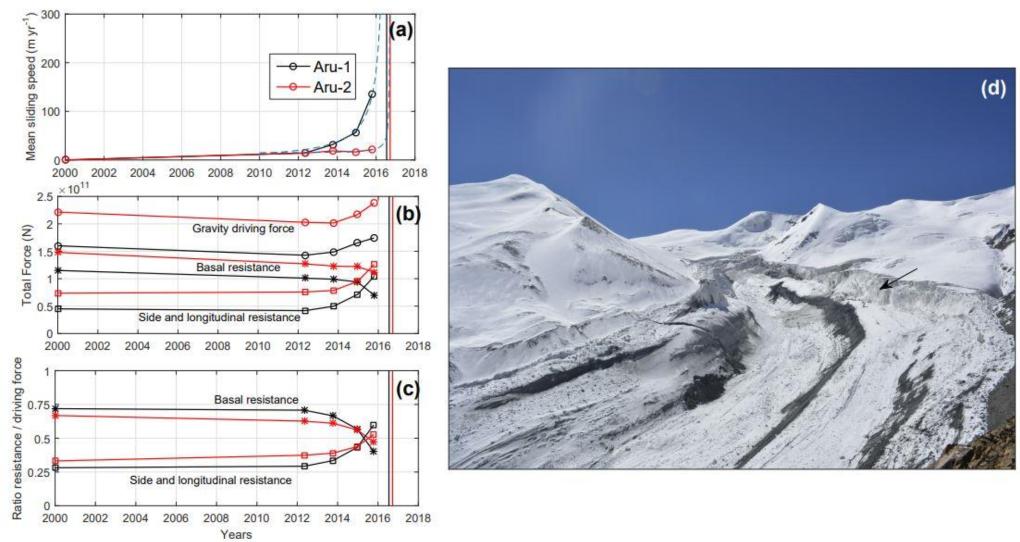


Figure 9. **(a)** Mean sliding speed of the detachment zone for Aru-1 (black) and Aru-2 (red) glaciers. The dashed blue lines show predicted speed following an empirical law of slope failure (Voight, 1990). **(b)** Force balance acting on the detachment of Aru-1 (black) and Aru-2 (red). **(c)** Ratio of resisting force over driving force for Aru-1 (black) and Aru-2 (red). Vertical lines show collapse dates in the three panels. **(d)** The Aru-2 glacier detachment zone on 4 October 2016 (Picture from T. Yao). The side resistance computed in the force balance analysis arises from lateral shearing on the right side of the detachment (black arrow).

Glacier related hazards

- glacier lake outburst floods (+ resulting events)
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- glacier length variations
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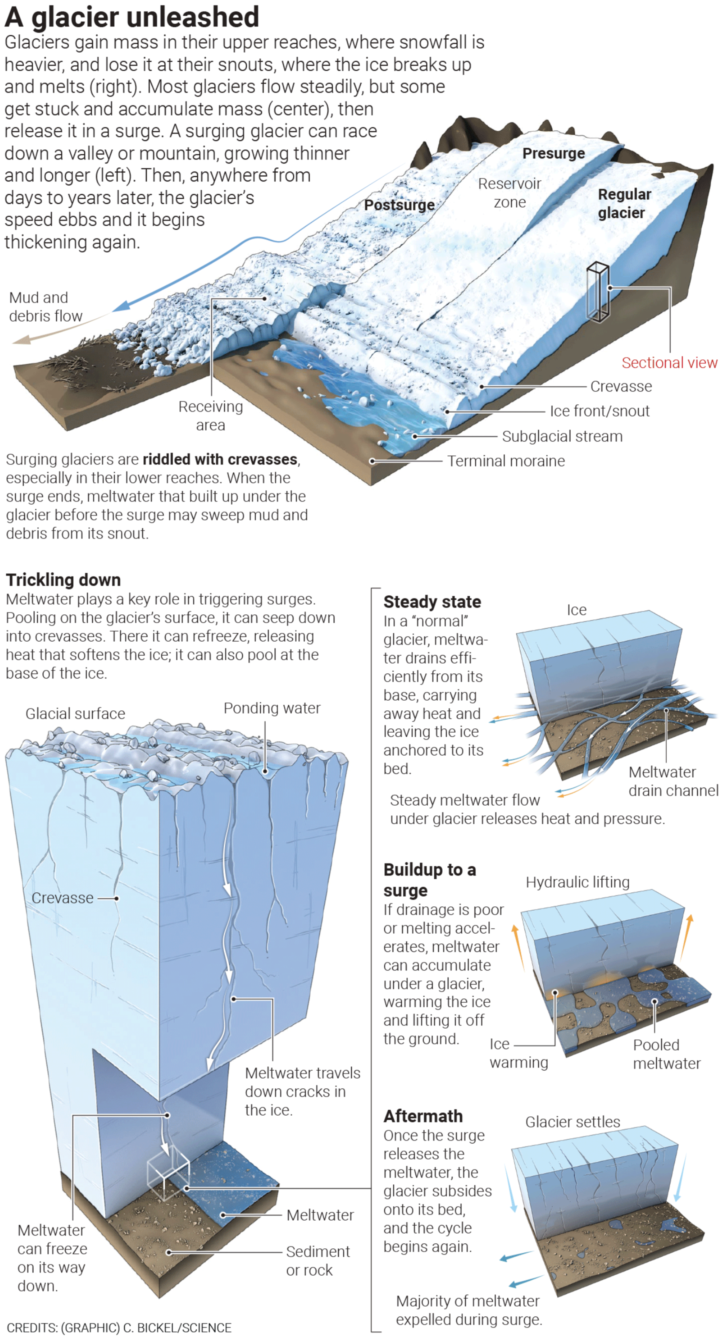
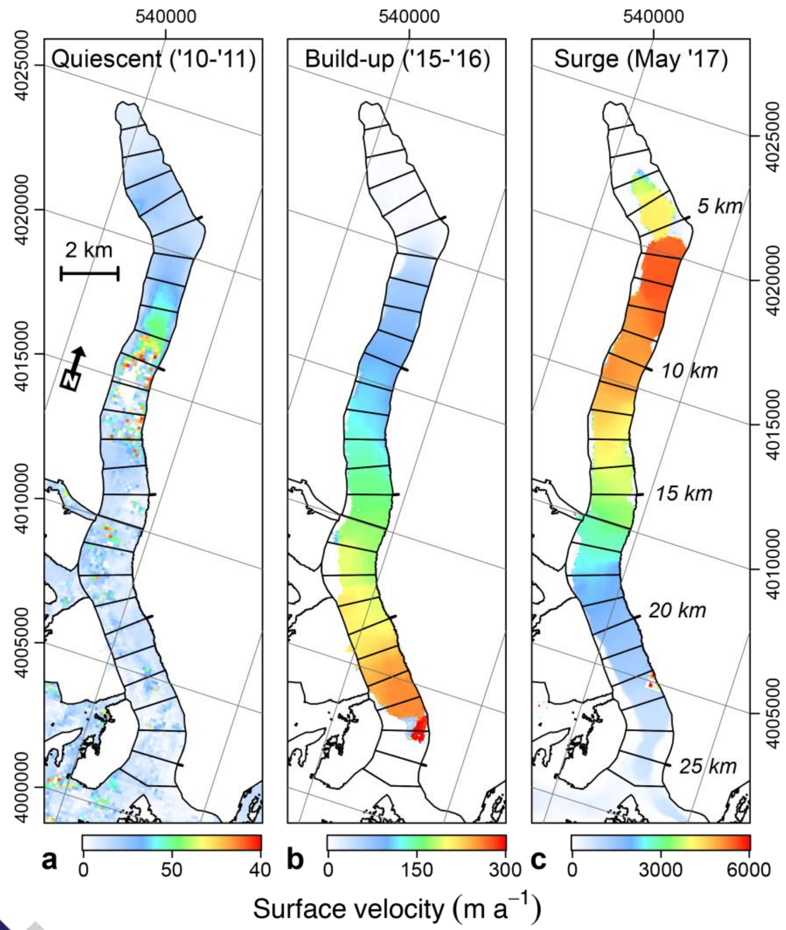
Glacier length variations surges

- Glacier tongues extend within days to weeks by 100s of meters
- Decadal return period
- No net mass gain or loss
- Unclear why these events happen – no apparent link to changing climate



Surge in Karakoram 2017

- Glacier velocities from remote sensing



Steiner et al., 2018, Cryosphere

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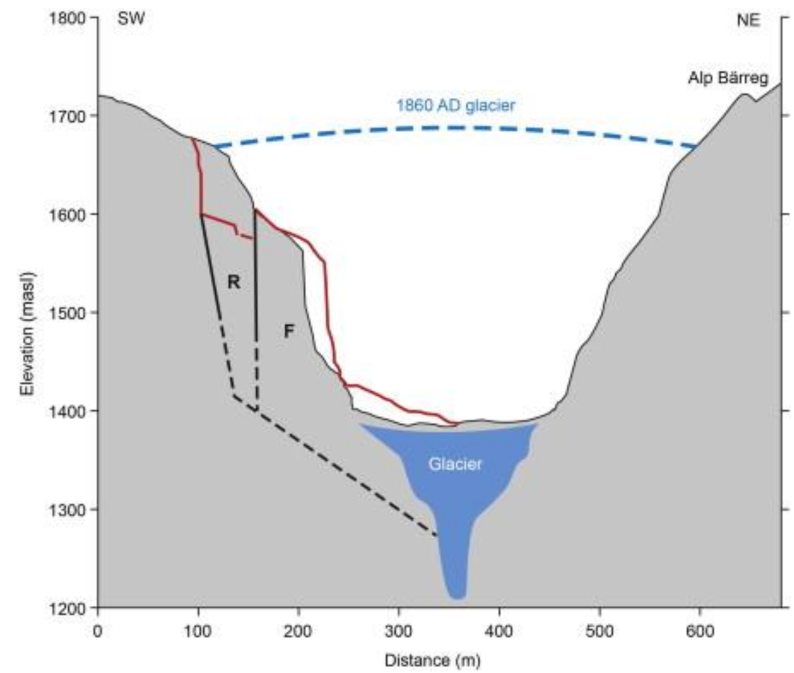
Kaab et al., 2005

Destabilization of frozen soil

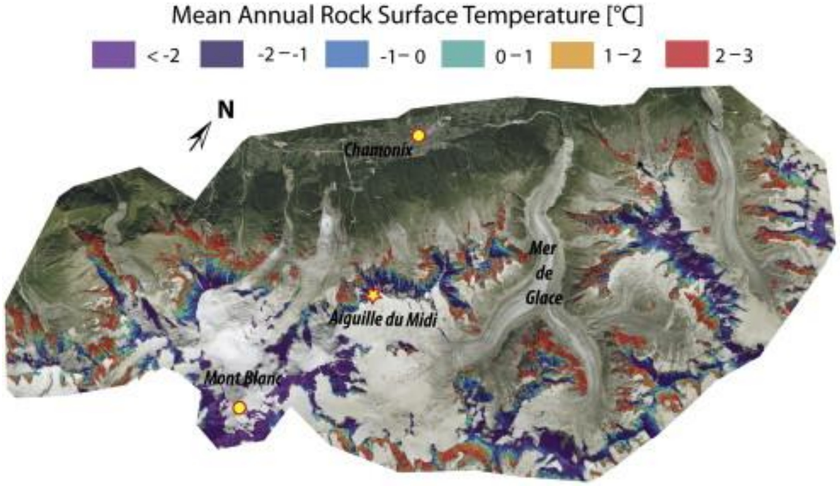
- Increased rock slope failure in post-glaciated environments
- Dependent on geology
- Freeze-thaw within rock cracks
- Isostatic rebound after deglaciation

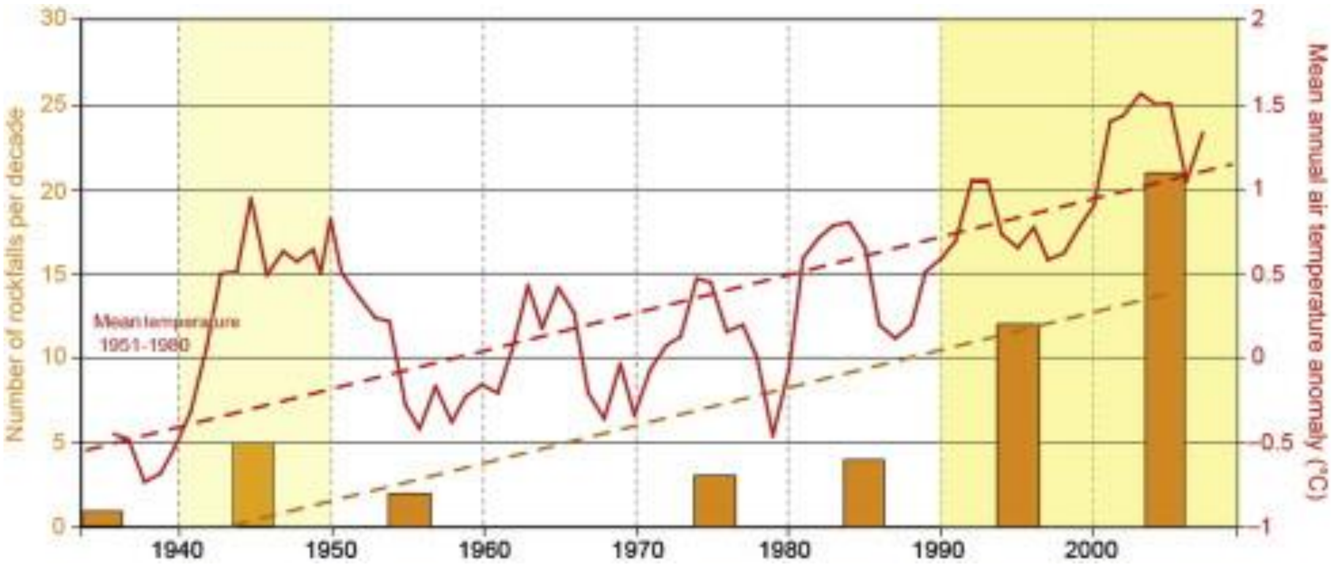


Deline et al., 2015

Destabilization of frozen soil

- Likely direct link with increasing temperatures





Deline et al., 2015

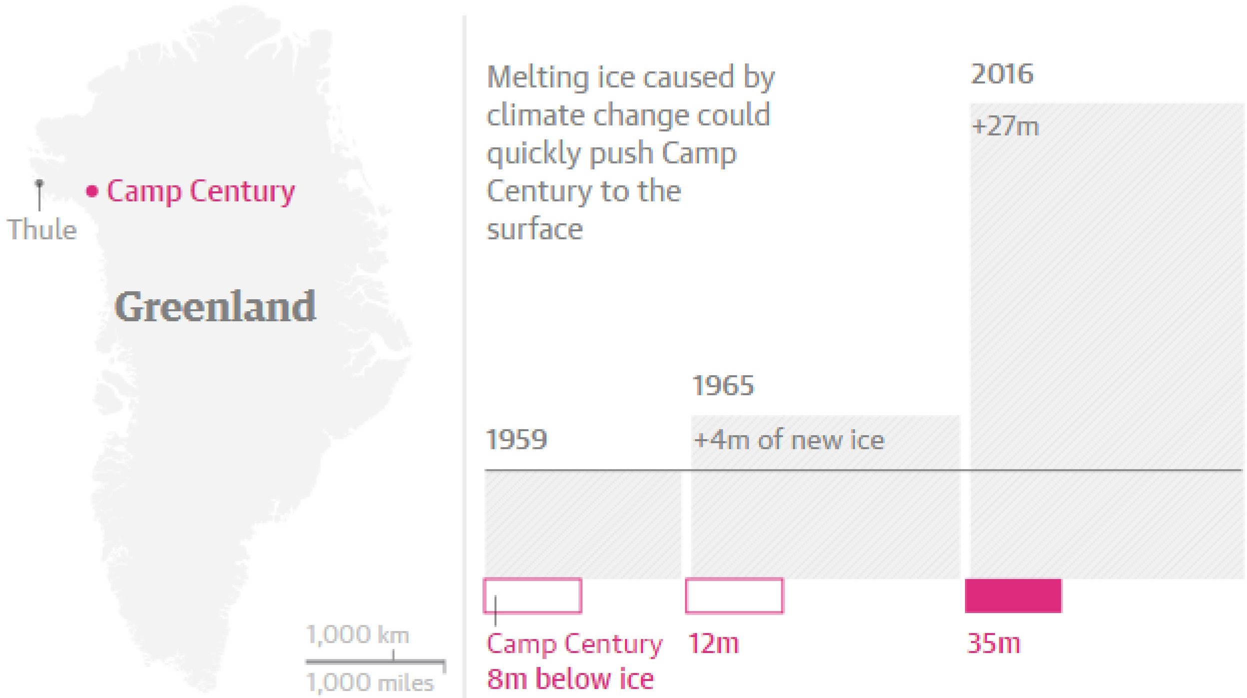
Destabilization of frozen soil

- https://www.youtube.com/watch?v=RYRfPrhCWzs

- https://www.youtube.com/watch?v=BcXsJzzlNNk

Hazards of deglaciation on ice sheets

- Deglaciation over hazardous materials



Graphic: The Guardian, 27/09/2016

- Nuclear waste originally deposited 10 m below the surface in the accumulation area
- Today >30 m below the ice
- Change in ice density/weight
- In future?

Colgan et al., 2016, GRL

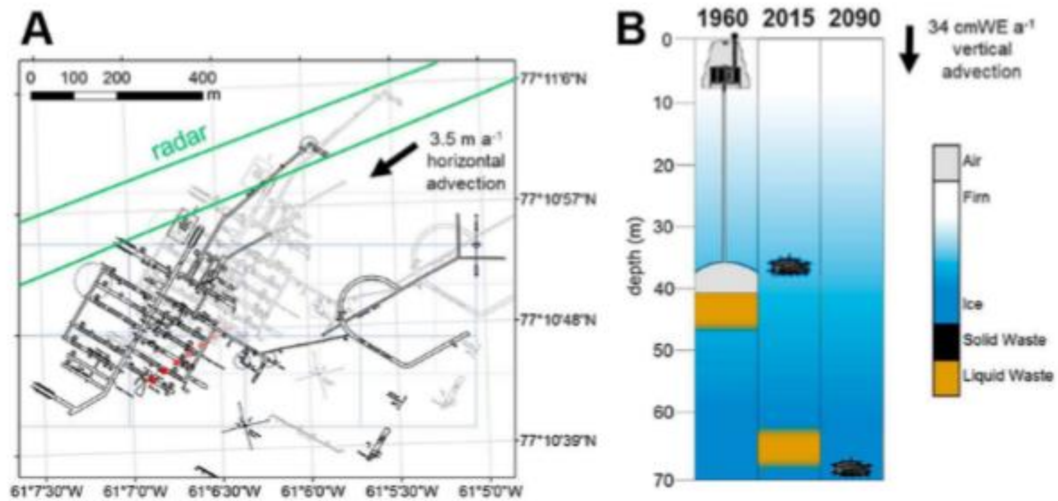


Figure 2. (a) Camp Century "as built" map georeferenced to 1960 (grey) and 2020 (black) locations [*Kovacs*, 1970], based on past surveys of the borehole location and horizontal advection associated with ice flow (Supplementary Methods). The red points denote decadal borehole location from 1960 to 2020. The green lines denote radar profiles shown in Figure 3. (b) Estimated Camp Century solid and refrozen liquid waste depths in 1960, 2015, and 2090, based on vertical advection rates (Figure S3). The horizontal extent of the liquid waste, while large relative to tunnel width, is small relative to camp width.

Future Ice melt in a changing climate …

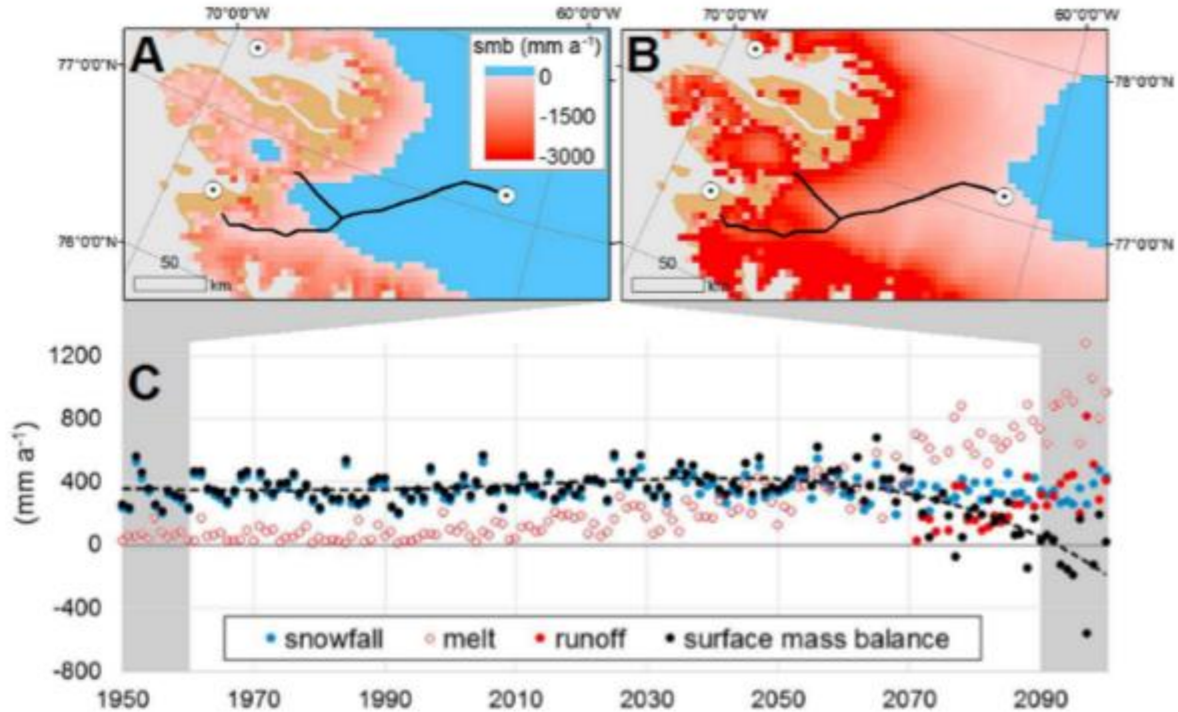


Figure 4. (a) Surface mass balance in Northwest Greenland during the 1950s (1950–1959) and (b) 2090s (2090–2099) as simulated by MAR v3.5 forced by CanESM2 under RCP8.5 [*Fettweis et al.*, 2013]. The color bars saturate at minimum and maximum values. The blue shading denotes the accumulation area where surface mass balance is positive. (c) Surface mass balance, and its components, at Camp Century during 1950–2100 as simulated by MARv3.5 and forced by CanESM2. The dashed line denotes polynomial trend. The NorESM1 simulation is shown in Figure S2.

Colgan et al., 2016, GRL

… what about horizontal movement?

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Hazard Assessment

- 2 tier assessment procedure
- Rapid and long-term assessment
- Communication to affected population (alertness vs unnecessary fear)

Allen et al., 2017, GAPHAZ

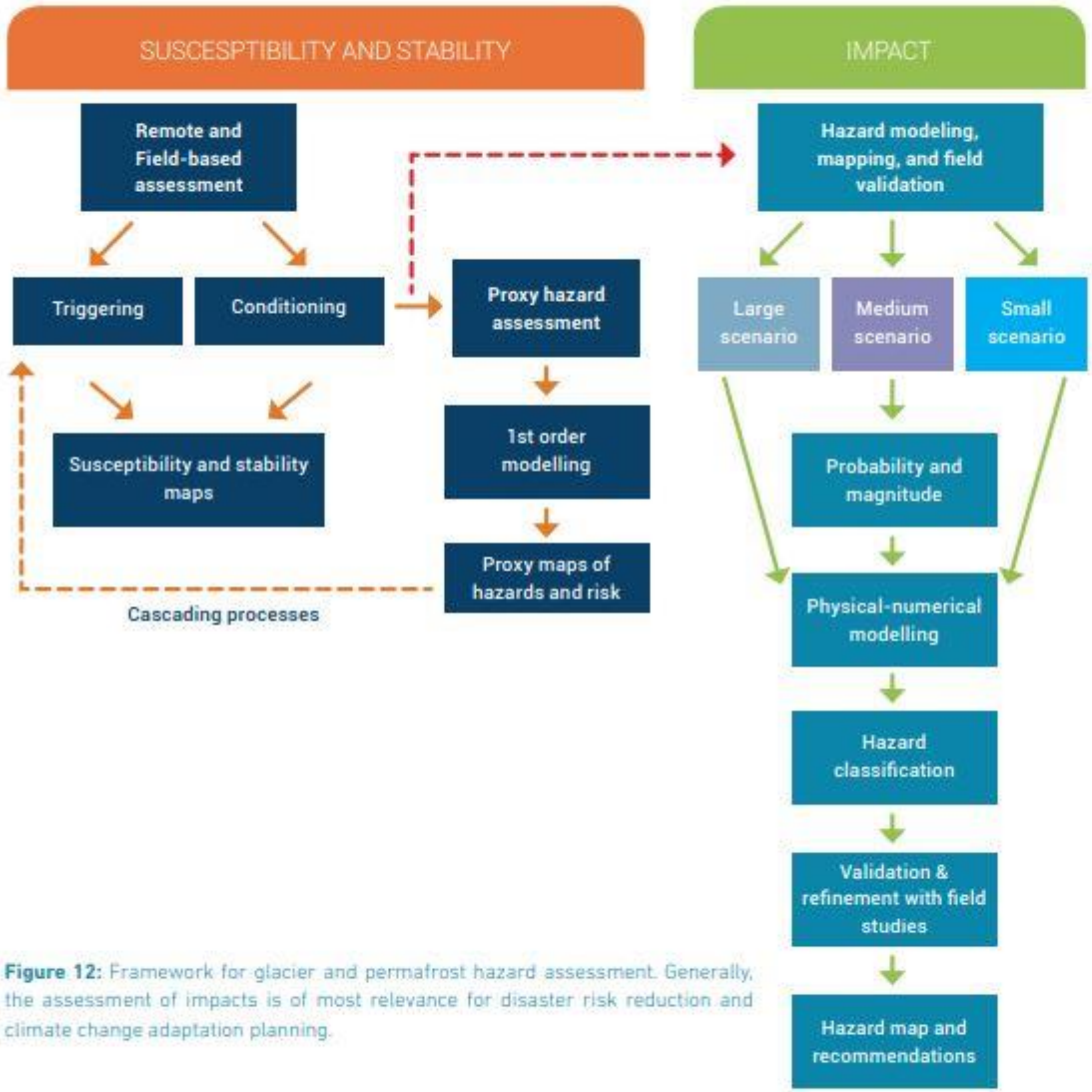


Figure 12: Framework for glacier and permafrost hazard assessment. Generally, the assessment of impacts is of most relevance for disaster risk reduction and climate change adaptation planning.

Hazard Mapping

- Remote sensing
  - Maps of potential instable areas
  - Identification of weak moraines/ice cores/rapid surface changes on glaciers
  - Slope maps + exposure to solar radiation (freeze thaw cycle)
  - Exposure maps
- Field based
  - Runout lengths
  - Damage classification (pressure, inundation)
  - Interviews

Example GLOFs – *Susceptibility*

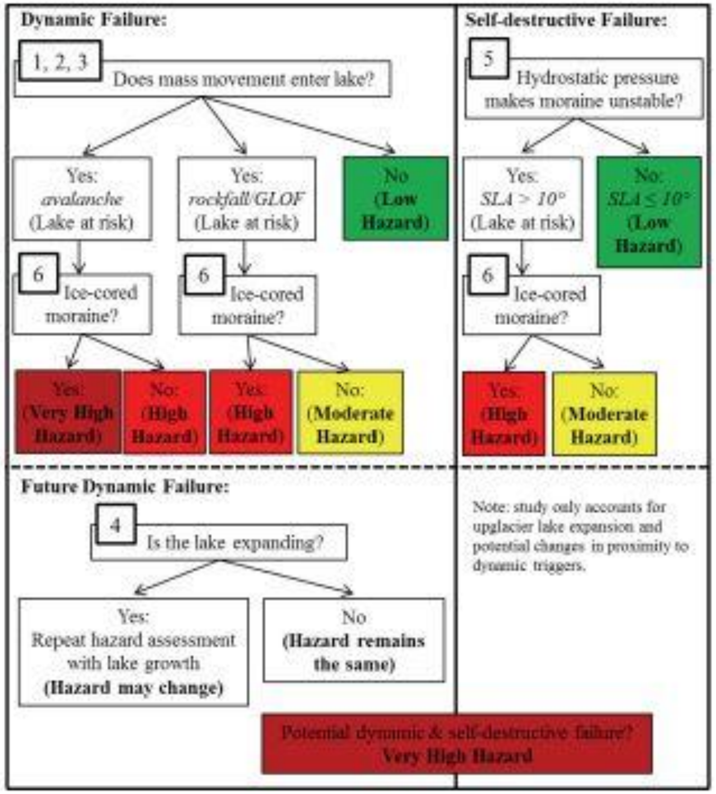


Figure 4. Hazard classification flow chart for determining the hazard associated with a glacial lake (numbers refer to hazard parameters in Fig. 2).

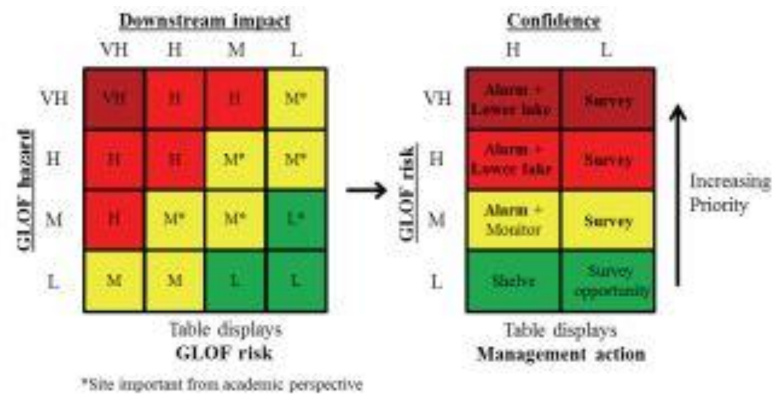
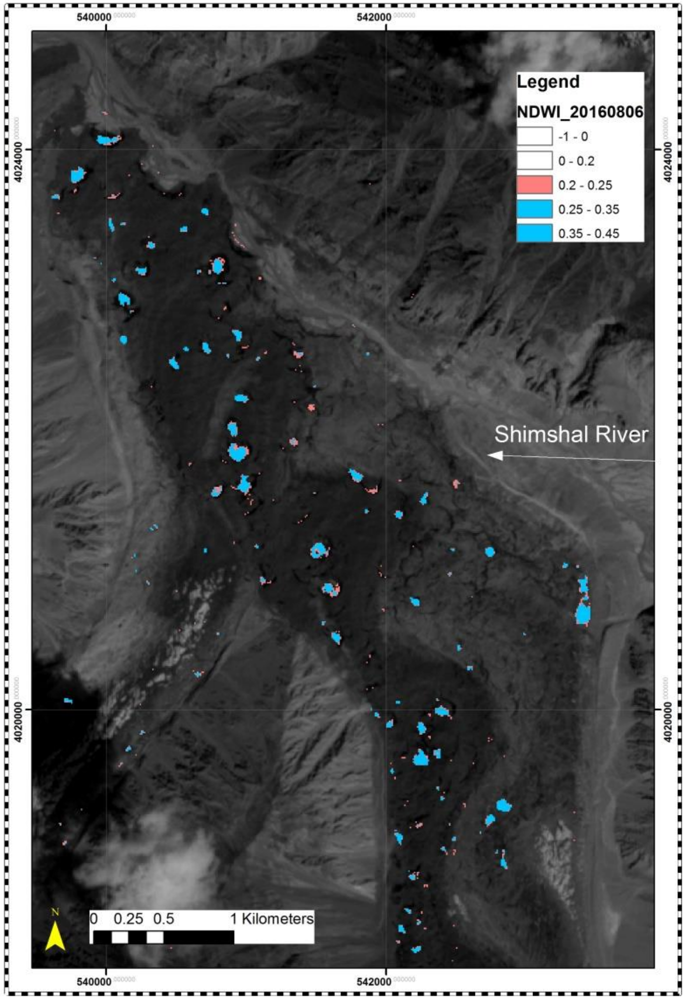


Figure 5. Risk management and action framework. Left table: GLOF risk is a function of the hazard and downstream impact. Right table: the recommended course of action for a given glacial lake based on the type of assessment.

Rounce et al., 2015

Example GLOFs – *Proxy Hazard Assessment*

- Accumulating water (using e.g. Landsat)
- Increasing velocities (using optical imagery)



Example GLOFs – *Impact*

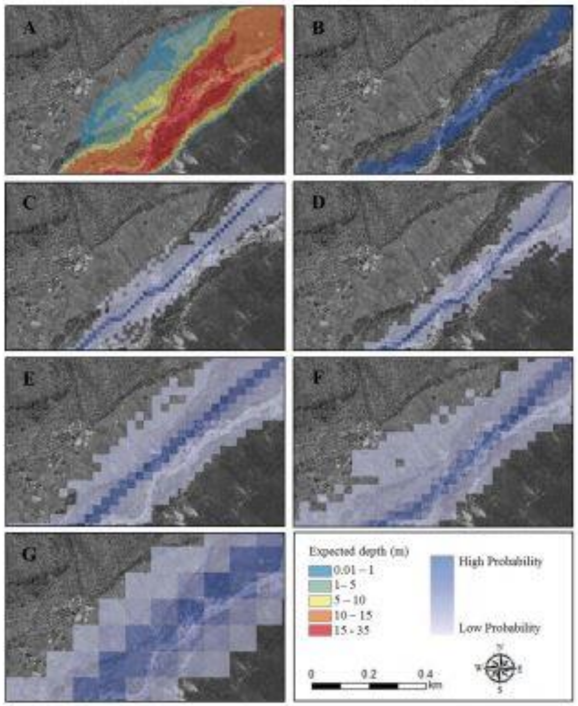


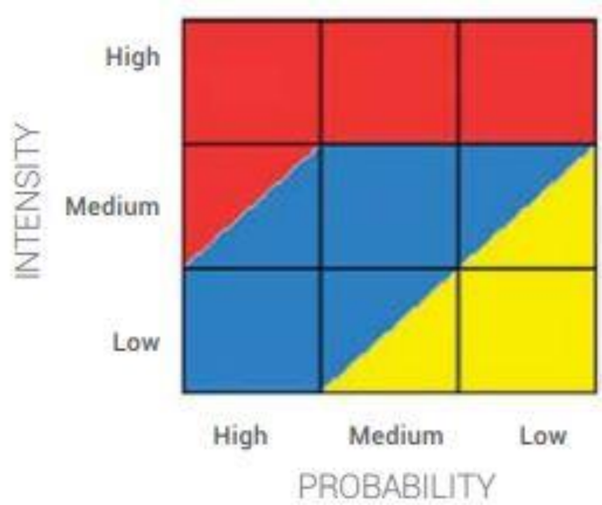
Figure 3. Inundated areas at Dingboche for a GLOF from Imja Tsho using **(a)** FLO2D (Somos-Valenzuela et al., 2015), **(b)** the MSF model using the GDEM, and **(c–g)** the MC-LCP model with various DEMs and pixel sizes: **(c)** SRTM 90 m resampled 15 m, **(d)** GDEM 30 m resampled 15 m, **(e)** SRTM 90 m resampled 30 m, **(f)** GDEM 30 m, and **(g)** SRTM 90 m.

Rounce et al., 2015

Table 4. Descriptions of downstream impact classifications.

Classification	Description of downstream impact
Very high	Potential loss of life with no warning (lodges/buildings) *and* the loss of costly infrastructure (e.g., hydropower)
High	Potential loss of life with no warning (lodges/buildings) *or* the loss of costly infrastructure (e.g., hydropower)
Moderate	Damage that is disruptive, which includes agricultural lands, bridges, trails, etc.
Low	No impact on humans, infrastructure, or other projects

Final Assessment



Red	High hazard
Blue	Moderate hazard
Yellow	low hazard

Table 1. Indicative values for the intensity classification for various high mountain hazards as used in Swiss practice (after, Hürlimann et al., 2006; Raetzo et al., 2002). E Kinetic energy; v Velocity; h flow depth or height of the deposit.

Phenomena	Low intensity	Medium intensity	High intensity
Rockfall	E < 30 kJ	30 < E < 300 kJ	E > 300 kJ
Rock avalanche			E > 300 kJ
Landslide	v≤2cm/year	v: dm/year (>2cm/year)	v > 0.1 m/day for shallow landslides; displacement > 1m per event
Debris flow (single parameter)		h < 1 m	h > 1 m
Debris flow (multiple parameter)		h < 1 m or v < 1m/s	h > 1 m and v > 1m/s

Allen et al., 2017

Impact

- Focus Group Workshops
- Interviews
- Awareness Raising

Topics

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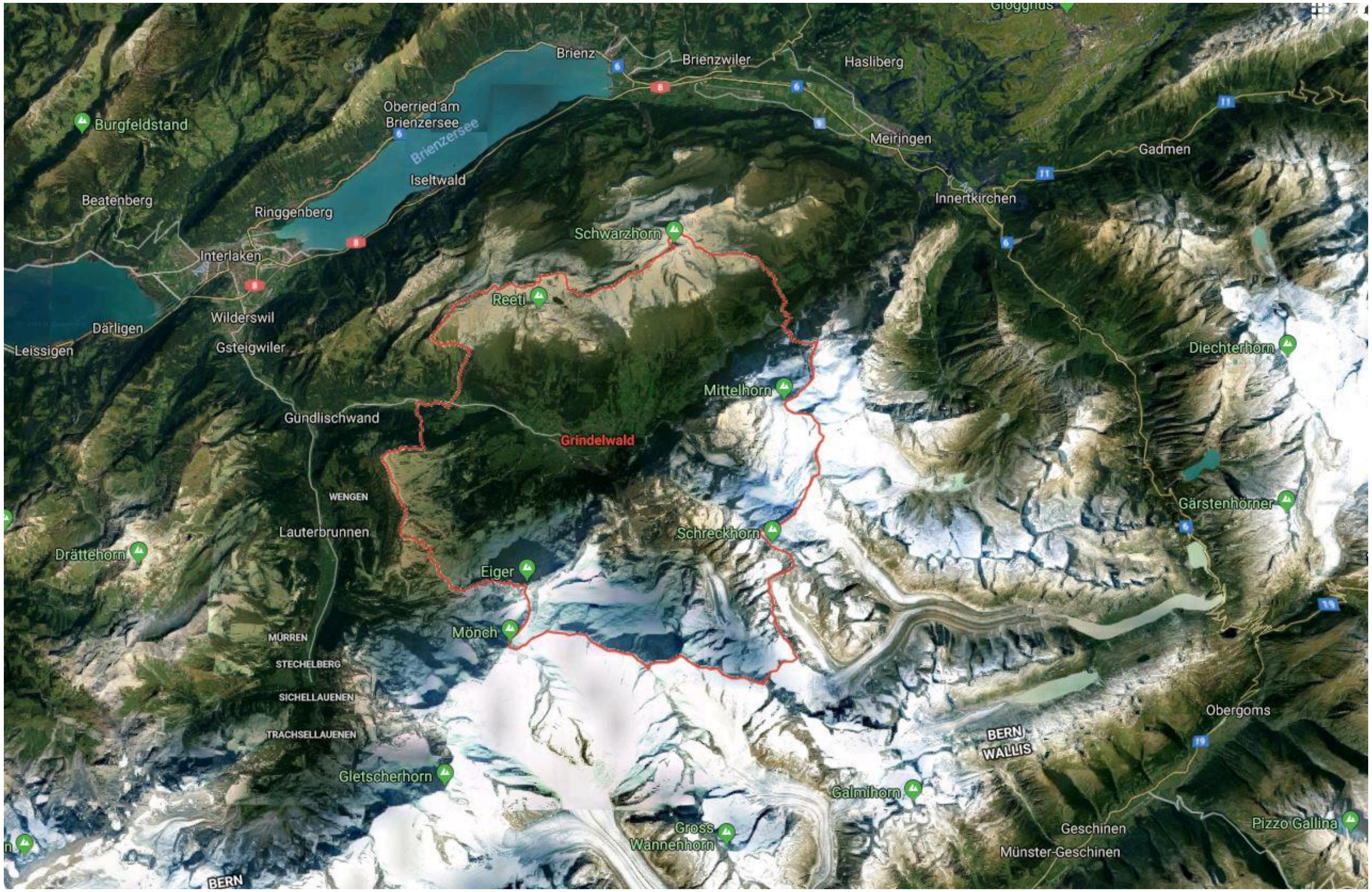
Local Challenges – Alps vs Himalaya

- Similar glacial hazards
- Population in relatively remote areas directly exposed
- Expensive infrastructure (Nepal/Pakistan: trade to China; India: connection to tourism areas; Switzerland: everything is expensive …)
- (Geo-)Politics? Willingness/ability to pay? Institutional development?

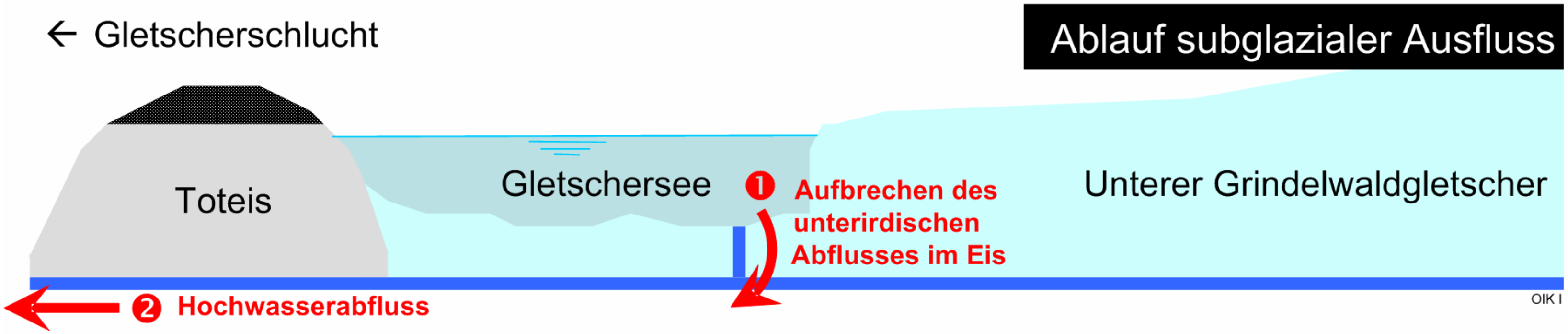
Grindelwald Switzerland

- Glacial lake formed repeatedly
- Concerns about possible downstream damages
- Classical compound event
- Who decides? Who pays?

Grindelwald Switzerland

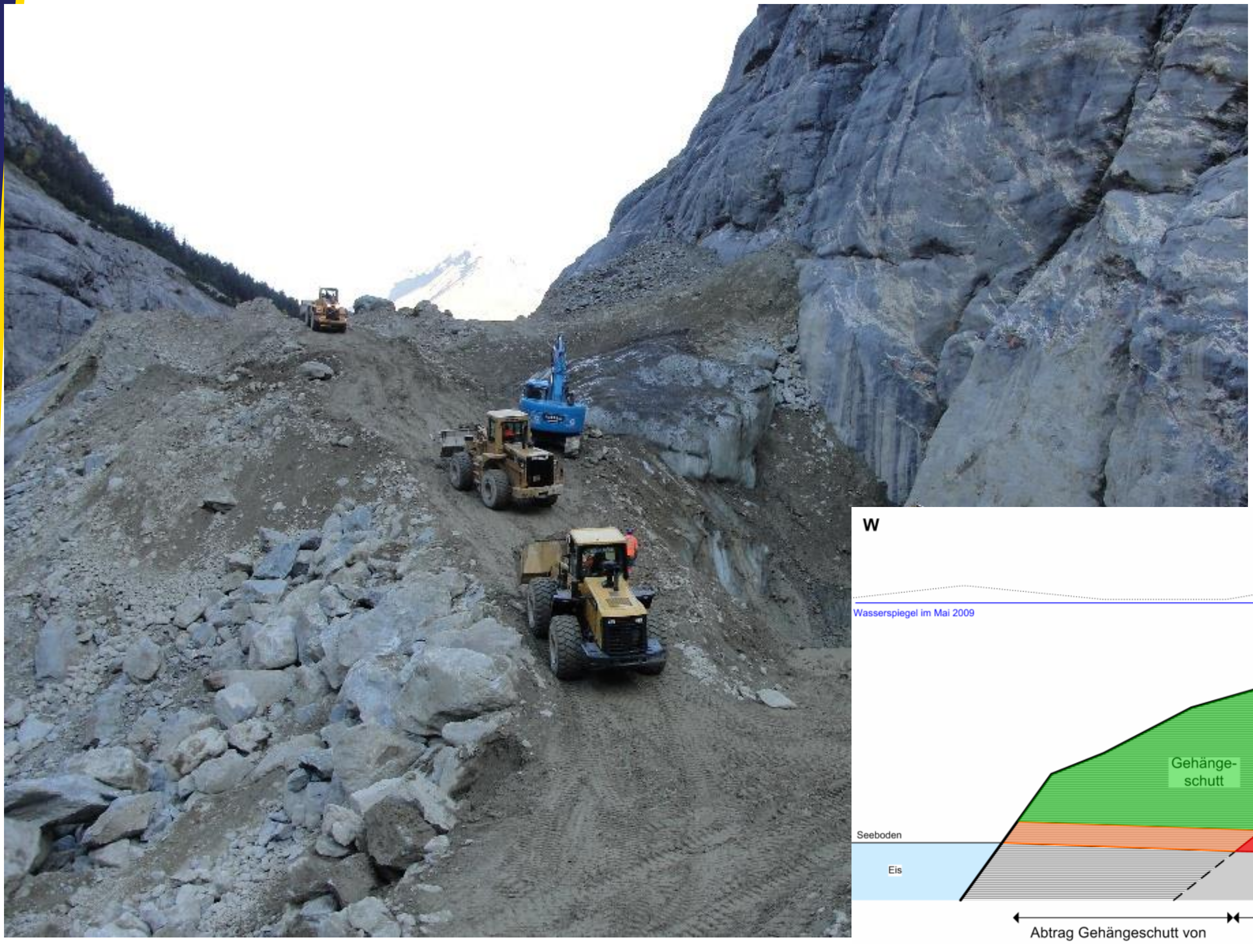


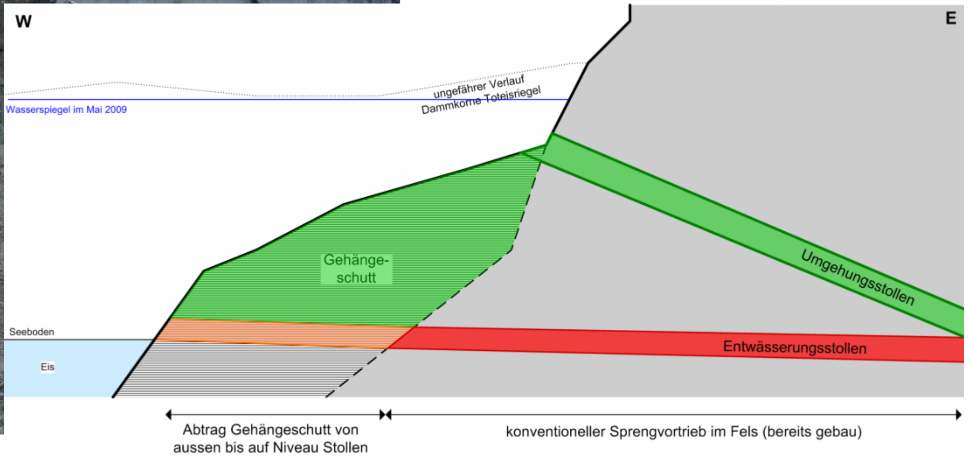
Formation of a glacial lake



Slumping moraines and rockfall

Decision to build a tunnel …





… and then the lake emptied naturally

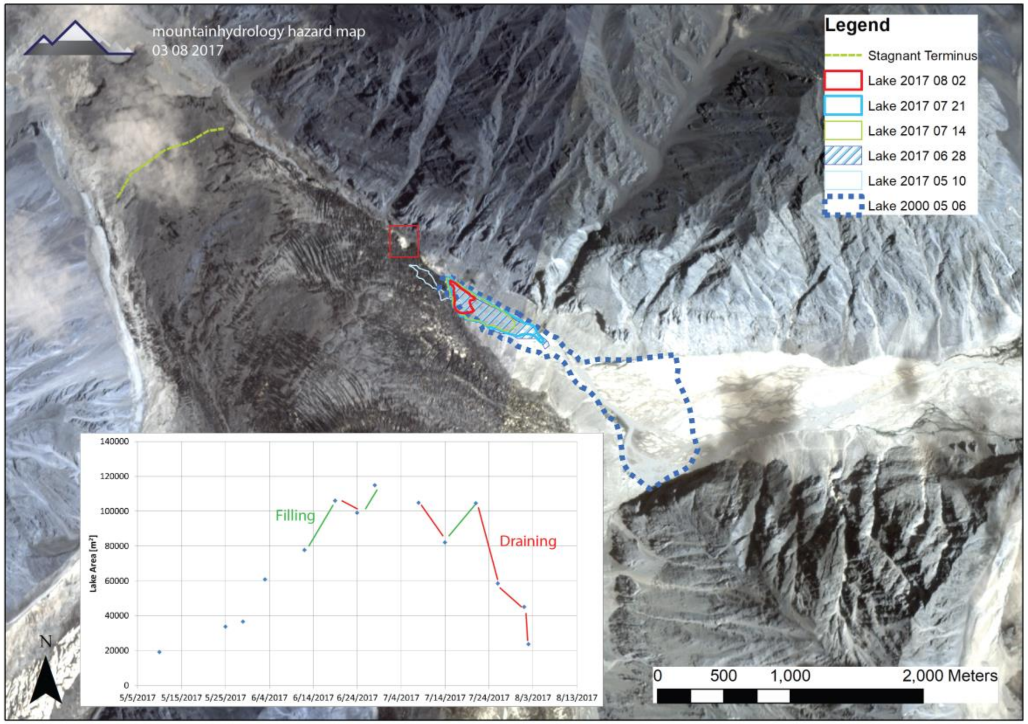
Shimshal Glacial Lake (Pakistan)

- Lake forms as a result of a glacier surge
- Damages to local roads and agriculture

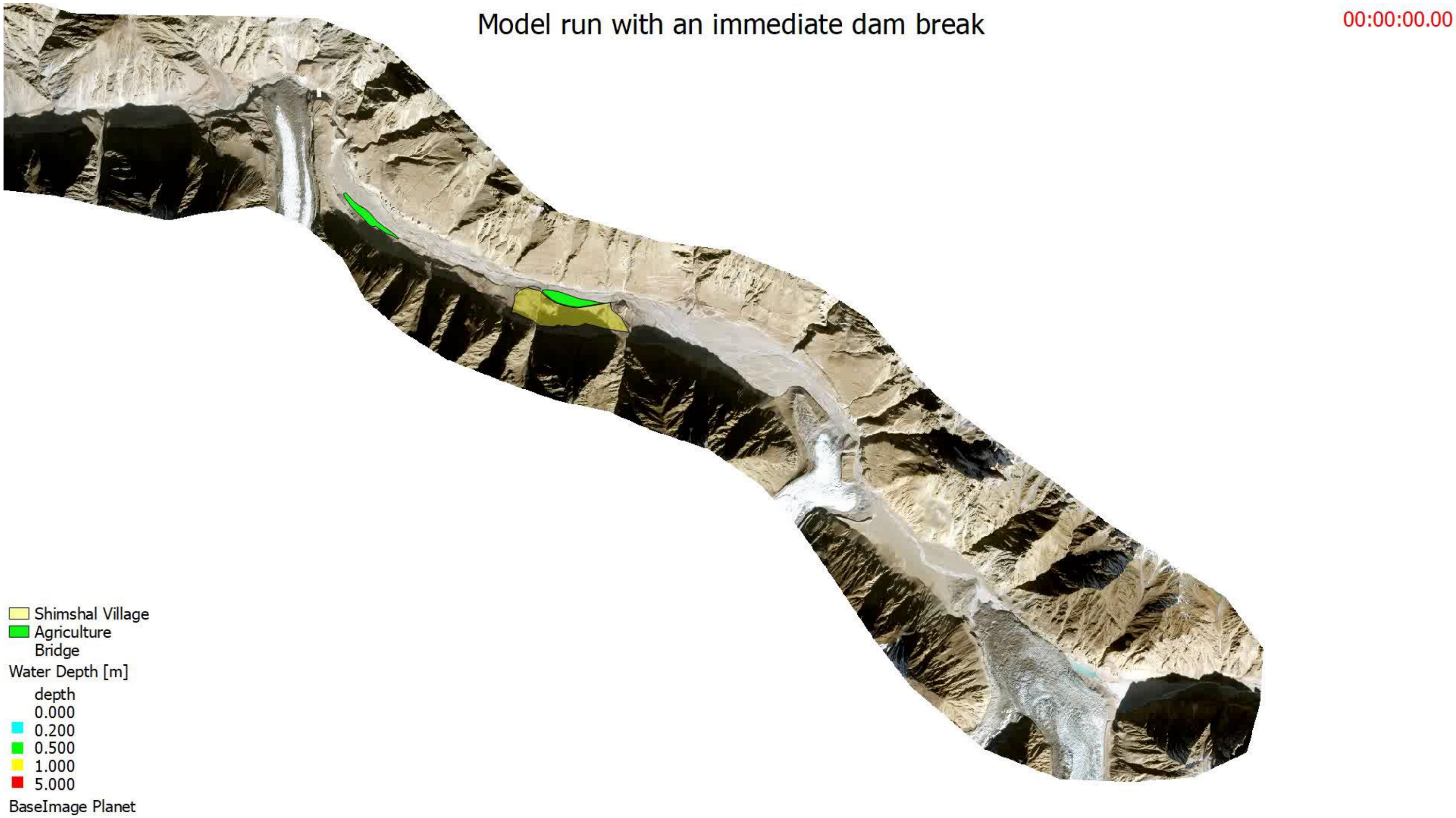
- Politically instable
- Difficult to access (no telephone, bad roads)

Scenarios

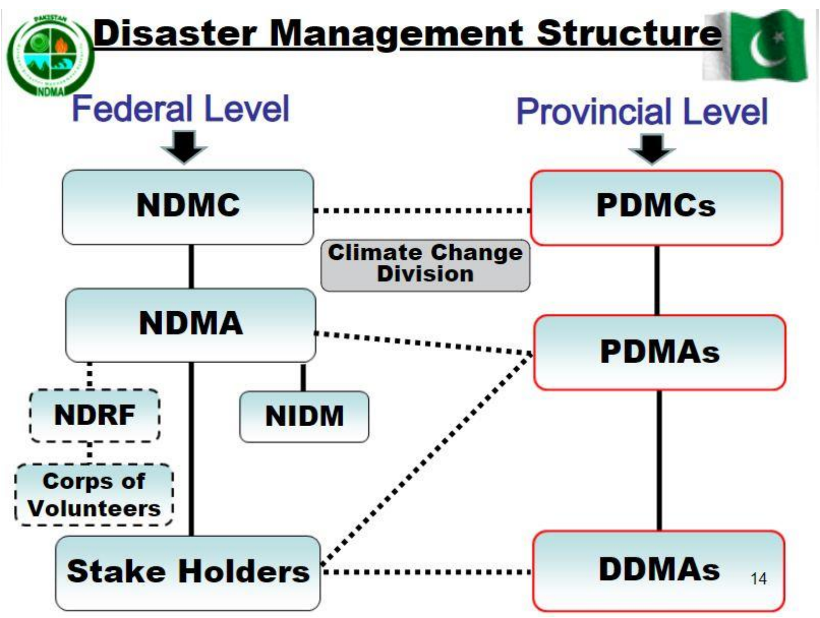
- Volume = f(Area)
- Discharge = f(Volume, dam break scenario)

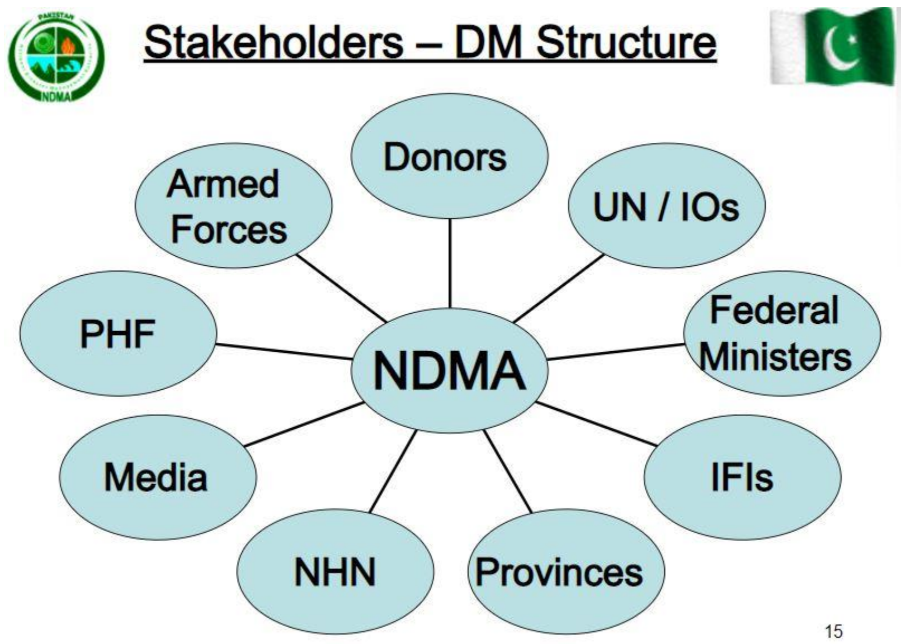


Hydrodynamic Modelling



Institutional challenge





Cost Implications and Interventions - NDMP

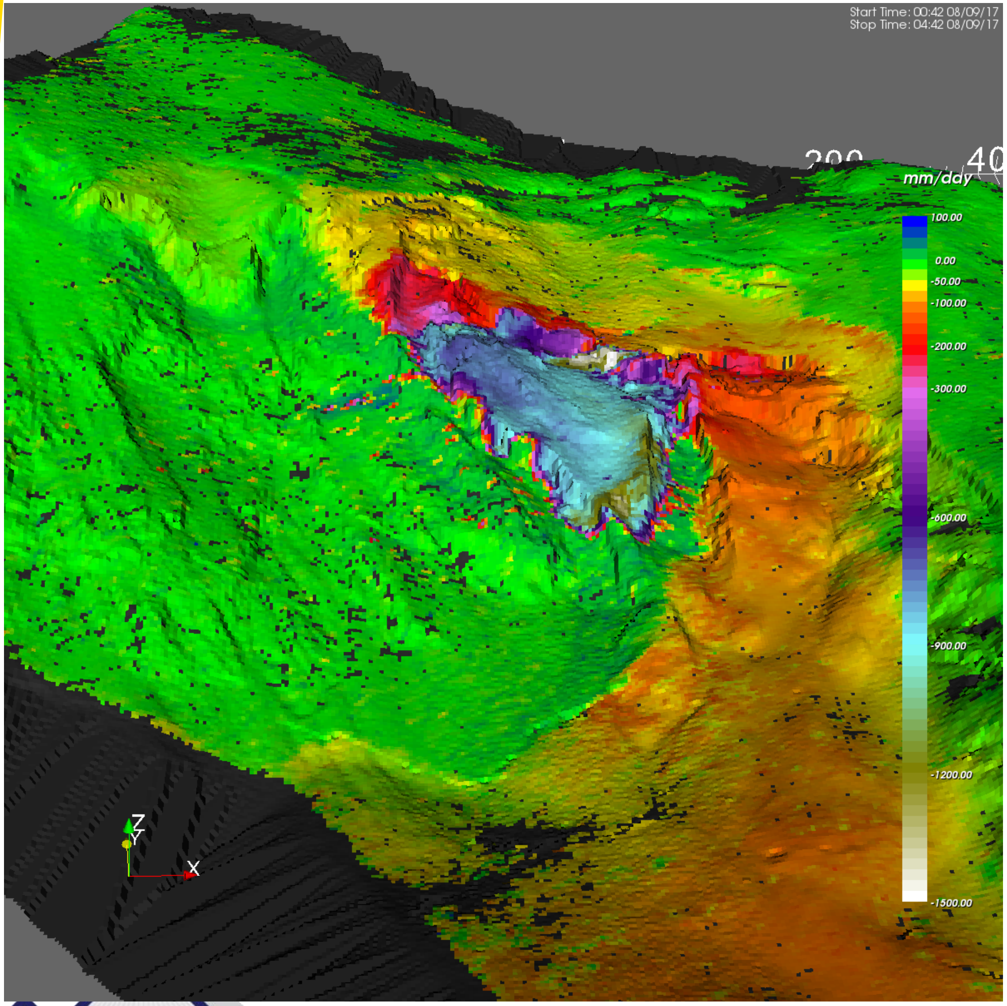
Cost Implication

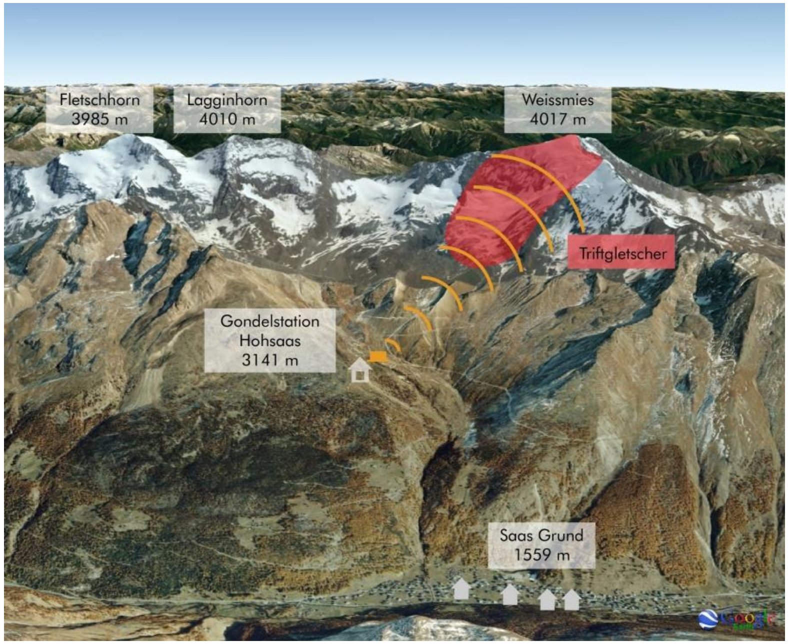
Component	Estimated Cost (Ten Yrs) US$ (million)		Estimated Cost (Ten Yrs) PKR (million)
Main Volume: NDMP	774.1	→	6,843.04
Volume-I HRD	64.3	→	568.41
Volume-II EWS	188.5	→	1,666.34
Volume-III CBDRM	14.00	→	123.73
Total Cost	1,040.90		9,201.52

Monitoring and Risk Mitigation

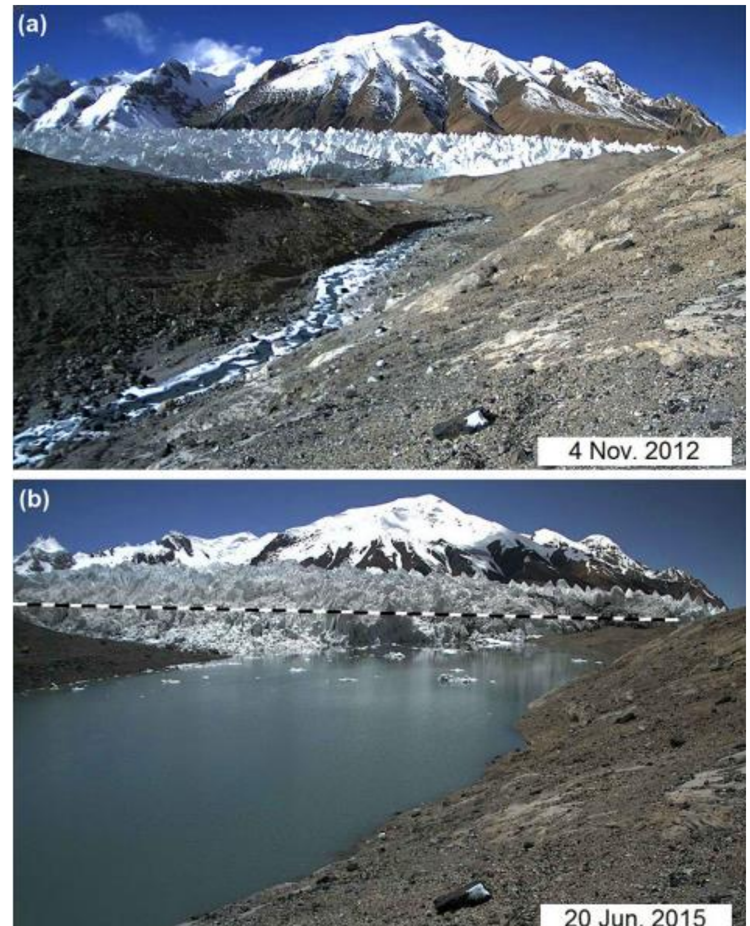
- Remote Sensing
  - new near real-time products for observations (Planet, Sentinel)
  - Temperature/Precipitation products
- Field based
  - climate and discharge monitoring
  - radar monitoring

Monitoring ice falls

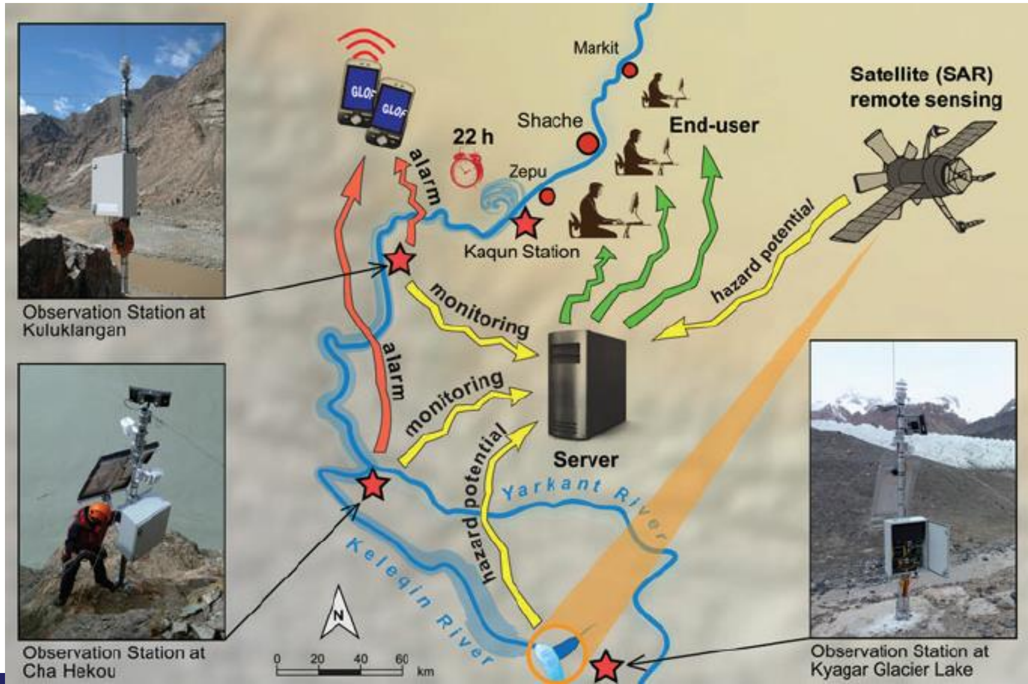




Monitoring Glacial Lake




DCP
Tipping Bucket
RLS
Volumetric Water Content
Sensor
Siren


Markit
Shache
Zepu
22 h
End-user
Satellite (SAR)
remote sensing
alarm
Kaqun Station
hazard potential
monitoring
Observation Station at
Kuluklangan
alarm
monitoring
Server
hazard potential
Yarkant River
Keleqin River
Observation Station at
Cha Hekou
Observation Station at
Kyagar Glacier Lake
N
0 20 40 60
km