SWAT-G
-
A freely and openly available glacier routine for SWAT

Timo Schaffhauser
Technical University of Munich
Chair of Hydrology & River Basin Management

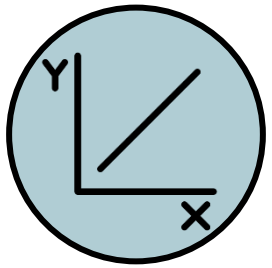
Motivation

SWAT widely used in alpine & glaciated catchments

- Glacier processes often neglected or insufficiently considered

Past efforts not freely or easily accessible

- FAIR principles



Past efforts often focus on simplistic approaches

- Volume-Area scaling
- Static approaches
- Offline-coupling to external glacier models

How suitable is SWAT in these catchments?

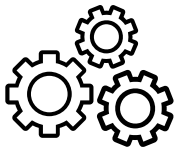
Can we improve SWAT‘s applicability?

SWAT-G to Overcome Current Obstacles

- **SWAT-G** = A revised version of **SWAT** considering:

Glacier Processes!

- What do we mean with glacier processes?



1. **Glacier Mass Balance Routine**
   - Melt, Accumulation, Sublimation (daily)
2. **Glacier Evolution Routine**
   - (Dynamic) Glacier Change
   - Retreat, Advance (restricts e.g. flow)

Martelltal, Langenferner Glacier. Reference: foto-webcam.eu

Vision of SWAT-G

- **Encourage** community to…
  - model **glaciated** basins **properly** to avoid misapplication in glaciated basins
  - make model code **available** and **easily accessible!**
- Provide different approaches for glacier-related processes
  - User flexibility!
- Develop **SWAT+-G** as soon as possible!

SWAT

S+

- Do not stick to glaciers only, but…
  - improve snow module simultaneously!
- A lot of efforts efforts have been made in the past, but…
  - work is fragmented and was never coordinated
  - tools were never collected and provided in a coupled way
  - different groups made same work (redundancy)

SWAT-G: Components

Mass Balance Routine

- Melt, Accumulation, Sublimation
- Daily Scale
- Annual Aggregation

Glacier Evolution Routine

- (Dynamic) Glacier Change
- Retreat, Advance (restricts e.g. flow)
- Δh-Parameterization
- Annual Scale

Preprocessing & Technical Implementation

- Initialization of SWAT-G
- Land Use Modification
- Initial Glacier Mass
- Initial Glacier Area
- Subbasin Scale

SWAT-G: Mass Balance

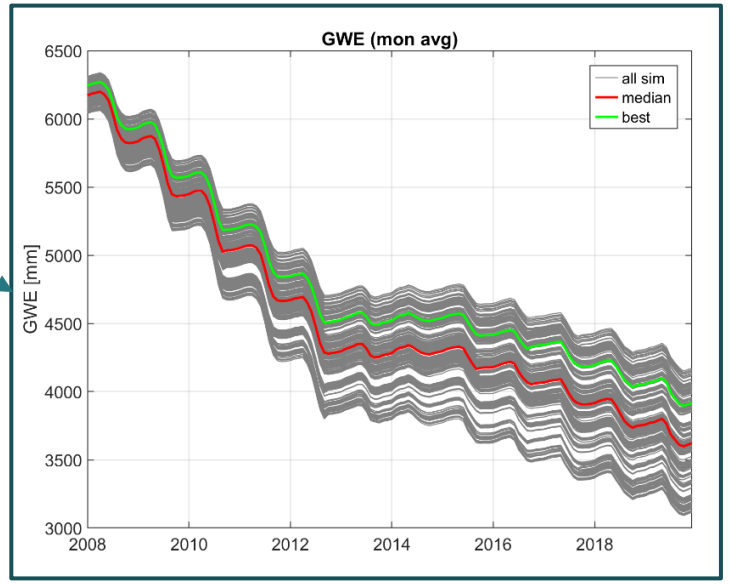
Formulation

$$EW_t = EW_{t-1} - M_t \cdot (1 - \beta_f) - S_t + C_t$$

EW:	*Water Equivalent of Ice [mm]*
M:	*Glacier Melt [mm/d]*
β_f*:*	*Refreezing Rate [-]*
S:	*Sublimation [mm/d]*
C:	*Glacier Accumulation [mm/d]*

Technical Implementation

- Merged with *snow* & *surface* routine
- HRU-based
  Aggregation per subbasin & year
- New outputs in *output.hru*



Mass Balance Components: Melt

$$EW_t = EW_{t-1} - M_t \cdot (1 - \beta_f) - S_t + C_t$$

$$M_t = \begin{cases} (T_{mx,t} - T_{gmlt}) \cdot b_{gmlt}, & if\ T_{mx,t} > T_{gmlt}\ and\ A_{sc} < A_{gc} \\ 0, & if\ T_{mx,t} < T_{gmlt}\ or\ A_{sc} < A_{gc} \end{cases}$$

Tmx:	*Max. Daily Temp. [°C]*
Tgmlt:	*Threshold Temp of Glacier Melt [°C]*
bgmlt:	*Ice Melt Factor [mm/(d*°C)]*
Asc:	*Snow Cover Fraction of Subbasin [-]*
Agc:	*Glaciated Fraction of Subbasin [-]*

$$b_{gmlt} = \frac{(b_{gmlt,mx} + b_{gmlt,mn})}{2} + \frac{(b_{gmlt,mx} - b_{gmlt,mn})}{2} \cdot \sin\left[\frac{2\pi}{365}(t - 81)\right]$$

bgmlt,mx:	*Melt factor June 21 [mm/(d*C°)]*
bgmlt,mn:	*Melt factor December 21 [mm/(d*C°)]*
T:	*Day of year [-]*

- **Degree-Day Approach**
- Occurs when **HRU snow-free** & $\boldsymbol{T_{gmlt}}$ **exceeded**
- **Snow cover (SC)** & **Glacier cover (GC)** comparison
  - E.g.: 70% SC and 80% GC
  - 10% of glacier area can generate melt
- **Albedo** of ice < albedo of snow
  - Thus: $b_{gmlt} > b_{smlt}$
  - If $b_{gmlt} < b_{smlt}$ then $b_{gmlt} = b_{smlt}$
- **Refreezing factor β_f** to control high melt rates
  - 0-30% of glacier melt able to refreeze

SWAT-G: Components

Mass Balance Routine

- Melt, Accumulation, Sublimation
- Daily Scale
- Annual Aggregation

Glacier Evolution Routine

- (Dynamic) Glacier Change
- Retreat, Advance (restricts e.g. flow)
- Δh-Parameterization
- Annual Scale

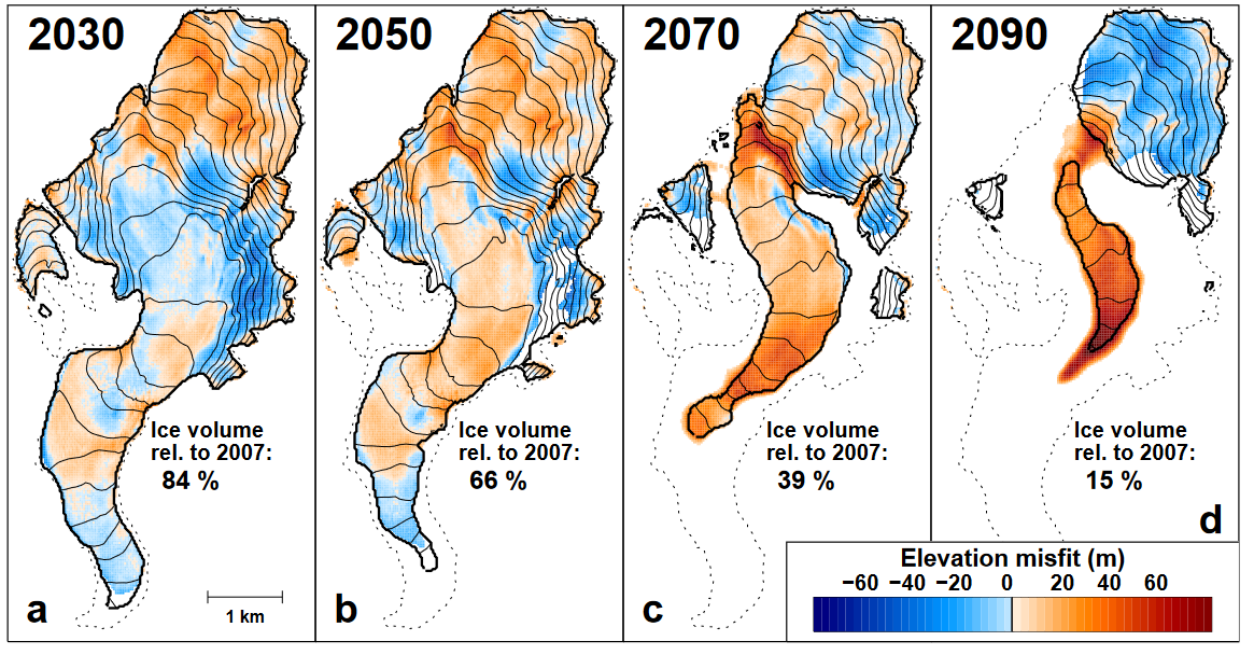
Preprocessing & Technical Implementation

- Initialization of SWAT-G
- Land Use Modification
- Initial Glacier Mass
- Initial Glacier Area
- Subbasin Scale

SWAT-G: Glacier Evolution

= Representation of **spatio-temporal** glacier **dynamics** such as **advance** or **retreat**

Example:



Reference: Huss et al. 2010

Concept

- Annual **mass balance changes translated** to **glacier area changes**
  - Elevation-dependent transfer
- Overcomes limitations of static approaches
  - Considers hydro-glaciological feedbacks
  - E.g. Runoff rates affected by area changes
- Spatially-distributed glacier changes

How?

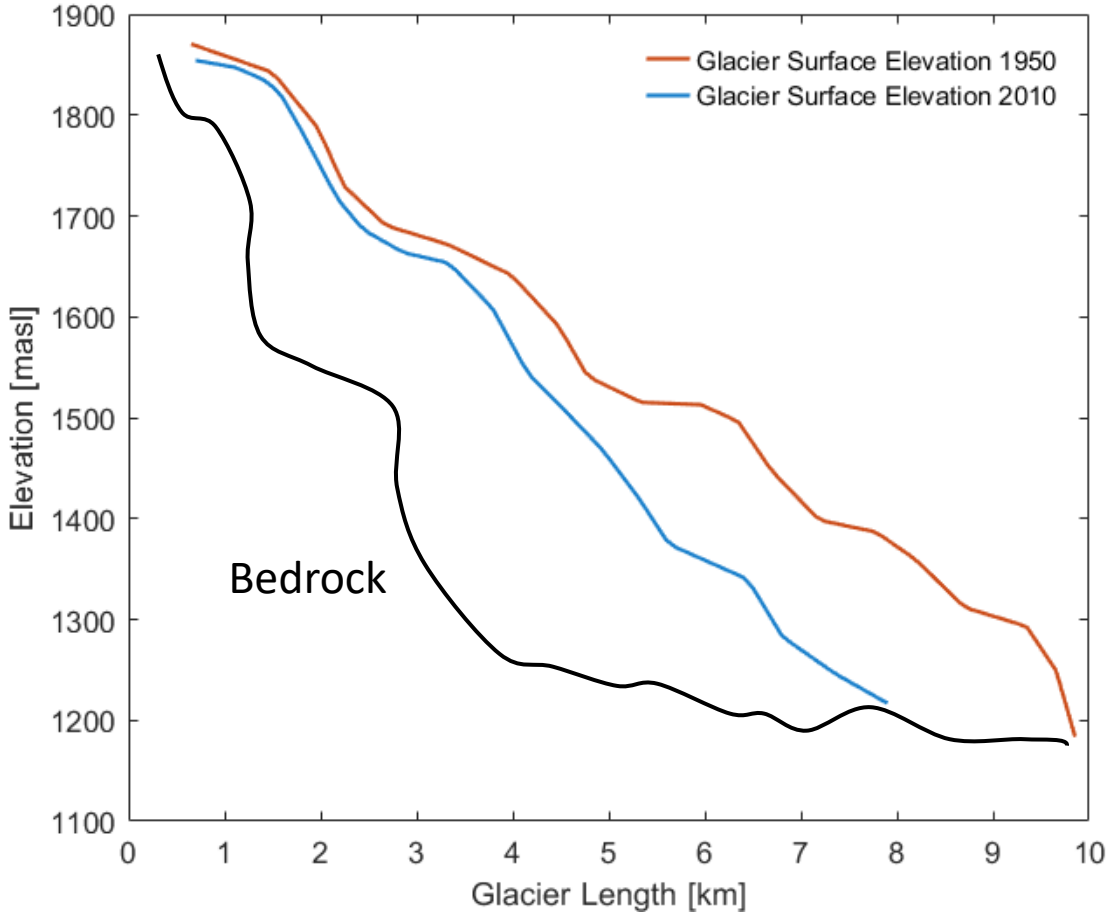
- **Δh-Parameterization** *(Huss et al. 2008)*
- Set relationship of ice thickness change & elevation

Ice Thickness Change & Elevation

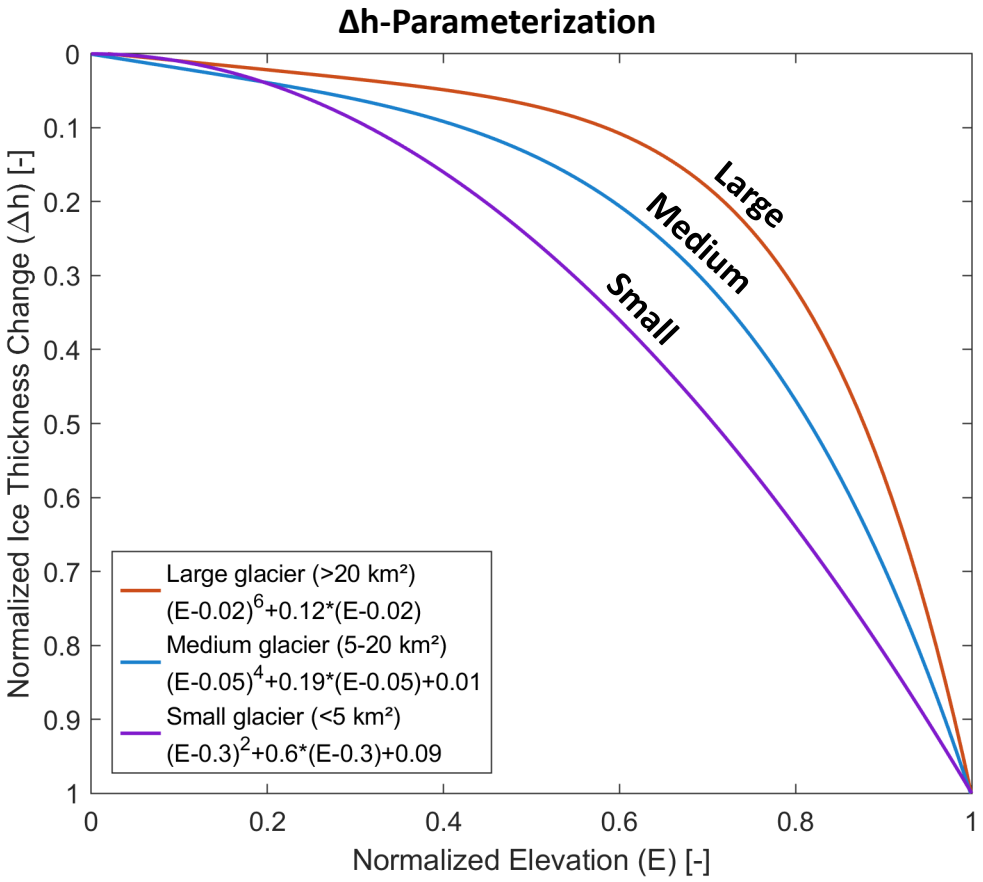
What do we mean with:

- Spatially-distributed ice thickness change?
- Relationship of ice thickness change & glacier surface elevation?

Relationship can be derived from
2 DEMs from **different times**!



Glacier Evolution: Δh-Parameterization



Δh-Parameterization:
Relationship of spatially distributed ice thickness changes caused by mass balance changes
Ice thickness changes highest at glacier terminus

Method Details

- *Normalized* ice thickness change **(Δh)** & *normalized* glacier elevation **(E)**
- Relationship depends on glacier size
- Mass balance change must equal the $\sum \Delta h \cdot A_{gl}$ of all elevation sections
- **Scaling factor** to convert dimensionless Δh & update glacier elevation

$$f_s = \frac{dV_a}{\sum_{i=1}^{n} A_i \cdot \Delta h_i}$$

$$h_{i,1} = h_{i,0} + f_s \cdot \Delta h_i$$

If $h_{i,1} \leq 0$ for a section i it is not glacierized anymore (**recession**)

SWAT-G: Components

Mass Balance Routine

- Melt, Accumulation, Sublimation
- Daily Scale
- Annual Aggregation

Glacier Evolution Routine

- (Dynamic) Glacier Change
- Retreat, Advance (restricts e.g. flow)
- Δh-Parameterization
- Annual Scale

Preprocessing & Technical Implementation

- Initialization of SWAT-G
- Land Use Modification
- Initial Glacier Mass
- Initial Glacier Area
- Subbasin Scale

In the following please remember the term:
Elevation Section (ES)

- ES divide glaciers in elevation-based zones on which the Evolution Module is applied

SWAT-G: Preprocessing for Δh-Parameterization

New Input Requirements:

Data
- Glacier thickness
- Glacier outlines

Files
- 2 new files

New Preprocessing:

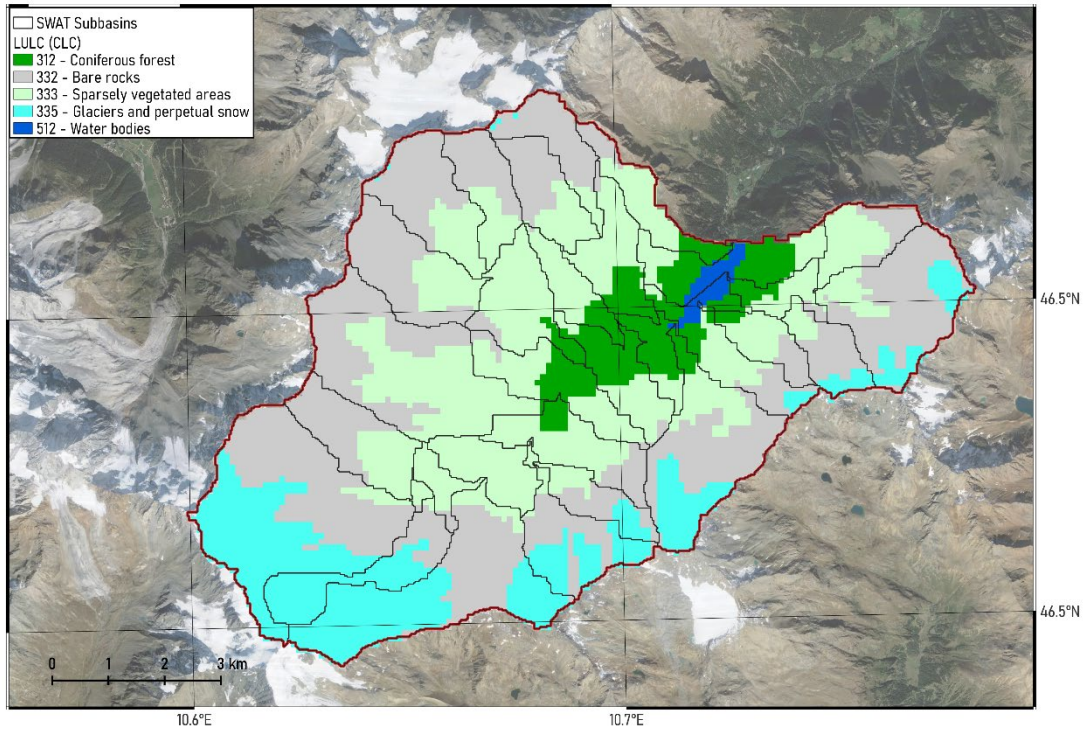
- Define ES spacing
- Modify Land Use map & add new class to crop database
- Determine initial glacier thickness & area per ES

New Outputs:

Files
- Modified *output.hru* for daily mass balance results
- New file for annual mass balance changes per ES

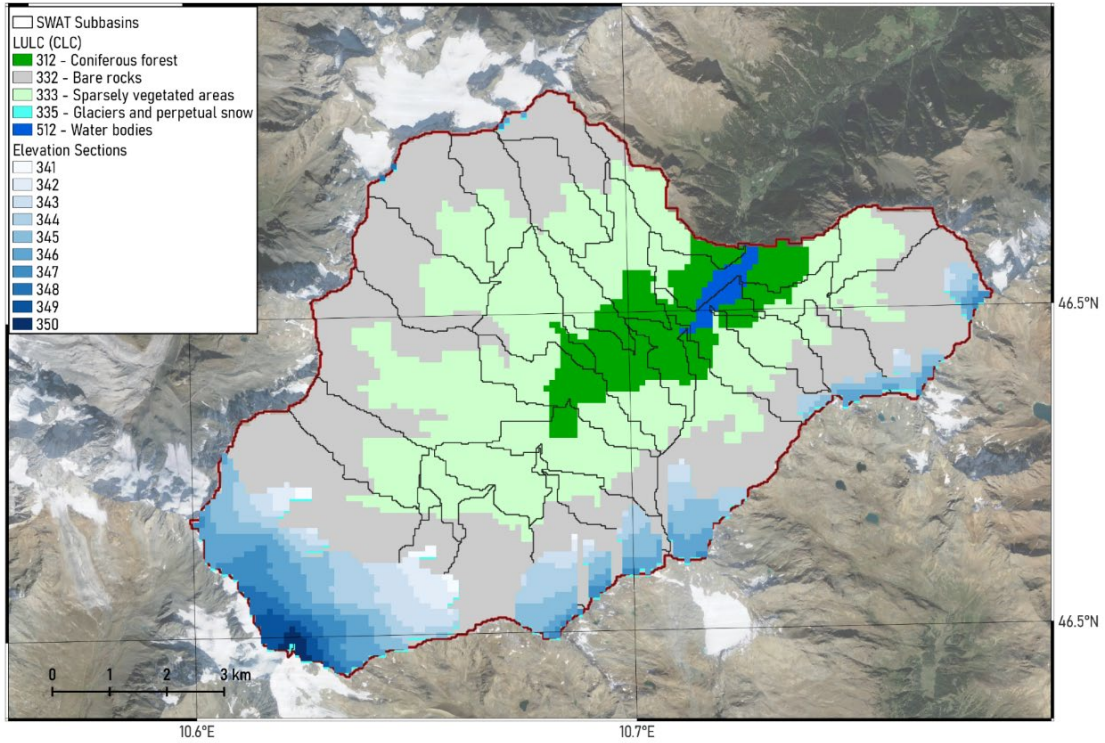
Preprocessing: Land Use Modification

Status Quo



- Standard Land Use Map

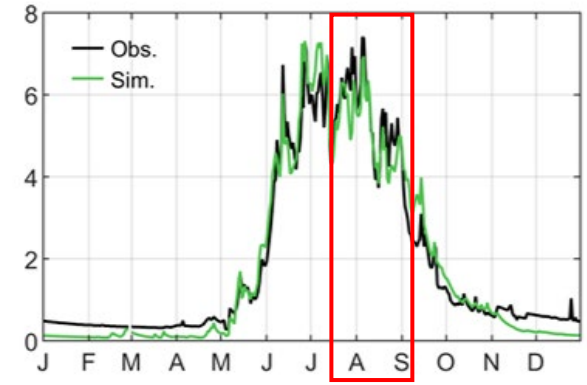
What we Need



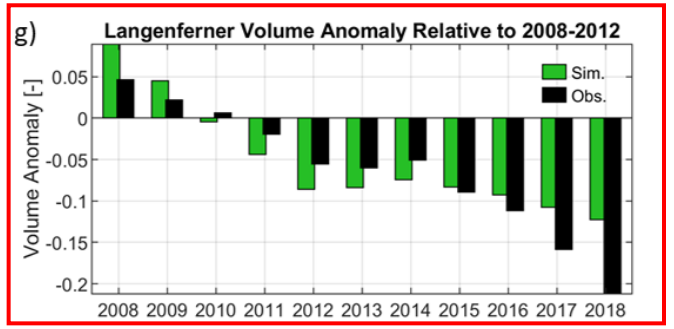
- Modified Land Use Map
  Considering Sections of Glacier Elevation
  Logically, DEM information required here

SWAT-G: Example Martelltal

Adequate **discharge** representation in glacier melt-dominated season

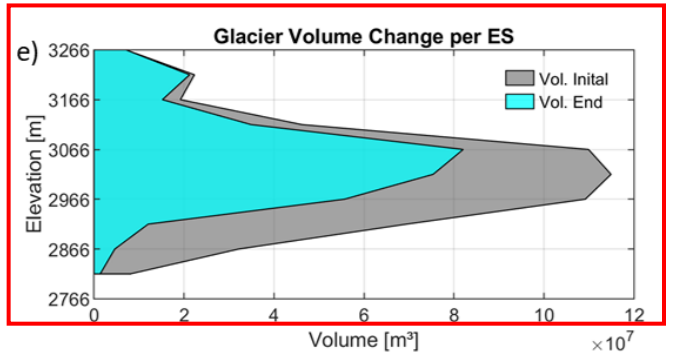


Calibration on **mass balance** (anomalies) work relatively well



Plausible elevation-dependent **glacier retreat**

- E.g. Weaker recession in upper parts



Summary

- SWAT-G enables an **appropriate modelling of glaciated basins**
  …with a minimum of additional input & processing requirements
- **Easily & openly accessible** to encourage the community to make code & models available and to foster model development
- When using SWAT/SWAT+ in its standard version **in highly glaciated catchments**, be at least careful :)

Outlook

- Implementation of **further concepts** & **alternative approaches**
  - Glacier & Snow
- **SWAT-G+ Transfer**
- **Benchmarking Study** for 4 glaciers in the US
  (will be submitted soon)
- Finalize Gitlab Documentation

Thanks for your attention!

Feel free to contact me!
t.schaffhauser@tum.de

Feedback, reuse & further development highly appreciated

SWAT-G GitLab Repo

Backup Slides

SWAT-G Application: Martelltal

Basin: 77 km²
Glacier: 11.7 km² (15%)

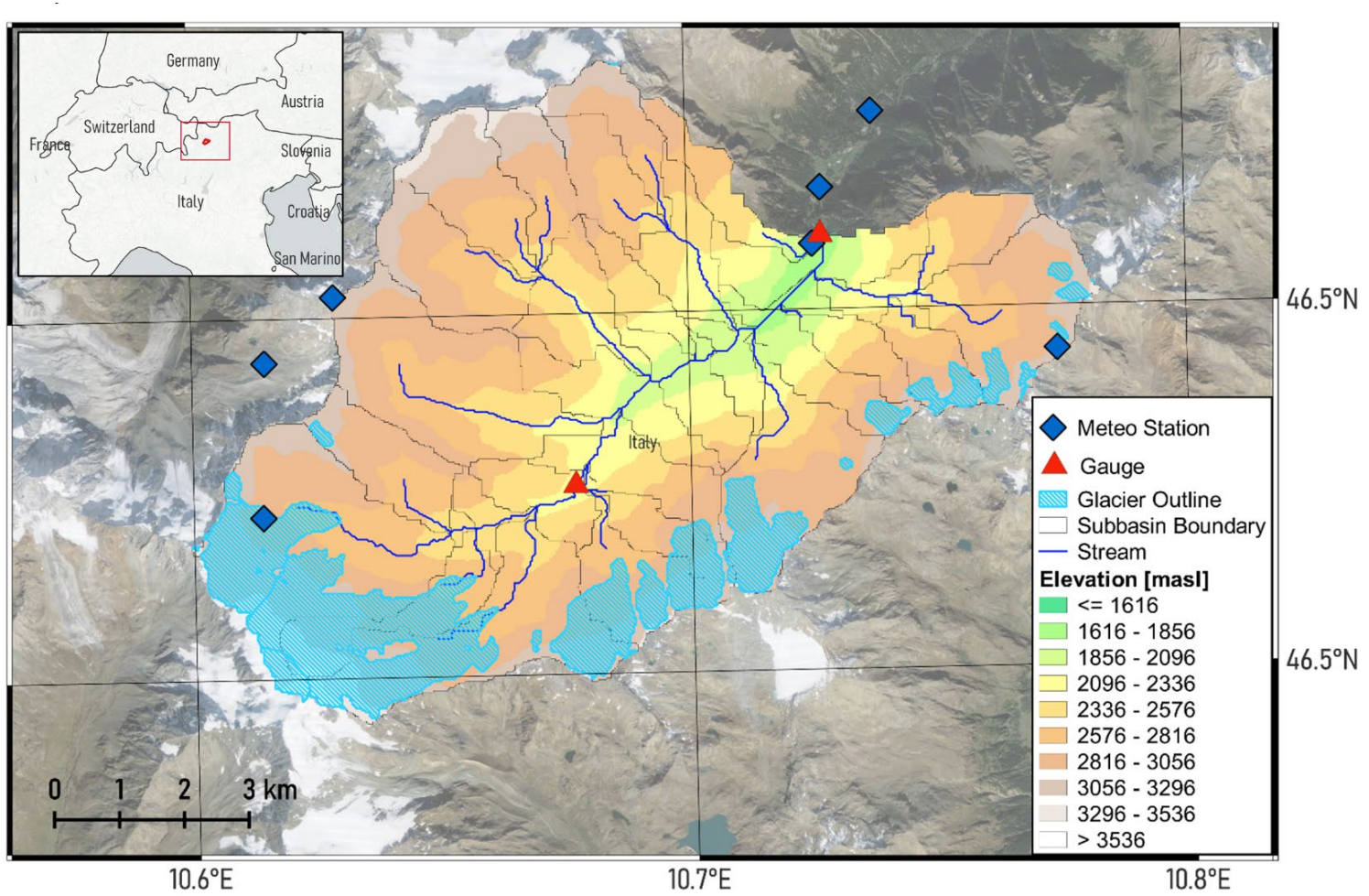
Precipitation: ~1400 mm

Melt components crucial
Nivo-glacial regime

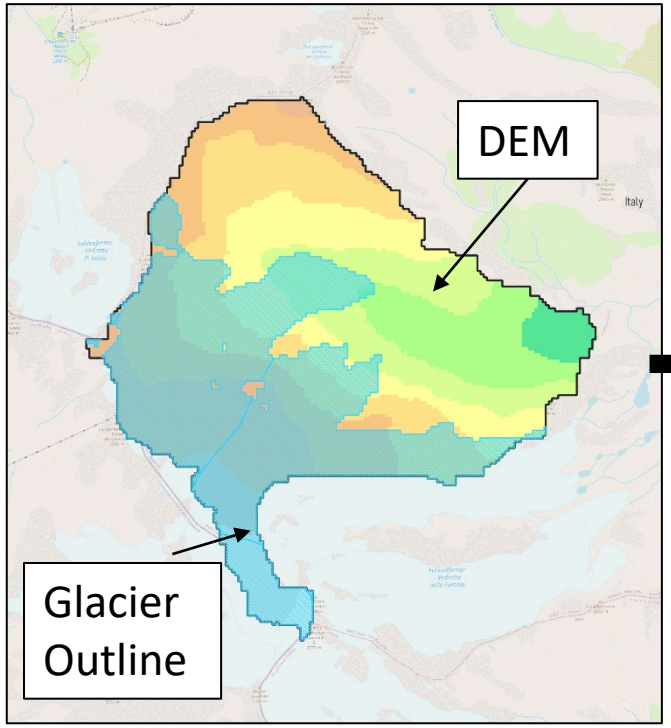
Data

- **Glacier area** & **mass balance** data for Langenferner (~17 years)
- **Discharge** of 2 gauges

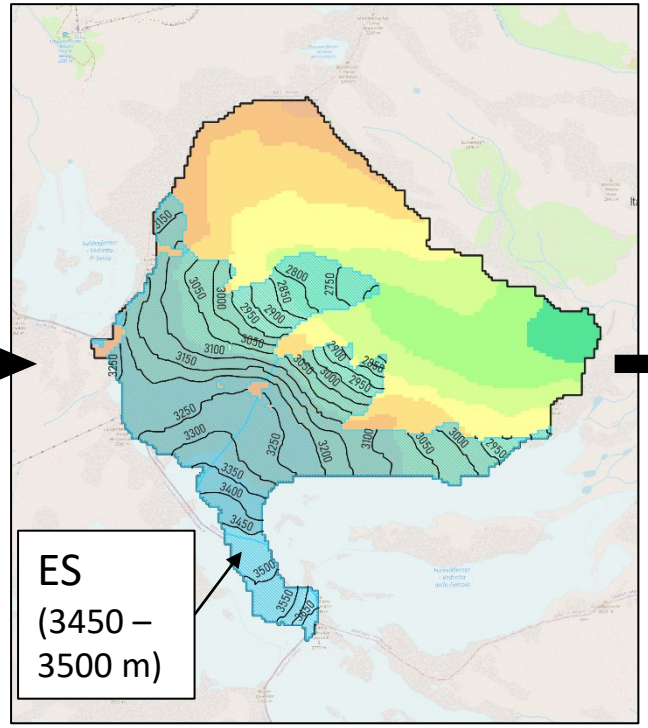
HRUs: 415 | **Subbasins**: 32



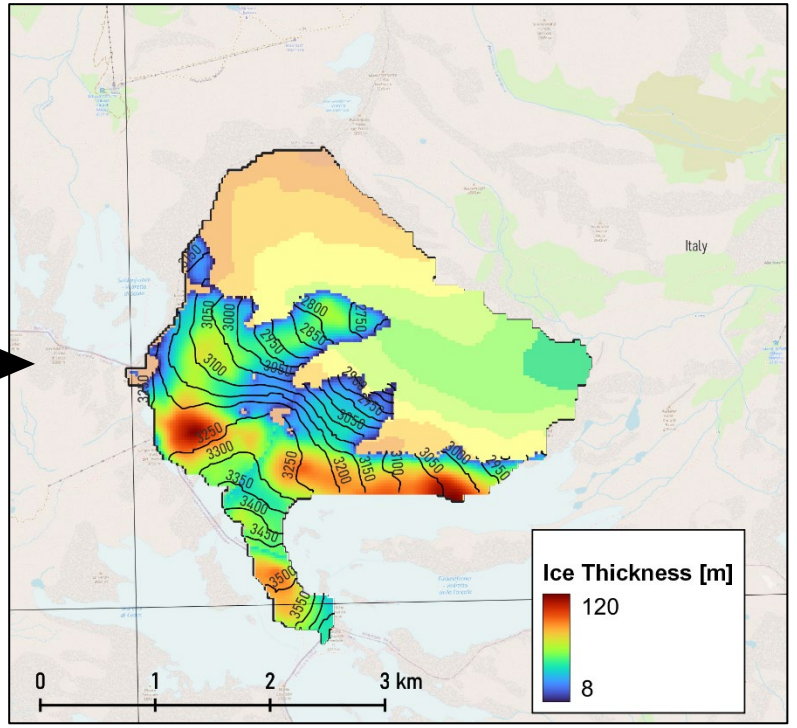
Preprocessing: Define ES & Initialize Glaciers



- Define ES spacing: 50 m



- Results in 20 ES 2700 m – 3700 m



- Extract ice thickness & glacier area for each ES

Note:
Glacier Initialization on the subbasin scale

Mass Balance Components: Sublimation & Accumulation

$$EW_t = EW_{t-1} - M_t \cdot (1 - \beta_f) - S_t + C_t$$

$$C_t = SWE_t \cdot f_{acc}$$

C:	Accumulation [mm/d]
SWE:	Snow Water Equivalent [mm]
f_{acc}:	Accumulation Factor [-]

$$S_t = ETP_t \cdot \alpha$$

S:	Sublimation [mm/d]
ETP:	Potential Evapotranspiration [mm/d]
α:	Sublimation Factor [-]

- **Improvements likely here**
- Accumulation *from Luo et al. 2013*
  - Alternative from *Wortmann et al. 2016*
- Sublimation from *Luo et al. 2013*
  - Alternative from *Wortmann et al. 2016*
- Literature is lacking information here
  - Most papers do not provide infos on sublimation & accumulation but only melt
- Sublimation & accumulation factors of *Luo et al. 2013*
  - Just the same formulas as for melt factor…

SWAT-G: Mass Balance

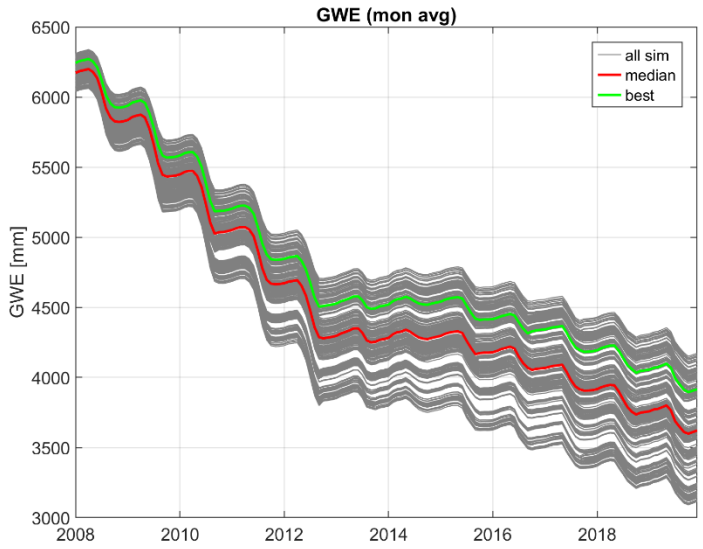
Formulation

$$EW_t = EW_{t-1} - M_t \cdot (1 - \beta_f) - S_t + C_t$$

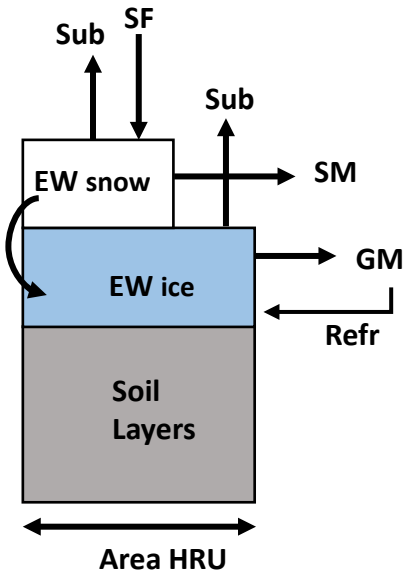
EW:	*Water Equivalent of Ice [mm]*
M:	*Glacier Melt [mm/d]*
β f:	*Refreezing Rate [-]*
S:	*Sublimation [mm/d]*
C:	*Glacier Accumulation [mm/d]*

Technical Implementation

- Merged with snow routine
- HRU-based
  - Individual storages
  - Aggregation per subbasin & year
- New outputs in *output.hru*



Glacier & Snow Processes on HRU Scale

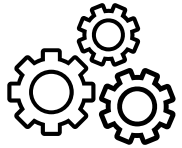


SWAT-G as Starting Point to Overcome Current Obstacles

- A revised version of **SWAT** considering:

Glacier Processes!

- What do we mean with glacier processes?



1. **Glacier Mass Balance Routine**
   - Melt, Accumulation, Sublimation (daily)
2. **Glacier Evolution Routine**
   - (Dynamic) Glacier Change
   - Retreat, Advance (restricts e.g. flow)

- Efficient integration of glaciers as new spatial object
  …without impairing existing spatial units
- Easy to use with a minimum of additional requirements
  …and easy to access!

Martelltal, Langenferner Glacier. Reference: foto-webcam.eu

Vision of SWAT-G

- **Encourage** community to…
  - model **glaciated** basins **properly** to avoid misapplication in glaciated basins
  - make model code **available** and **easily accessible!**
- Provide different approaches for glacier-related processes
  - User flexibility!
- Develop **SWAT+-G** as soon as possible!

SWAT

S+

- Do not stick to glaciers only, but…
  - improve snow module simultaneously!
- A lot of efforts efforts have been made in the past, but…
  - work is fragmented and was never coordinated
  - tools were never collected and provided in a coupled way
  - different groups made same work (redundancy)

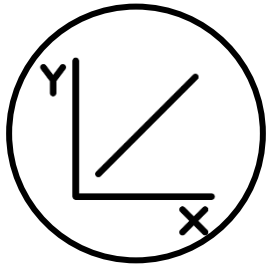
Motivation

SWAT widely used in alpine & glaciated catchments

- Glacier processes often neglected or insufficiently considered

Past efforts not freely or easily accessible

- FAIR principles



Past efforts often focus on simplistic approaches

- Volume-Area scaling
- Static approaches
- Offline-coupling to external glacier models

How suitable is SWAT in these catchments?

Can we improve SWAT‘s applicability?