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
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
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
- SWAT
- HBV
- GSM
- GERM
- ...
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

+ Portions of grids which are located in each sub-basin
Tools for automation of overlaying

- Upper surface (e.g. DEM 1957)
- Lower surface (e.g. DEM 1999)

- Cut Fill
- Cut_Fill_1999_2009

- Select subbasin
- Subbasins layer

- Value

- Iterate Feature
- Subbasin

- Extract by Mask
  - Volume change output raster between

- Cut_Fill_1000_2009

- Table to Table
- No_B%value%Tab

- Add Field
- B%name%Table

- Calculate Field
  - B%name%Table

- Input: Subbasins layer

- Select subbasin name field

- aletsch_dem_index.asc

- Iterate Feature Selection

- Merge

- Output Dataset
**GERM** daily **Accumulation** for each grid:

\[
P_{\text{soild}_{i}} = P_{\text{ref}} \times (1 + C_{\text{perc}})[1 + \frac{\text{Elev}_{i} - \text{Elev}_{\text{ref}}}{1000} \frac{dp}{1000}] \times D_{\text{snow}_{i}} \times r_{s}
\]

- **\(P_{\text{ref}}\)**: precipitation at reference location (mm)
- **\(C_{\text{perc}}\)**: correction factor for the gauge-catch deficit (Bruce and Clark 1981)
- **\(\text{Elev}_{i} - \text{Elev}_{\text{ref}}\)**: 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)
- **\(D_{\text{snow}_{i}}\)**: spatially distributed factor which account for snow redistribution processes (Tarboton et al. 1995, Huss et al. 2009)
- **\(r_{s}\)**:
  \[
  T_{\text{ave}} \leq -1 \rightarrow r_{s} = 1 \\
  T_{\text{ave}} \geq 1 \rightarrow r_{s} = 0 \\
  -1 \leq T_{\text{ave}} \leq 1 \rightarrow r_{s} = \frac{1 - T_{\text{ave}}}{2} 
  \]

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

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

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

- **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
- **\( r_{snow} \) 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 occurs
**GERM** Annul update of surface topography and outline:

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 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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**Soldier 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
Runoff simulation in Glacierized Catchments

- **Initial Simulation**

- **What we want after calibration**
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 (1957-2009)

<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**
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

<table>
<thead>
<tr>
<th>GCM</th>
<th>Scenarios</th>
<th>Institute</th>
</tr>
</thead>
<tbody>
<tr>
<td>GFDL-ESM2M</td>
<td>RCP 8.5</td>
<td>NOAA/Geophysical Fluid Dynamics Laboratory (USA)</td>
</tr>
<tr>
<td>HadGEM2-ES</td>
<td>RCP 8.5</td>
<td>Met Office Hadley Centre (United Kingdom)</td>
</tr>
<tr>
<td>IPSL-CM5A-LR</td>
<td>RCP 8.5</td>
<td>Institute Pierre-Simon Laplace (France)</td>
</tr>
<tr>
<td>MIROC</td>
<td>RCP 8.5</td>
<td>AORI, NIES and JAMSTEC (Japan)</td>
</tr>
<tr>
<td>NoerESM1-M</td>
<td>RCP 8.5</td>
<td>Norwegian Climate Center (Norway)</td>
</tr>
</tbody>
</table>
Impact of Climate Change on Aketsch Glacier retreat?

<table>
<thead>
<tr>
<th>Years</th>
<th>Ice Volume (km³)</th>
<th>Ice Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020</td>
<td>12.4-14.7</td>
<td>20.9</td>
</tr>
<tr>
<td>2040</td>
<td>8.5-11</td>
<td>18.2</td>
</tr>
<tr>
<td>2080</td>
<td>4-7.5</td>
<td>10.2</td>
</tr>
</tbody>
</table>
Thank you for your attention!
Daily generated runoff is calculated based on mass balance at each grid

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