Glaciers and Hydrology
On the glacier meltwater contribution to river runoff

Sergiy Vorogushyn
Section 5.4: Hydrology
GFZ German Research Centre for Geosciences Potsdam

CATCOS Summer School Bishkek, 2015
Hydrological cycle and the basic equation in Hydrology

\[ Q = P - E - \Delta S \]

- **\( \Delta S \):** Storage change (glacier, snow, soil moisture, groundwater)
- **P:** Precipitation
- **E:** Evapotranspiration
- **Q:** Runoff
Storages and Fluxes

- Ice & snow
- Soil
- Inland surface water bodies
- Groundwater
- Atmosphere
- Ocean

Storage

Fluxes
Introduction

• „For the whole Tien Shan, the glacial runoff is 15-20% of total volume of river runoff“ (Aizen et al., 1995, Water Resources Bulletin)

• „…but there is little doubt that melting glaciers provide a key source of water for the region [Himalya-Hindu Kush] in the summer month: as much as 70% of the summer flow in the Ganges and 50-60% of the flow in other major rivers (references)“ (Barnett et al., 2005, Nature)
Introduction

• „For the whole Tien Shan, the glacial runoff is 15-20% of total volume of river runoff“ (Aizen et al., 1995, Water Resources Bulletin)

• „...but there is little doubt that melting glaciers provide a key source of water...“ (Himalya-Hindu Kush) in the summer month: as much as 70% of summer flow in the Ganges and 50-60% of the flow in other major rivers (references)“ (Barnett et al., 2005, Nature)

Such statements make no sense! Be very careful!
Definition of glacier melt runoff

Source

- Glacier meltwater
- Glacier meltwater + Snow melt
- Glacier meltwater + Snow melt + Rainfall on glacier surface

Fraction Stat vs. Non-st.

- Stationary glacier melt contribution: MB = 0
- Non-stationary glacier melt contribution: MB < 0

Temporal scale

- Long-term (multi-year) average
- Annual average
- Seasonal average
- Monthly average
- Daily average
Back-of-the-envelope calculation of the total non-stationary runoff contribution

- Determine the total glacier mass loss in a time period
- Relate glacier meltwater share to the total runoff volume
Mass Balance Measurements
Ice volume estimation based on DEM differencing

DTM Difference 1964 – 1999
Corona - SRTM

DTM Difference 1999 – 2012
SRTM - ASTER

Source: Bolch, 2015, I&S
Ice volume estimation based on remote sensing surveys and volume inversion

1. Multiple remote sensing surveys of glacier surface areas

2. Application of the ice volume inversion schemes
   - Area-volume scaling
     \[ V = k A^\gamma \]
   - Ice thickness estimation

Ice thickness inversion from the vertical mass balance gradient, glacier surface topography and ice flow assumptions (Farinotti et al., 2009)
Ground Penetration Radar and Ice Volume Estimations

Source: Hagg et al. 2013, GPC
Glacier contribution to total runoff from glacier storage change ($\Delta S > 0$)

Source: Farinotti et al., 2015
Glacier contribution to total runoff from glacier storage change
Glacier contribution to total runoff from glacier storage change

Source: Farinotti et al., 2015
Back-of-the-envelope calculation

• Determine the total glacier mass loss in a time period
• Relate glacier melt share to the total runoff volume

• Back-of-the-envelope calculations are afflicted by climatic (evaporation), geological (groundwater recharge), and human (water abstraction) factors
• This calculation represents the maximum potential glacial meltwater contribution
Modelling approaches – Glaciersmelt

Conceptual approach

- Integrated approach, degree day factor
- High correlation between incoming radiation and air temperature

\[ M = \begin{cases} 
MF \cdot (T - T_m) & T > T_m \\
0 & T \leq T_m 
\end{cases} \]

- \( MF \) ...degree day factor (mm/d)
- \( T \) ...actual temperature (°C)
- \( T_m \) ...threshold temperature for melt

\[ MF_i = \frac{C_{\text{MAX}} - C_{\text{MIN}}}{2} \cdot \cos \left( \frac{2\pi}{\text{day}_{\text{max}}} \cdot i \right) + C_{\text{MIN}} + \frac{C_{\text{MAX}} - C_{\text{MIN}}}{2} \]
Modelling approaches – glacier evolution

Glacier evolution

Down wasting
• glacier as infinite storage
+ simple
+ good approximation for small time periods
- difficulties for projection runs
(HBV-ETH..)

Conceptual glacier area/mass update
• redistribution of glacier mass
+ useful for forward run
+ often good approx.
- redistribution parameters static from past processes
(GERM, WASA..)

Physical
• 3-D glacier flow dynamics
+ actual glacier dynamics described
+ useful for forward run
+ often good approx.
- complicated
- much calculation effort

- complicated
- much calculation effort
Downwasting
\( h_{\text{glacier}} = \text{constant/infinite}, \ A = \text{constant or variable} \)

Conceptual
\( A_{\text{glacier}} = f(h_0, MB, \Delta h), \)
\( h_{\text{glacier}} = \text{variable in time and space} \)
Modelling approaches – glacier evolution

1. Scheme of glacier surface in 2 sequential DEMs

\[
\text{norm\_elev} = (h_{\text{max}} - h) / (h_{\text{max}} - h_{\text{min}})
\]

\[
\text{norm\_}\Delta h = \Delta h / \Delta h_{\text{max}}
\]

2. \(\Delta h\)-curve from measurements for a sample glacier

- \(h_r\)...r
- \(a, b, c, \gamma\)...parameters
- by optimizing system of equations \(a, b, c\) and \(\gamma\) can be retrieved

3. Generalized \(\Delta h\)-curves for glaciers of different size classes

Source: Huss et al. 2010, HESS
Modelling approaches – glacier evolution

- After annual MB calculation

\[ f_s = \frac{B_a}{\rho_{\text{ice}} \cdot \sum_{i=0}^{i=h_r} A_i \cdot \Delta h_i} \]

- If \( h_1 = 0 \text{ m} \) → area loss for elevation zone

\[ h_1 = h_0 + f_s \cdot \Delta h_i \]

\( B_a \)... annual MB in kg
\( f_s \)... correction factor, to be calculated annually
\( \rho_{\text{ice}} \)... ice density
\( A_i \)... area of glaciated terrain component
\( \Delta h_i \)... dh for elevation band

- Only for mass/ area loss!
Hydrological modelling of glacier melt contribution

Sari-Djaz basin
Total area: 12,950 km²
Glacierization: 21%

Kakshaal basin
Total area: 18,410 km²
Glacierization: 4.4%

Rainfall gauge records (1960-1990):
190 – 320 mm/a
Hydrological modelling of glacier melt contribution
Modulation of river runoff at different time scales

Runoff modulation at seasonal and interannual time scales is of particular importance for water supply.

Runoff modulation is a function of catchment glacierization and climatic regime.

Source: Jansson et al., 2003
Runoff Variability – monthly time scale

- Shaligulanke, Kakshaal, Monthly discharge series
  - CV = 1.03

- Xiehela, Sari-Dzaz, Monthly discharge series
  - CV = 1.18
  - GLOF!

- Tailan, Monthly discharge series
  - CV = 1.11

Glacierization: 36%
Runoff variability – interannual time scale

Shaligullanke, Kakshaal, Annual discharge series

CV = 0.175

Xiehela, Sari-Djaz, Annual discharge series

CV = 0.13

Tallan, Annual discharge series

CV = 0.102
A rigorous statement about the glacier melt contribution to runoff...

... must include

- the runoff/input share in %
- the precise geographical location (gauge, point in the river network)
- a reference to the non-stationary or total melt share
- the reference period for which the share is determined
- the temporal scale which the share refers to
- the method and data basis used to derive the glacier melt contribution

Example:

„Based on the hydrological modelling for the period 1957-2001, the average summer (JJA) total glacier melt contribution to river runoff at the gauge Shaliguilanke (Aksu/Tarim) amounts XX% of the total runoff“
References


