Climate Change Impacts on Glaciers and Runoff in Alpine catchments

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Outline

1. SWATCH21 project
2. Importance of glacier retreat modeling in determination of runoff at basin scale (**Why?**)
3. How to quantify the glacier melt (**How**?)
4. The **"Glacier Evolution Runoff Model"** (GERM) + SWAT
5. Aletsch Glacier in Rhone river basin, Switzerland
6. Calibration protocol for discharge in mountainous catchments
7. Climate change impact on Aletsch Glacier

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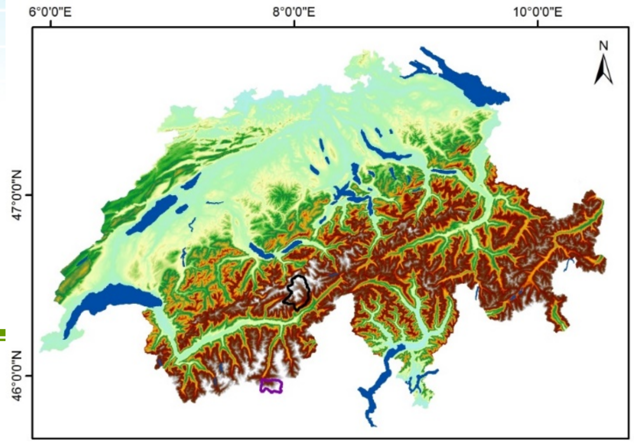
SWATCH21 Project

2017-2020, Founded by SNF



SWATCH21 Deliverables and Objectives

- ✓ Data collection for SWAT to model spatial distribution of water resources in Switzerland
- ✓ Build, calibrate and validate a hydrologic model of Switzerland with uncertainty analysis
- ✓ Quantify the impact of land use and climate change on water quantity, water quality, biodiversity and ecosystem services
- ✓ …
- ✓ **Modeling the glaciers retreat and evolution in Swiss Alps**

SWATCH21 team

Prof. Dr. Anthony Lehmann
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Prof. Dr. Daniel Farinotti
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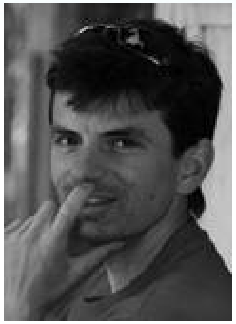

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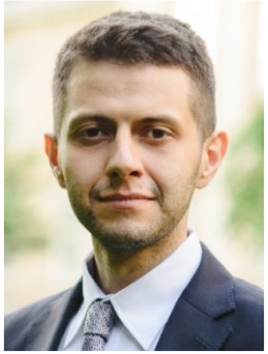

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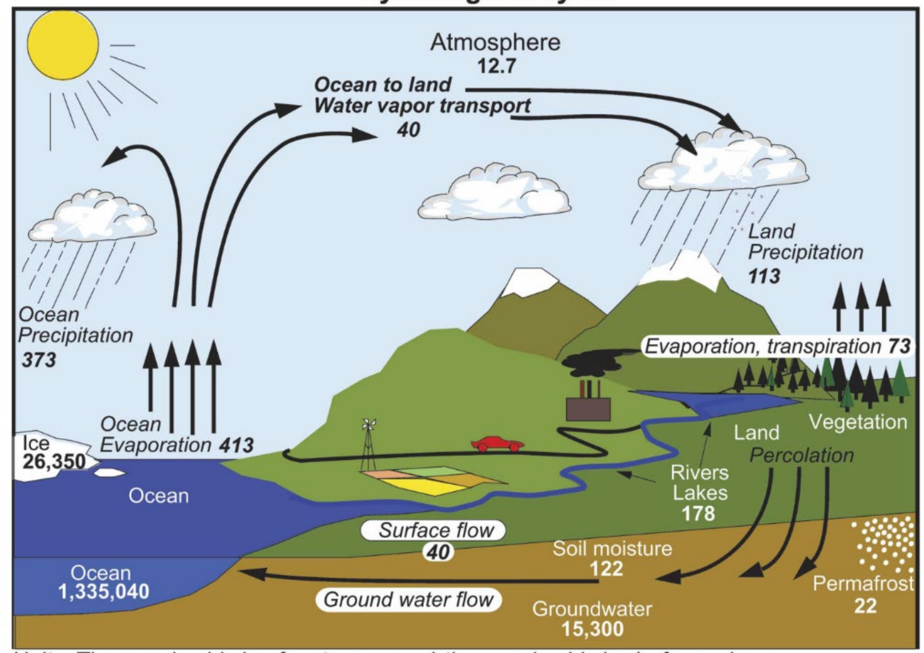
Why to quantify glacier melt?

Global water cycle

Ice caps and mountainous glaciers:

- contain less than 1% of all global ice (Meier et al. 2007)
- cover 734,400 km^2 of the Earth (Gardner et al. 2013)
- correspond to **one-third to on-half of global sea-level** rise in last decades(global)
- in the European Alps (ca. 2050 km^2 on 3800 glaciers) produce an annual average runoff volume of 5.28 ± 0.48 km^3 (Farinotti et al. 2009) (regional)

Hydrological Cycle



Units: Thousand cubic km for storage, and *thousand cubic km/yr* for exchanges

FIG. 1. The hydrological cycle. Estimates of the main water reservoirs, given in plain font in 10^3 km^3, and the flow of moisture through the system, given in slant font (10^3 km^3 yr^{-1}), equivalent to Eg (10^{18} g) yr^{-1}.

Trenberth et al. (2006)

Glacier retreat

- Ice melt contributes to the runoff especially in Summer time when other sources of water are limited.

Video by Prof. Dr. Hong Yang (2018), Iceland

Why to quantify ice melt contribution?

- **A contributor to the runoff**
- **Fluctuations of ice melt water lead to harmful environmental impacts**

Missing meltwater

- water shortages, and crop failure (Carey et al., 2017; Huss et al., 2017; Yang et al., 2014).

Increasing meltwater

- lake expansion, changes in seasonal hydropower generation (Gaudard et al., 2018; Schaefli et al., 2019), and overflowing of recreational areas due to the rising water of the rivers

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How to quantify Ice melt?

1. Physical based model

Clarke et al., 2015
Farinotti et al., 2012
Fitzpatrick et al., 2017
Huss et al., 2008
Huss et al., 2014

Model different physical processes

2. Statistical models

Koboltschnig and Schoner, 2011
Trachsel and Nesje, 2015
Zekollari and Huybrechts, 2018

Find correlation between glaciers signatures (such as area and volume) and runoff

3. Process-based numerical models

Geuzaine and Remacle, 2009
Jouvet et al., 2009
Jouvet et al., 2011
Jouvet and Rappaz, 2014
Michel et al., 2013

Use different numerical methods such as Lagrangian or Eulerian to simulate changes of ice surface topography and generated runoff

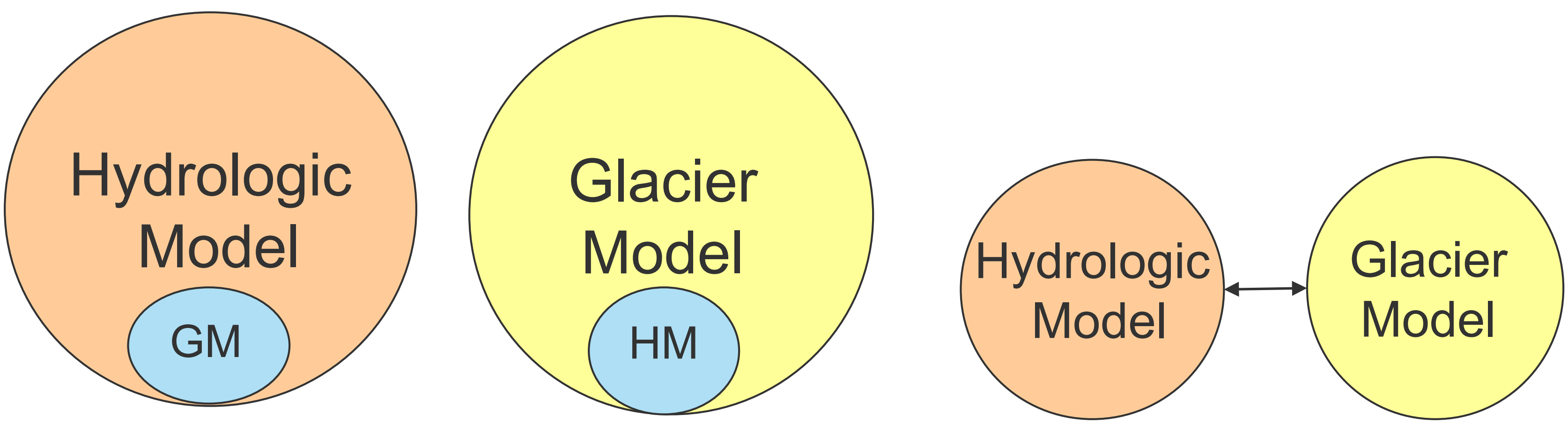
4. Image processing and remote sensing approaches

Quiroga et al., 2013
Rastner et al., 2016

Study satellite images of different years

Hydrological modeling vs Glacier retreat modeling

- Glacier melt is not the only component in hydrological cycle,
- For discharge and crop yield we need rainfall, temperature, evapotranspiration, groundwater storage, and etc.
- Concurrent modeling of glacier evolution and hydrological systems is mainly there are three approaches for simultaneous modeling of glacier evolution and hydrological cycle



Which hydrologic model should be coupled to which glacier model?

WaSiM-ETH

HSPF

MIKE SHE

HEC

HBV

.....

SWAT

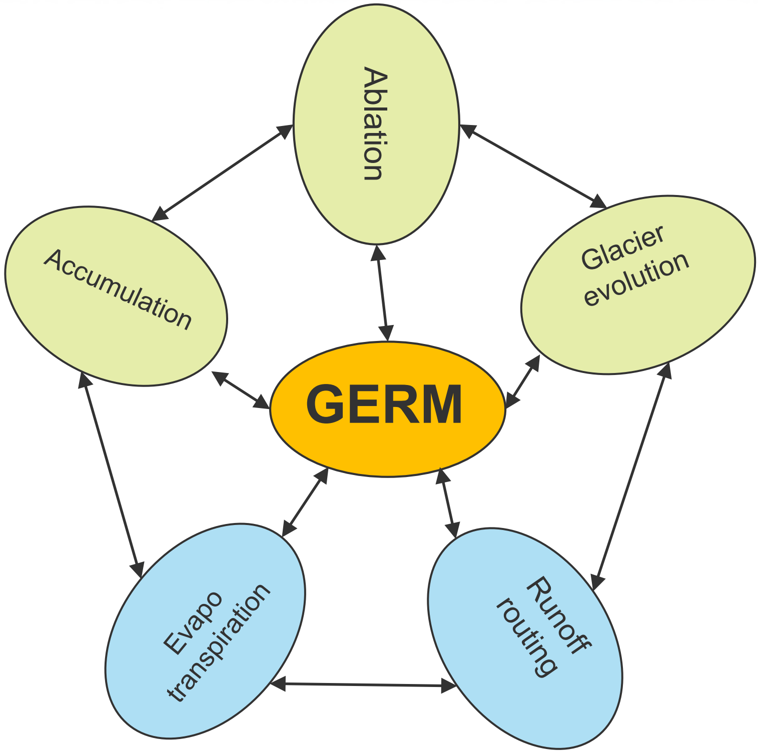
GERM

GSM

....

Glacier Evolution Runoff Model (GERM)

- Has been widely applied to model the glaciers retreat, changes in topography and outline of glaciers, runoff generated by glacier melt and model the impact of climate change on glacier retreat

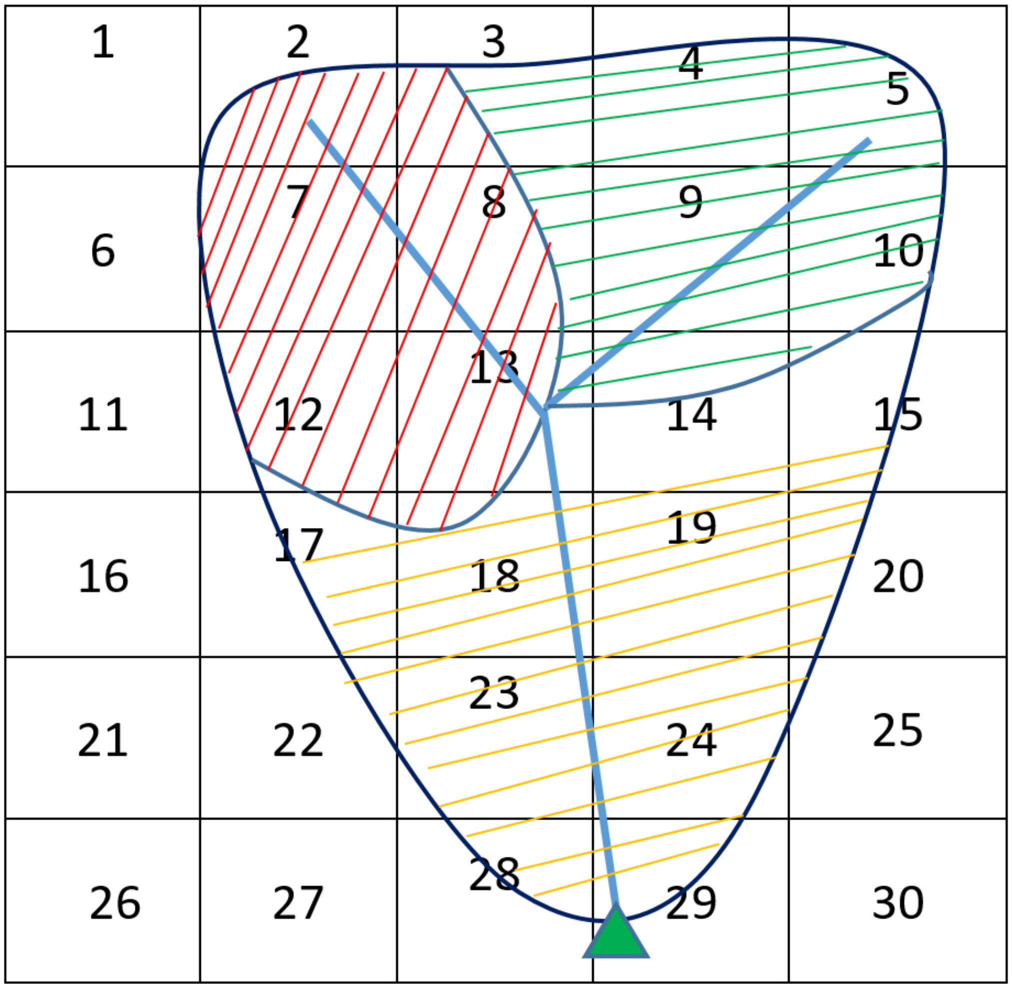


GERM Characteristics:

- Continuous time
- Physically based
- Distributed parameter
- Flexible basin discretization
- Climate drivers: Temperature and precipitation

The daily generated runoff from ice melt (simulated by GERM) is added to the daily time series of flow of point sources in SWAT

Overlaying SWAT Sub-basins map with GERM grids



- Sub1

2,3,7,8,12,13

- Sub2

3,4,5,8,9,13,141,15

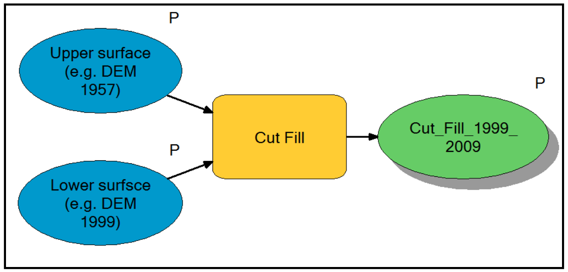
- Sub3

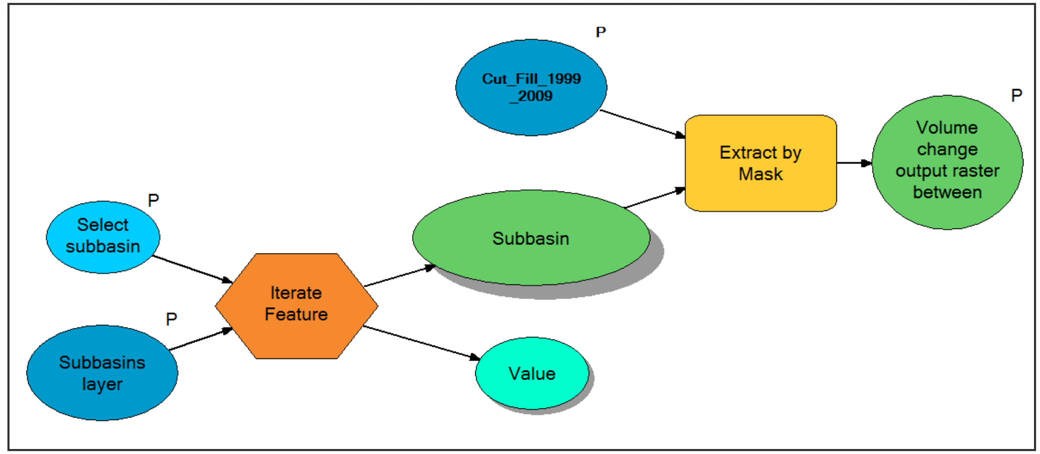
13,14,15,17,18,19,20

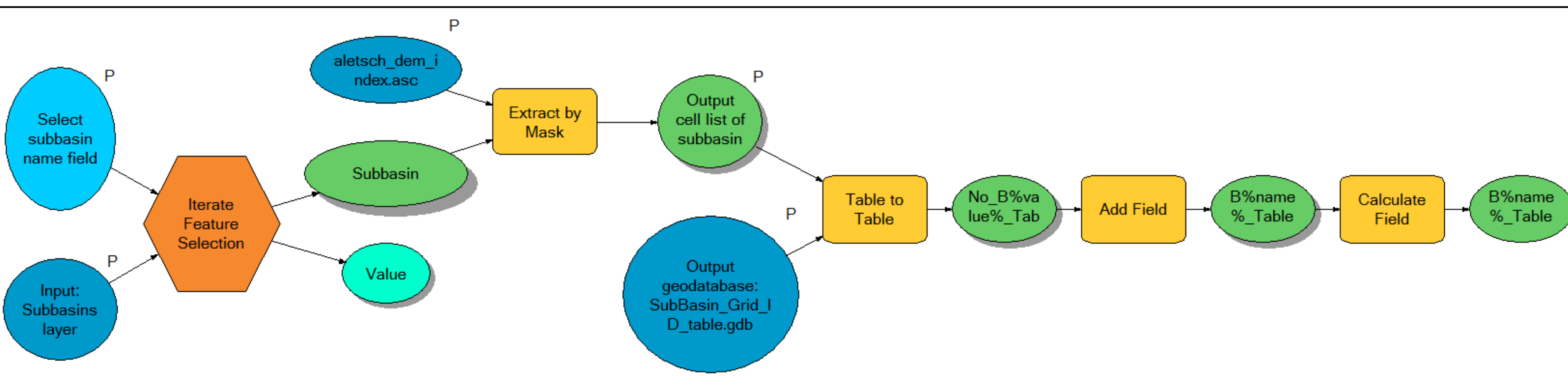
22,23,24,25,28,29

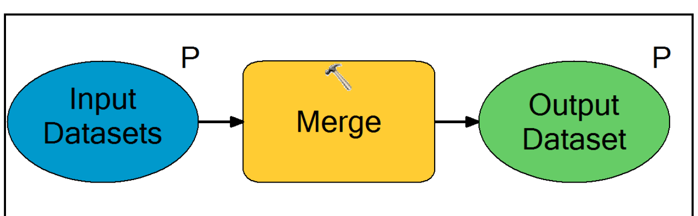
\+ portion's of grids which are located in each sub-basin

Tools for automation of overlaying









GERM daily **Accumulation** for each grid:

$$Psoild_i = P_{ref} \times (1 + C_{perc})[1 + \frac{Elev_i - Elev_{ref}}{1000} dp] \times Dsnow_i \times r_s$$

- P_{ref} : precipitation at reference location (mm)
- C_{perc}: correction factor for the gauge-catch deficit (Bruce and Clark 1981)
- $Elev_i - Elev_{ref}$: the elevation reference between the reference and considered location
- $\frac{dp}{1000}$: the lapse rate with which precipitation increases with elevation (Peck and Brown 1962)
- $\mathrm{Dsnow_i}$: spatially distributed factor which account for snow redistribution processes (Tarboton et al. 1995, Huss et al. 2009)
- r_s:

$$T_{ave} \leq -1 \rightarrow r_s = 1$$
$$T_{ave} \geq 1 \rightarrow r_s = 0$$
$$-1 \leq T_{ave} \leq 1 \rightarrow r_s = \frac{1 - T_{ave}}{2}$$

Huss et al 2008, 2010

Daily **Accumulation** for each grid:

$$Psoild_i = P_{ref} \times (1 + C_{perc})\left[1 + \frac{Elev_i - Elev_{ref}}{1000} dp\right] \times Dsnow_i \times r_s$$

Climate_ref folder:
45150p.txt
45150t.txt
45151p.txt
Pcp.txt
Tmp.txt

aletsch_dem_1957.grid

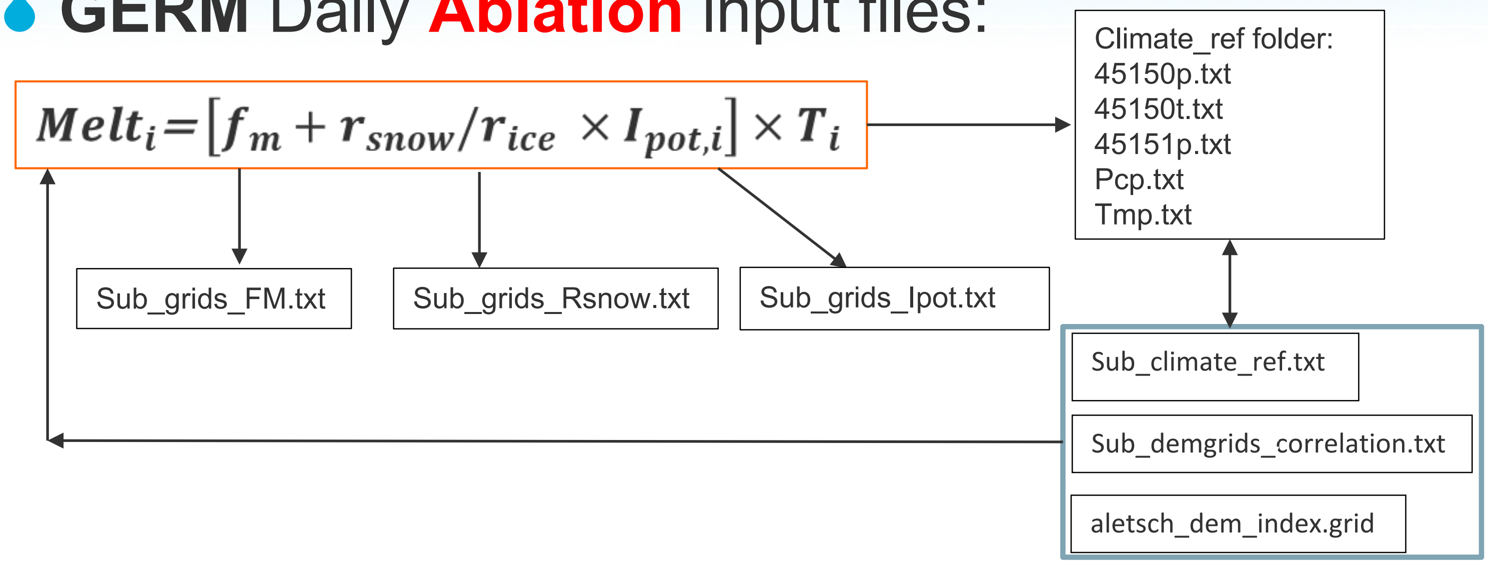
Sub_grids_Dsnow.txt

Sub_climate_ref.txt

Sub_demgrids_correlation.txt

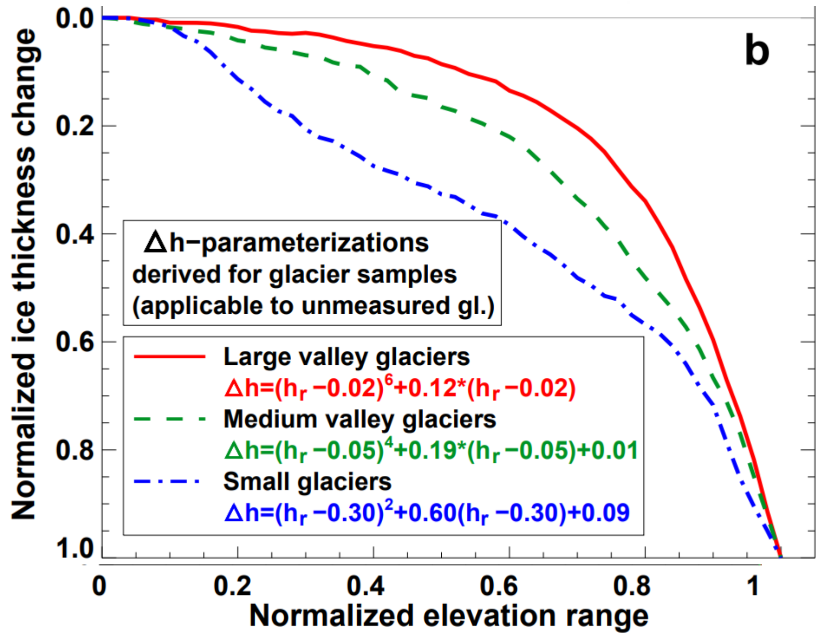
aletsch_dem_index.grid

GERM Daily Ablation input files:

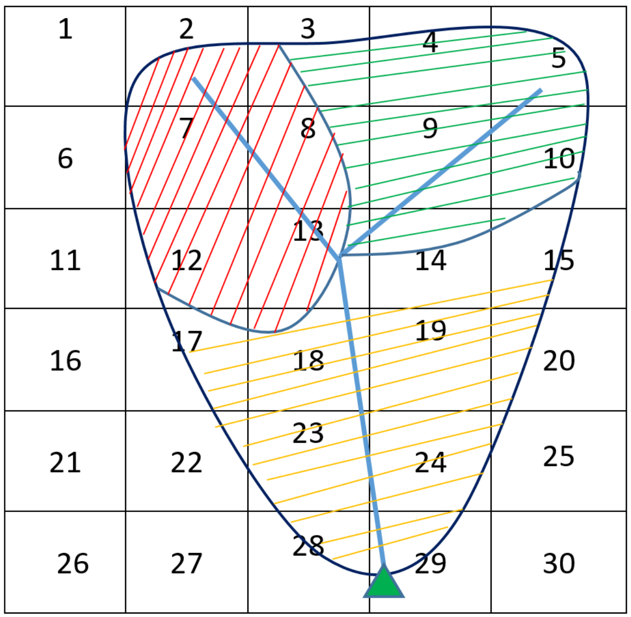


- Ablation is modeled with a distribution temperature-index approach
- f_m: melt factor
- r_{snow} or r_{ice} two distinct radiation factors for snow and ice
- $I_{pot,i}$: the potential direct clear sky solar radiation at grid cell i
- T_i: mean daily air temperature (C) , for T_i < 0 not melts occures

GERM annul update of surface topography and outline:



Huss et al 2010

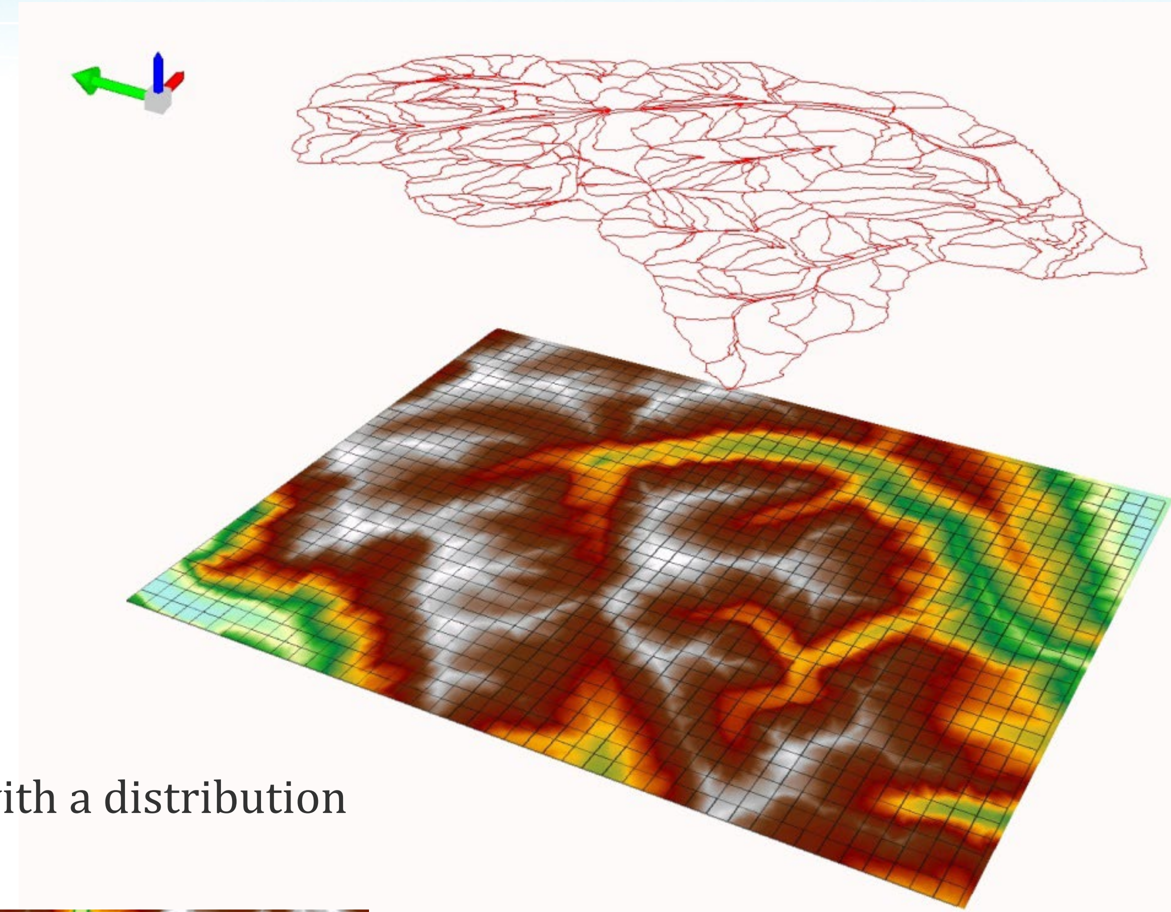


GERM Daily outputs

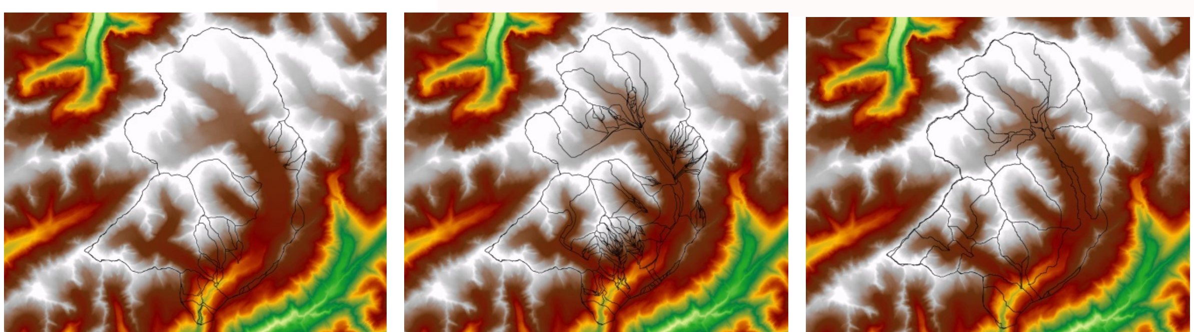
Daily generated runoff is calculated based on mass balance at each grid

$$Runoff_i = Accumulation_i - Ablation_i$$

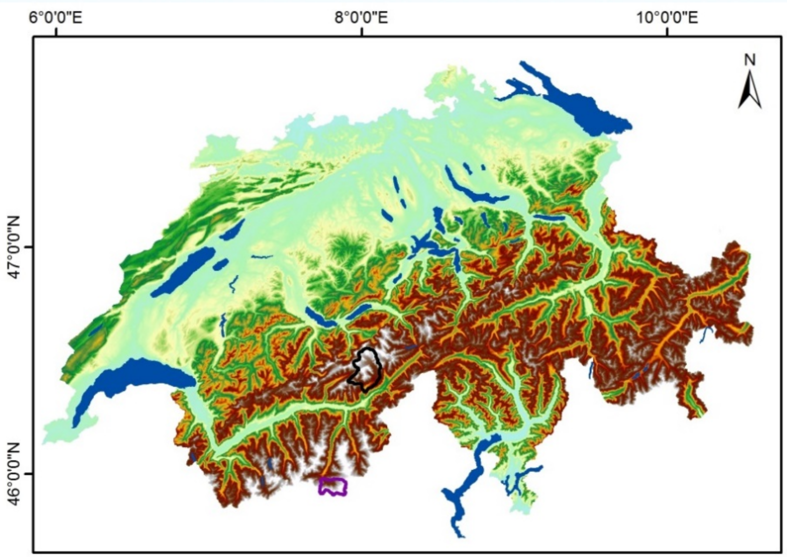
Flexible GERM Architecture

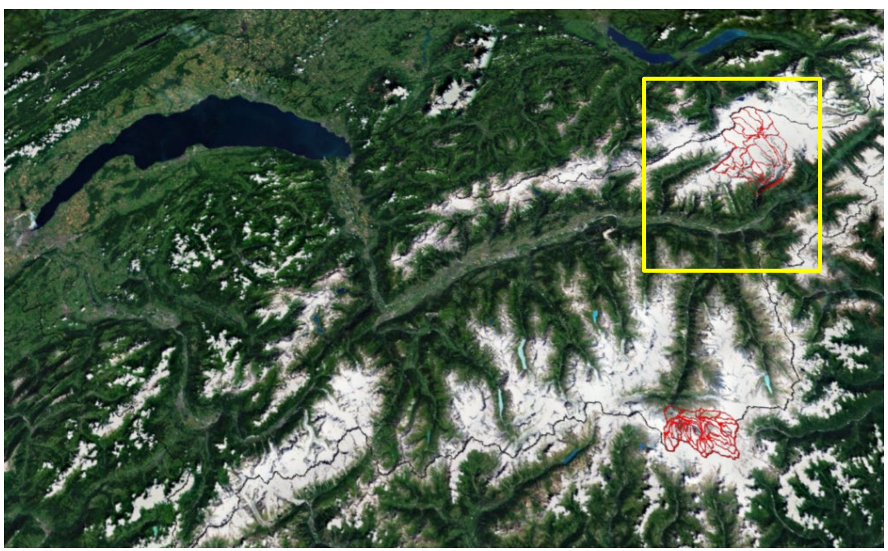


- Ablation is modeled with a distribution



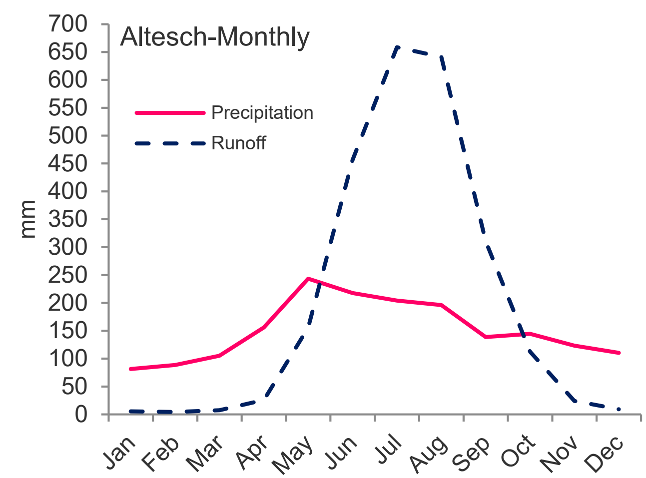
Study Area





Aletsch Glacier

- Total catchment area: 196 km^2,
- Glacier area: 82 km^2,
- Ice volume:15 km^3 ice (20% of Swiss ice)
- Simulation: 1957-2010



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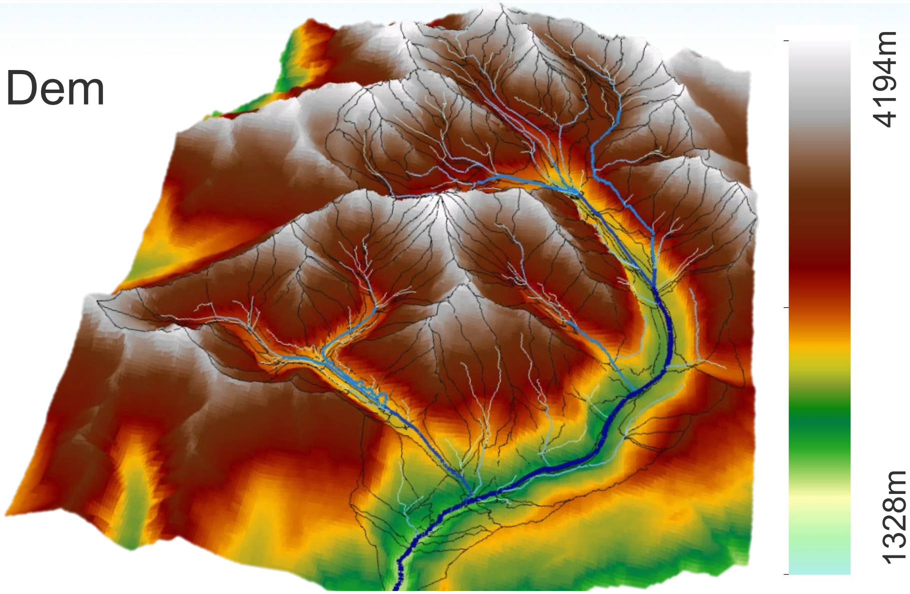
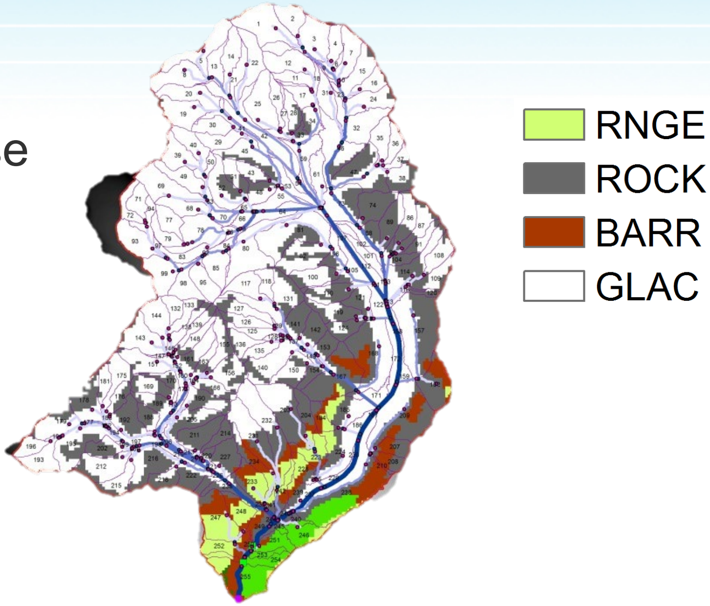
Altesch Glacier Project

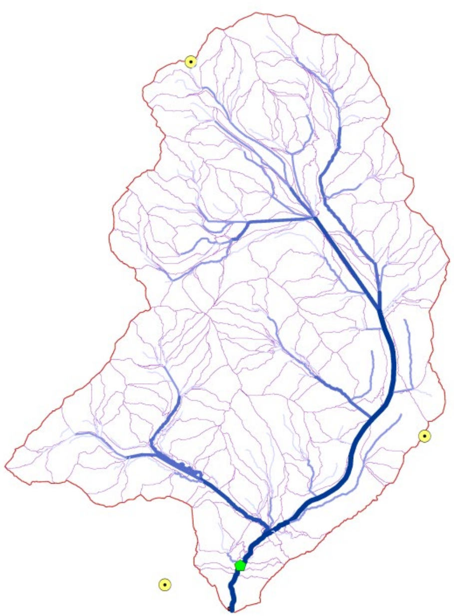
Dem



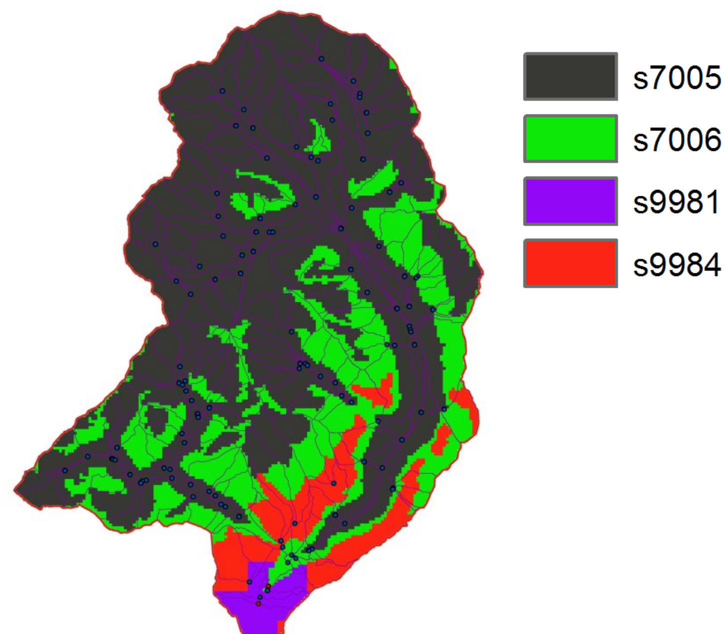
Landuse



Climate stns
Guage stn
River

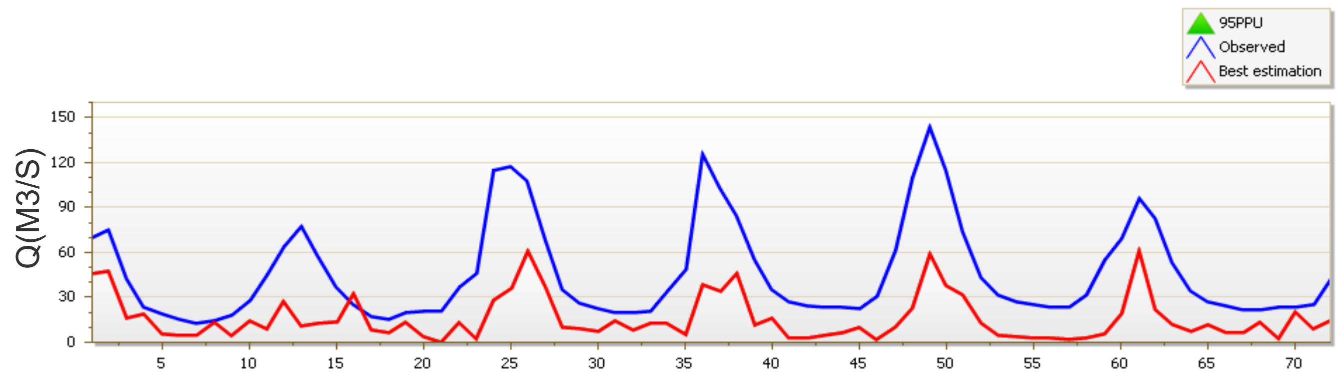


Soil

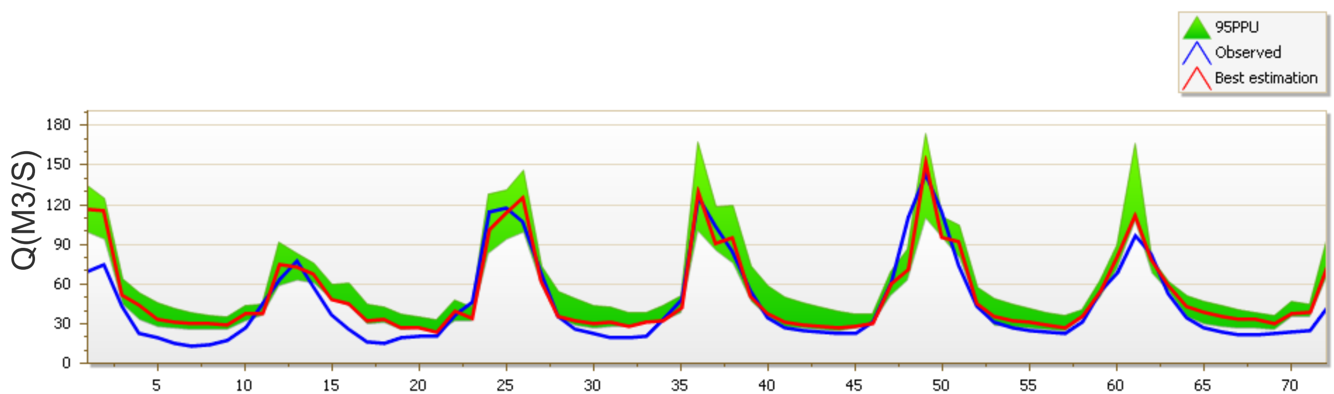


Runoff simulation in Glacierized Catchments

- **Initial Simulation**



- **What we want after calibration**



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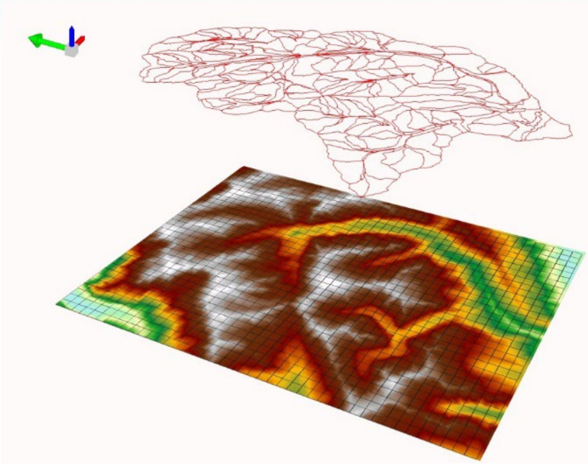
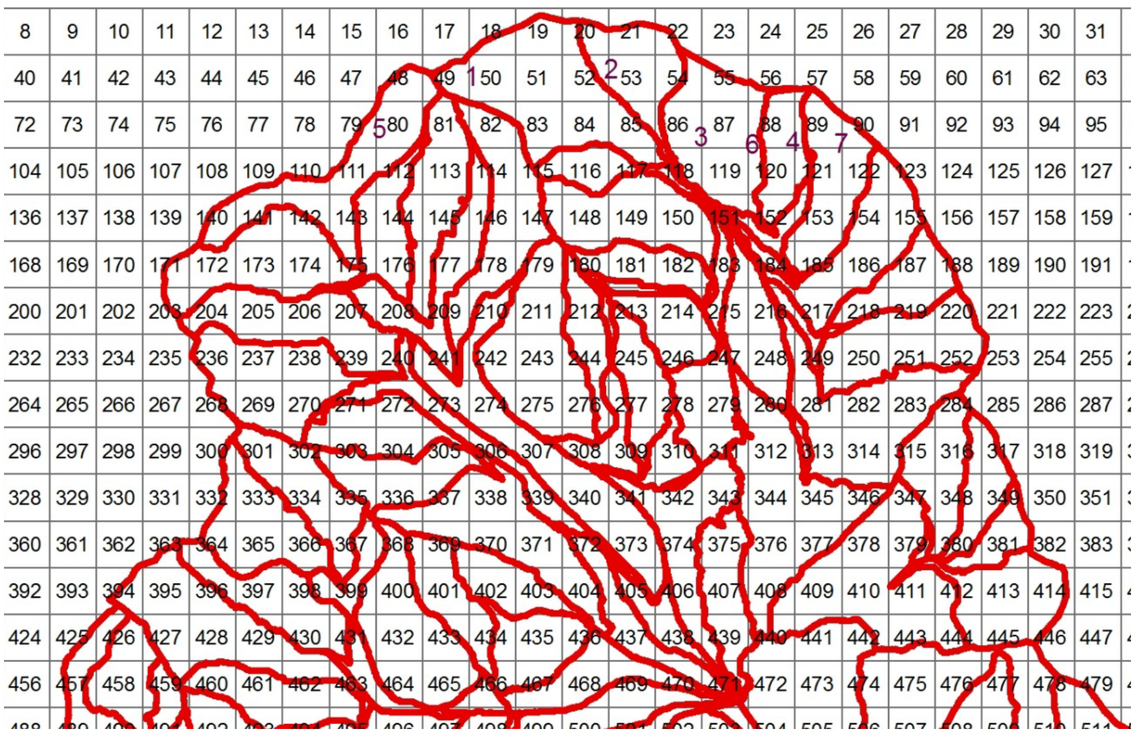
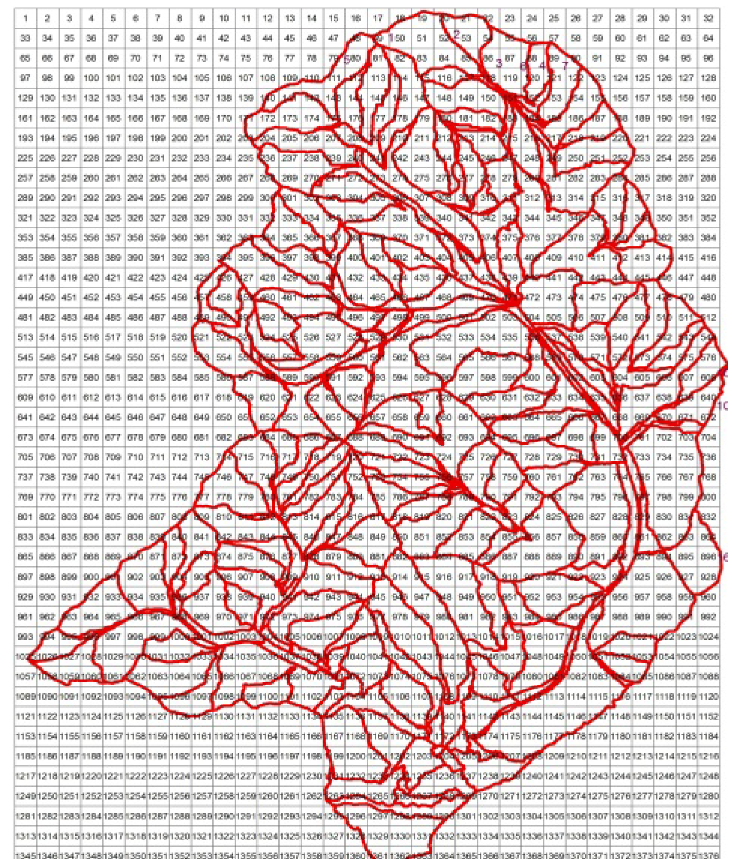
Building a model



- Overlaying Sub-basin map and rater (50m grids) map to obtain list of all sub-basins with located grids inside





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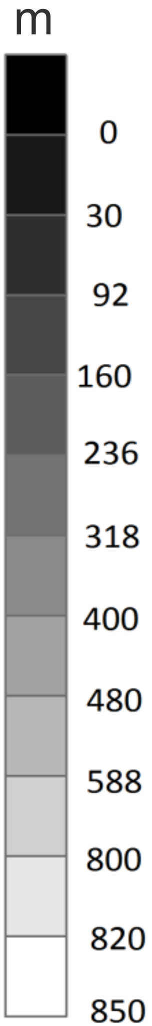
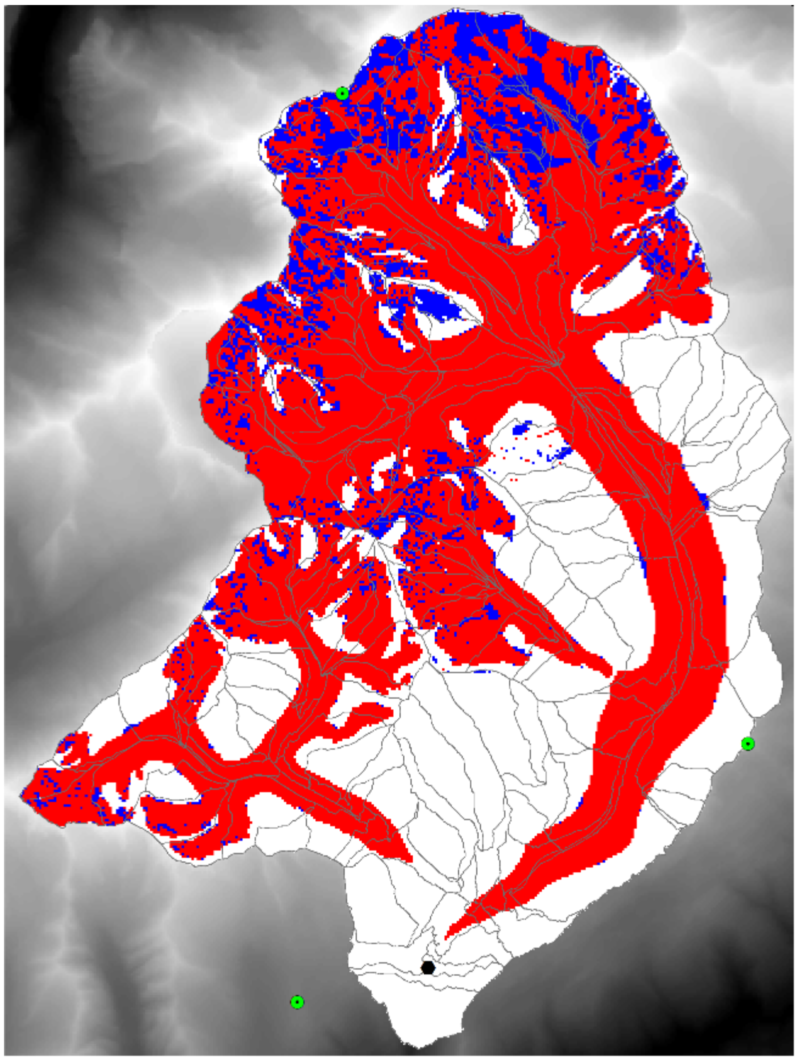


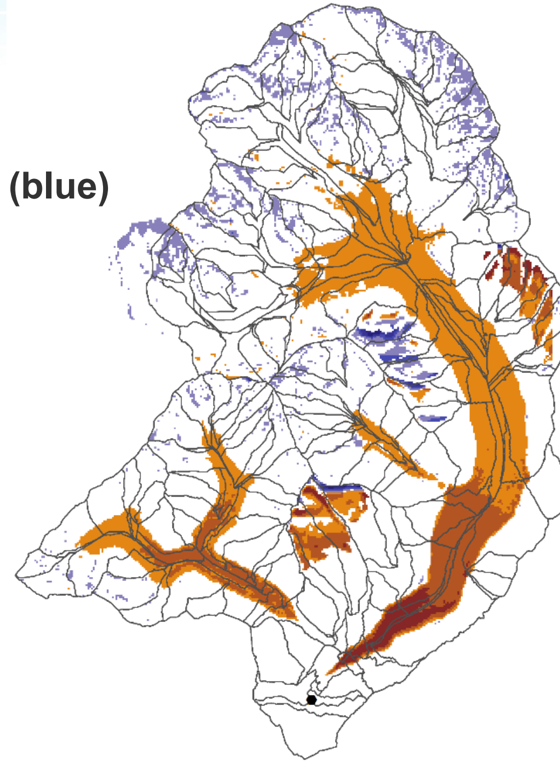
Results

- Ice Thickness (1957-2009)



Accumulation dominated (blue)

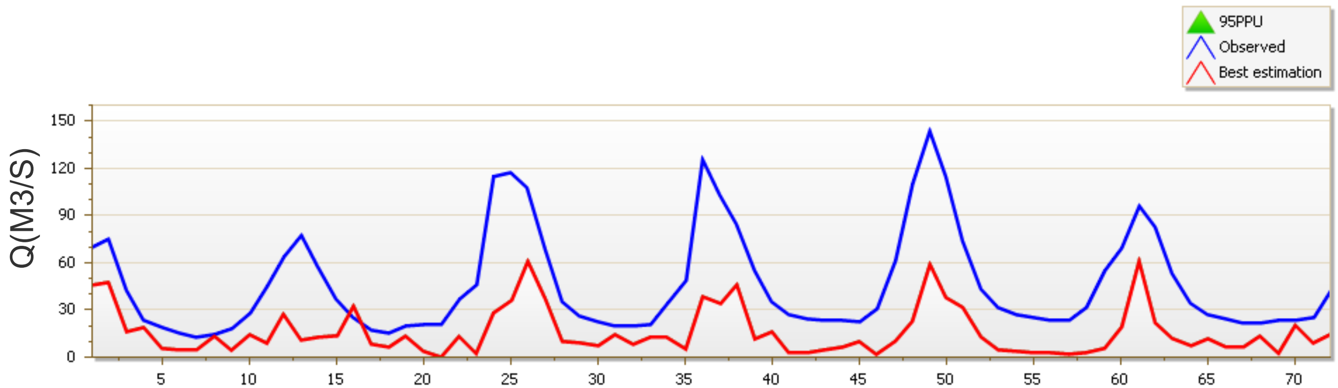
Ablation dominated (red)



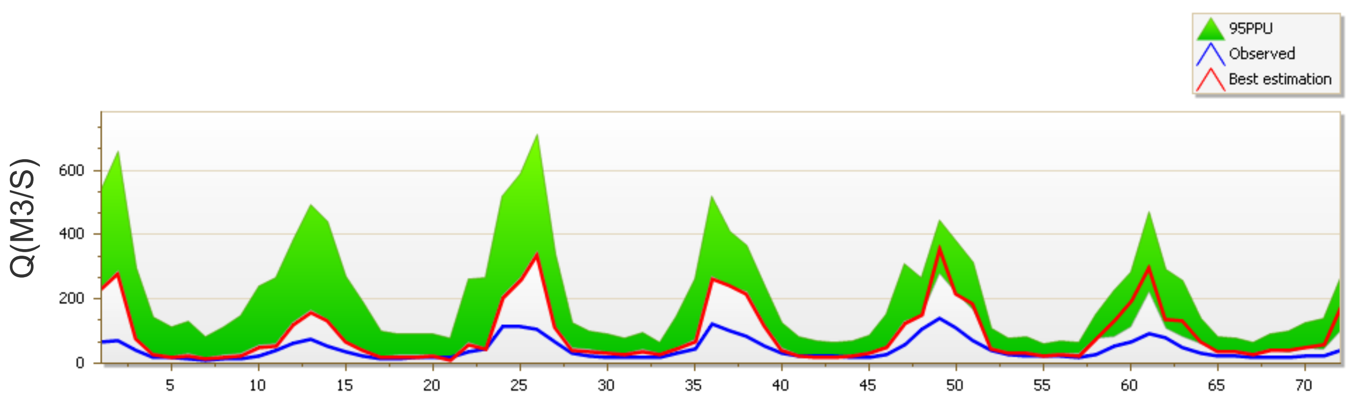
Years	Ice Volume (km3)	Ice Length (km)
1957	21.8	23
1999	18.2	21.4
2009	16.4	20.2

Calibration Protocol of Glacierized Catchments

- **1. Original Run**

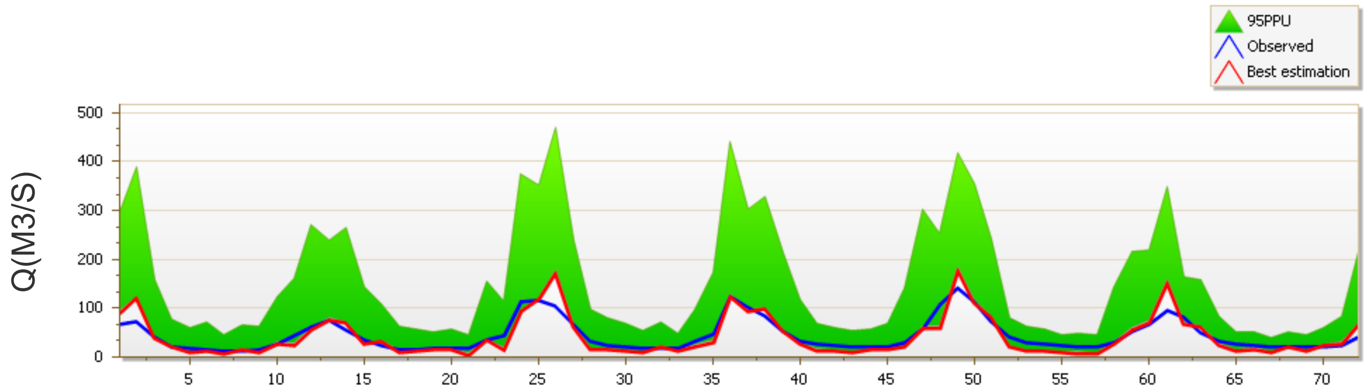


- **2. Tlaps and Plaps (1)**

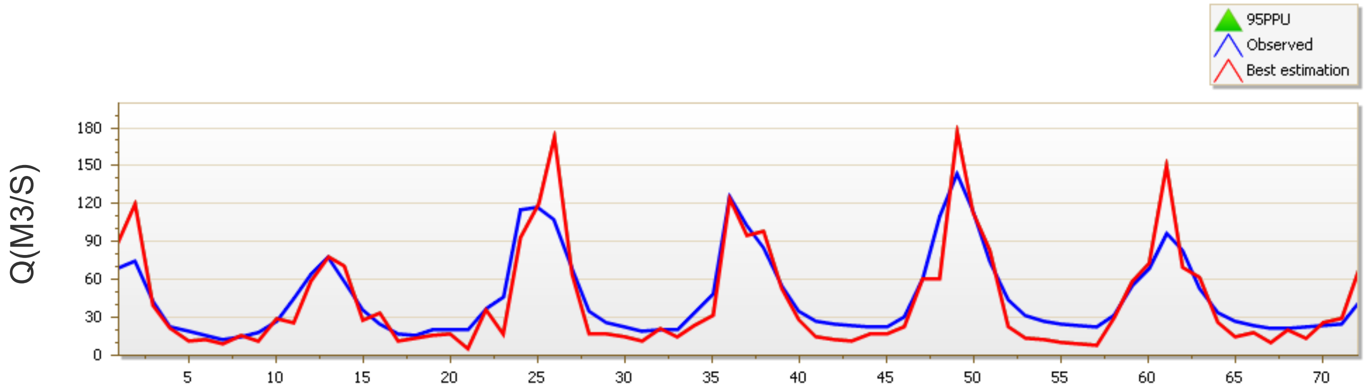


Calibration Protocol of Glacierized Catchments

- **3. Tlaps and Plaps (2)**

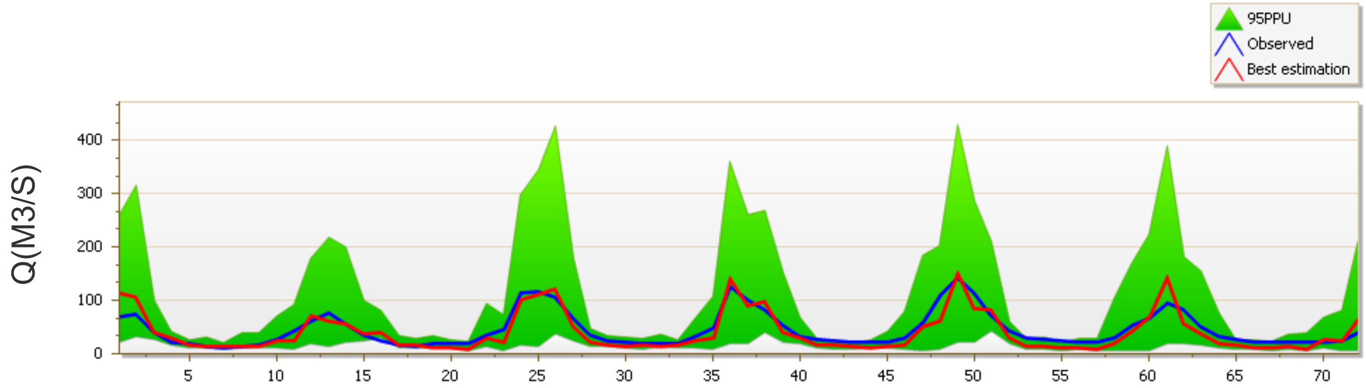


- **4. Tlaps and Plaps (fixed)**

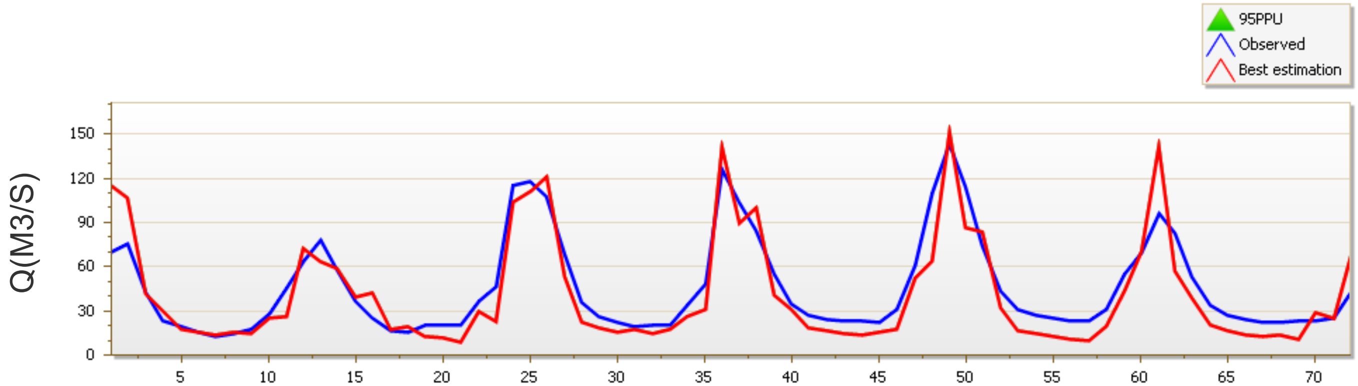


Calibration Protocol of Glacierized Catchments

- **5. Snow Parameters (1)**

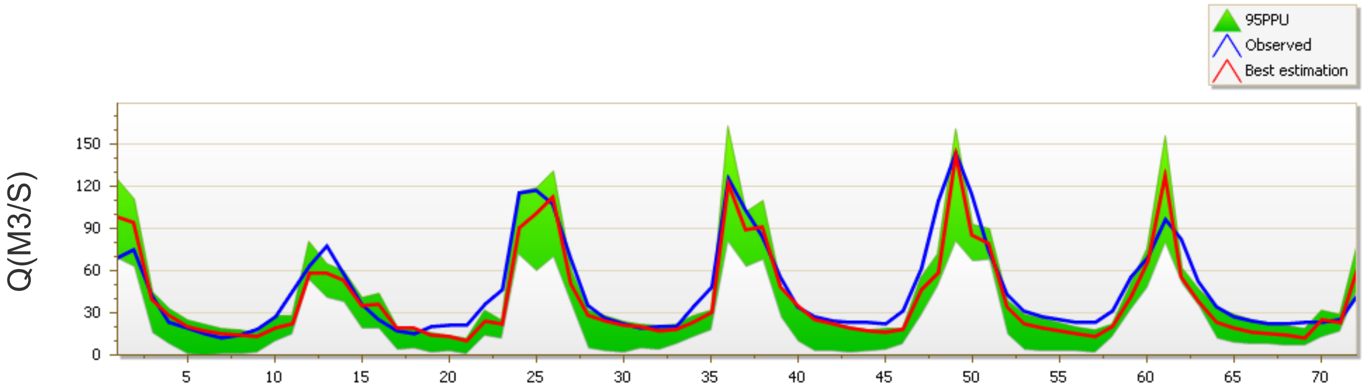


- **6. Snow Parameters (fixed)**

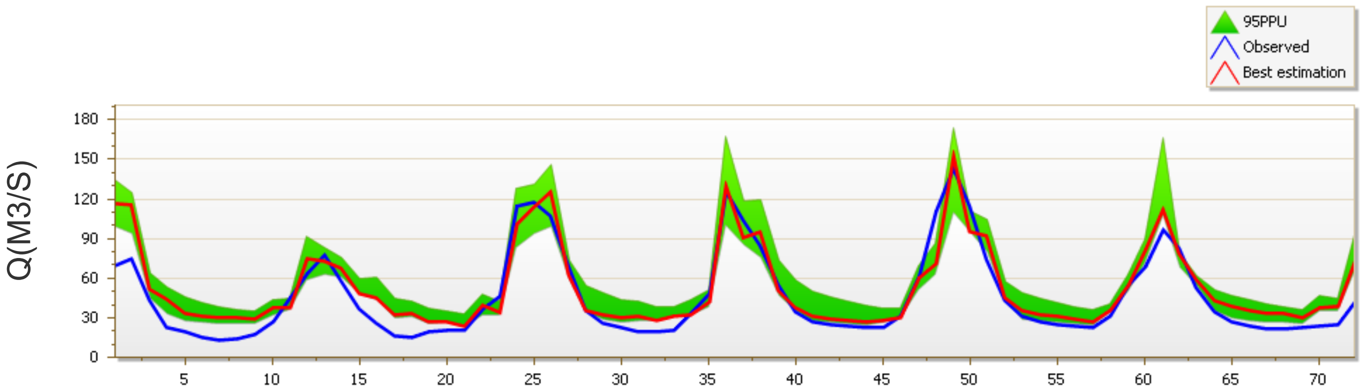


Calibration Protocol of Glacierized Catchments

- 7. General Hydrologic parameters (1)



- 8. General Hydrologic parameters (2) + glacier/springs

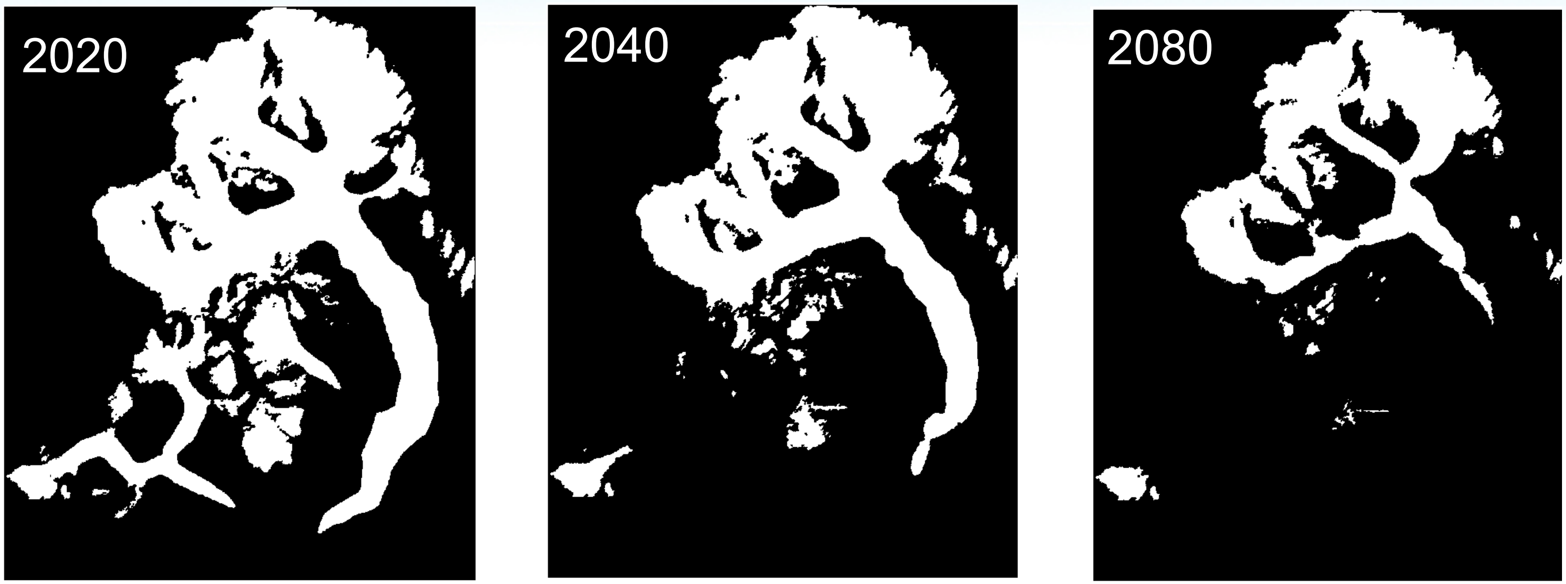


Impact of Climate Change on Aketsch Glacier retreat?

- 5 global GCMs, RCP8.5 (CMIP5) from ISI-MIP dataset available in SWAT format at www.2w2e.com
- (1950-2100) at 0.5 degree resolution
- Future 2010-2030, 2040-2060 and 2080-2100
- SWAT-formatted precipitation, max and min temperature

GCM	Scenarios	Institute
GFDL-ESM2M	RCP 8.5	NOAA/Geophysical Fluid Dynamics Laboratory (USA)
HadGEM2-ES	RCP 8.5	Met Office Hadley Centre (United Kingdom)
IPSL-CM5A-LR	RCP 8.5	Institute Pierre-Simon Laplace (France)
MIROC	RCP 8.5	AORI, NIES and JAMSTEC (Japan)
NoerESM1-M	RCP 8.5	Norwegian Climate Center (Norway)

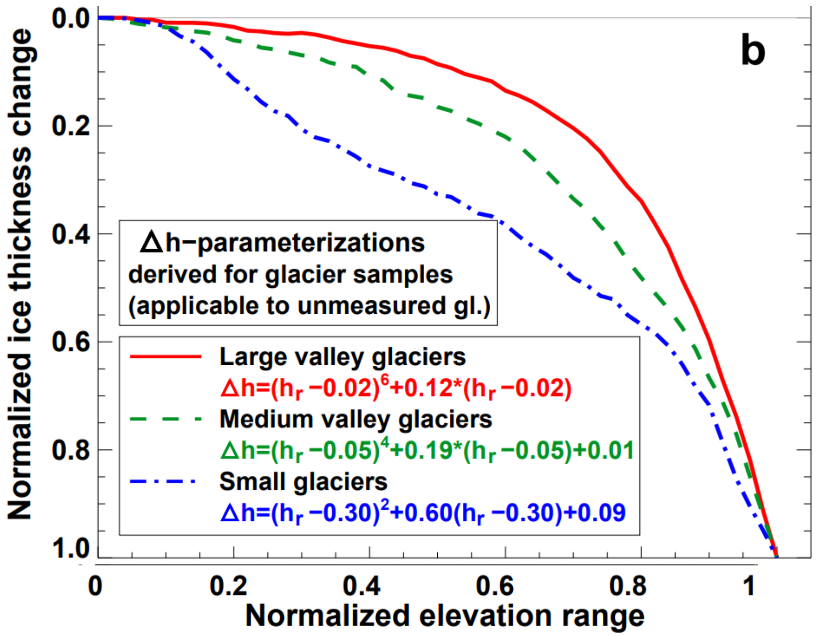
Impact of Climate Change on Aketsch Glacier retreat?



Years	Ice Volume (km3)	Ice Length (km)
2020	12.4-14.7	20.9
2040	8.5-11	18.2
2080	4-7.5	10.2


Thank you for your attention!

GREM annul update of surface topography and outline:



Huss et al 2010

GREM Daily outputs

Daily generated runoff is calculated based on mass balance at each grid

$$Runoff_i = Accumulation_i - Ablation_i - Evapotranspiration_i$$