Runoff determination in glacierized basins, using SWAT-GERM framework

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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
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

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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)
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
## 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
Runoff simulation in Glacierized Catchments

- **Initial Simulation**

- **What we want after calibration**
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.

![Diagram showing the relationship between Hydrologic Model (GM), Glacier Model (HM), and Hydrologic Model (HM), Glacier Model (GM) with arrows indicating the flow of information.](image-url)
Which hydrologic model should be coupled to which glacier model?

- WaSiM-ETH
- HSPF
- HBV
- MIKE SHE
- HEC
- SWAT
- GSM
- GERM
- .....
Soil and Water Assessment Tool (SWAT)

- Has been widely applied to predict the impact of landuse change, climate change, and management practices on water, sediment, nutrient and pesticide yields with reasonable accuracy on large, complex, ungaged watersheds over long periods of time.

**SWAT Characteristics:**
- Continuous time
- Physically based
- Distributed parameter
- Flexible basin discretization
- River basin scale program 100-many 1000’s of km2
- Land management component
- Water management component
- Runs on different data availability
- Open source model
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:

\[ P_{soild,i} = P_{ref} \times (1 + C_{perc}) \left[ 1 + \frac{Elev_i - Elev_{ref}}{1000} dp \right] \times D_{snow,i} \times r_s \]

- \( P_{ref} \): 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)
- \( D_{snow,i} \): spatially distributed factor which account for snow redistribution processes (Tarboton et al. 1995, Huss et al. 2009)
- \( r_s \):
  \[ \begin{align*}
  T_{ave} \leq -1 & \rightarrow r_s = 1 \\
  T_{ave} \geq 1 & \rightarrow r_s = 0 \\
  -1 \leq T_{ave} \leq 1 & \rightarrow r_s = \frac{1 - T_{ave}}{2}
  \end{align*} \]

Huss et al 2008, 2010
Daily **Accumulation** for each grid:

\[
Psoid_i = P_{ref} \times \left(1 + C_{perc}\right) \left[1 + \frac{Elev_i - Elev_{ref}}{1000} dp\right] \times D_{snow_i} \times r_s
\]
**GERM Daily Ablation** input files:

\[
Melt_i = [f_m + \frac{r_{\text{snow}}}{r_{\text{ice}}} \times I_{\text{pot},i}] \times T_i
\]

- **Sub_grids_FM.txt**
- **Sub_grids_Rsnow.txt**
- **Sub_grids_Ipot.txt**
- **Climate_ref folder:**
  - 45150p.txt
  - 45150t.txt
  - 45151p.txt
  - Pcp.txt
  - Tmp.txt
- **Sub_climate_ref.txt**
- **Sub_demgrids_correlation.txt**
- **aletsch_dem_index.grid**

**Ablation** is modeled with a distribution temperature-index approach

- **\( f_m \):** melt factor
- **\( r_{\text{snow}} \) or \( r_{\text{ice}} \):** two distinct radiation factors for snow and ice
- **\( I_{\text{pot},i} \):** the potential direct clear sky solar radiation at grid cell \( i \)
- **\( T_i \):** mean daily air temperature (C), for \( T_i < 0 \) not melts occurs
**GERM** Daily outputs

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

\[ \text{Runoff}_{i} = \text{Accumulation}_{i} - \text{Ablation}_{i} \]
Flexible GERM Architecture

- Ablation is modeled with a distribution
Study Area

- **Aletsch Glacier**
- **Total Area**: 196 km\(^2\), **Glacier area**: 82 km\(^2\), 15 km\(^3\) ice (20% of Swiss ice)
- **Simulation**: 1960-2010
Altesch Glacier Project

Dem

Climate stns
Guage stn
River

Landuse

Soil

- RNGE
- ROCK
- BARR
- GLAC

- s7005
- s7006
- s9981
- s9984
Building a model

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

Ice Thickness

1957

1999
Results

Ice Thickness

<table>
<thead>
<tr>
<th>Years</th>
<th>Ice Volume (km³)</th>
<th>Ice Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1957</td>
<td>21.8</td>
<td>23</td>
</tr>
<tr>
<td>1999</td>
<td>18.2</td>
<td>21.4</td>
</tr>
<tr>
<td>2009</td>
<td>16.4</td>
<td>20.2</td>
</tr>
</tbody>
</table>

Accumulation dominated (blue)

Ablation dominated (red)
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
Thank you for your attention!
GREM Daily outputs

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

\[ \text{Runoff}_{i} = \text{Accumulation}_{i} - \text{Ablation}_{i} - \text{Evapotranspiration}_{i} \]