Glaciers and Hydrology
On the glacier meltwater contribution to river runoff

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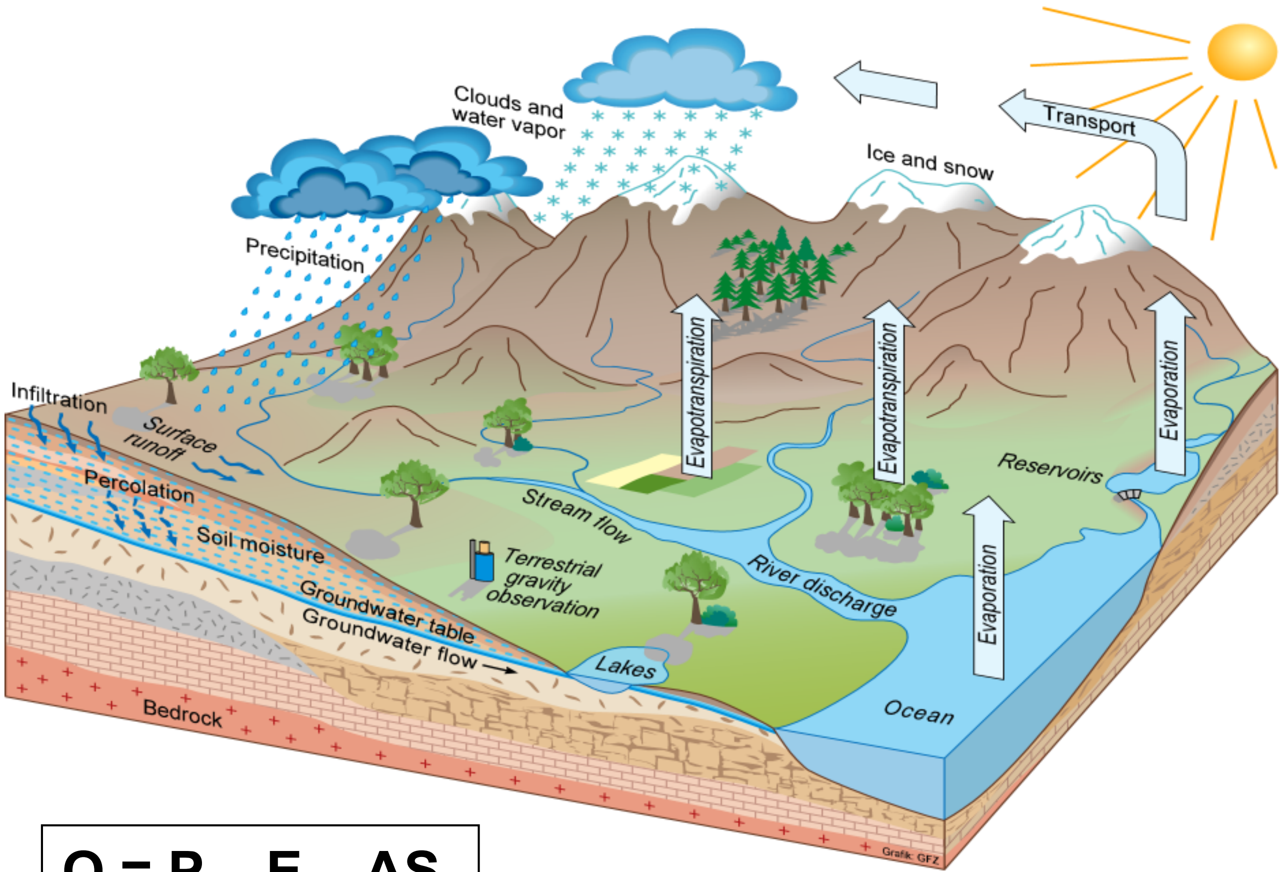
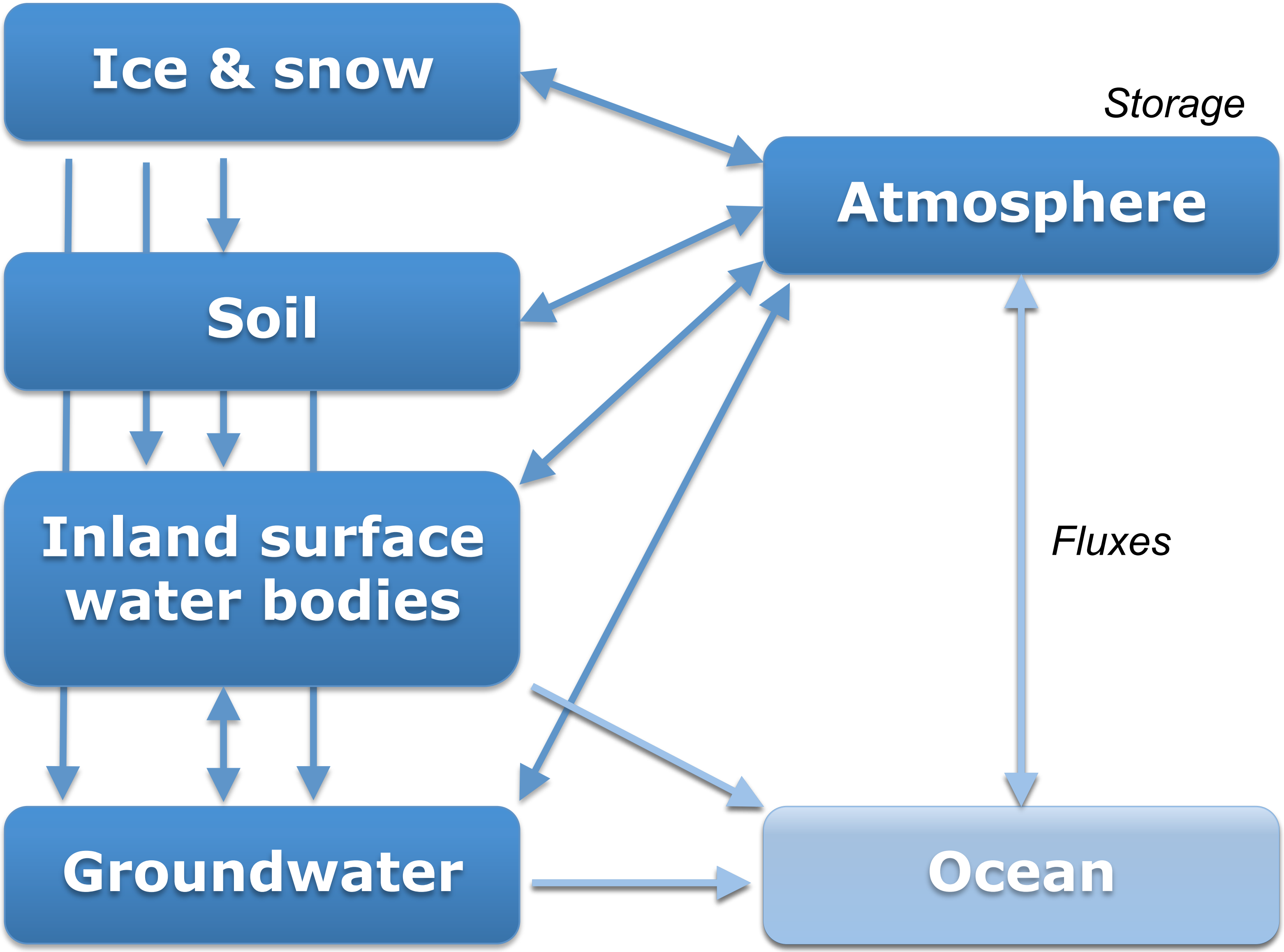
Hydrological cycle and the basic equation in Hydrology



$$Q = P - E - \Delta S$$

ΔS: Storage change (glacier, snow, soil moisture, groundwater)
P: Precipitation
E: Evapotranspiration
Q: Runoff

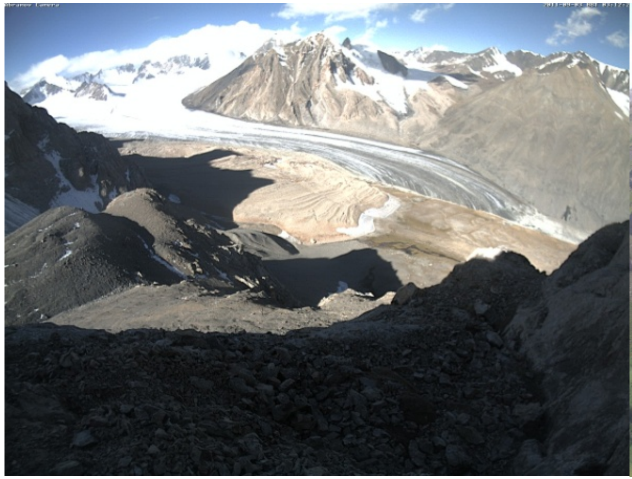
Storages and Fluxes



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

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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

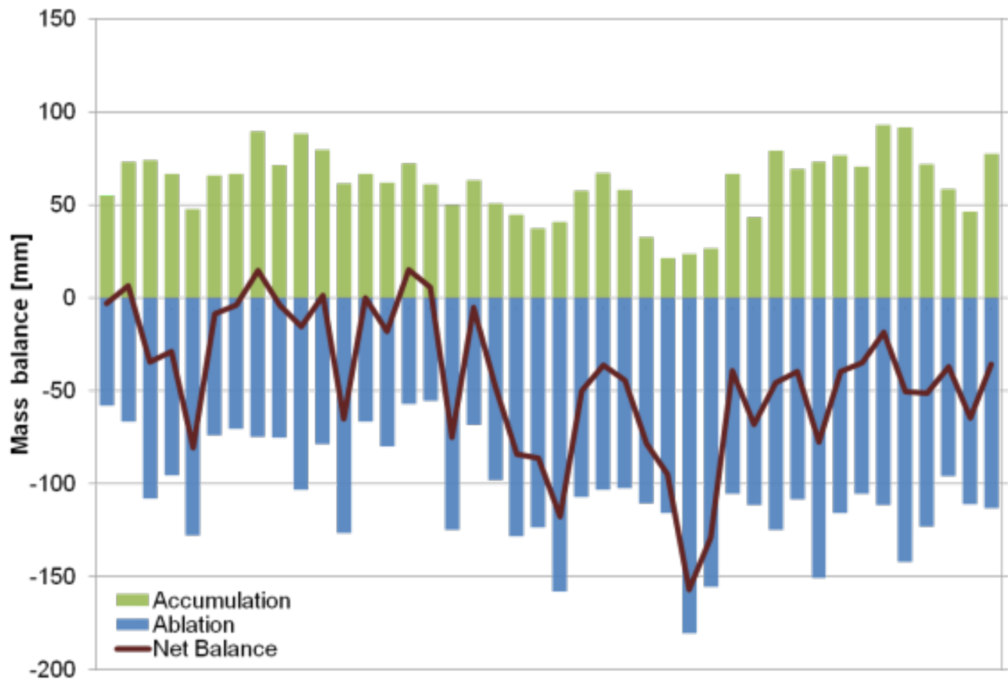
Annual average

Seasonal average
Monthly average
Daily average

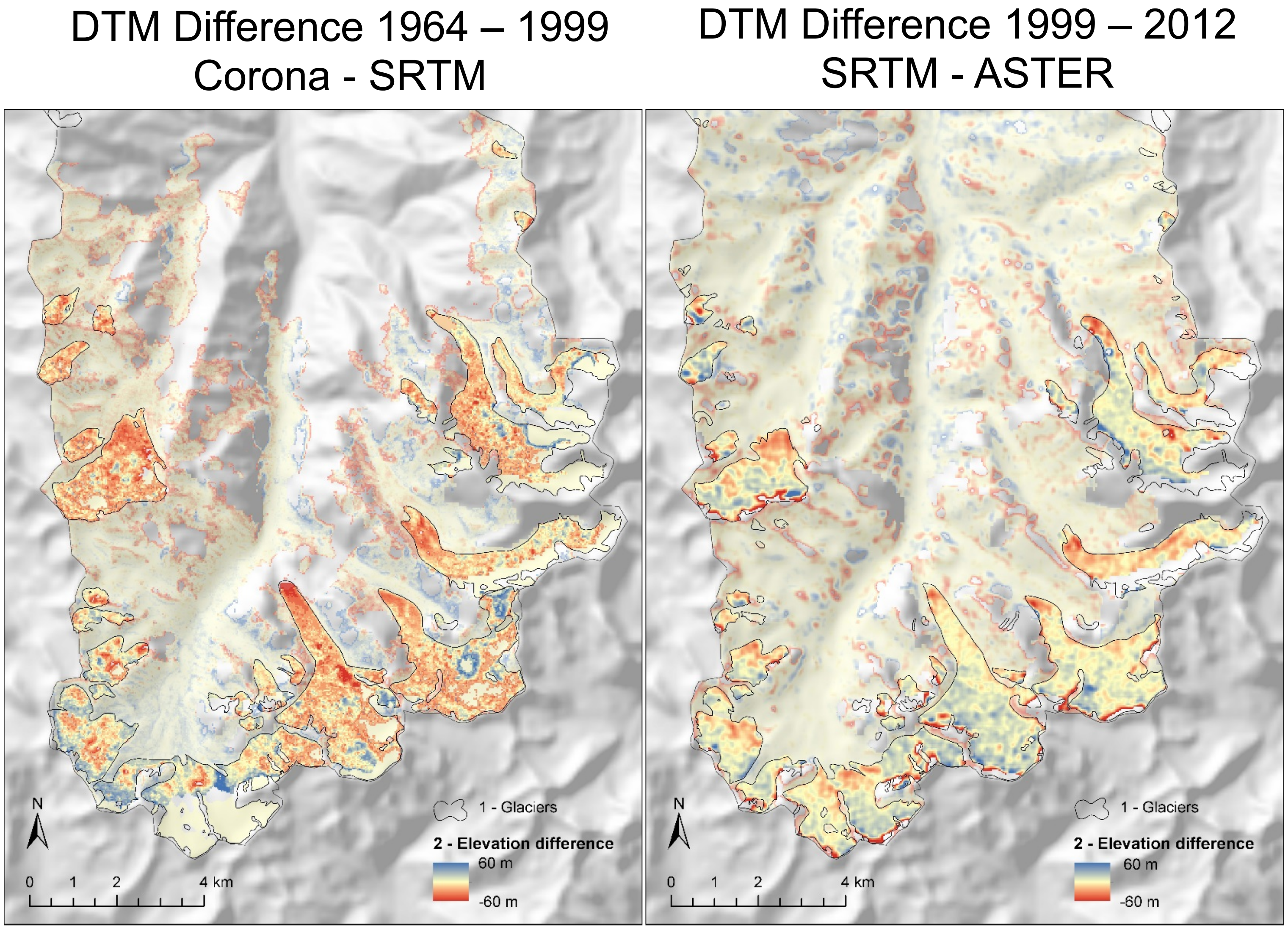
Back-of-the-envelope calculation of the total non-stationary runoff contribution

- Determine the total glacier mass loss in a time period
- Relate glacier meltwater share to the total runoff volume

Mass Balance Measurements

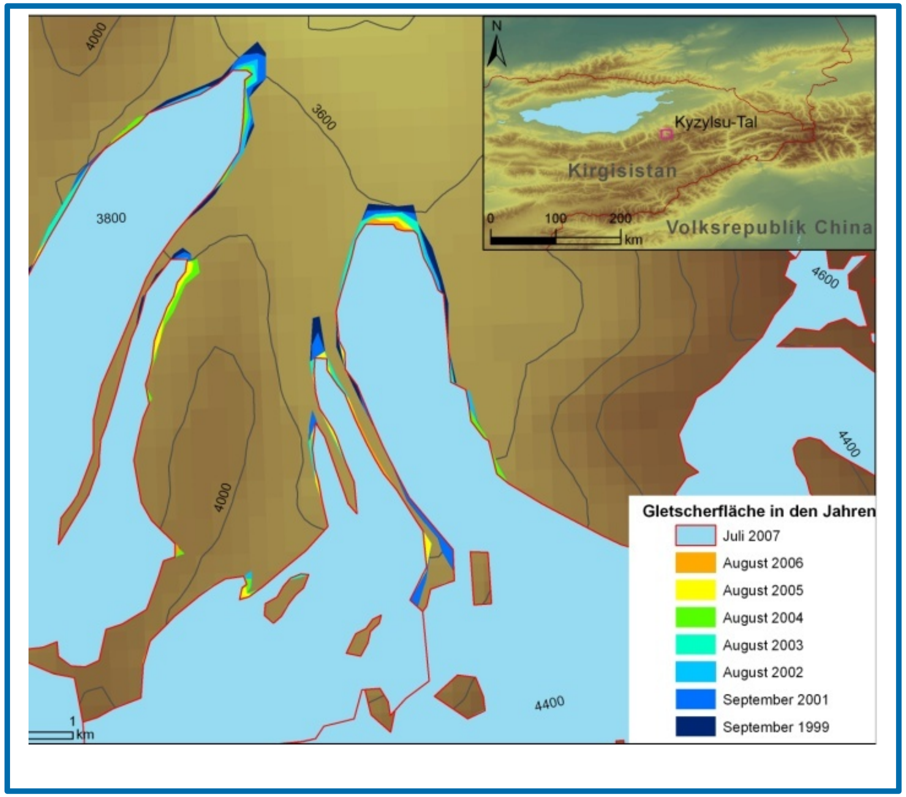


Ice volume estimation based on DEM differencing



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

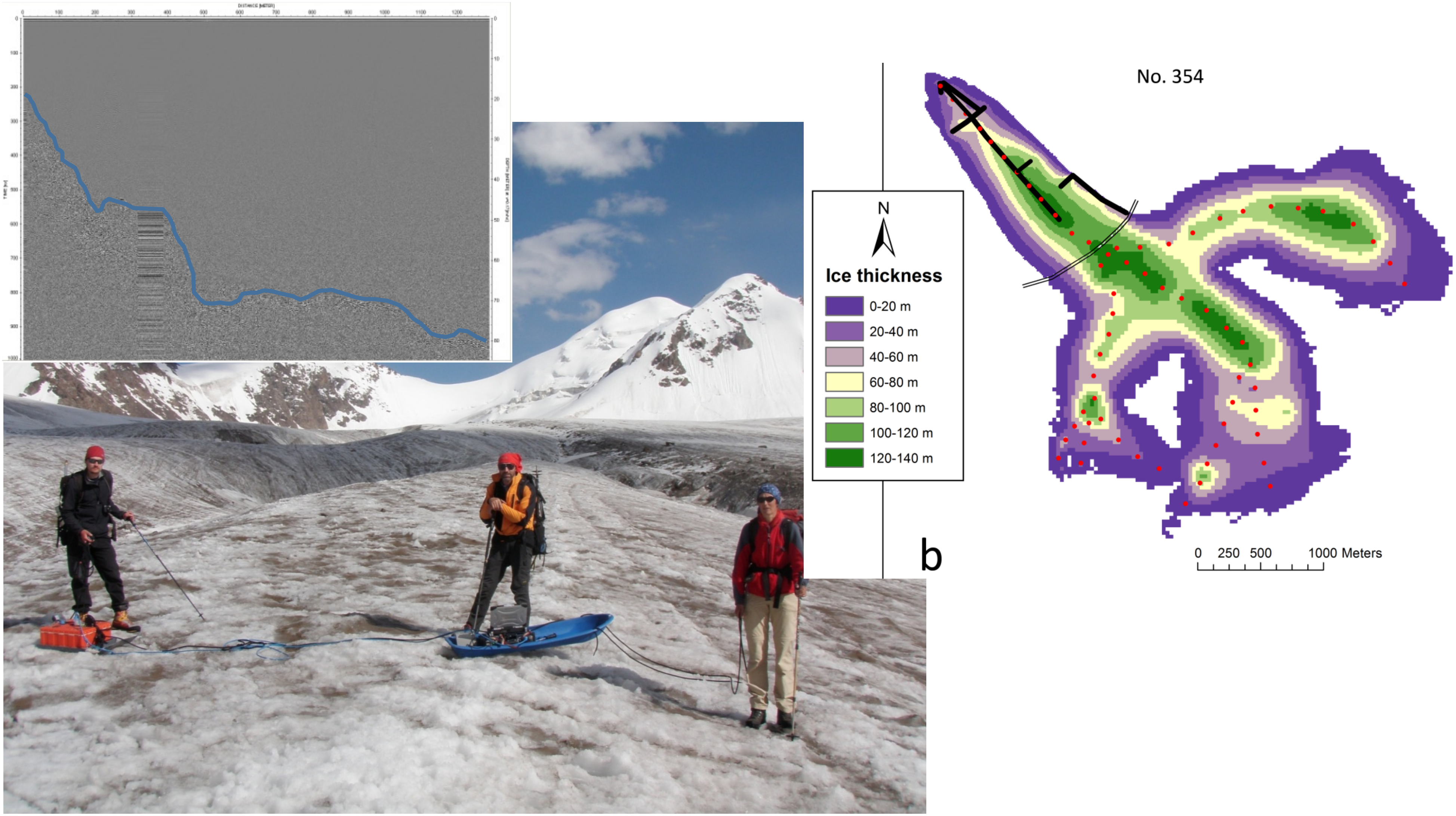
- Area-volume scaling

$$\boxed{V = k\,A^{\gamma}}$$

- Ice thickness estimation

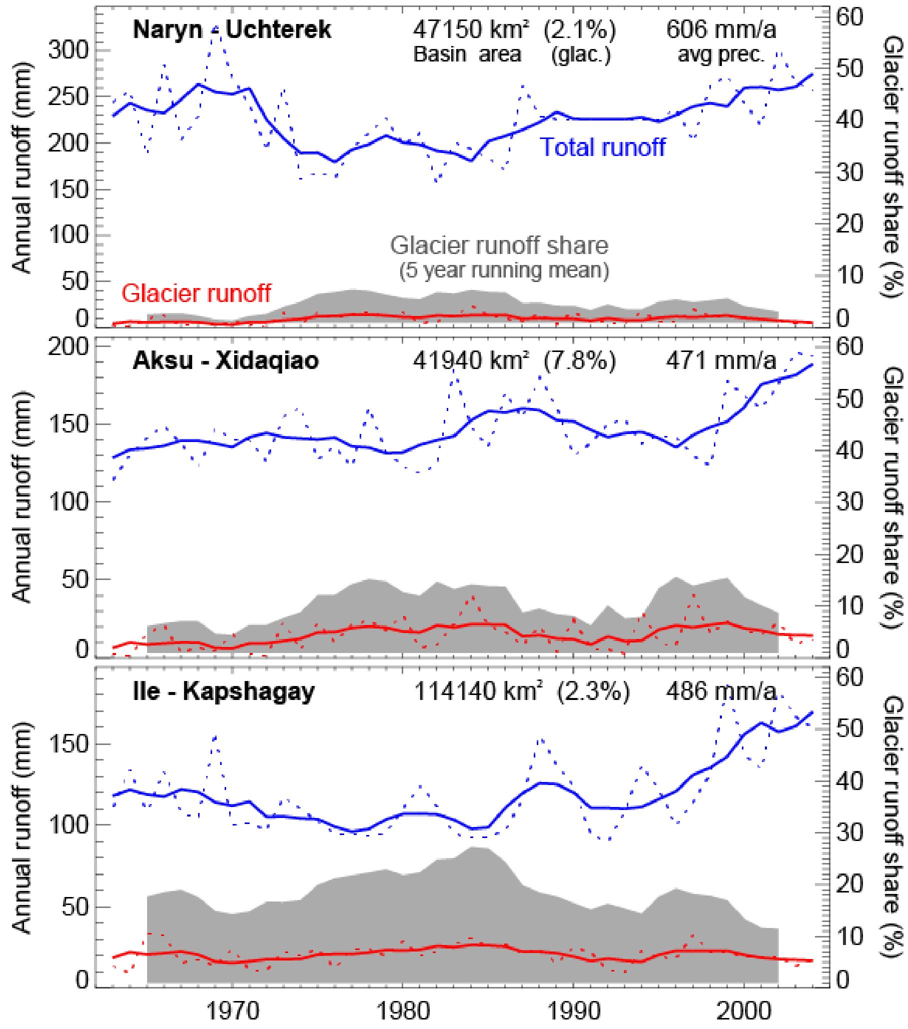
Ice thickness inversion from the vertical mass balance gradient, glacier surface topography and ice flow assumptions (Farinotti et al., 2009)

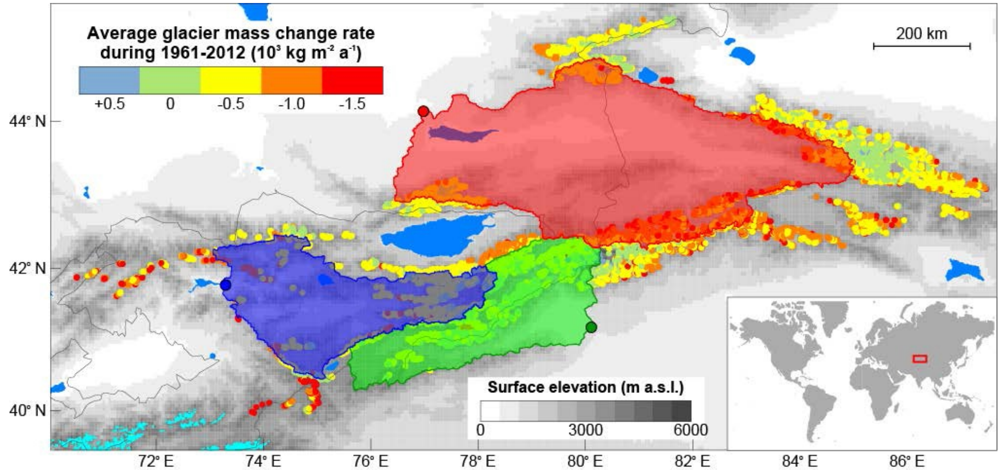
Ground Penetration Radar and Ice Volume Estimations



Source: Hagg et al. 2013, GPC

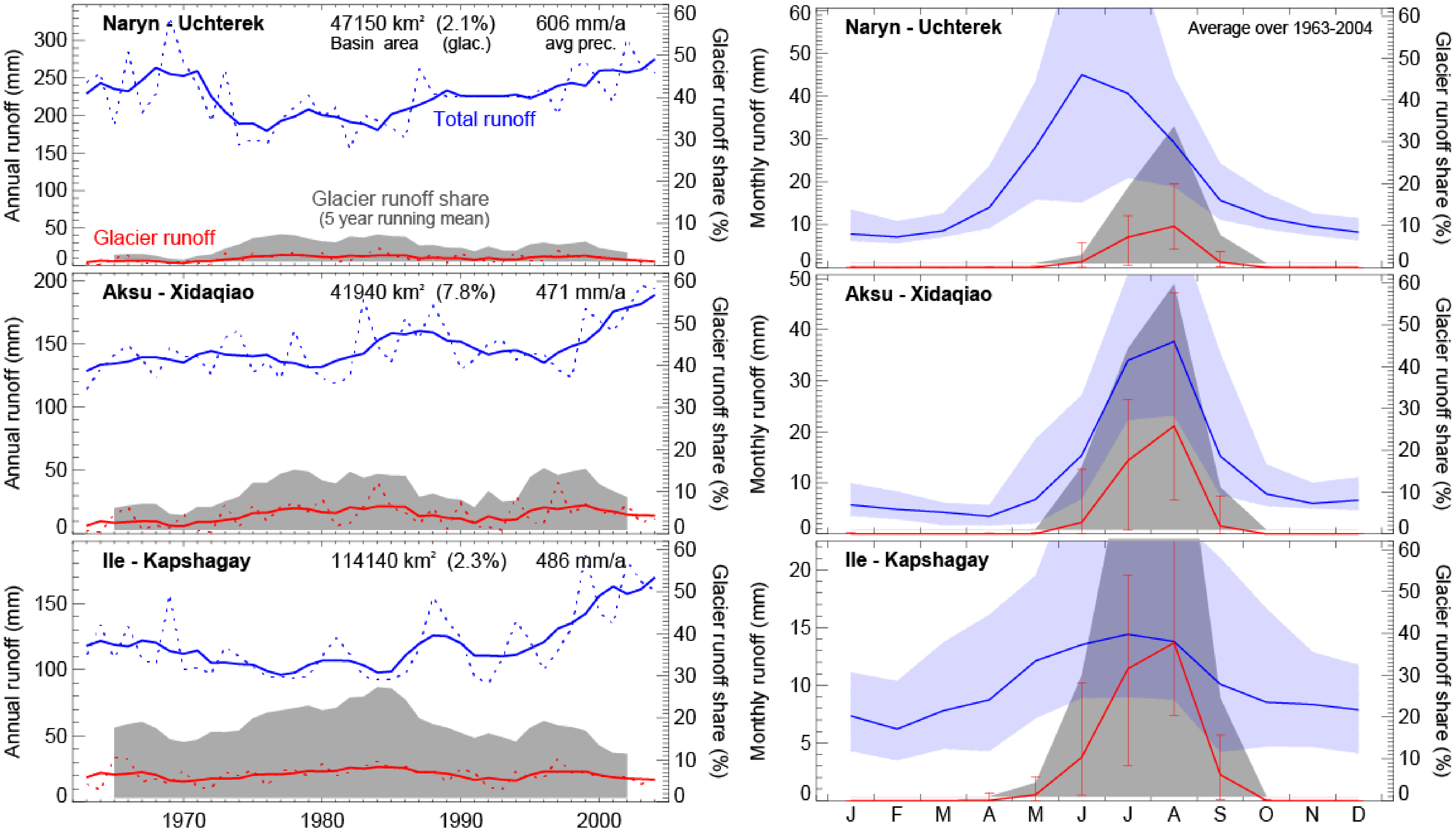
Glacier contribution to total runoff
from glacier storage change (ΔS > 0)





Source: Farinotti et al., 2015

Glacier contribution to total runoff from glacier storage change



Glacier contribution to total runoff
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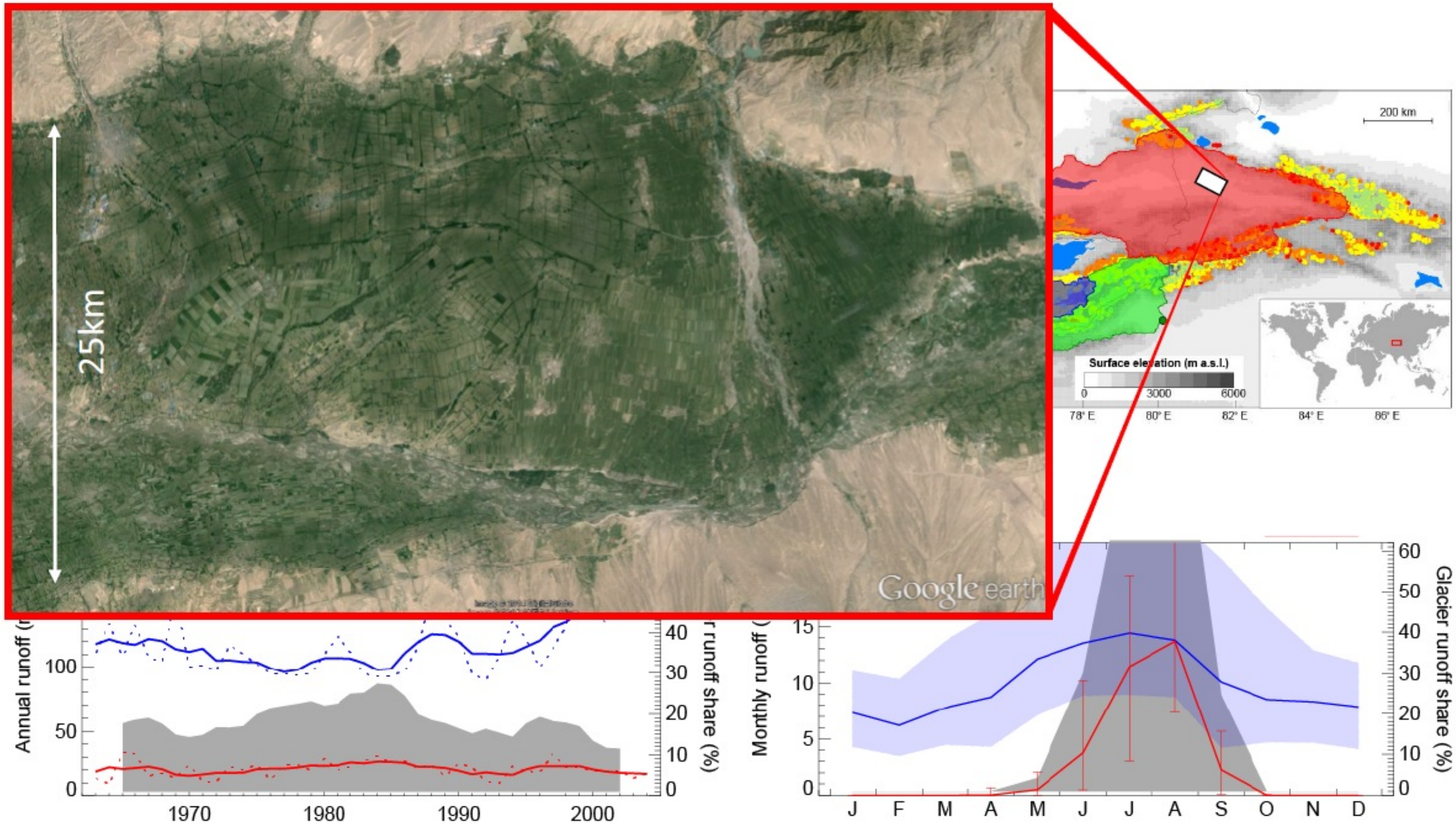


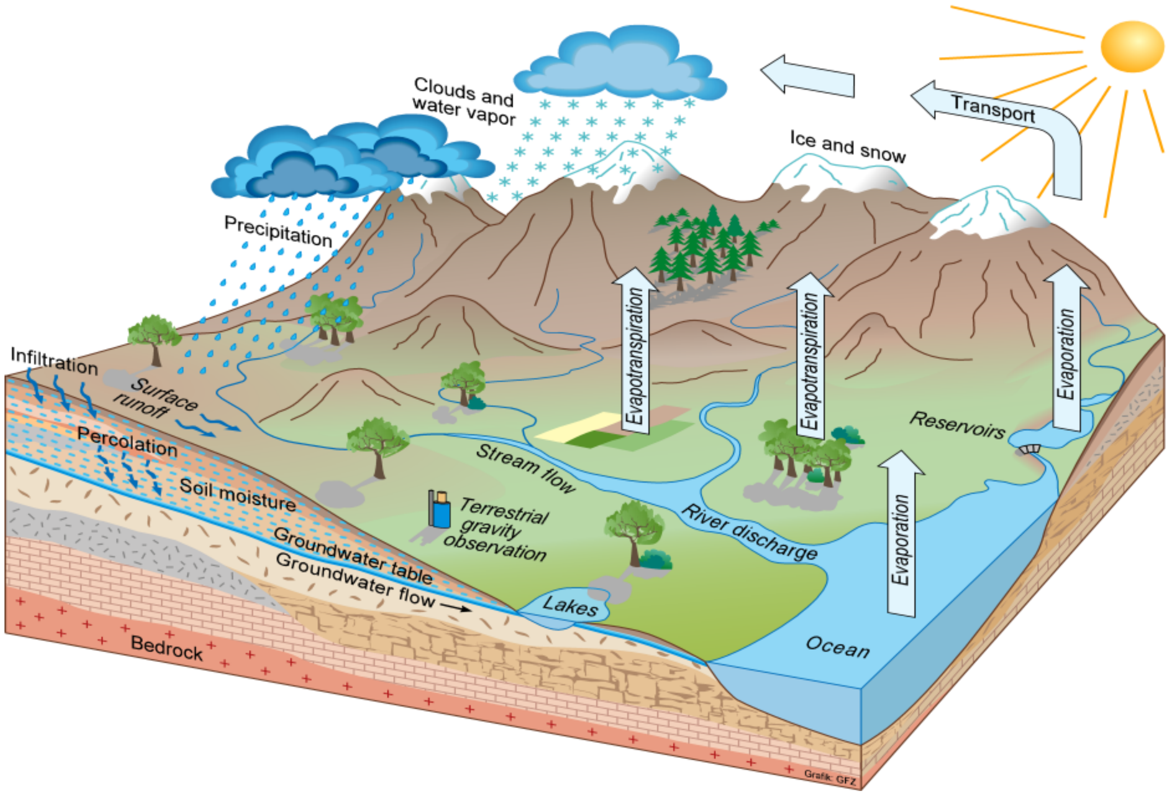
Source: Farinotti et al., 2015

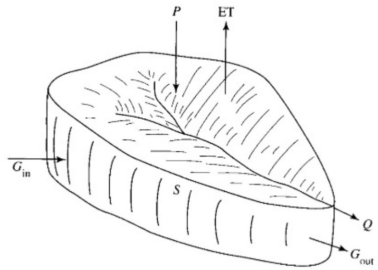
Back-of-the-envelope calculation

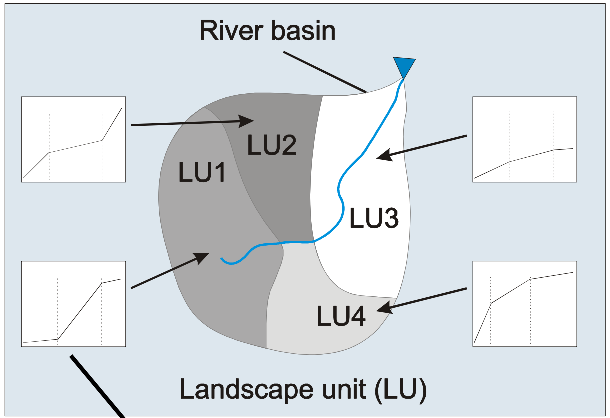
- Determine the total glacier mass loss in a time period
- Relate glacier melt share to the total runoff volume

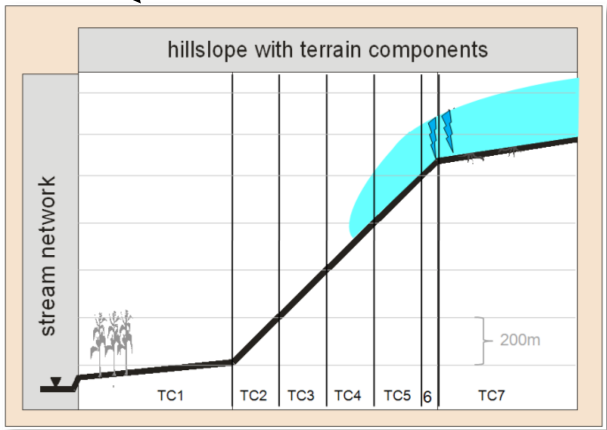
- Back-of-the-envelope calculations are afflicted by climatic (evaporation), geological (groundwater recharge), and human (water abstraction) factors
- This calculation represents the maximum potential glacial meltwater contribution

Hydrological Modelling Approach







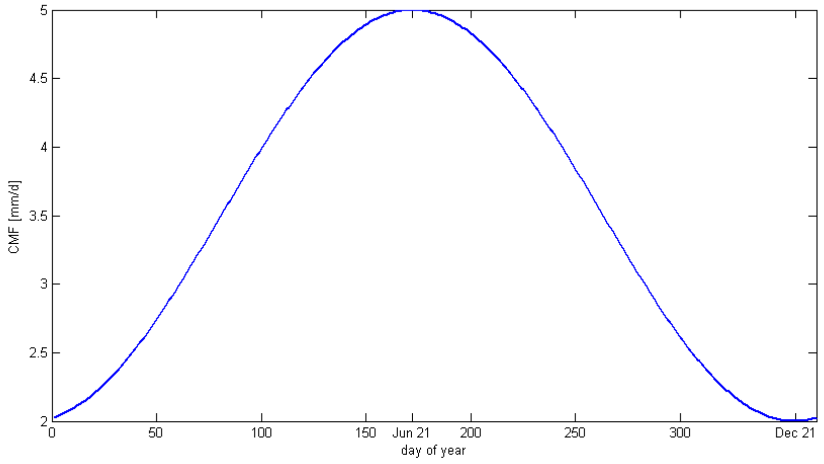


Modelling approaches – Glaciermelt

Conceptual approach

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

$$M = \begin{cases} MF * (T - T_m) & T > T_m \\ 0 & T \leq T_m \end{cases}$$



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

$$MF_i = \frac{CMAX - CMIN}{2} * \cos\left(\frac{2\pi}{day_{max}} * i\right) + CMIN + \frac{CMAX - CMIN}{2}$$

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

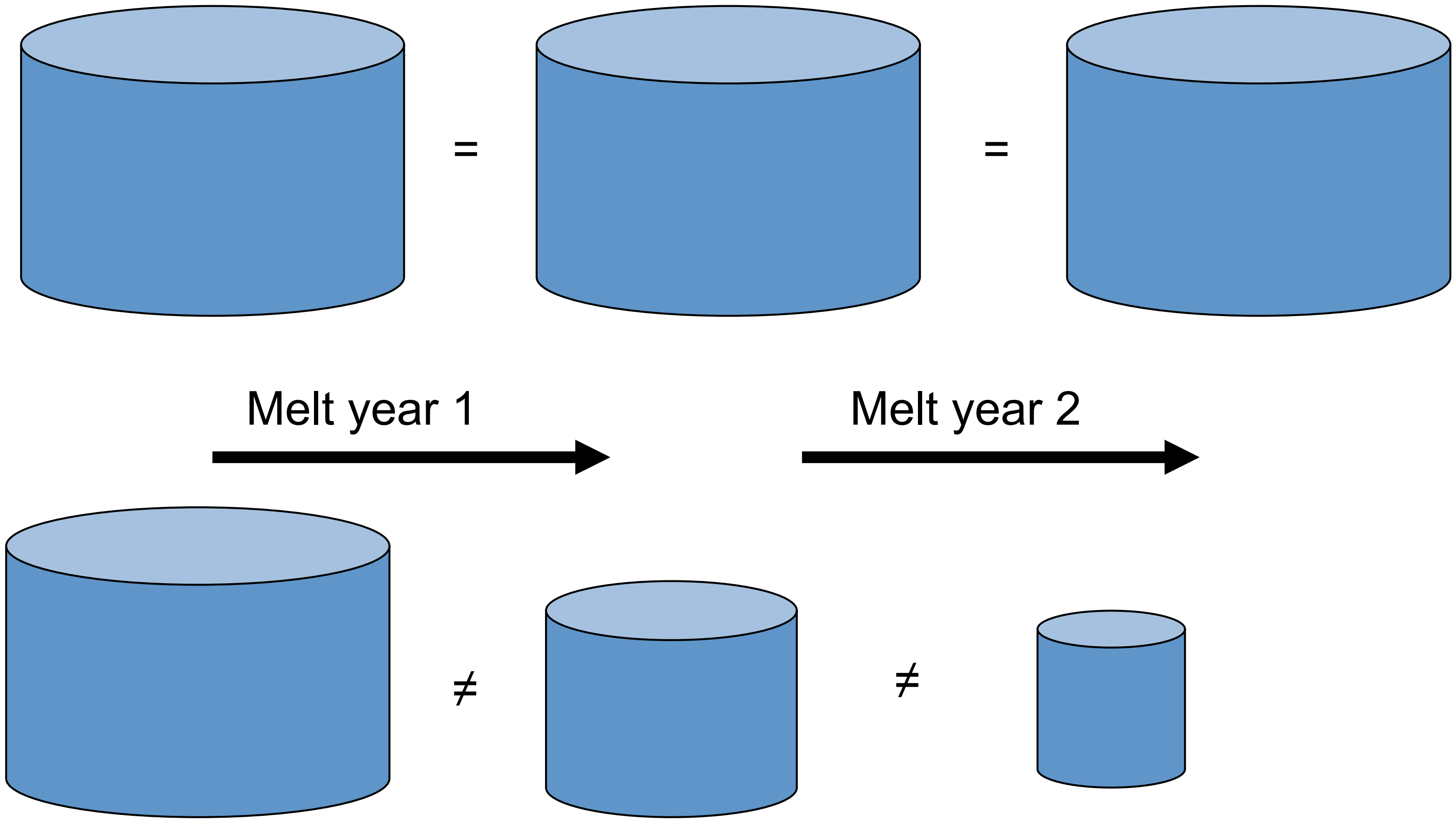
(GERM, WASA..)

Physical
- 3-D glacier flow dynamics

+ actual glacier dynamics described
+ useful for forward run
+ often good approx.
- complicated
- much calculation effort

Downwasting

$h_{glacier}$ = constant/infinite, A = constant or variable

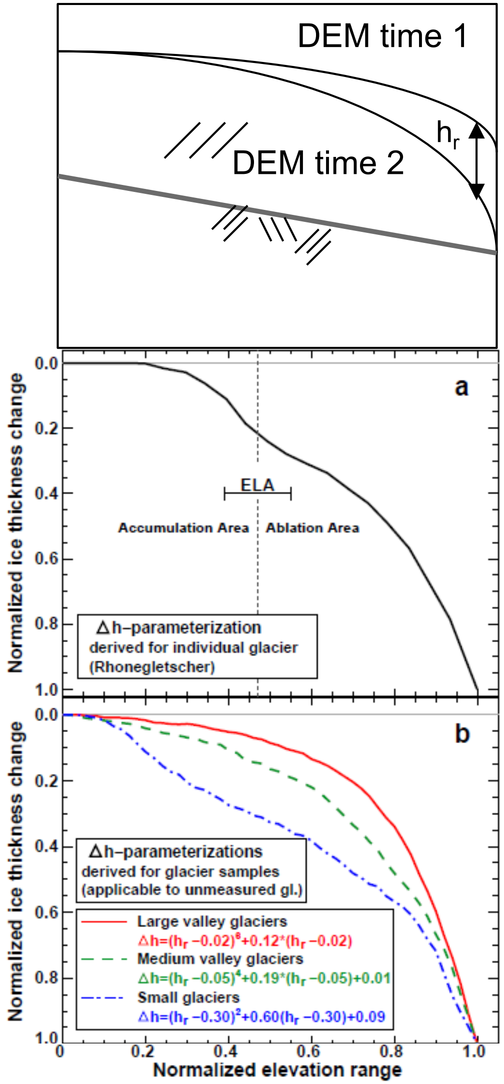


Conceptual

$A_{glacier} = f(h_0, MB, \Delta h)$,

$h_{glacier}$ = variable in time and space

Modelling approaches – glacier evolution



1. Scheme of glacier surface in 2 sequential DEMs

$$norm\_elev = (h_{max} - h)/(h_{max} - h_{min})$$

$$norm\_\Delta h = \Delta h / \Delta h_{max}$$

2. Δh-curve from measurements for a sample glacier

$$\Delta h = (h_r + a)^{\gamma} + b \cdot (h_r + a) + c$$

- hr...r
- a, b, c, γ...parameters
- by optimizing system of equations a, b, c and γ can be retrieved

3. Generalized Δh-curves for glaciers of different size classes

Source: Huss et al. 2010, HESS

Modelling approaches – glacier evolution

- After annual MB calculation

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

$$h_1 = h_0 + f_s \cdot \Delta h_i$$

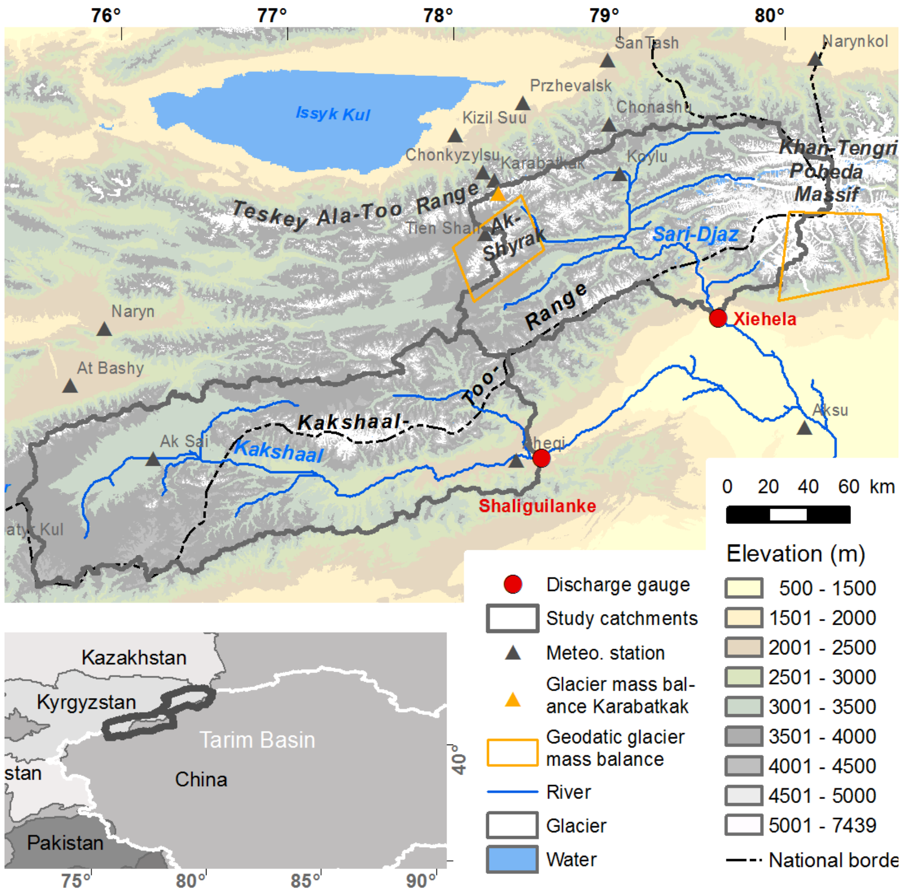
B_a... annual MB in kg
f_s...correction factor, to be calculated annually
ρ_{ice}... ice density
A_i...area of glaciated terrain component
Δh_i...dh for elevation band

h_0...initial glacier thickness
h_1...updated glacier thickness

- If h1 = 0 m → area loss for elevation zone

→ Only for mass/ area loss!

Hydrological modelling of glacier melt contribution



Sari-Djaz basin

Total area: 12,950 km2
Glacierization: 21%

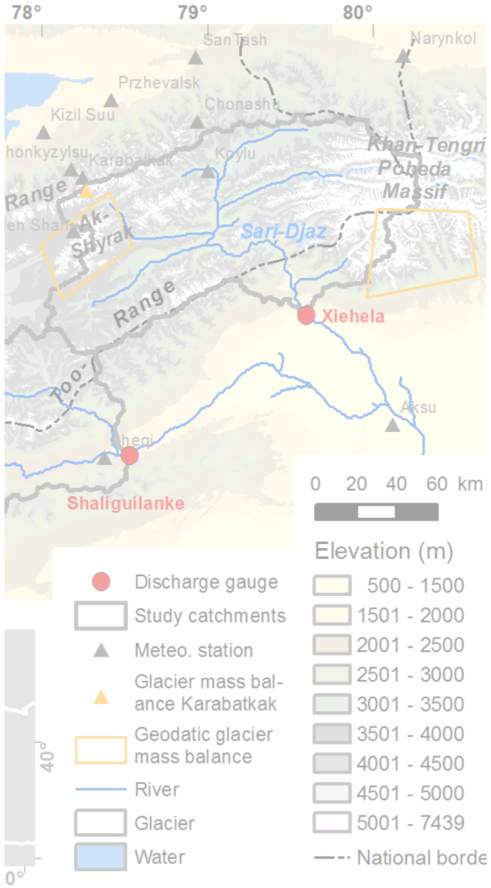
Kakshaal basin

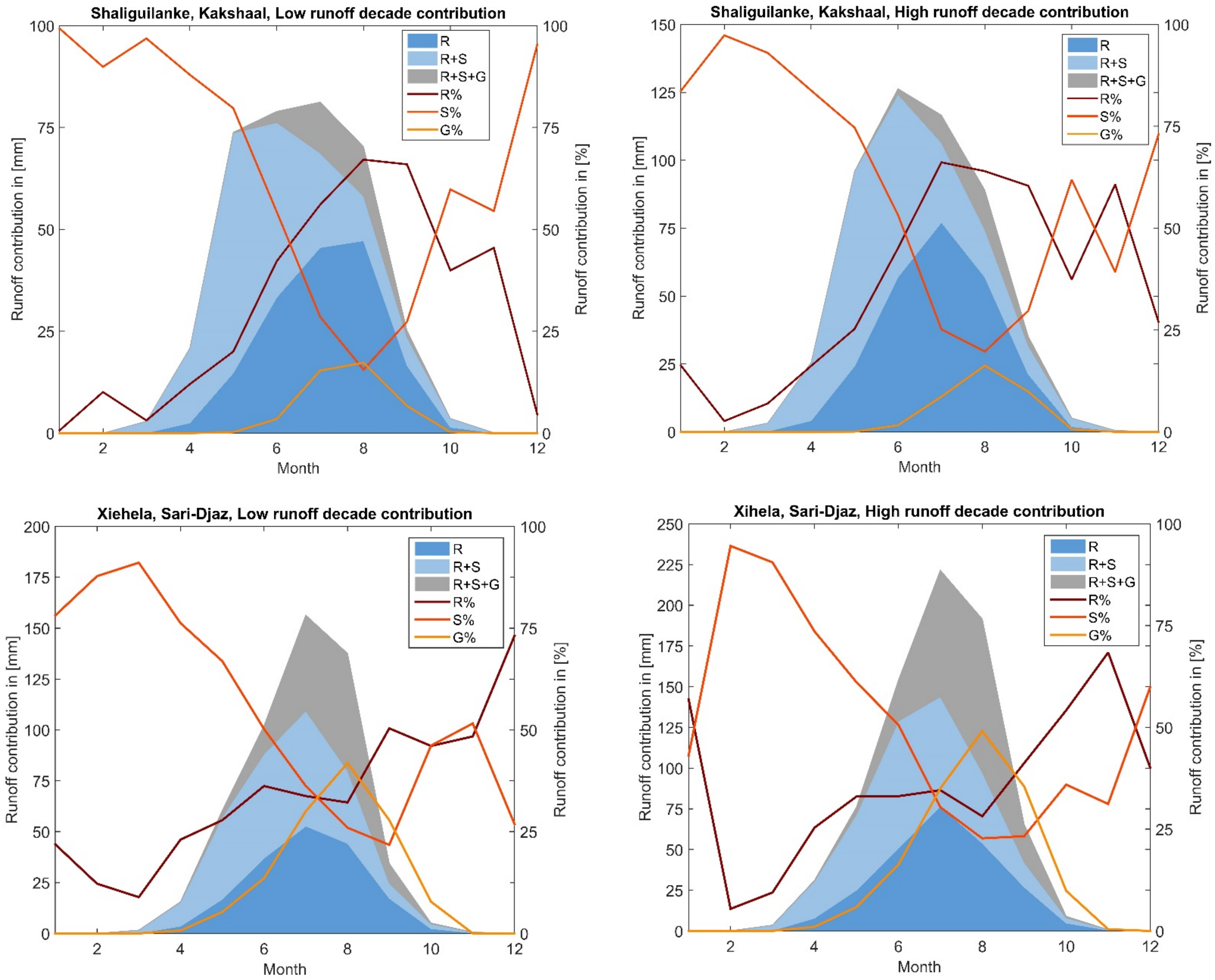
Total area: 18,410 km2
Glacierization: 4.4%

Rainfall gauge records (1960-1990):

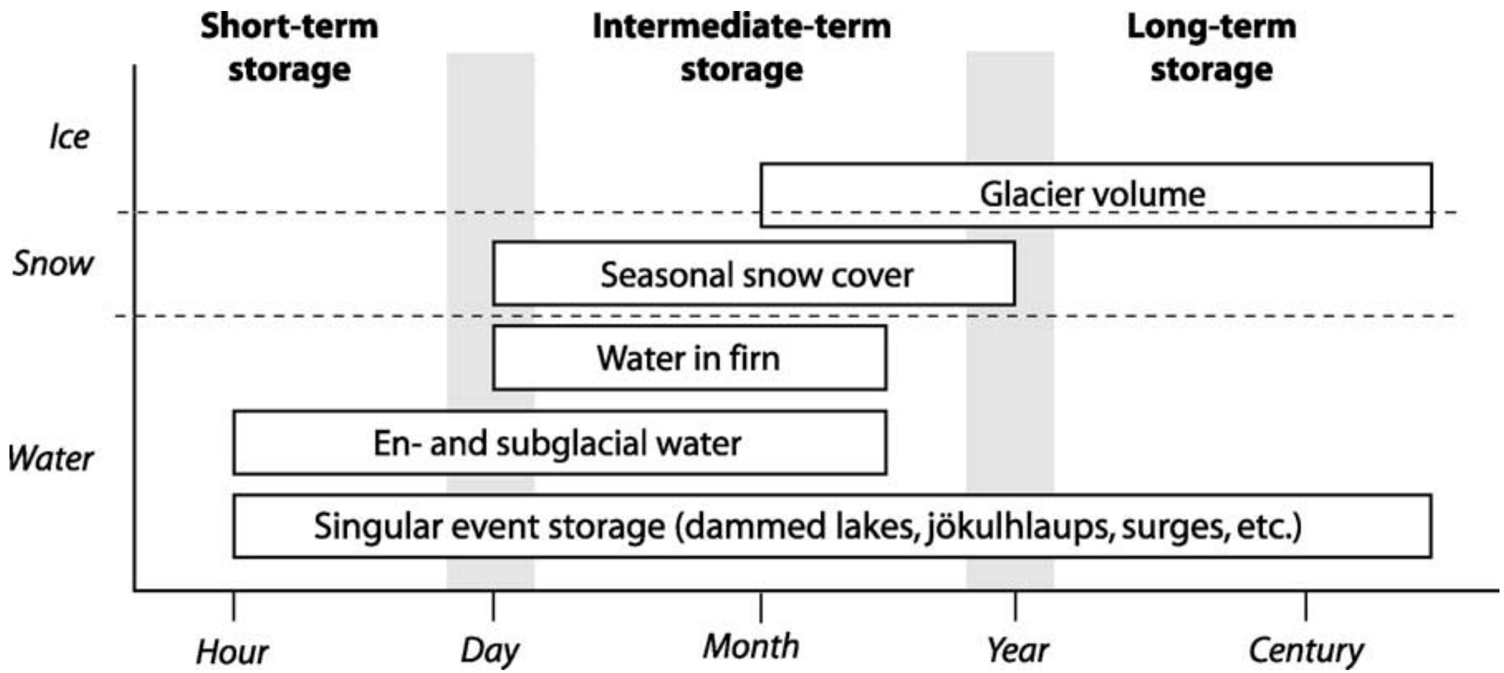
190 – 320 mm/a

Hydrological modelling of glacier melt contribution





Modulation of river runoff at different time scales

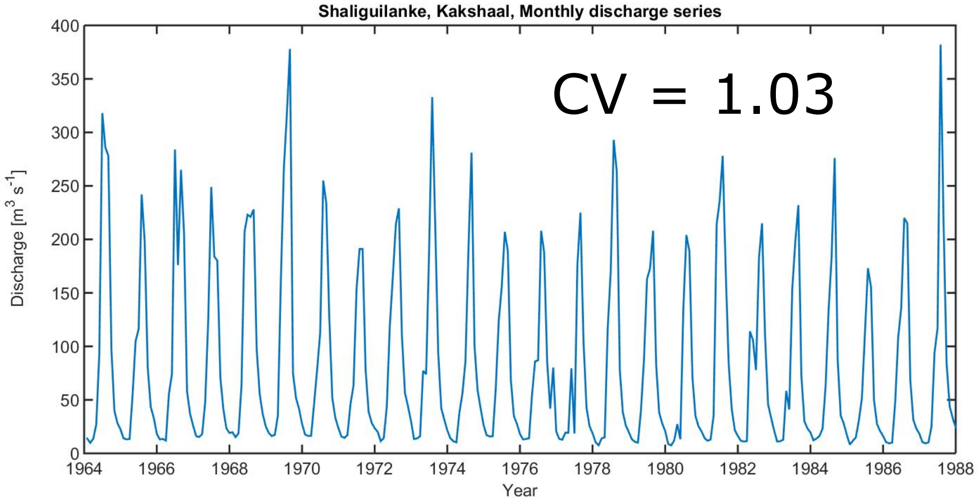


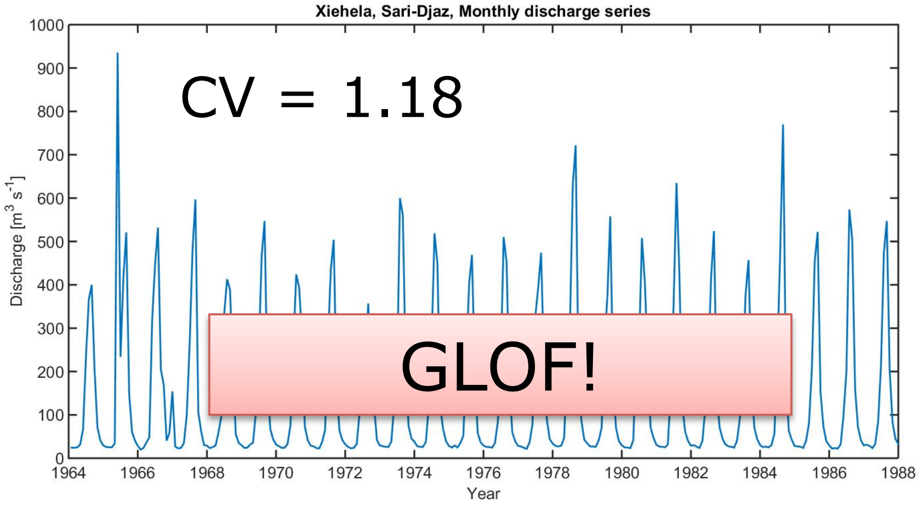
Source: Jansson et al., 2003

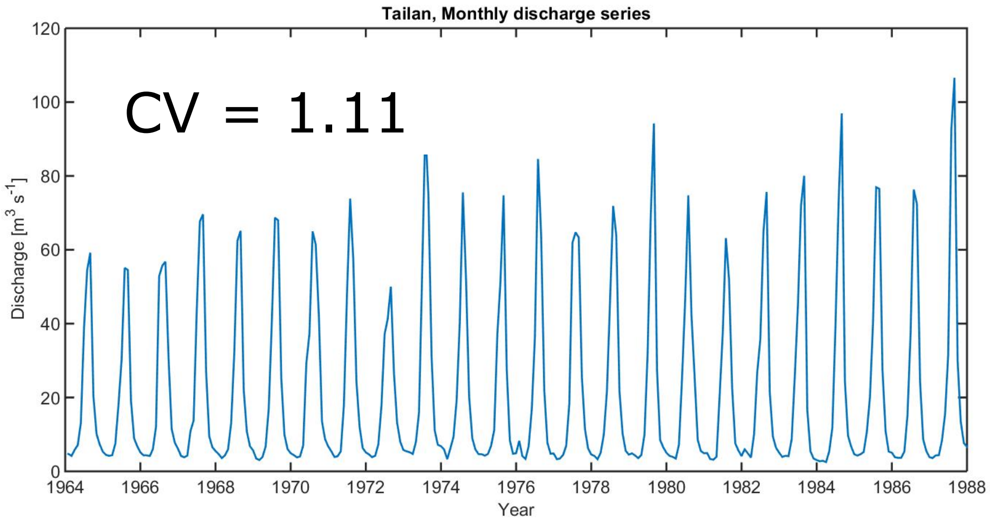
Runoff modulation at seasonal and interannual time scales is of particular importance for water supply

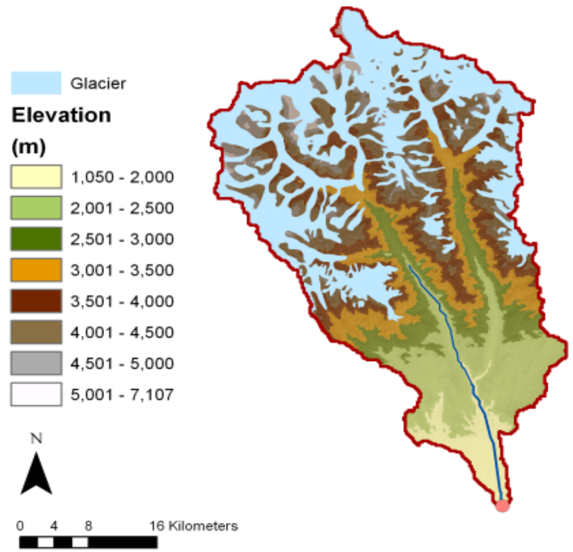
Runoff modulation is a function of catchment glacierization and climatic regime

Runoff Variability – monthly time scale



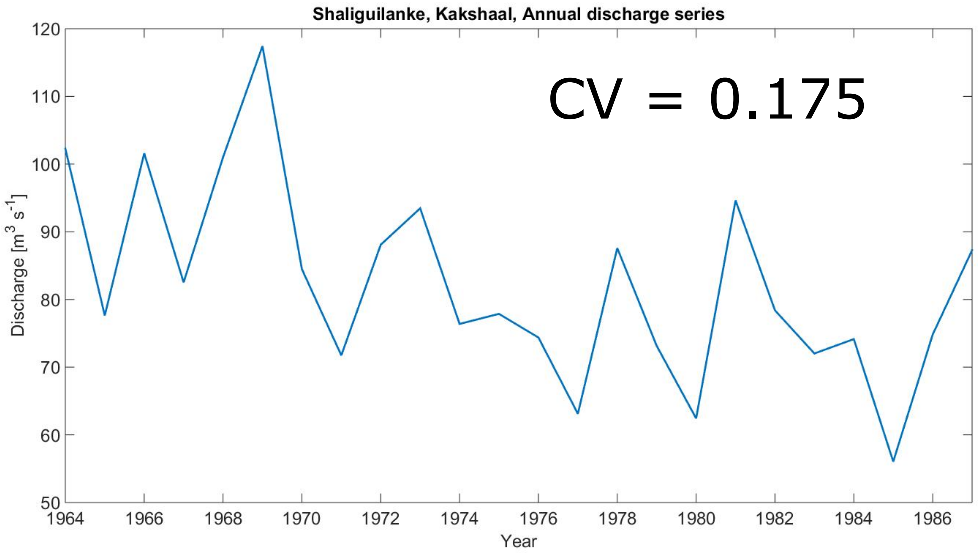


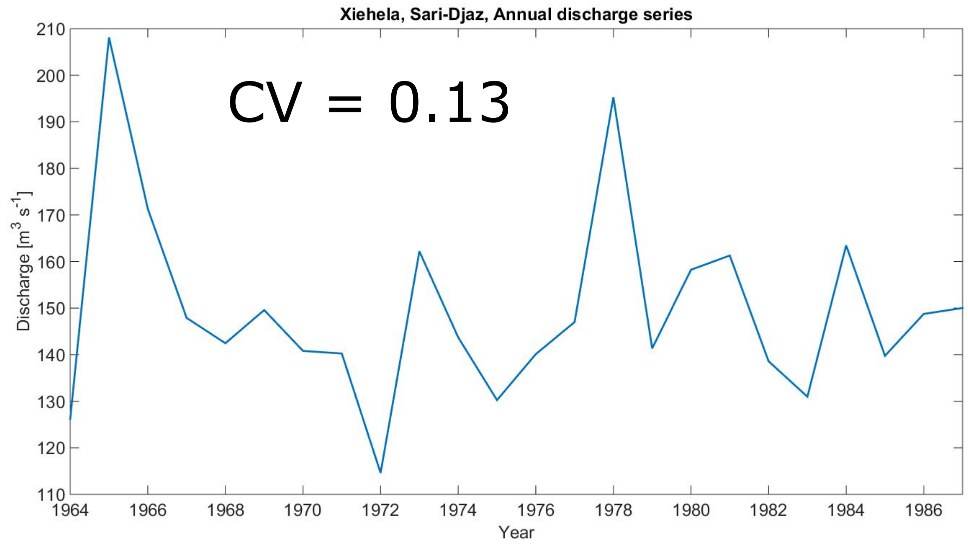


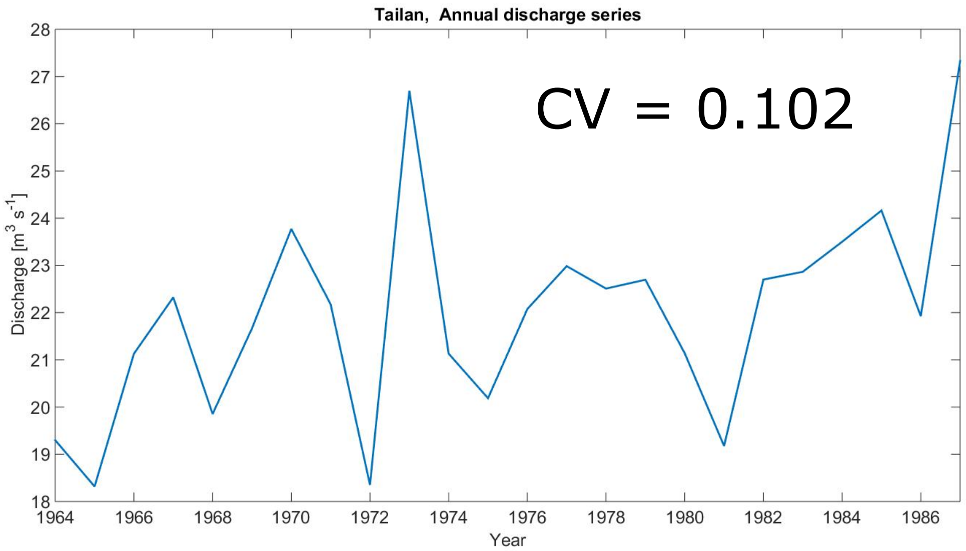


Glacierization: 36%

Runoff variability – interannual time scale







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

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