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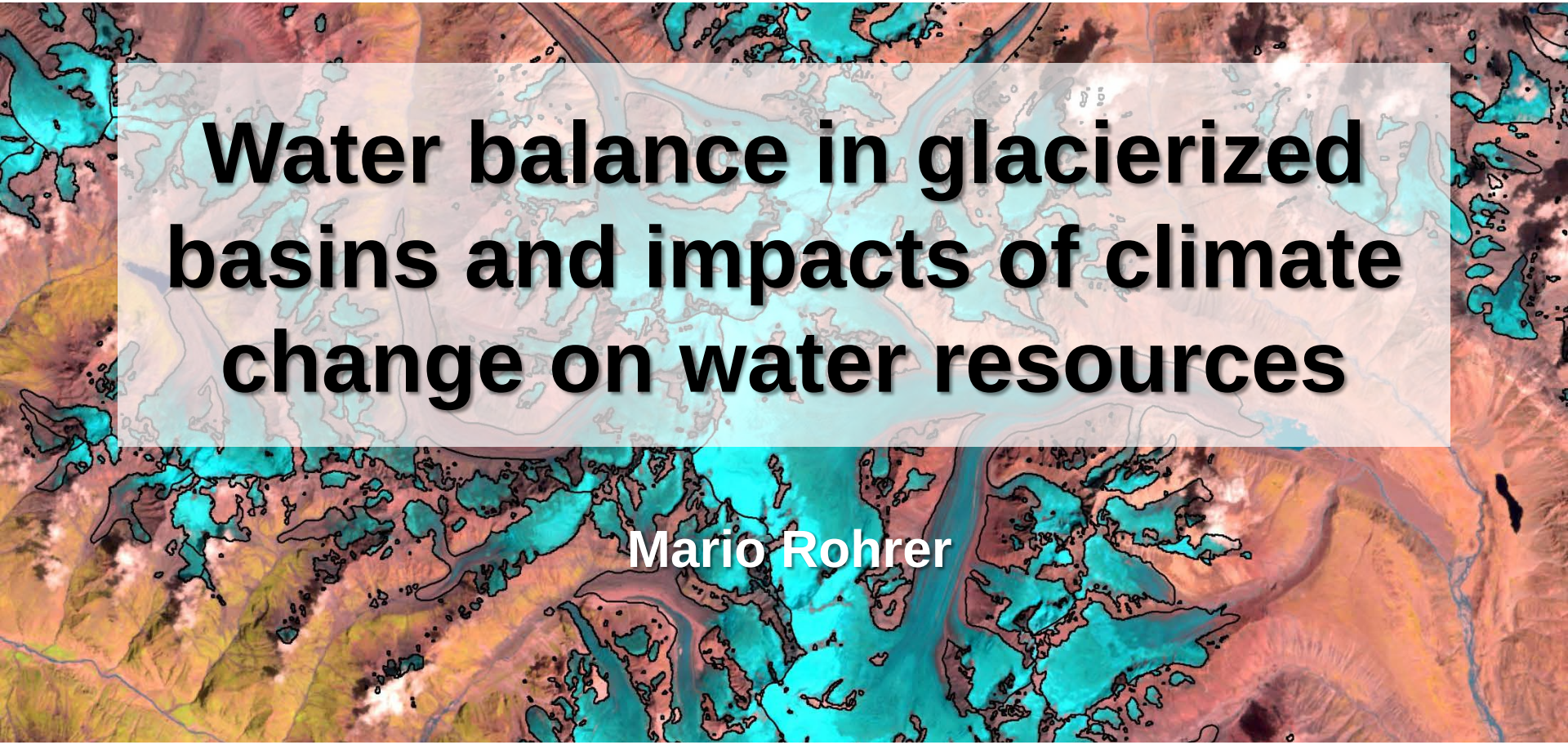


Water balance in glacierized basins and impacts of climate change on water resources

Mario Rohrer

IHCAP – Indian Himalayas Climate Change Adaptation Programme
Capacity building programme “Cryosphere” Level-2 (January, 2015)

Contents

Introduction

Glacier portal with glacier discharge of Triftgletscher, Switzerland

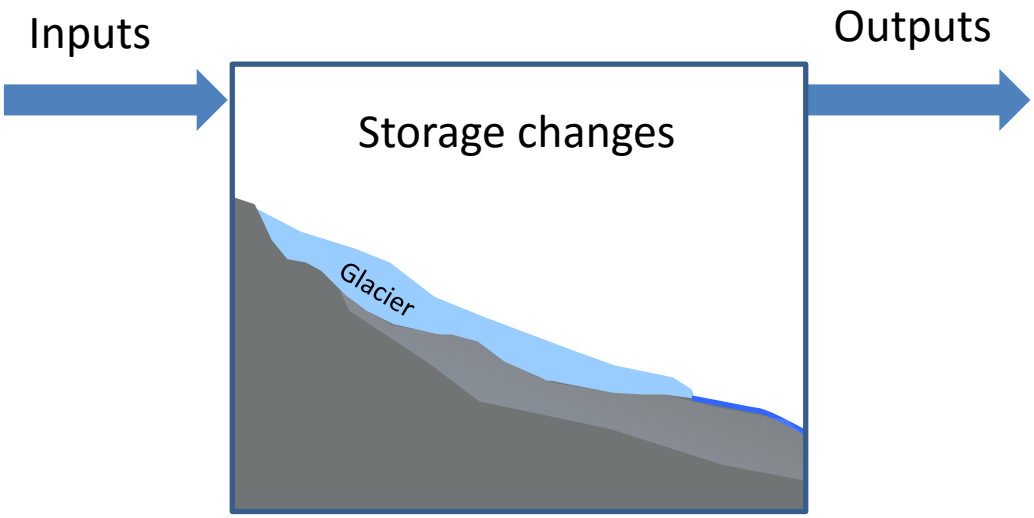
(Alean & Hambrey, 2012)

Introduction

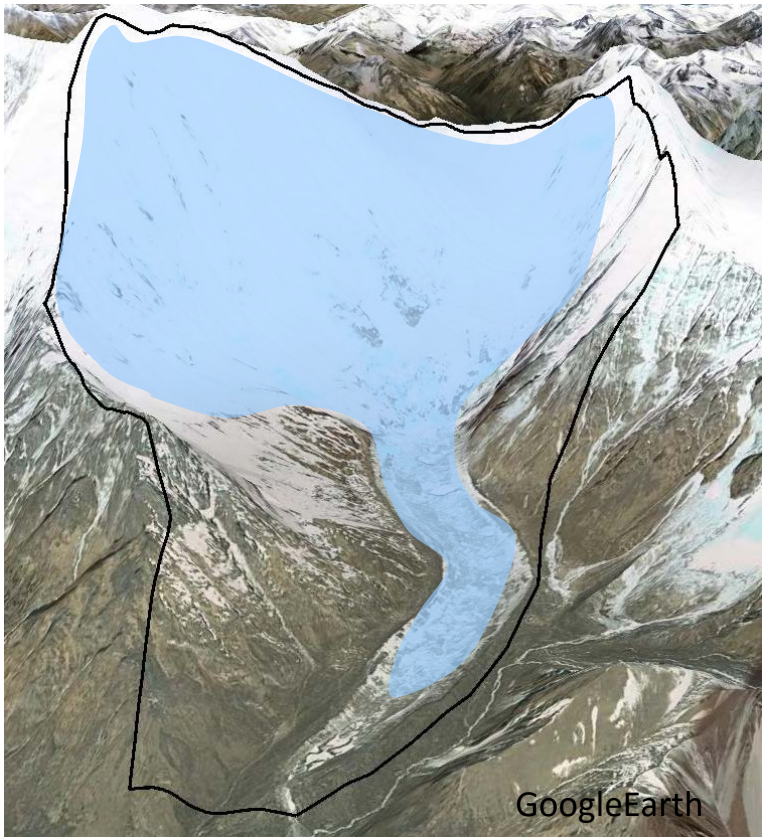
http://www.wsl.ch/fe/gebirgshydrologie/schnee_hydro/gebirgshydrologie

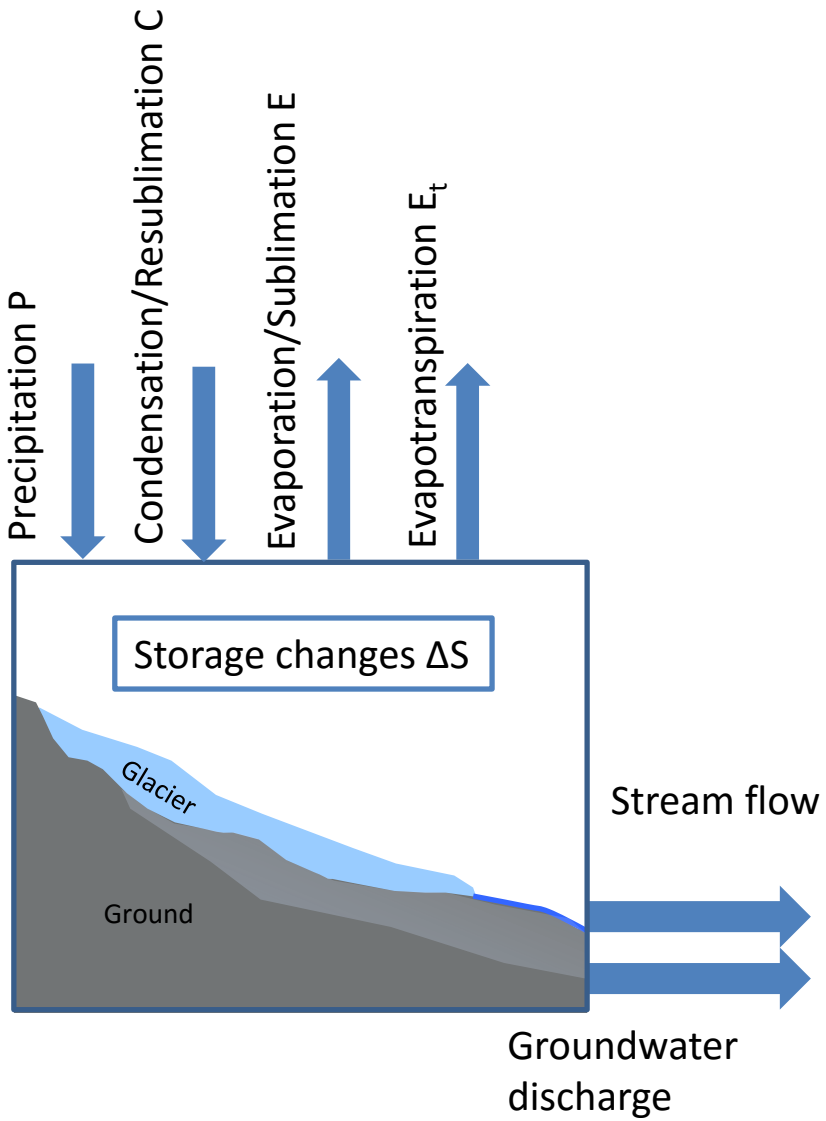
Water balance of a glacierized catchment

- How is the water balance of a glacierized region defined?

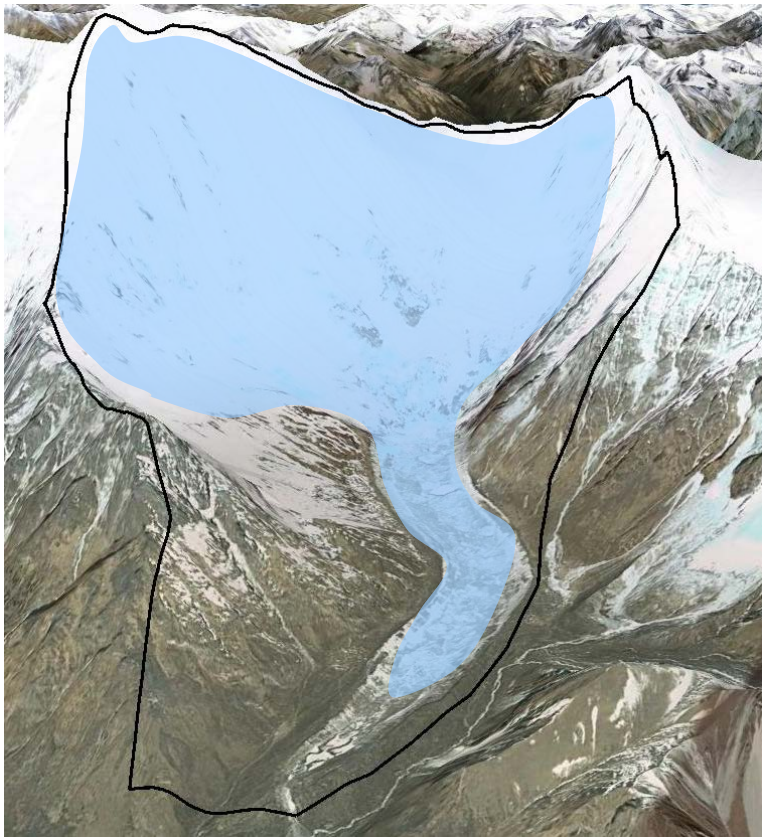


Water balance of a glacierized catchment





Water balance of a glacierized catchment



Lirung glacier, Nepal, GoogleEarth

$$\Delta S = (INPUTS) - (OUTPUTS)$$

$$\Delta S = (P + C) - (E + E_t + Q_{stream} + Q_{ground})$$

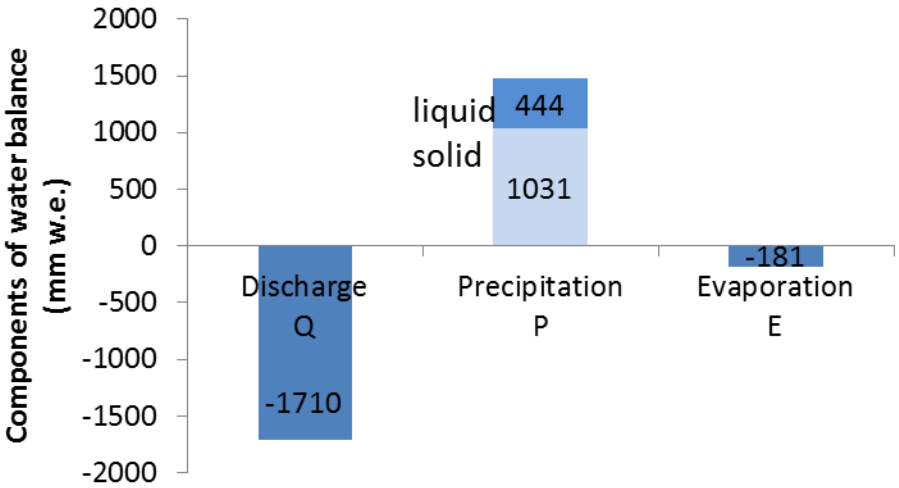
ΔS	Storage changes
P	Precipitation
C	Condensation, resublimation
E	Evaporation, sublimation
Et	Evapotranspiration
Q_{stream}	Stream flow
Q_{ground}	Groundwater discharge

$\Delta S > 0$, if (INPUTS) > (OUTPUTS)
$\Delta S < 0$, if (INPUTS) < (OUTPUTS)

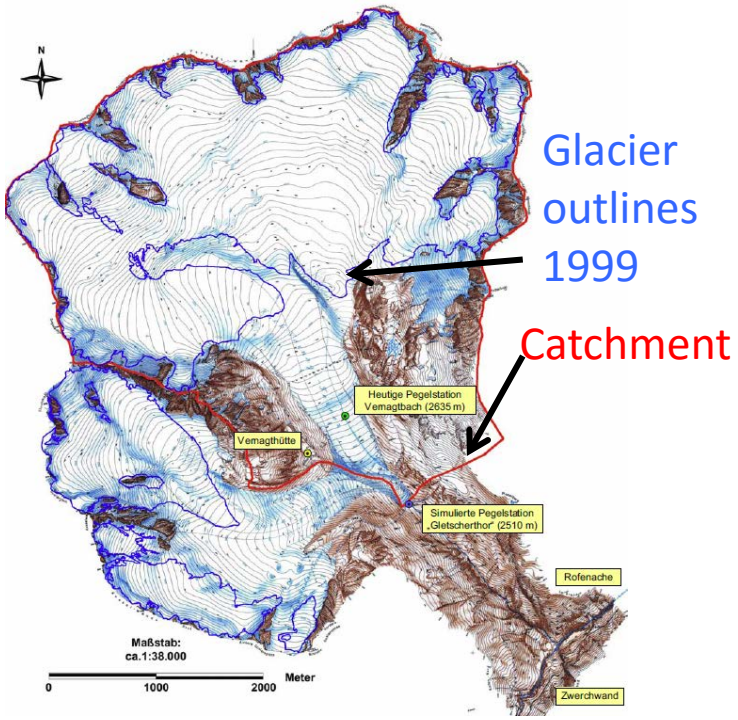
Water balance of a glacierized catchment

ΔS= (INPUTS) - (OUTPUTS)

here: ΔS = (P) - (Q+E) =
= 444+1031-1710-181 = -416 mm w.e.
=> 24% of total discharge is from storage change



Components of the waterbalance:
Mean specific annual amounts in mm w.e.
(period: 1980/81-85/86, Schulz 1999)



Vernagtferner, Austria, 1889

What happens to Q if ΔS is zero?

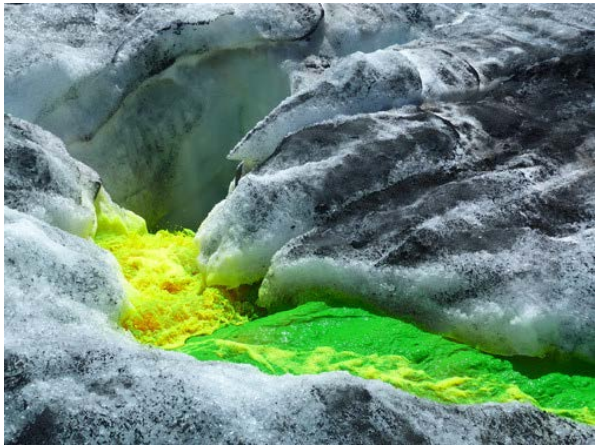
Water balance of a glacier

- Where is meltwater principally produced and how is meltwater drained through the glacier?

Supraglacial channels

http://beringia.com/climate/content/runningwater.shtml

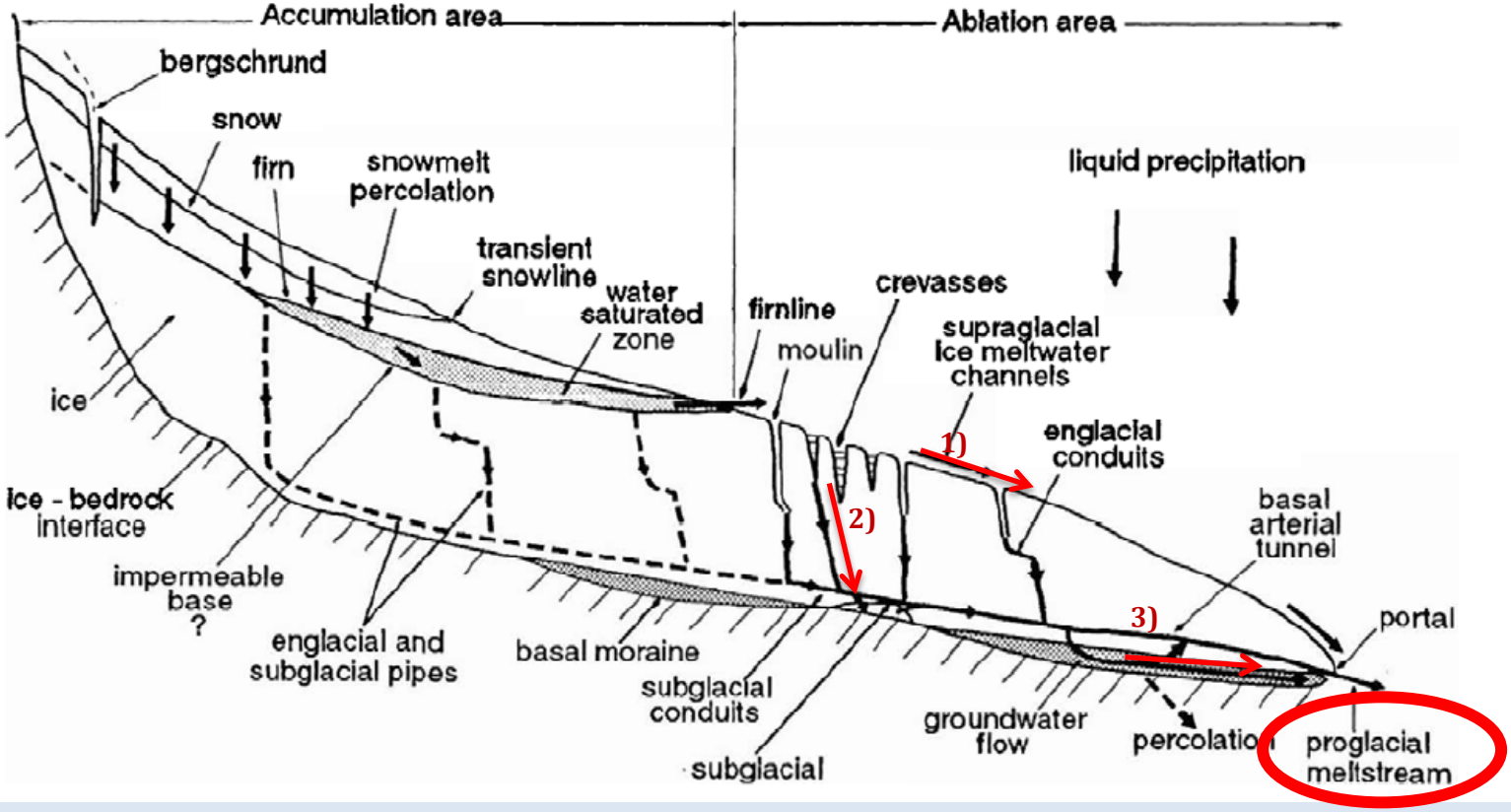
Moulin



http://fingerd.jimdo.com/projects/tracer-experiments-to-assess-melt-water-flow-paths/

Water balance of a glacier

Hydrological systems and locations of water storage in a temperate glacier



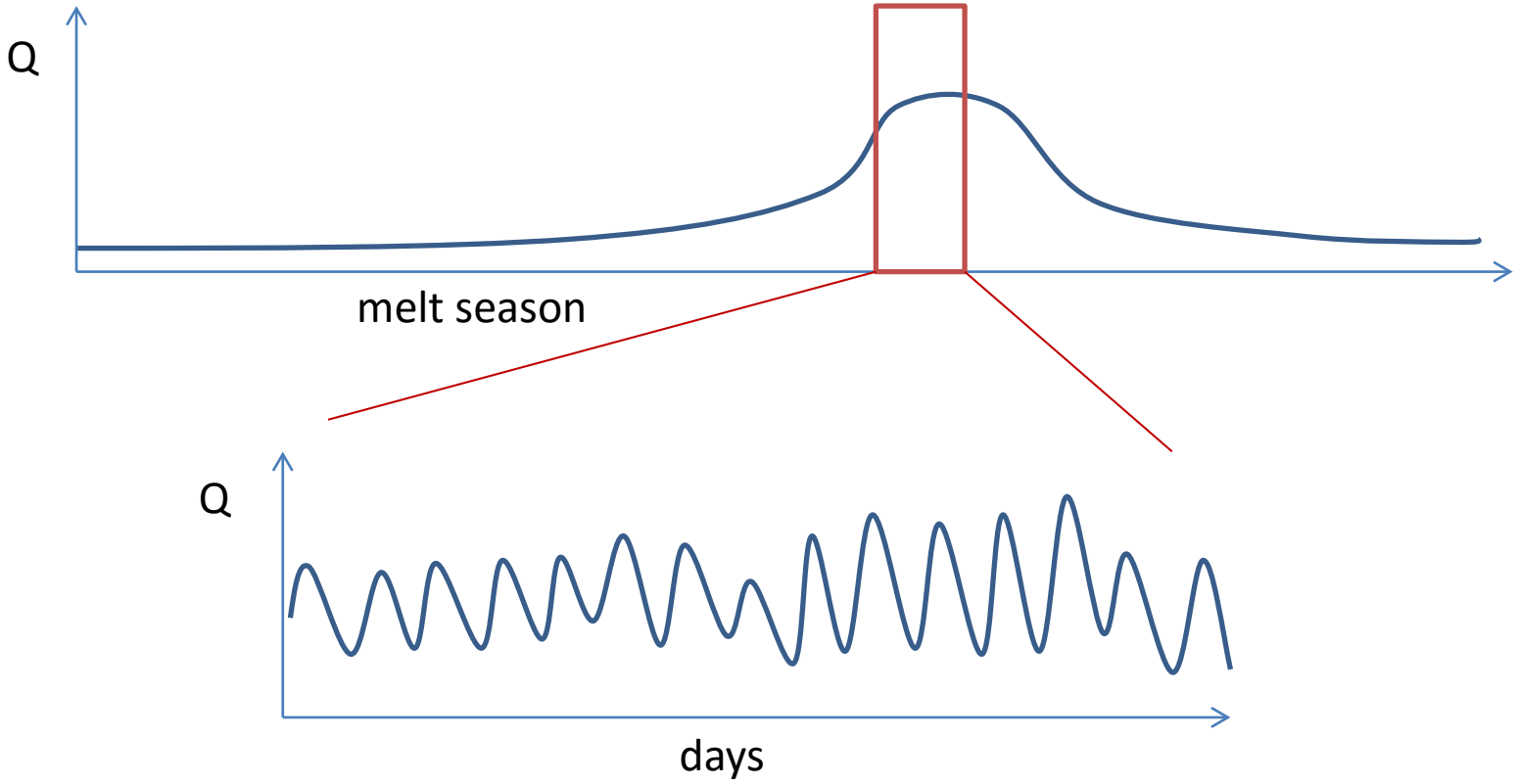
(Roethlisberger & Lang, 1987)

1. Supraglacial drainage: Flow within the snow-firn layer and along the ice surface
2. Intraglacial drainage: The passage through the interior of the glacier
3. Subglacial drainage: The drainage pathways at the glacier bed

Water balance of a glacier

Diurnal cycle of runoff

- How does melt water from glaciers influence seasonal and diurnal runoff variability of a glacierized catchment?



Diurnal cycle of runoff

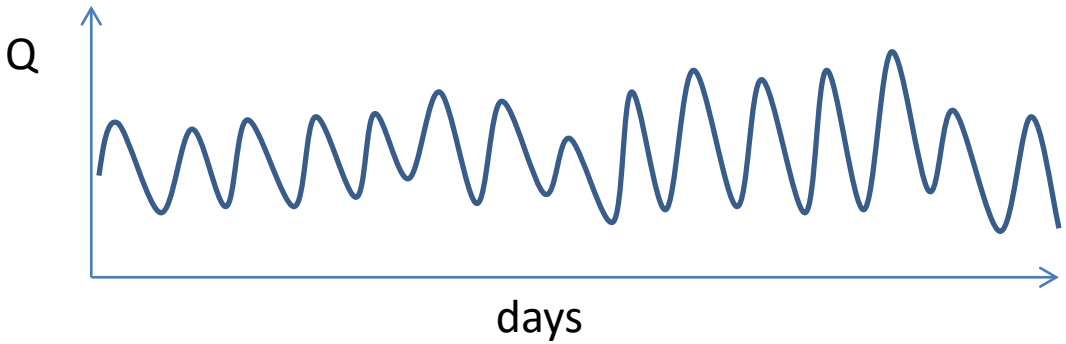
L. Braun

Hydrograph of hourly discharge at Vernagtferner, Alps, Austria, 1990, displaying **seasonal and diurnal variations** typical of glacier regimes.

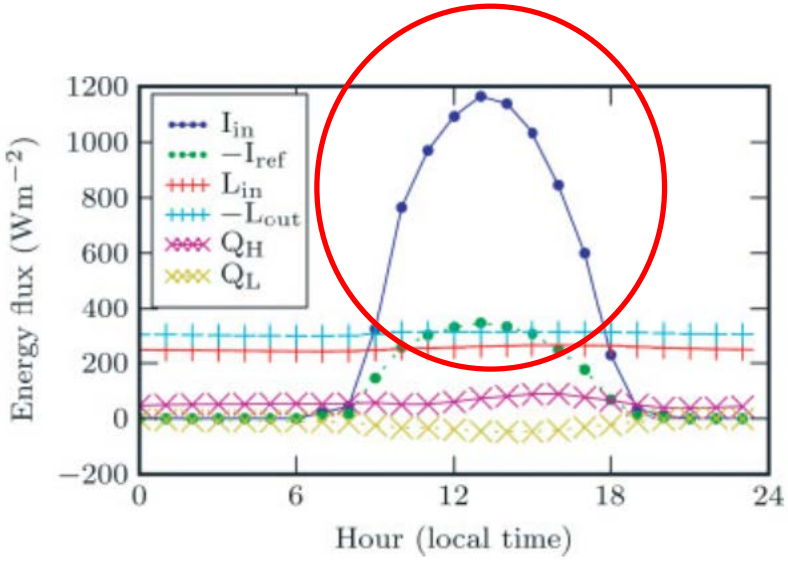
Hock, 2005

Diurnal cycle of runoff

- Why this strong diurnal fluctuation in stream flow?



Diurnal cycle of runoff

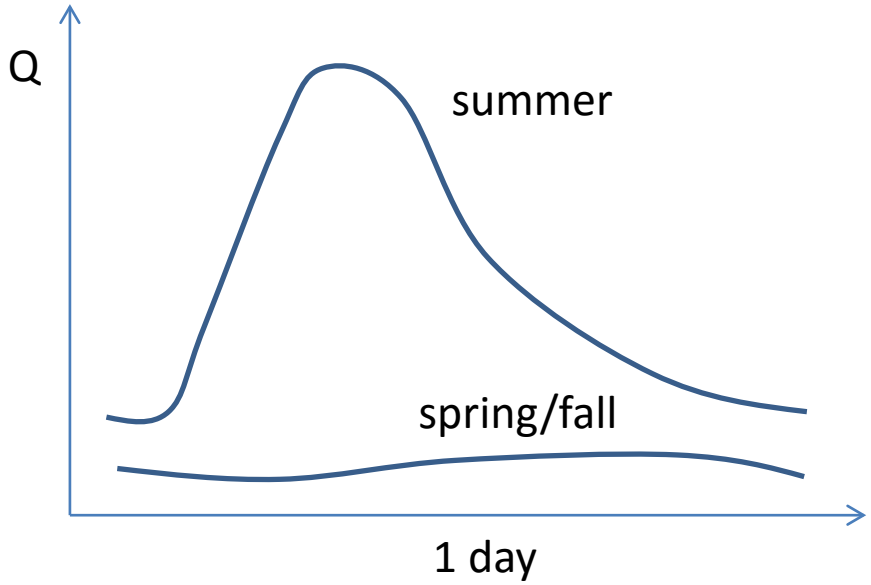


Mean daily cycle of the components of the surface energy balance at an automatic weather station on Juncal glacier, Andes, Chile.

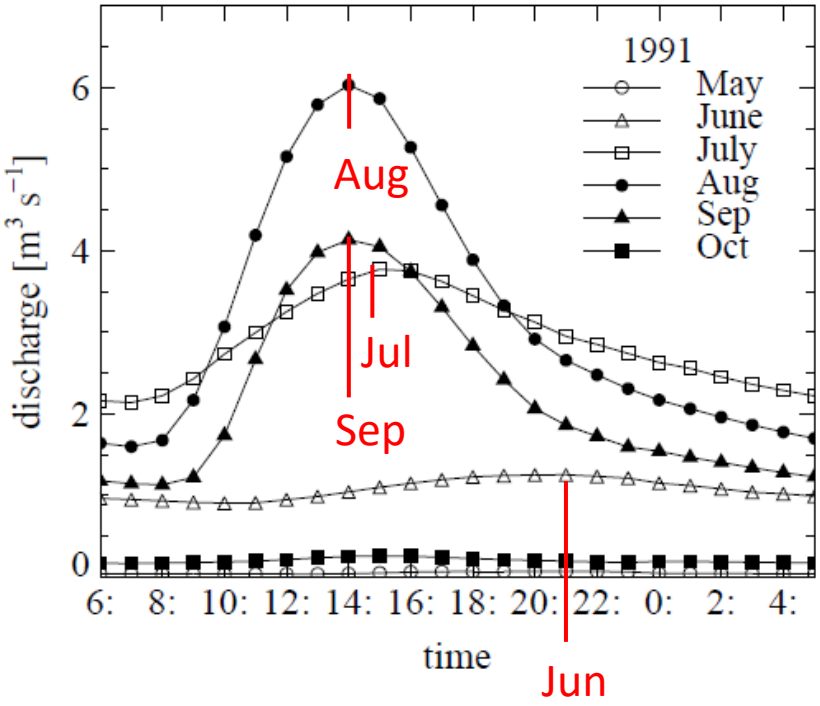
Pellicciotti, et al. 2008

Seasonal runoff variability

- How does diurnal runoff evolve over a melting period?



Seasonal runoff variability

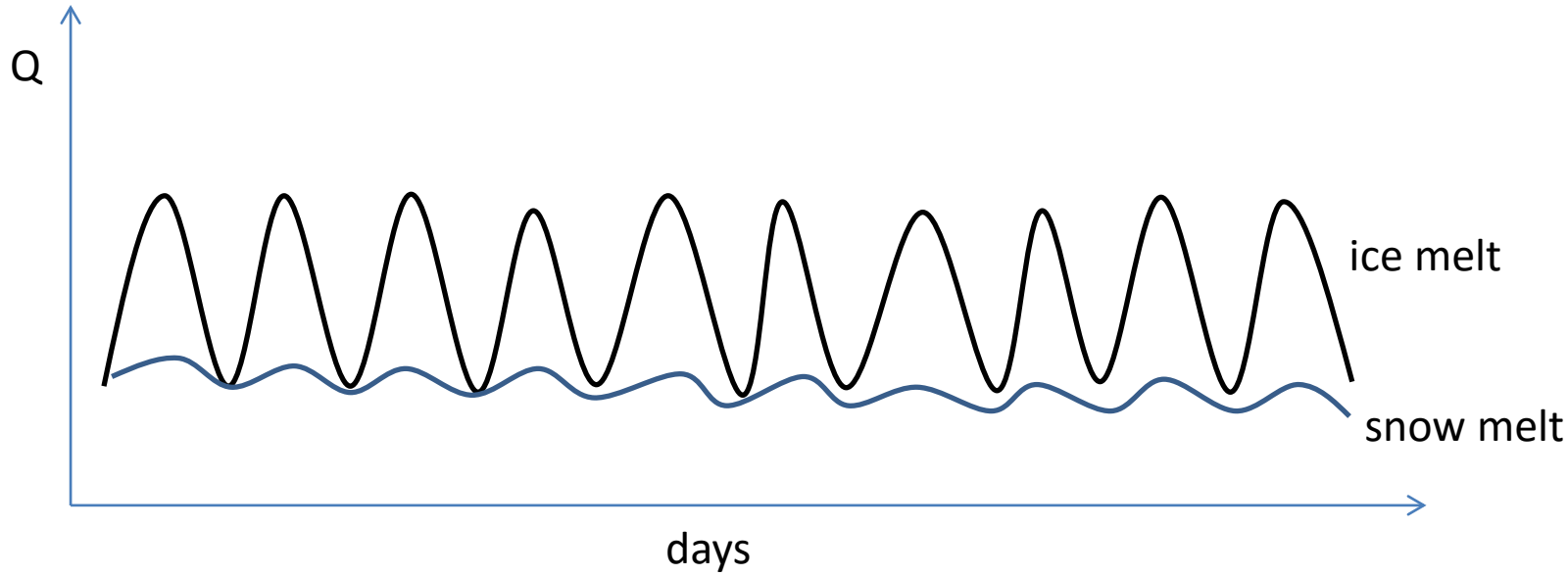


- Mean diurnal variation of discharge from Vernagtferner during the ablation season June to September 1991
- faster arrival of peak discharge as the season progresses

Escher-Vetter H. & Reinwarth, 1994

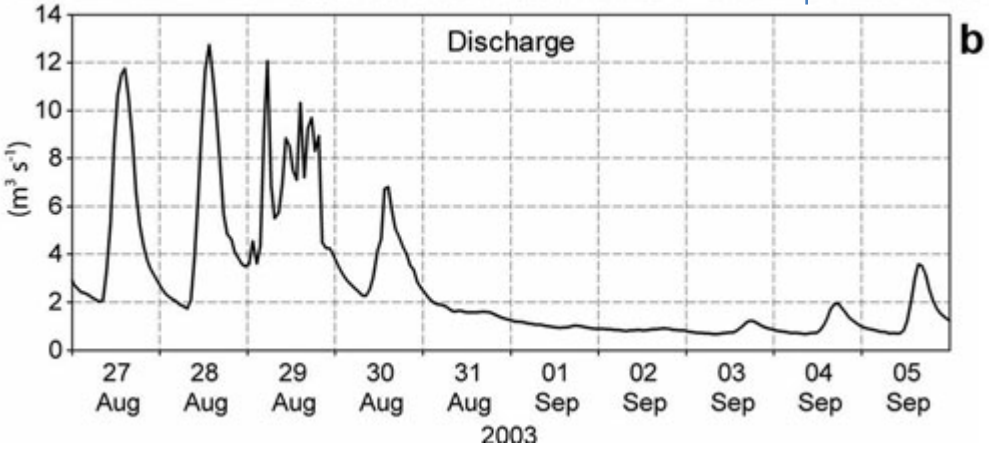
Seasonal runoff variability

- Which are differences in runoff from a snow-covered or bare ice surface?



Seasonal runoff variability

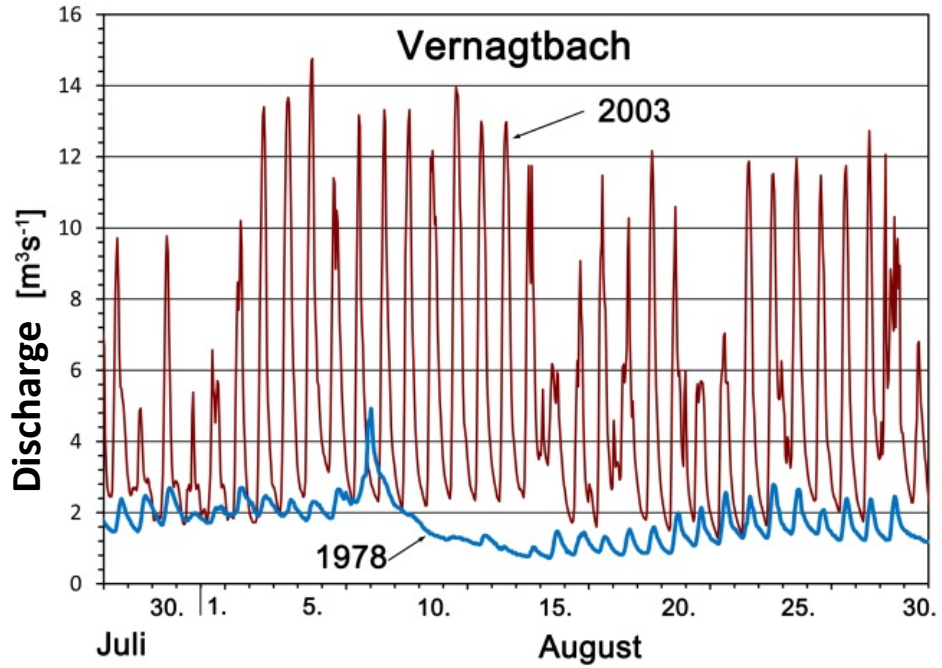
Photographs of the western part of the Vernagtach basin



Hydrograph of the Vernagtbach stream for the period 27 August - 6 September 2003

Escher-Vetter & Siebers, 2007

Interannual runoff variability

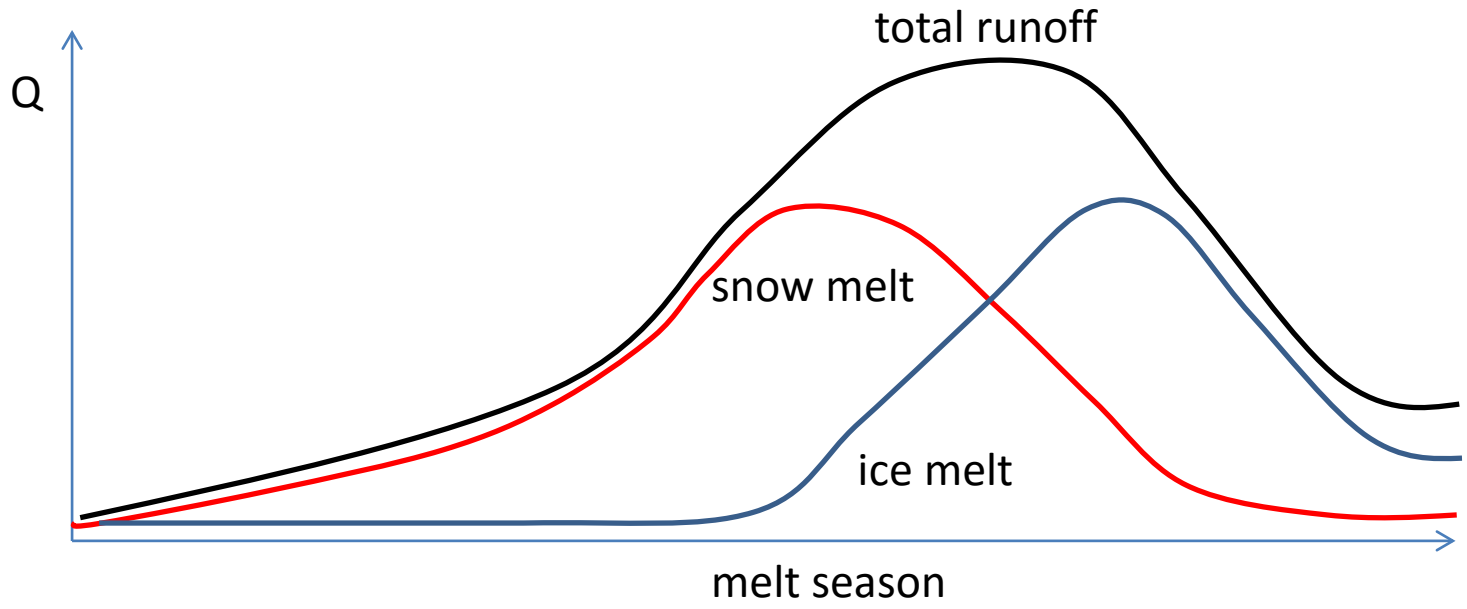


Daily discharge variation of Vernagtbach in summer 1978 and 2003

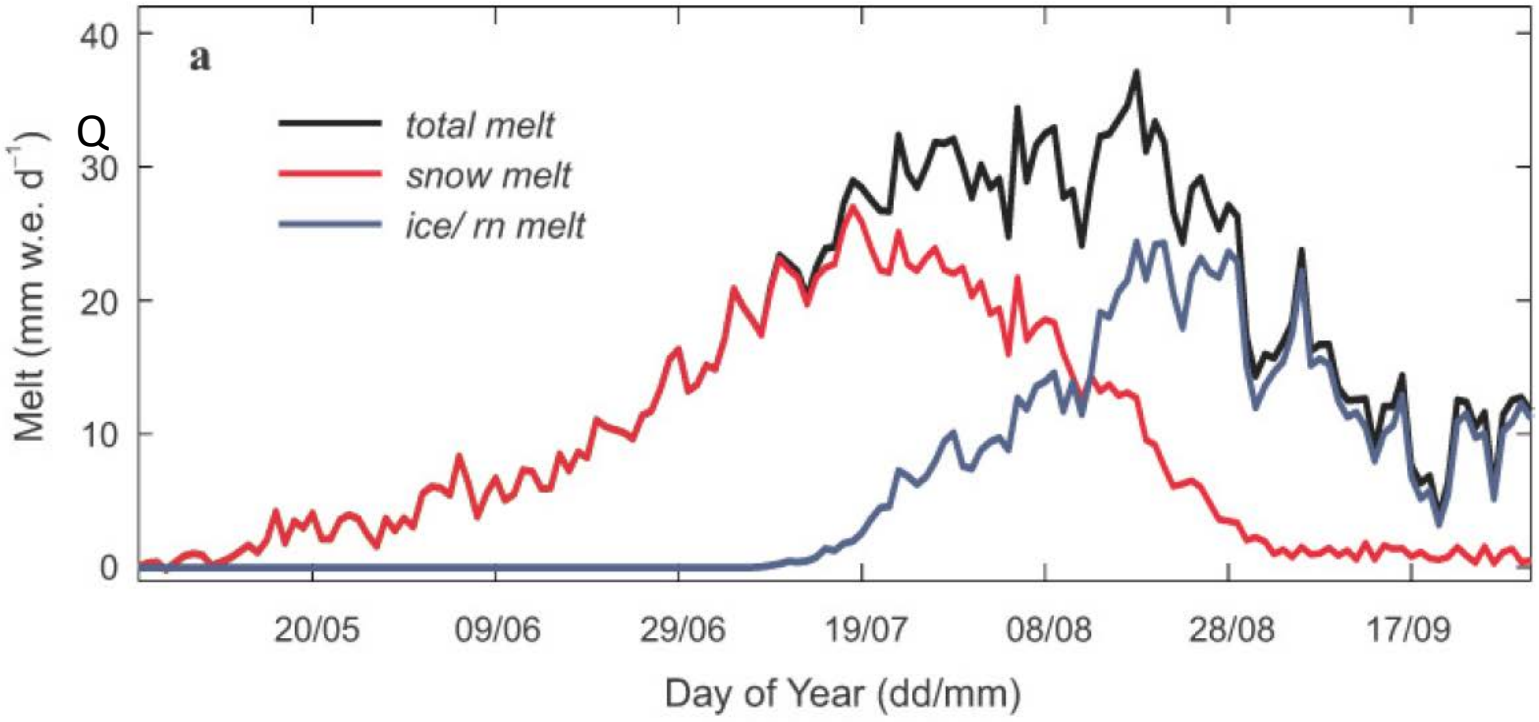
Braun et al. 2011

Seasonal runoff variability

- How does snow/ice contribute to seasonal runoff?



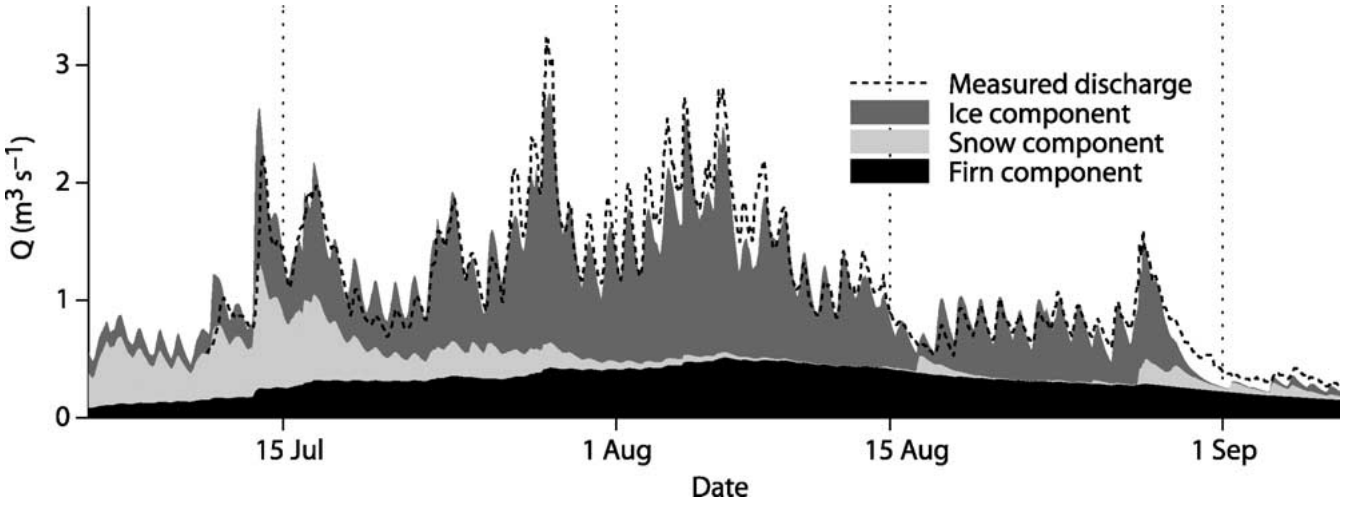
Seasonal runoff variability



Daily runoff from Haig Glacier 1 May - 30 September, based on average daily values from 2002-2013.

Marshall 2014

Seasonal runoff variability

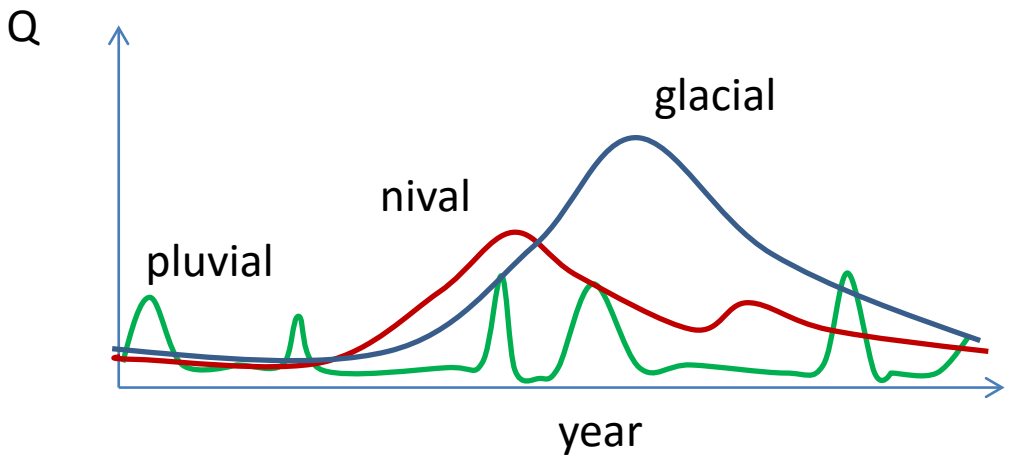


- Simulated and measured hourly discharge at Storglaciären 1994
- The shaded areas mark the contributions of the firn, snow and ice reservoirs to total discharge.
- The snow reservoir contribution decreases as the snow line moves upglacier.

(Regine Hock, 1998, Dissertation)

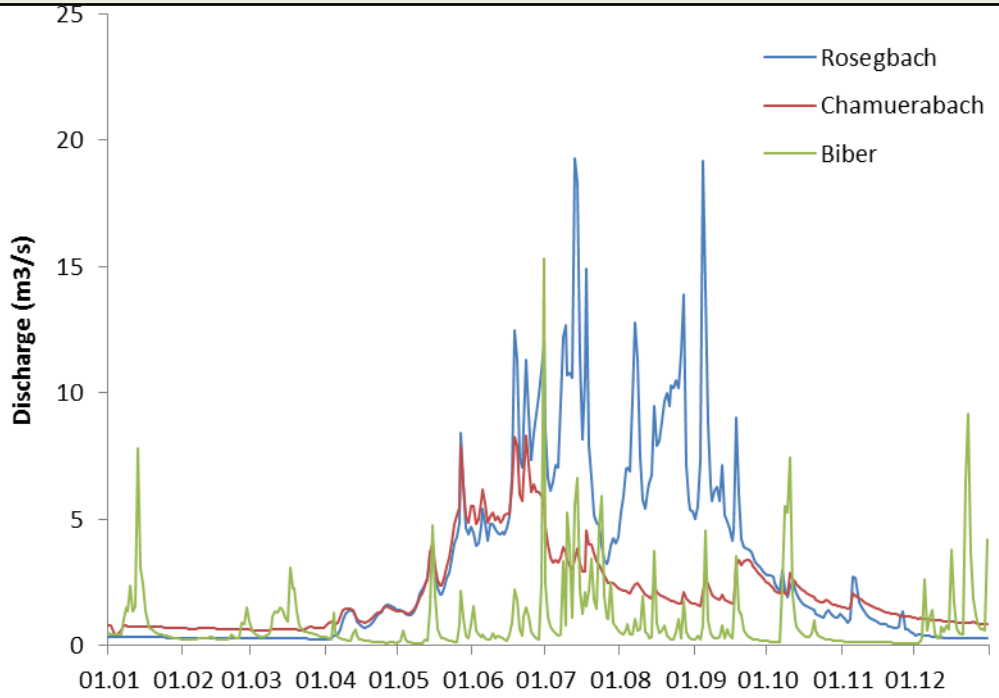
Seasonal runoff variability

- Which are differences in runoff in relation to catchment types: glacial, nival, pluvial



Seasonal runoff variability

Basins	Area (km^2)	Basin type	Mean Elev. (m)	Glacier (%)
Rosegbach	66.5	glacial	2716	32.6
Chamuerabach	73.3	nival	2549	0
Biber	31.59	pluvial	1009	0

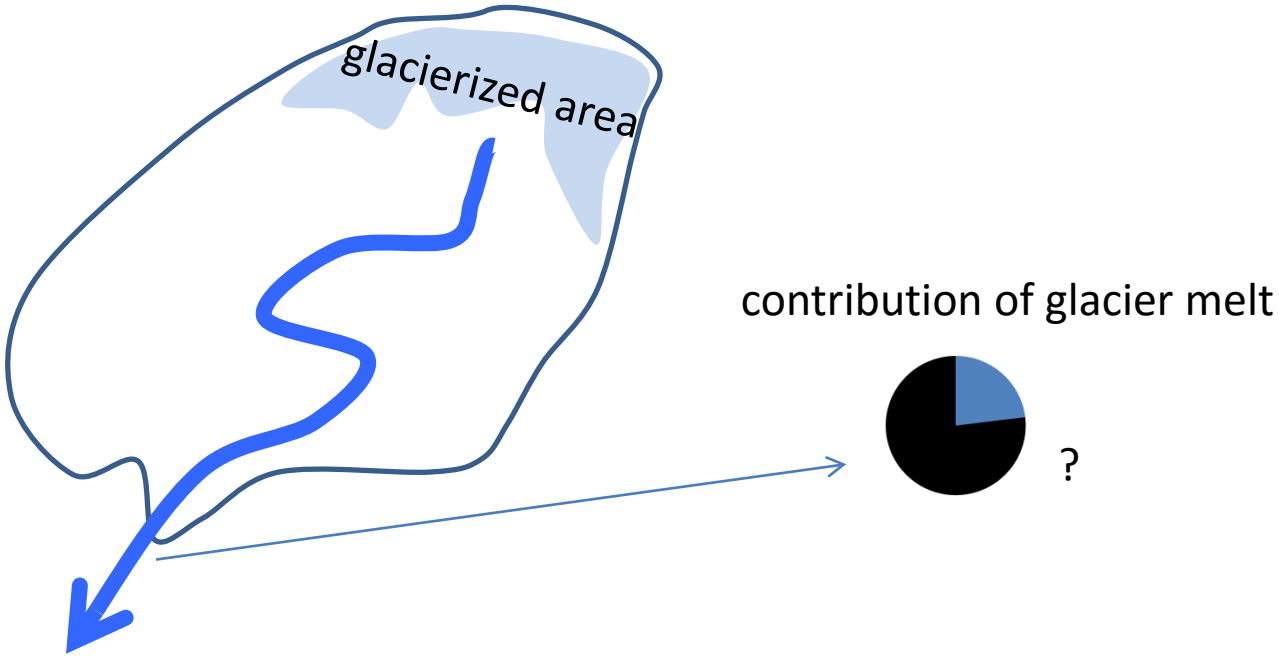


Daily runoff over the year 2011 for three catchments in the Swiss Alps

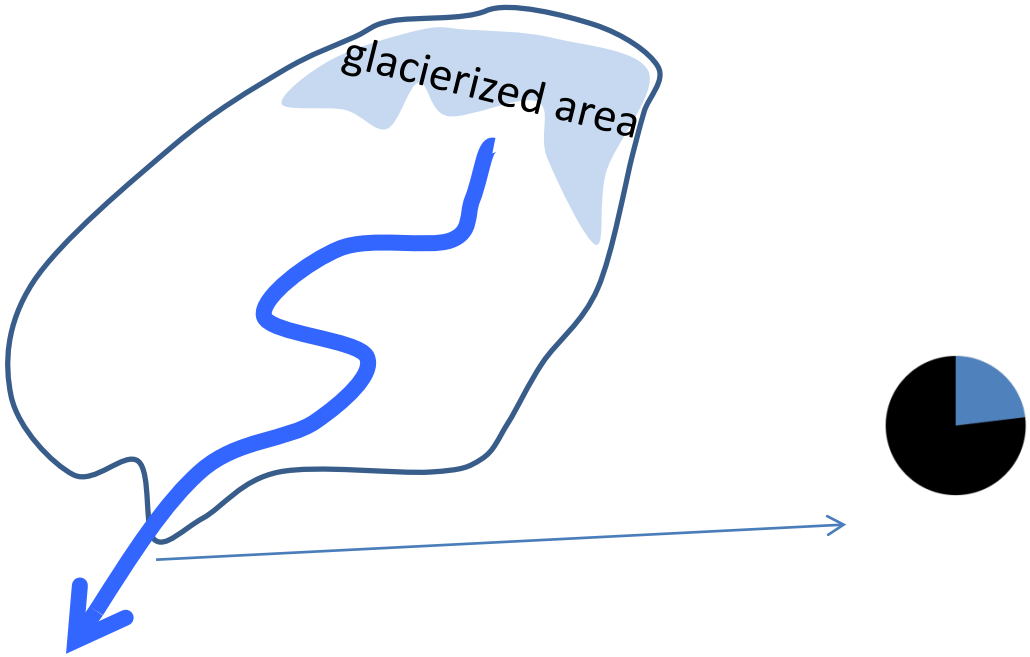
www.bafu.ch

Contribution of glacier melt to stream flow

- Which is the contribution of glacier melt to annual stream flow?



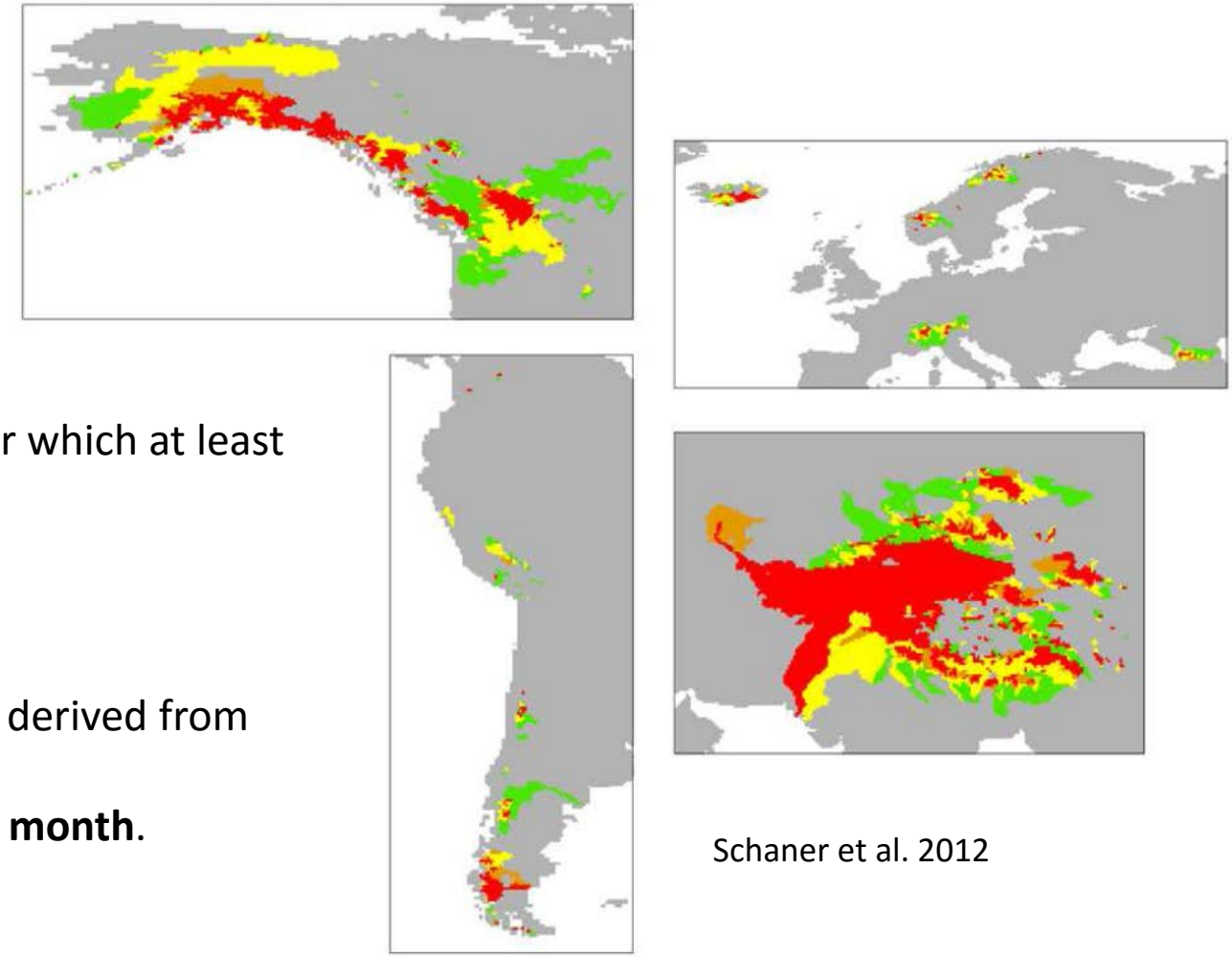
Contribution of glacier melt to stream flow



Contribution of glacier melt $c_{glacier}$

$c_{glacier} = Q_{glacier} / Q_{tot}$

Contribution of glacier melt to stream flow

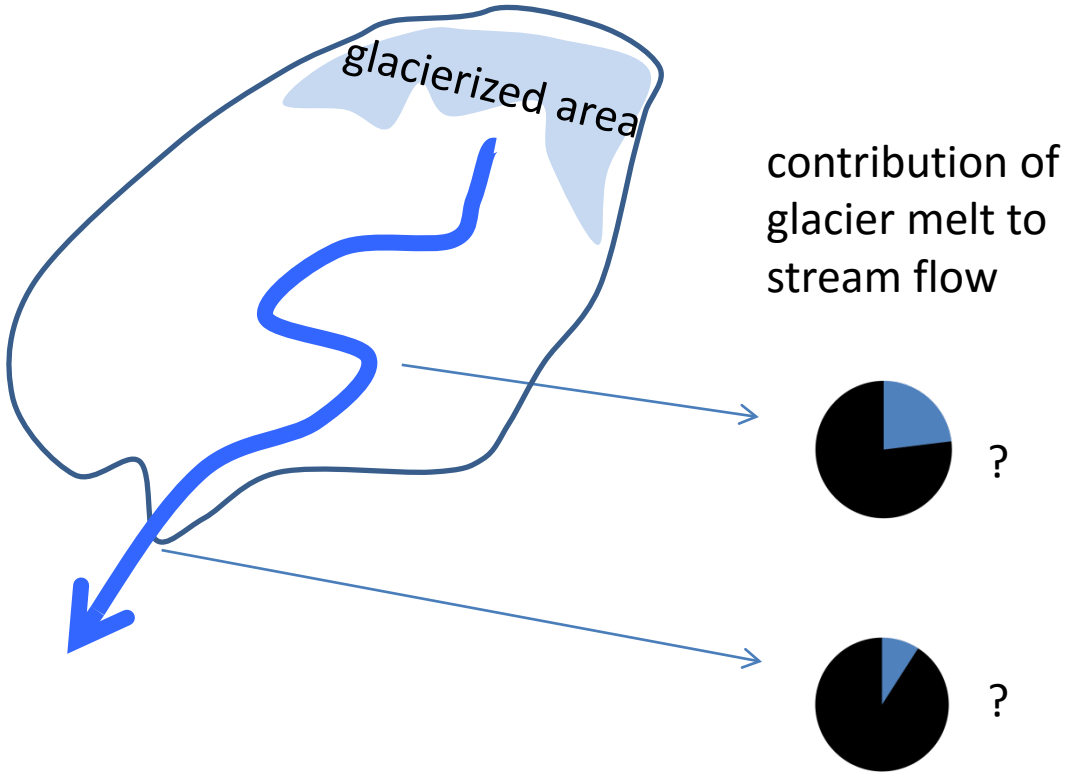


River basins for which at least
5%
10%
25%
50%
of discharge is derived from glaciers
in **at least one month**.

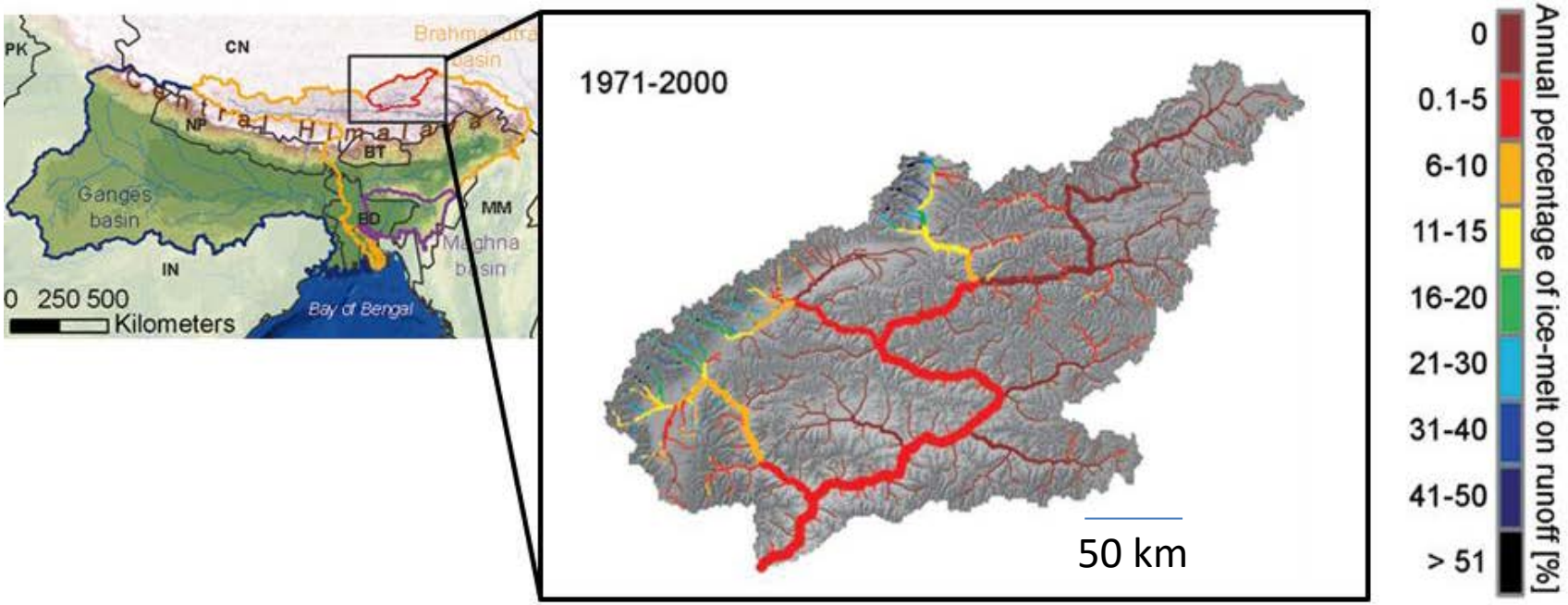
Schaner et al. 2012

Contribution of glacier melt to stream flow

- Which is the contribution of glacier melt to annual stream flow at different locations?



Contribution of glacier melt to stream flow

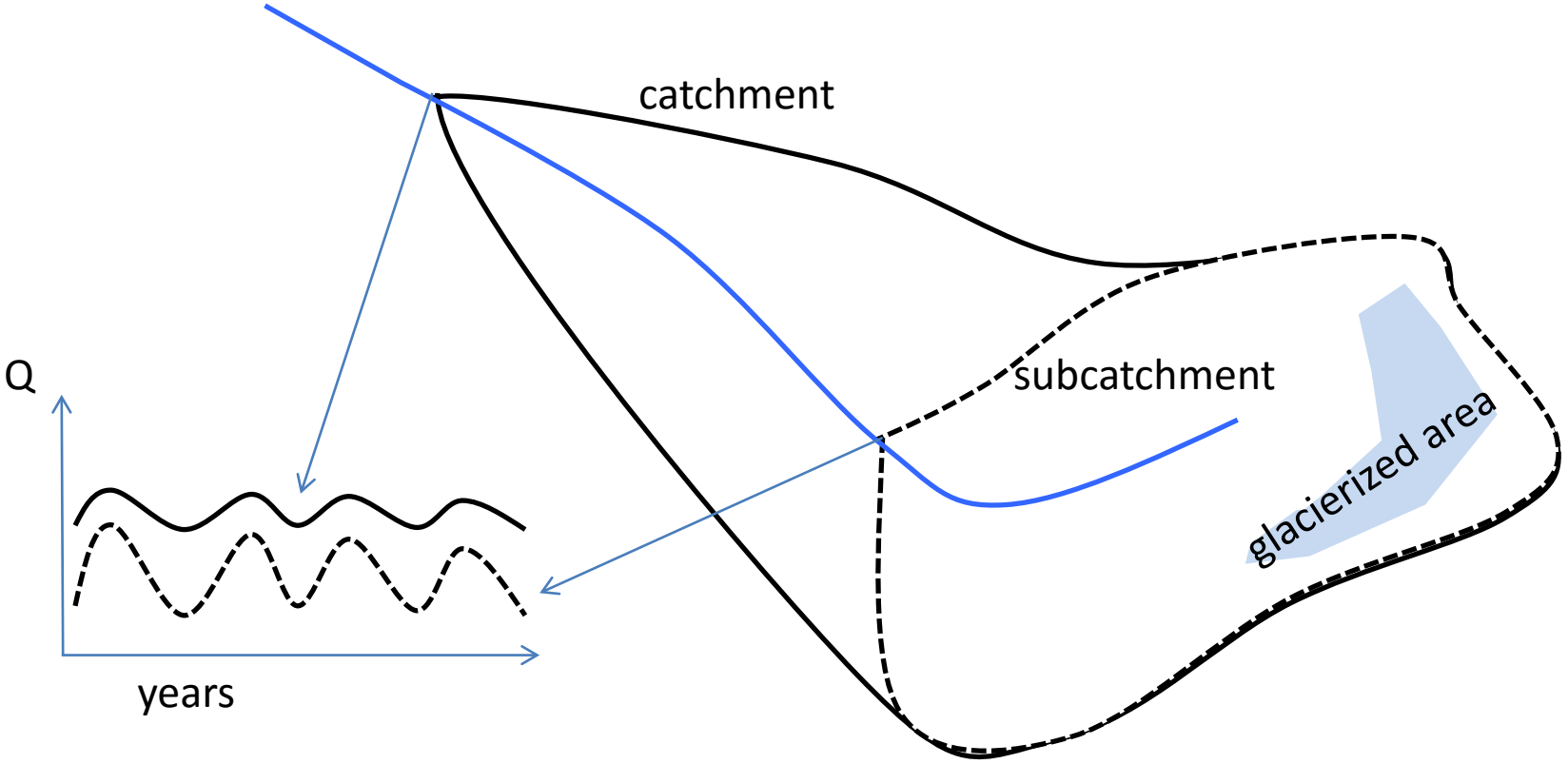


- Mean annual runoff fraction of ice-melt throughout the river network.
- The percentage is shown for rivers with an average runoff above 0.5 m^3s^{-1} for the past (1971-2000).
- The studied Lhasa River basin is contributing runoff to Brahmaputra in High Asia.

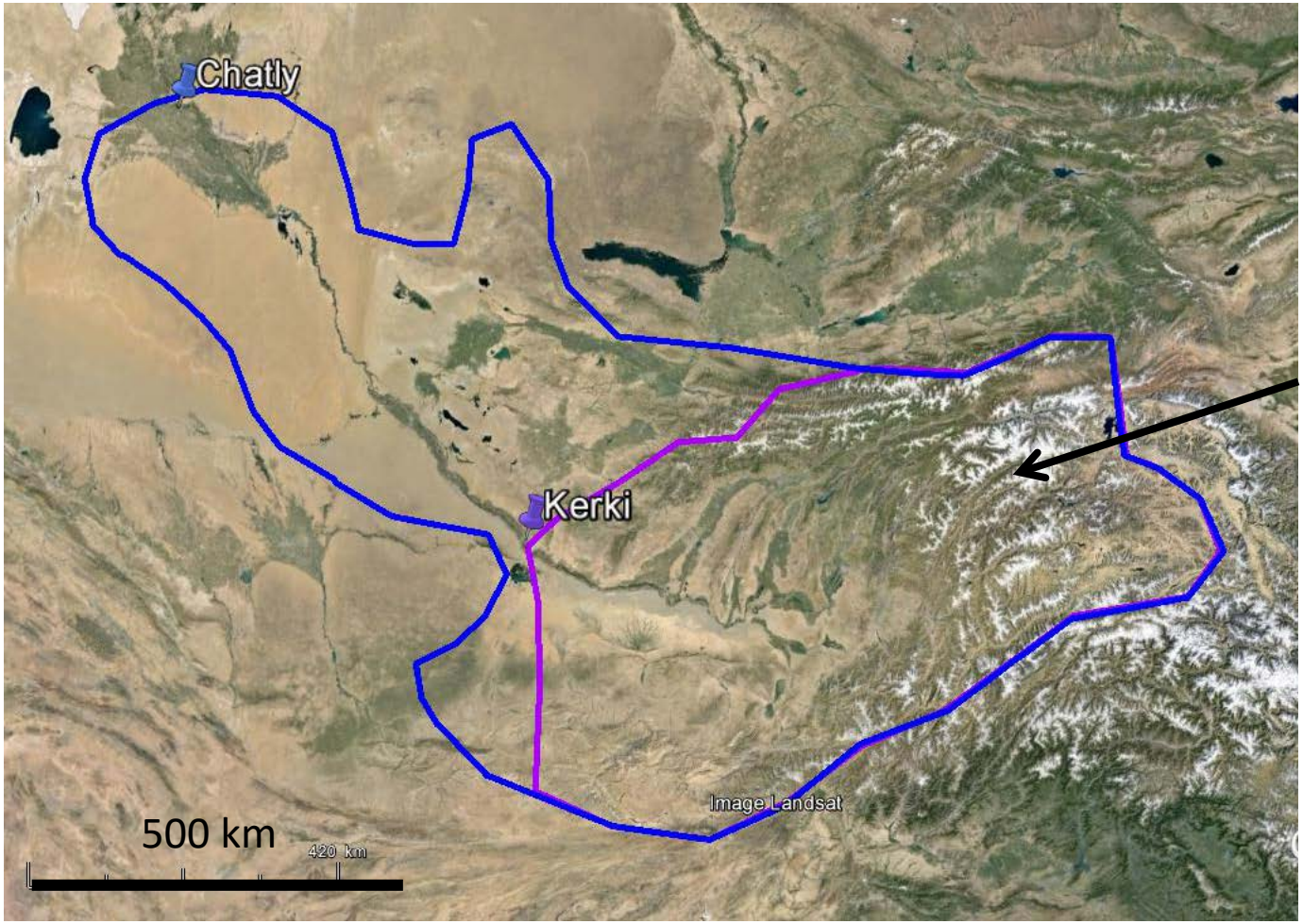
Prasch et al. 2013

Contribution of glacier melt to stream flow

- Which are differences in seasonal stream flow of a catchment and its subcatchment?

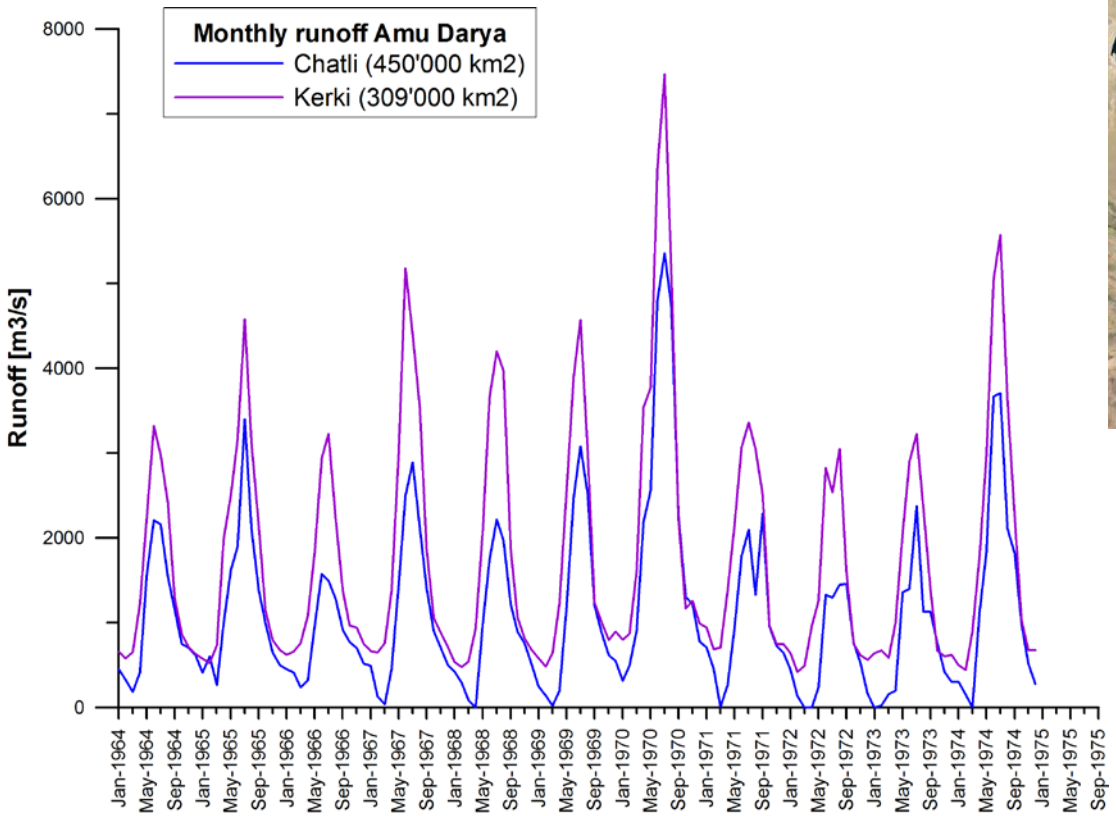


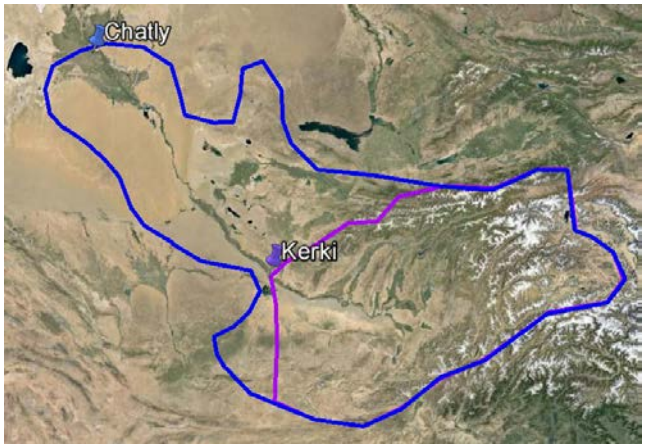
Contribution of glacier melt to stream flow



glacierized area

Contribution of glacier melt to stream flow

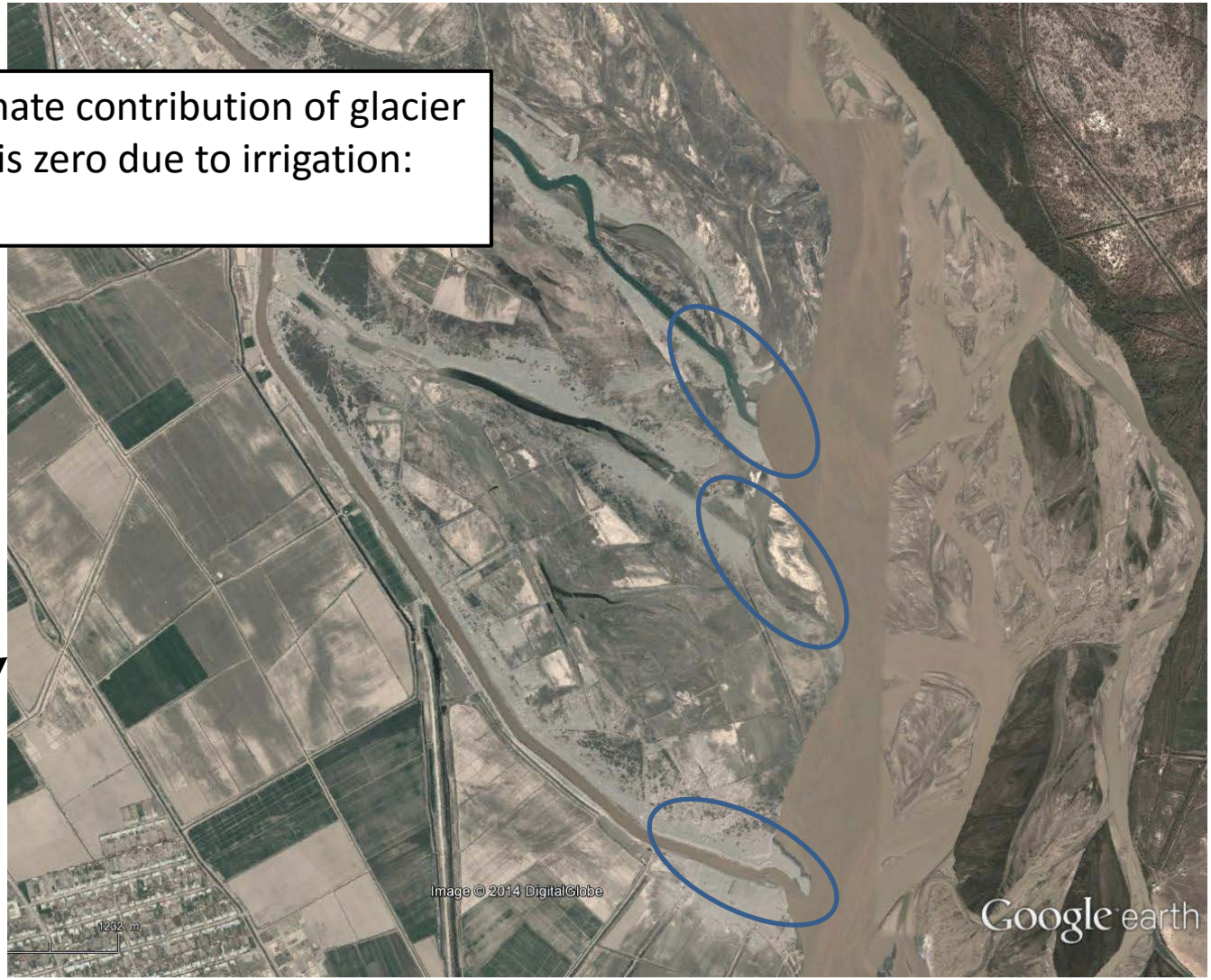


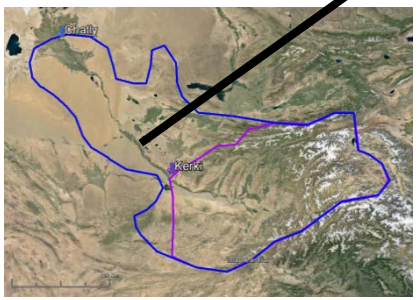


Would you expect this?
Explain!

Contribution of glacier melt to stream flow

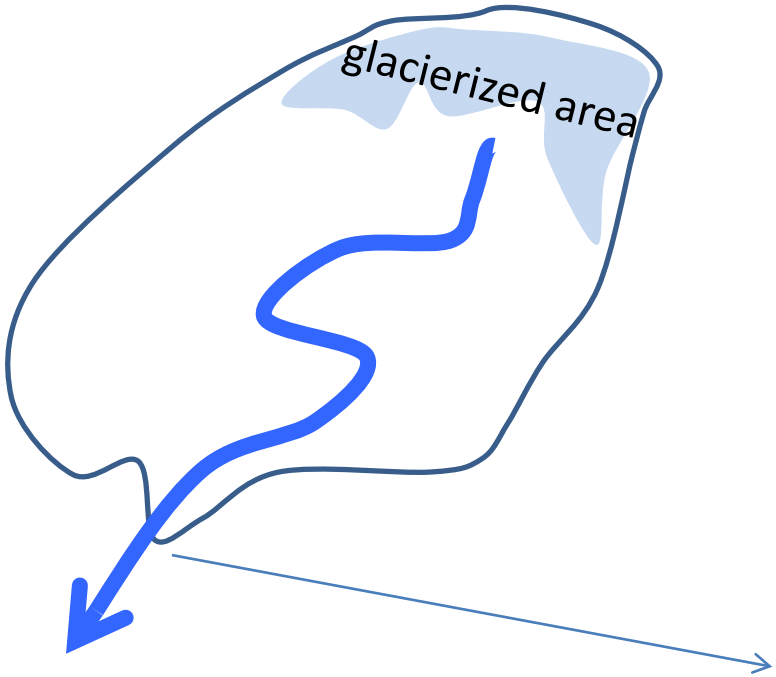
Implications to estimate contribution of glacier melt by if discharge is zero due to irrigation:
$c_{glacier}=Q_{glacier}/Q_{tot}$

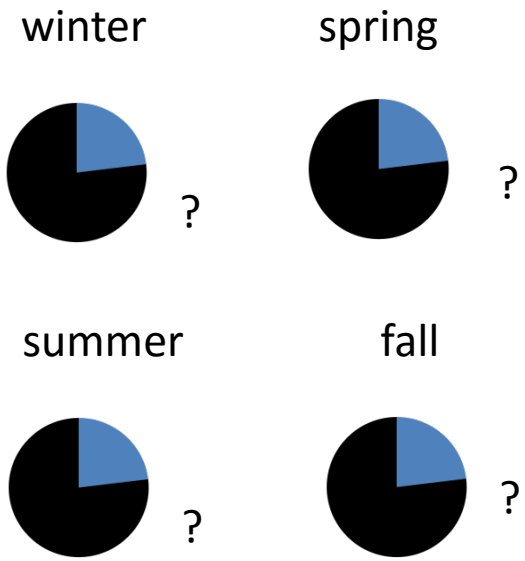




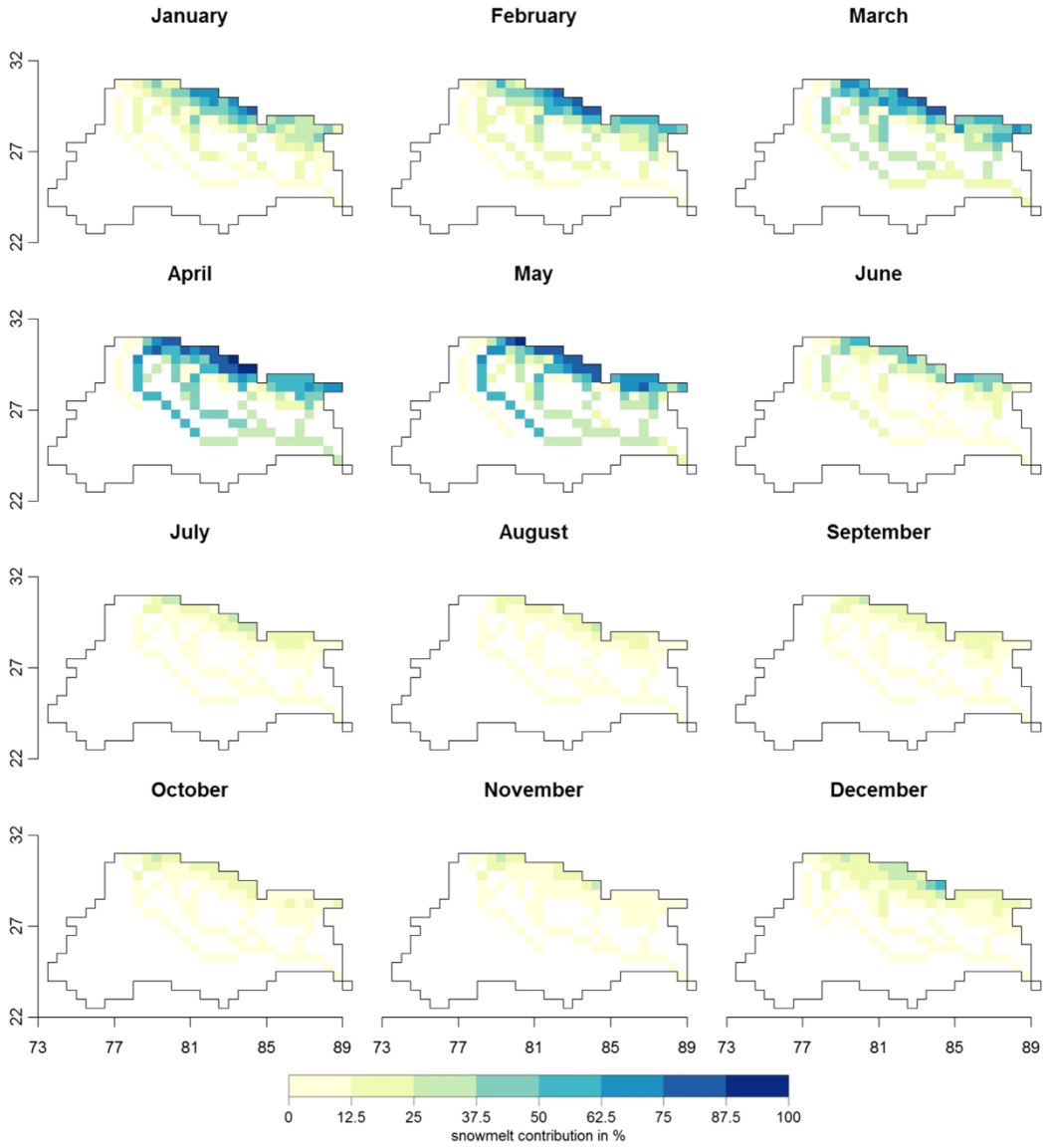
Contribution of glacier melt to stream flow

- Which is the contribution of glacier melt to seasonal stream flow?

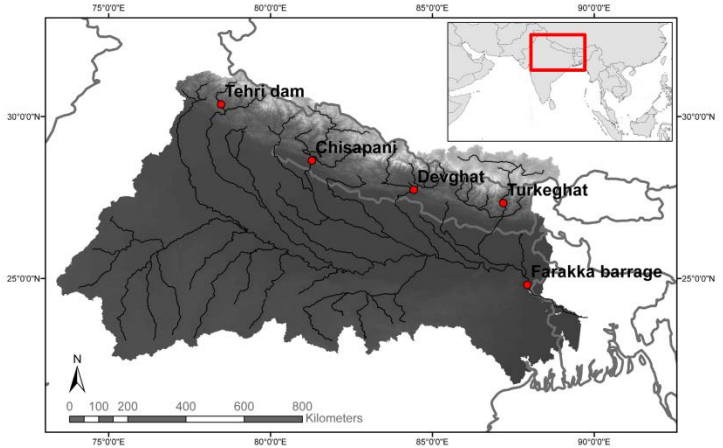




Contribution of snowmelt to stream flow

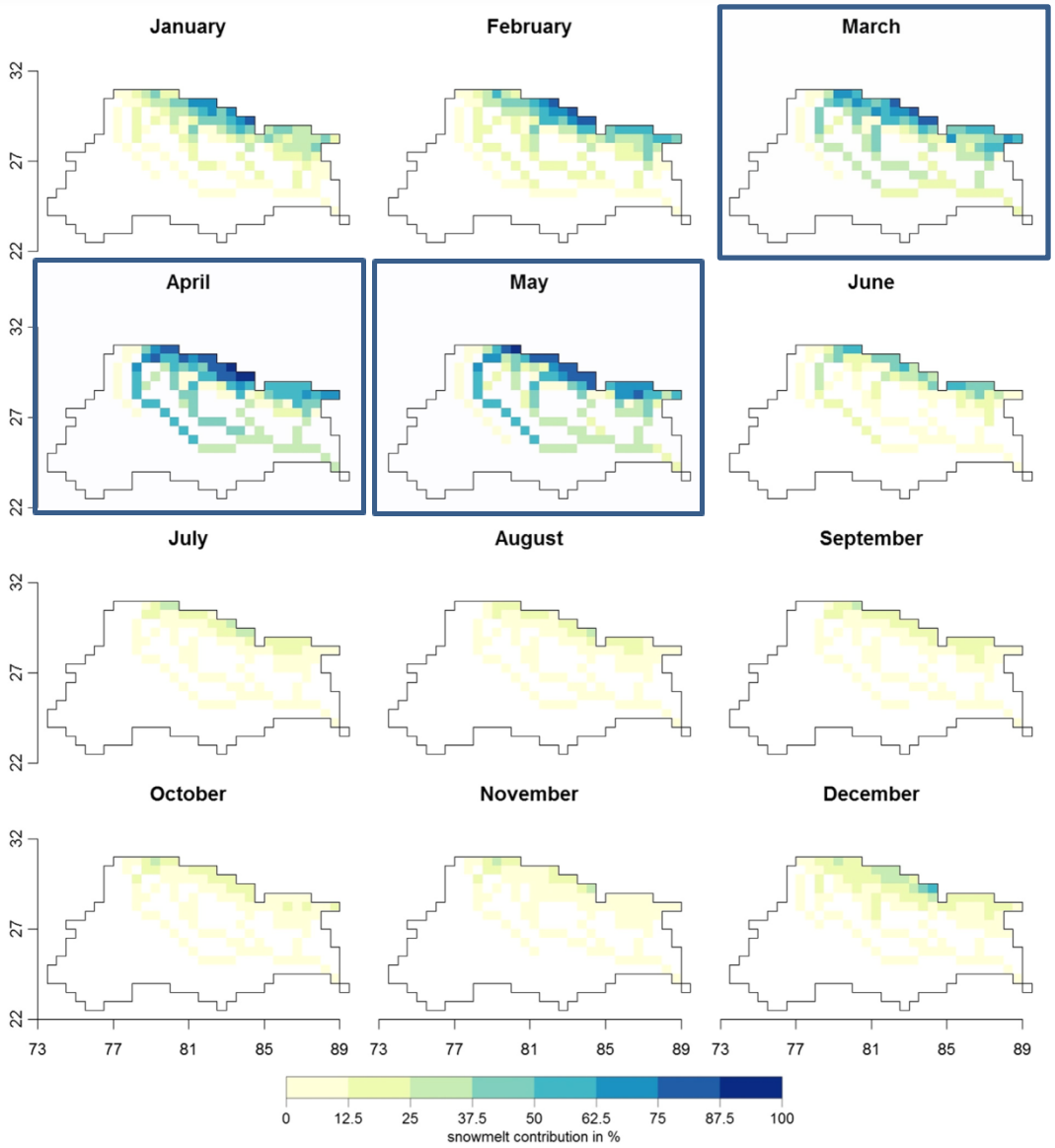


Estimation with 4 different hydrological models:
Ganges at **Farakka** barrage:
~ **1% to 5% snowmelt** contribution to **yearly runoff**

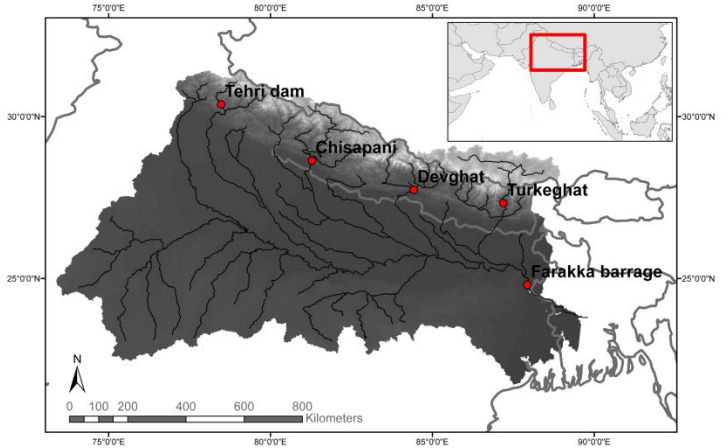


Siderius et al. 2013

Contribution of snowmelt to stream flow



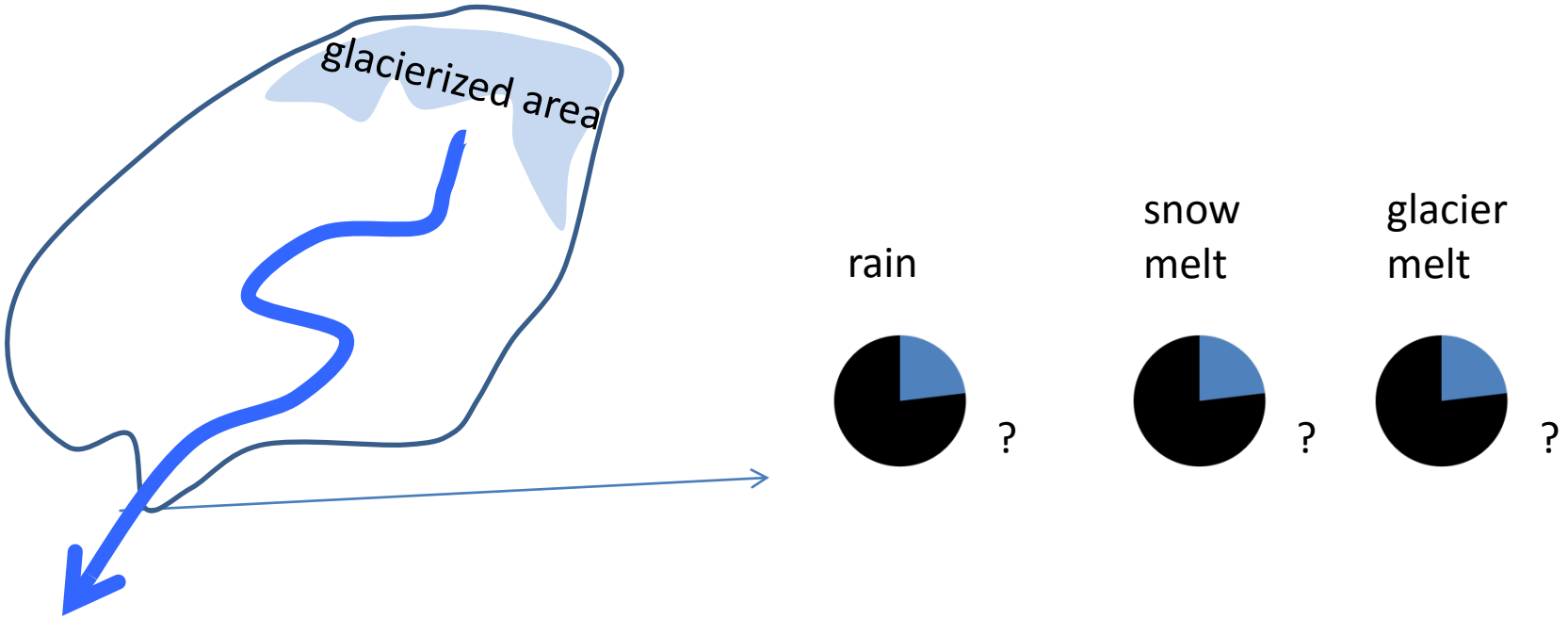
Estimation with 4 different hydrological models:
Ganges at **Farakka** barrage:
~ **12% to 38% snowmelt** contribution to **March-April-May** **runoff**



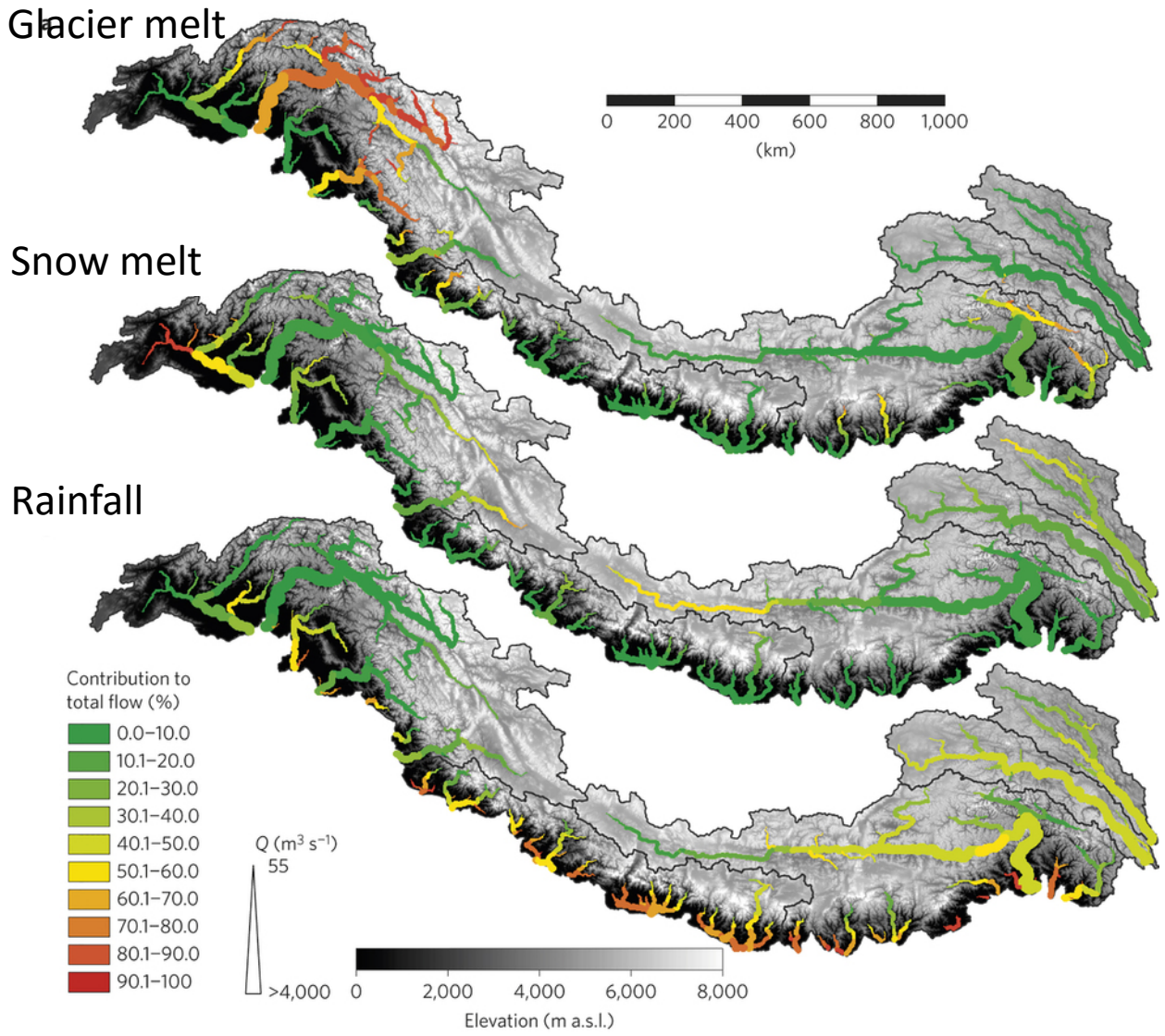
Siderius et al. 2013

Contribution of glacier melt to stream flow

- Which is the contribution of glacier melt, snow melt and rain?



Contribution of glacier melt to stream flow

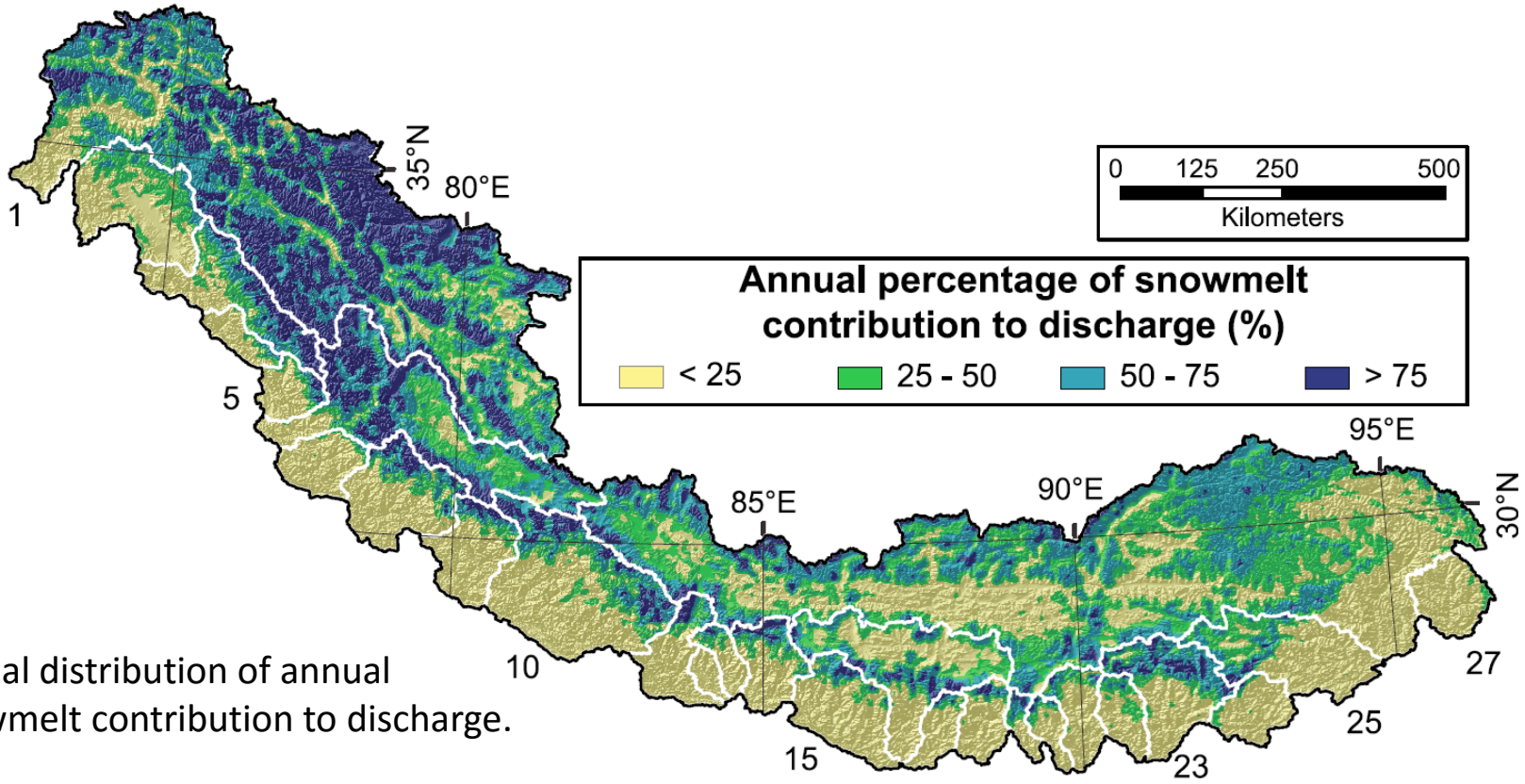


Contribution to total flow by flow components in major streams during the reference period (1998-2007)

Line thickness = average discharge during the reference period

Lutz et al. 2014

Contribution of glacier melt to stream flow



Spatial distribution of annual snowmelt contribution to discharge.

- high percentages in the western catchments as well as in the high elevations
- The frontal areas are dominated by rainfall and thus have low snowmelt contribution.

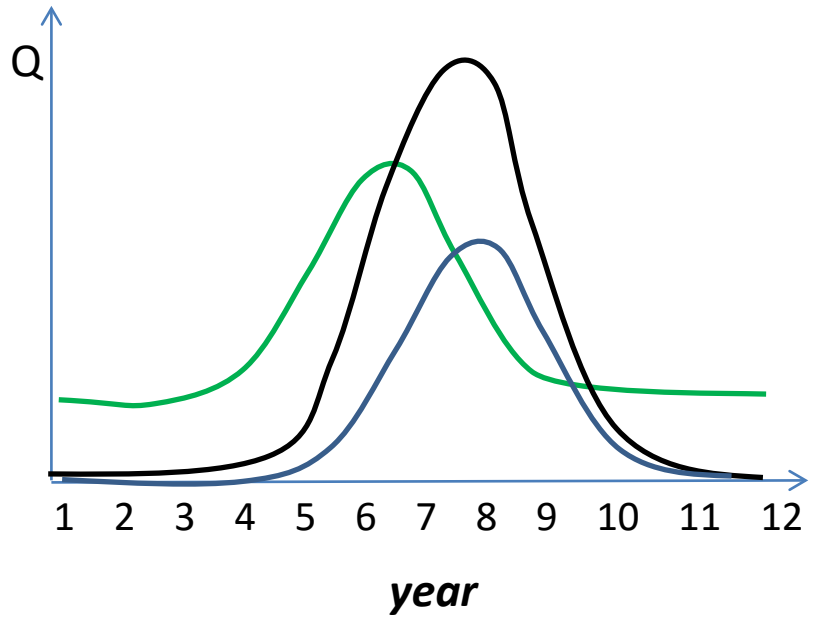
Bookhagen and Burbank, 2010

Contents

Changes in runoff in the past

- How could glacier retreat affect annual discharge in the past/future?

Total runoff? Time to peak?

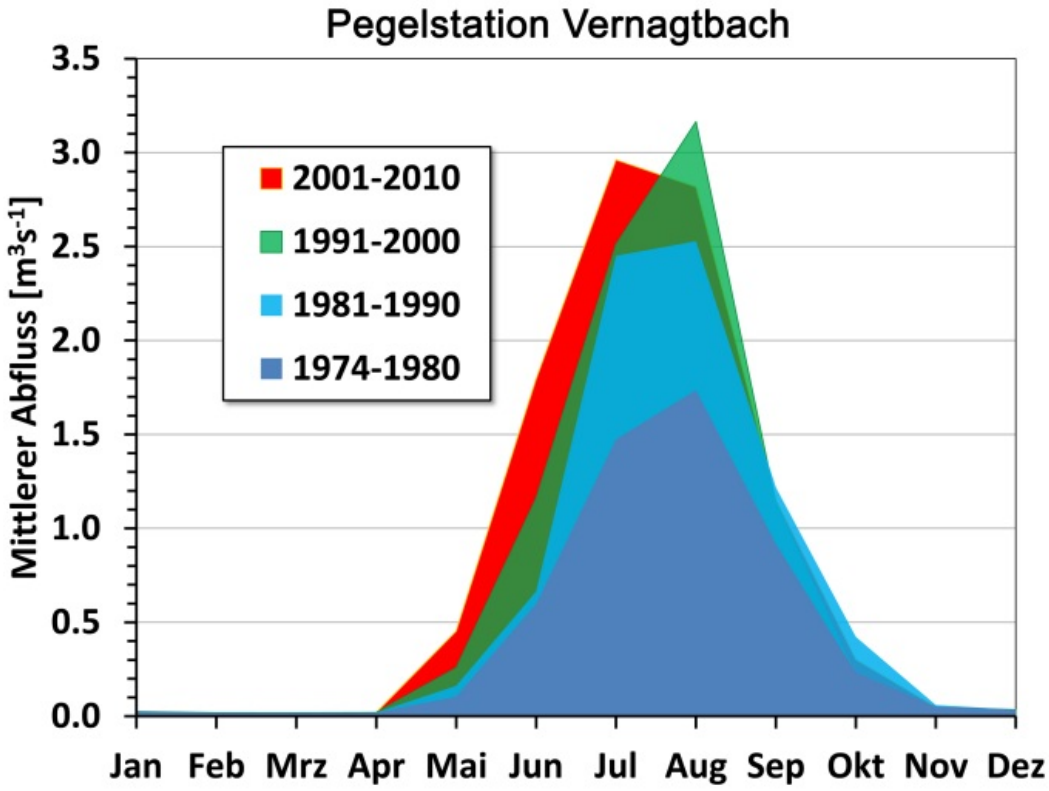


past, 20th century

present

future, 2100+

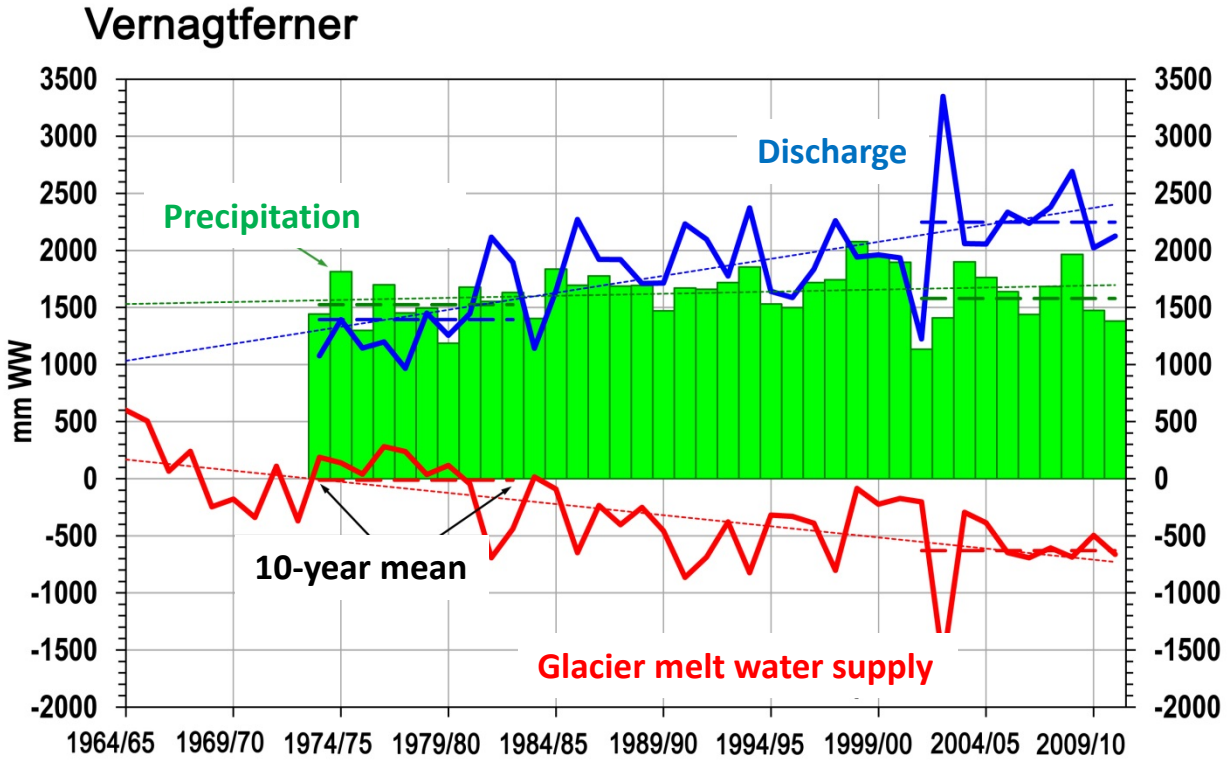
Changes in runoff in the past



Mean monthly discharge at Vernagtbach gauging station at 2635 m asl
-> a clear increase in the last 40 years!

Braun et al. 2011

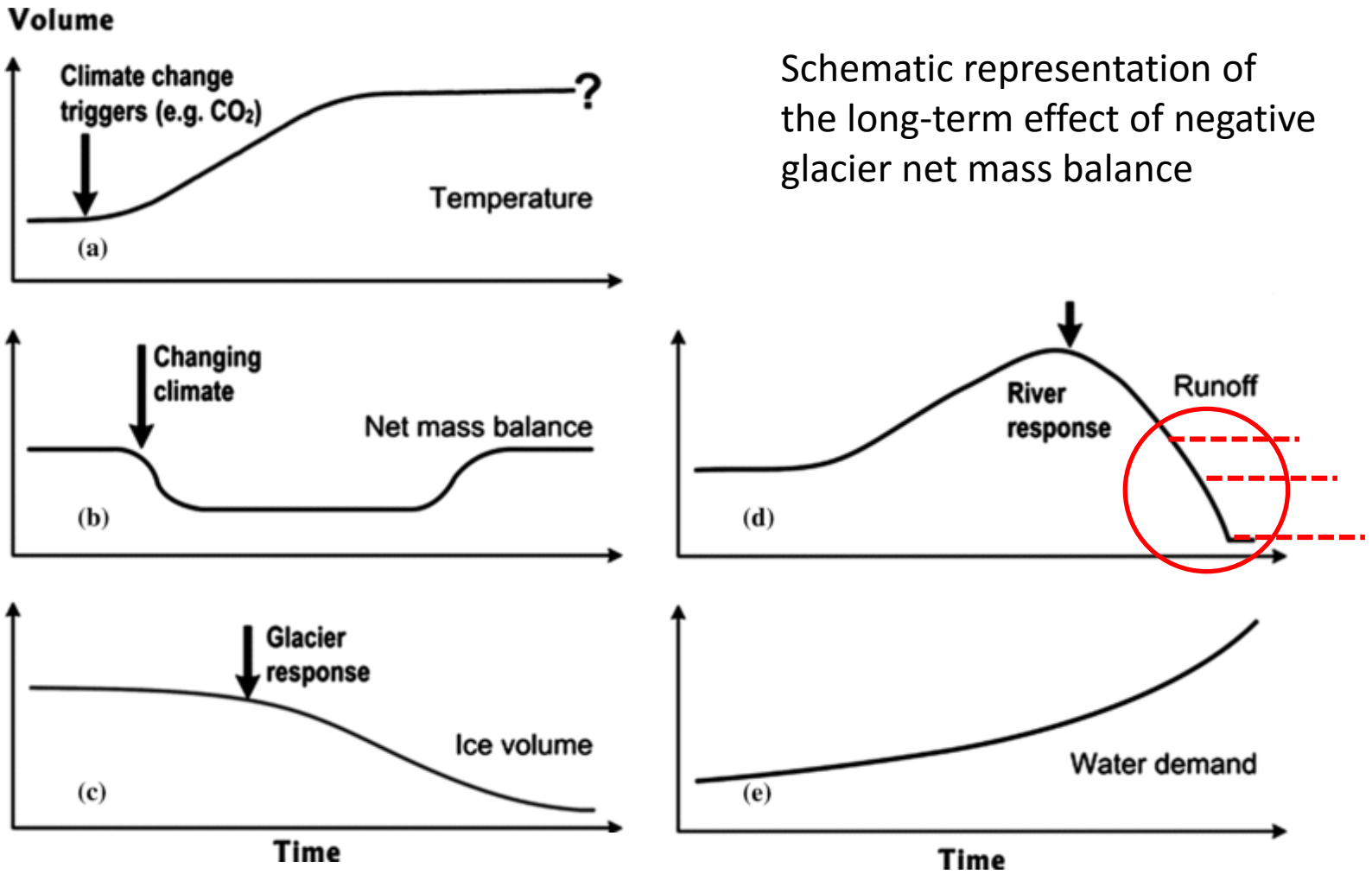
Changes in runoff in the past



The water balance components
basin precipitation, glacier mass balance, runoff
of the Vernagt basin

(Braun et al. 2007)

Impacts of cc on water resources



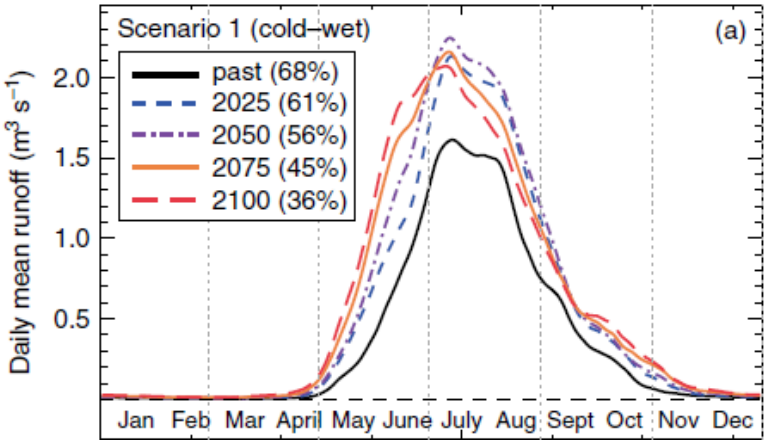
Schematic representation of the long-term effect of negative glacier net mass balance

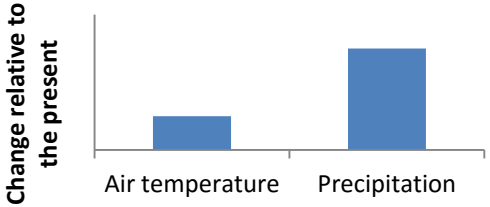
(Xu et al., 2009)

Impacts of cc on water resources: Alps

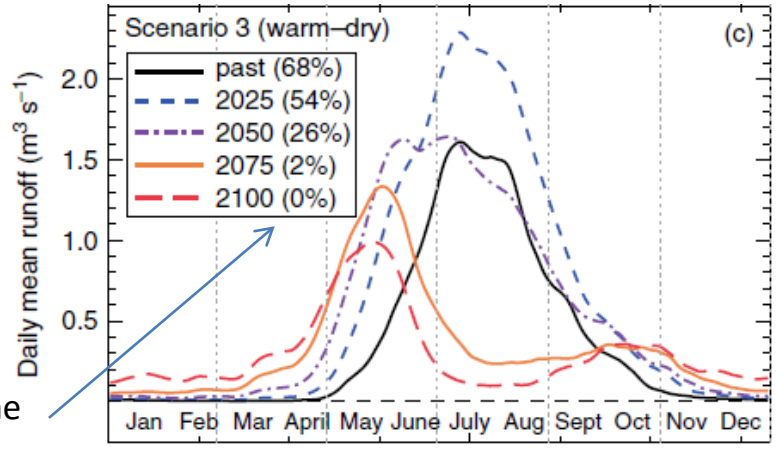
Annual cycle of runoff of Glacier de Moming for two scenarios shown for the past (1961-1990) and four snapshots in the future

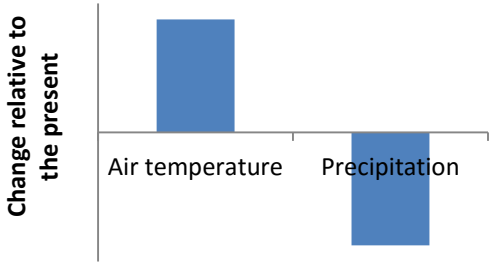
cold-wet





warm-dry



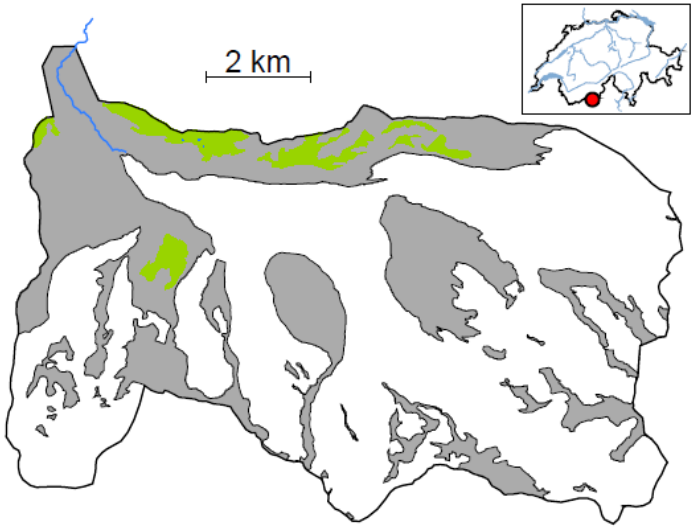


(glaciation of the catchment)

Huss et al., 2008

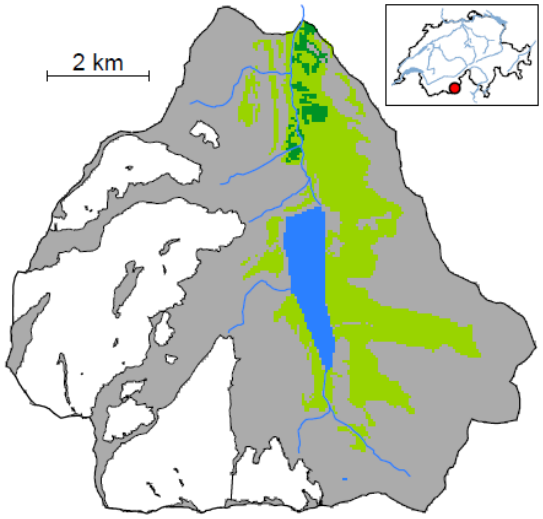
Impacts of cc on water resources: Alps

GORNER



Catchment:
- Area: 81 km^2
- 63% glacierized

MATTMARK



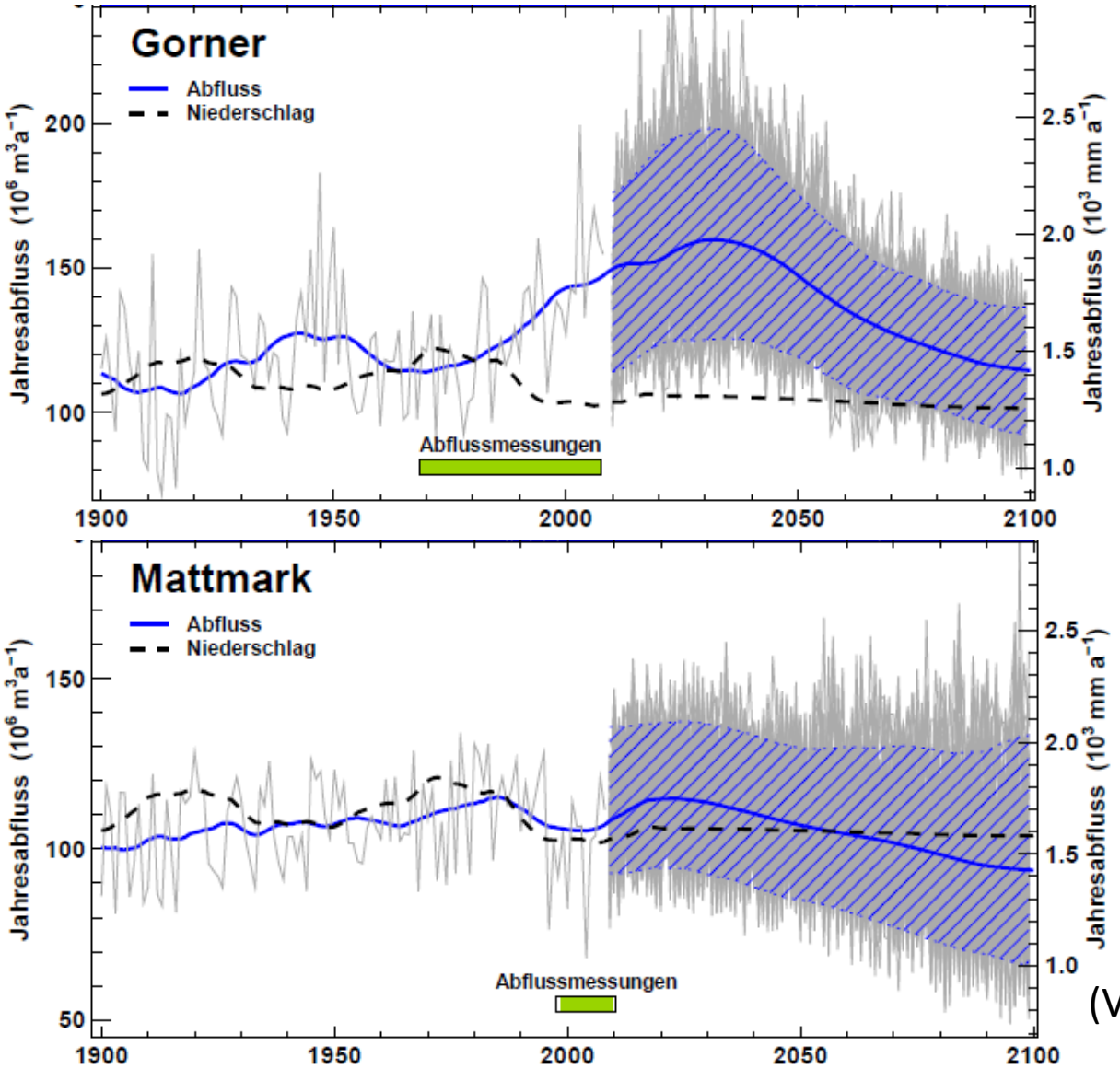
Catchment:
- Area: 66 km^2
- 30% glacierized

VAW, 2011

Impacts of cc on water resources: Alps

GORNER

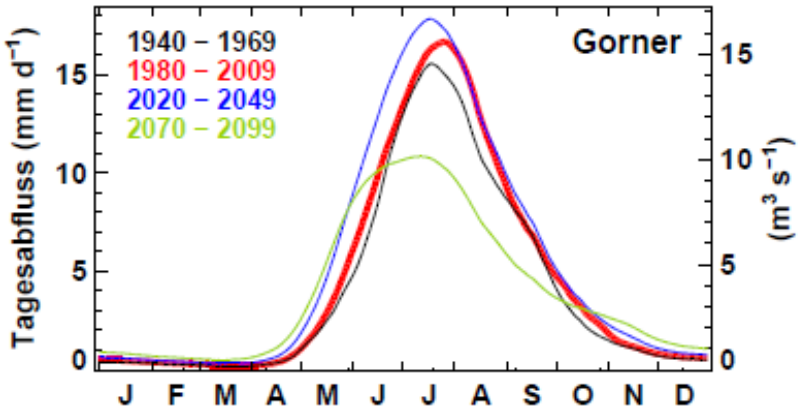
MATTMARK



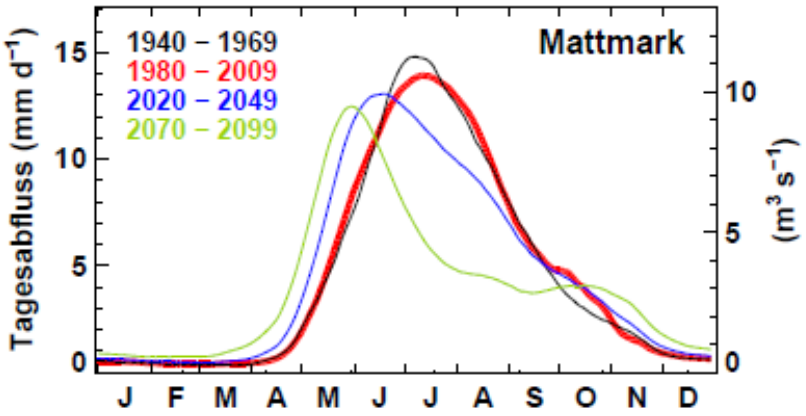
(VAW, 2011)

Impacts of cc on water resources: Alps

GORNER

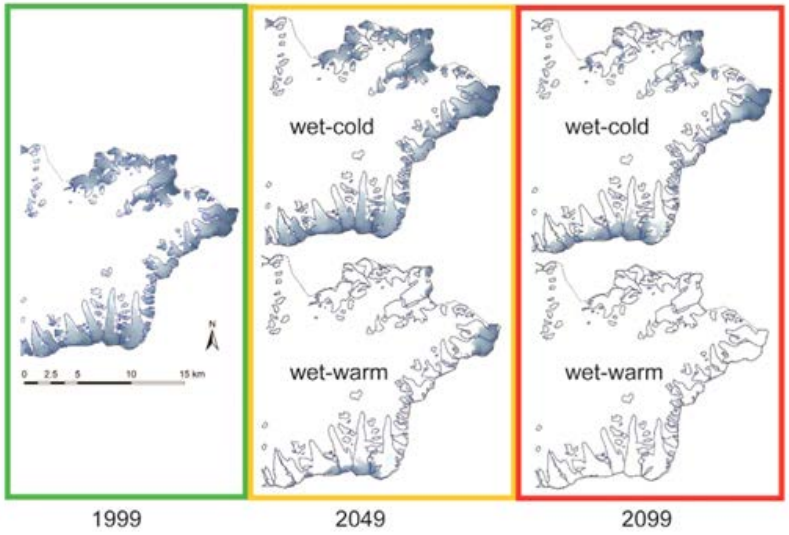


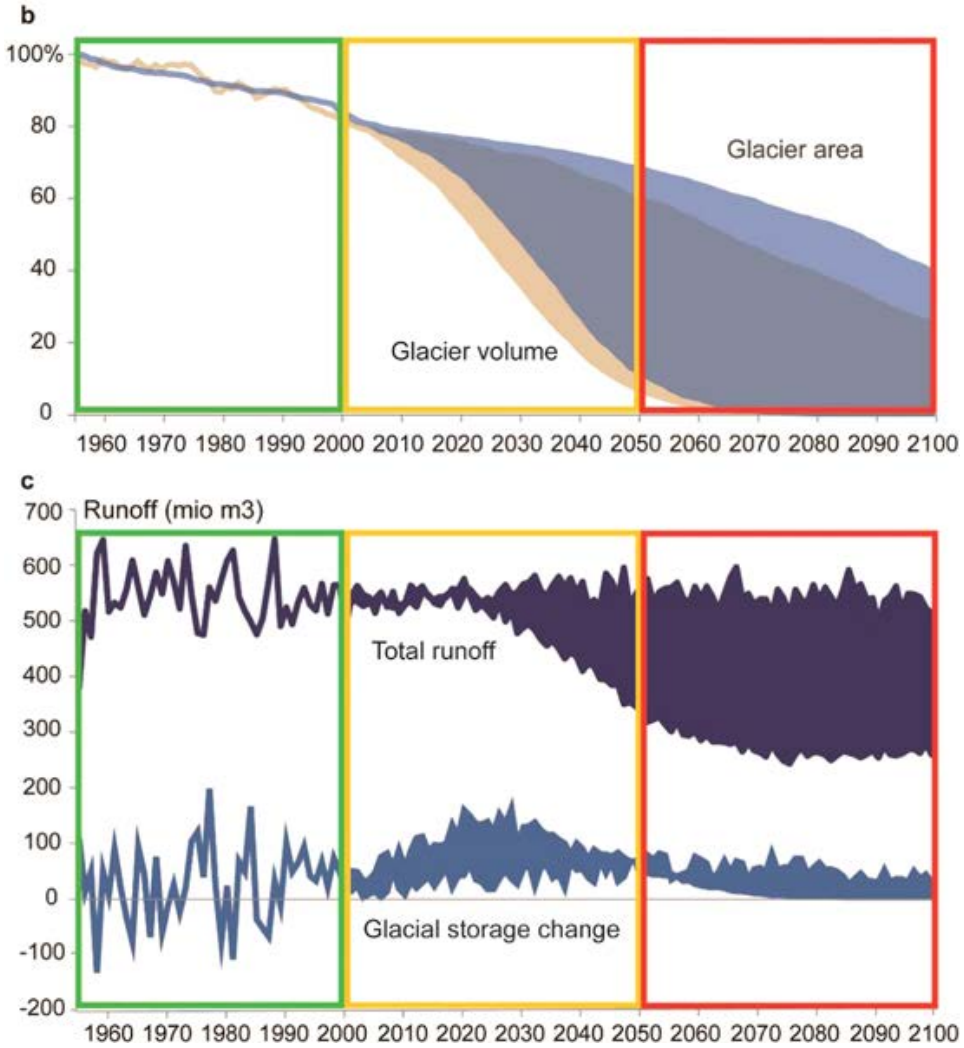
MATTMARK



(VAW, 2011)

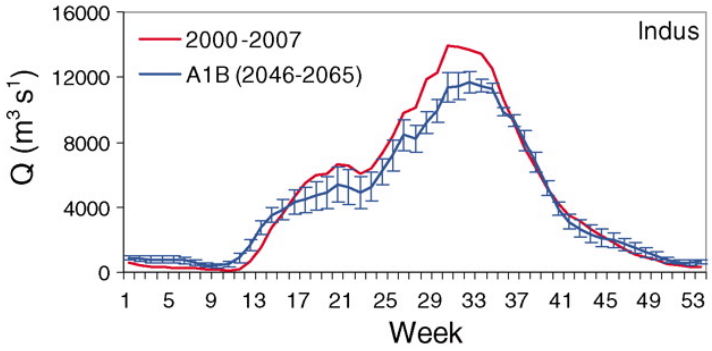
Impacts of cc on water resources: Asia

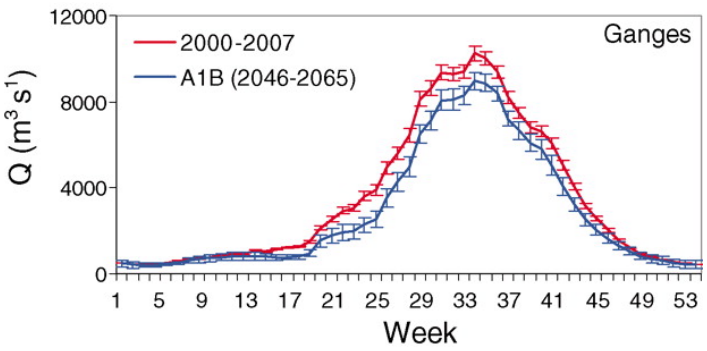


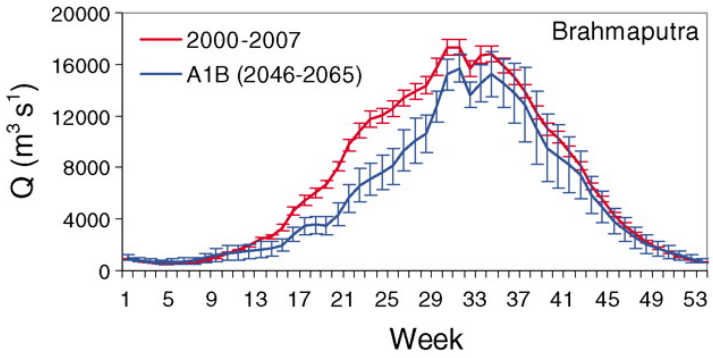


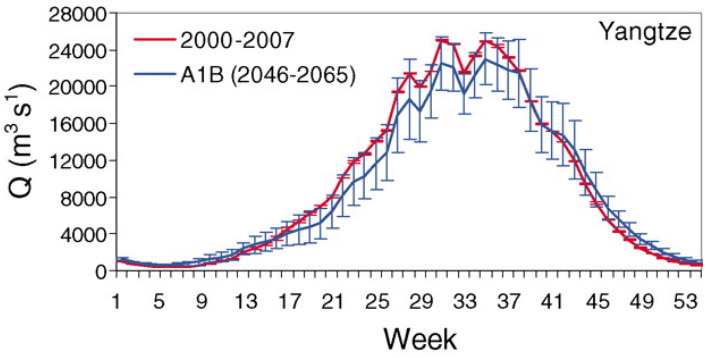
Sorg et a., 2014

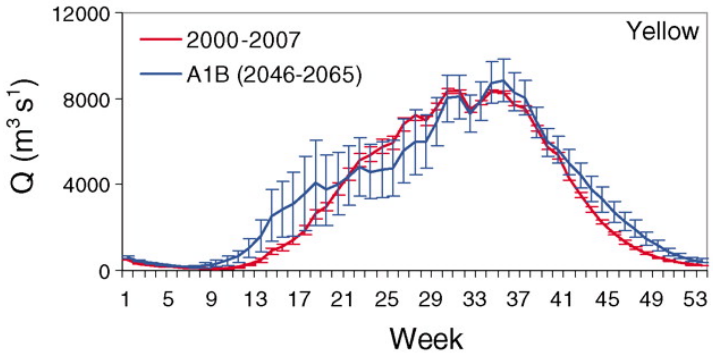
Impacts of cc on water resources: Asia







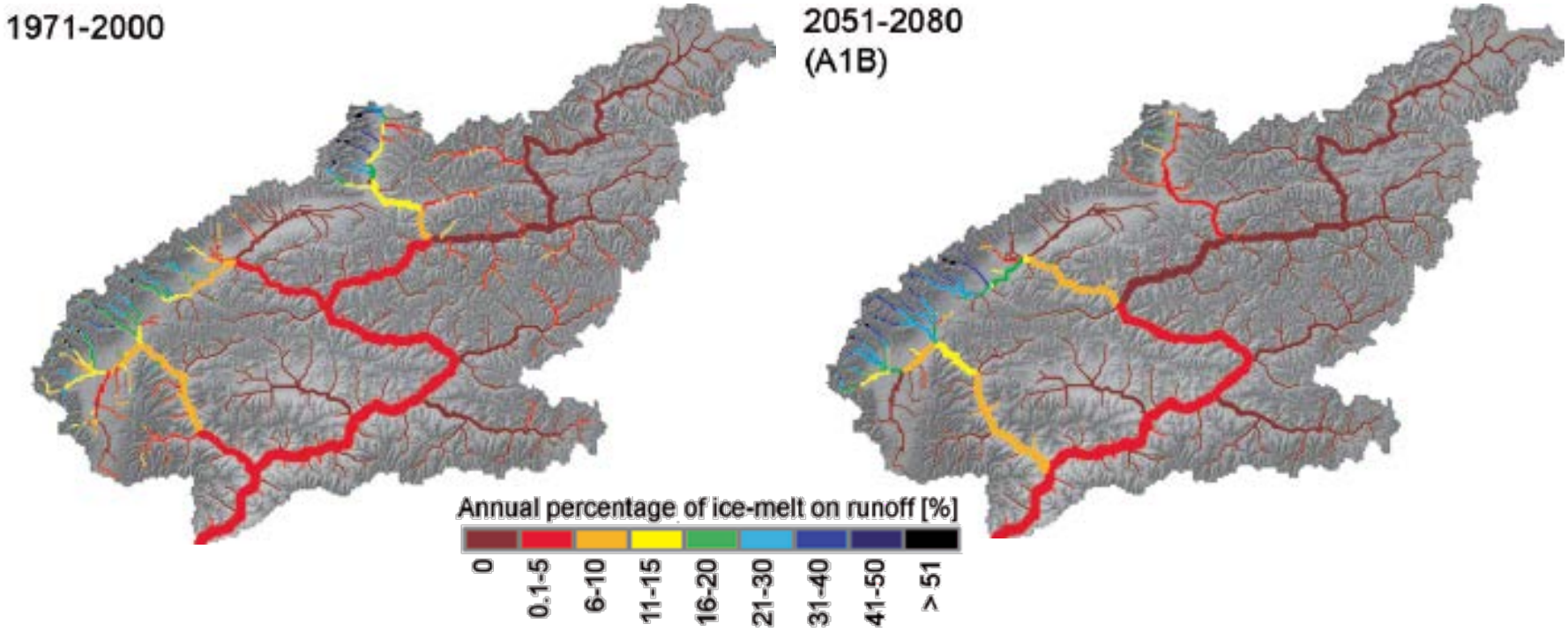




Simulated mean upstream discharge (in areas higher than 2000 m) for the present (2000 to 2007) and future climate for the A1B SRES scenario.

(Immerzeel et al., 2010)

Impacts of cc on water resources: Asia



- Mean annual runoff fraction of ice melt throughout the river network.
- Colored rivers contain ice-melt water; no ice melt contributes to runoff of brown rivers.
- The percentage is shown for the past (1971 to 2000) and the future SRES-A1B scenario period (2051–2080)

(Prasch et al. 2013)

Exercise

Exercise

Introduction

Several studies show:

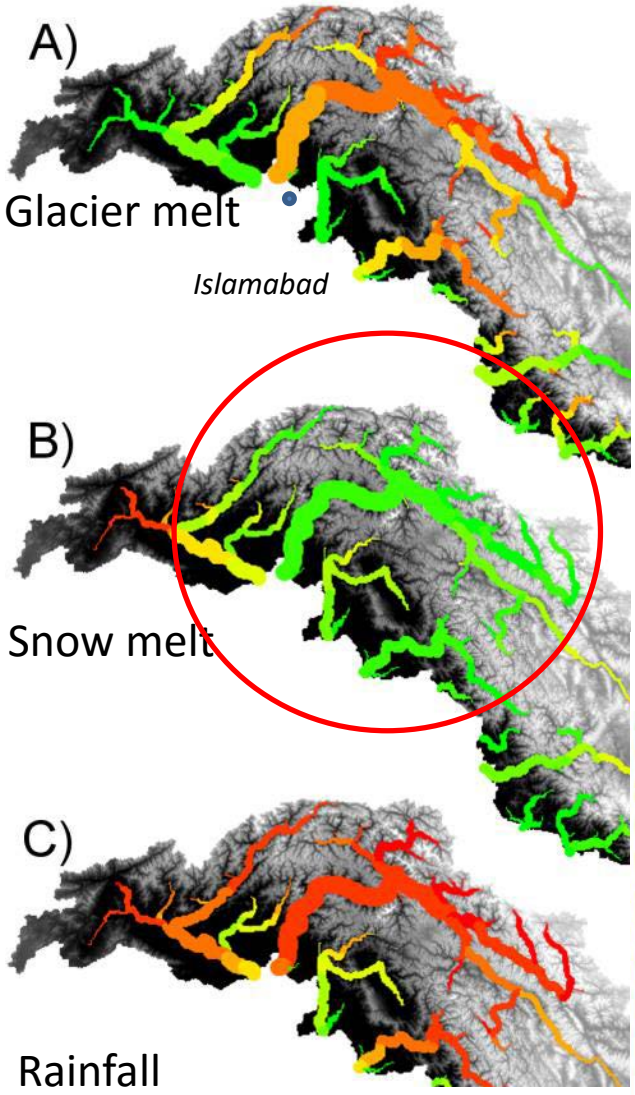
Glacier and snow meltwater affects the runoff regime of mountainous basins and is an important source of runoff in the summer months

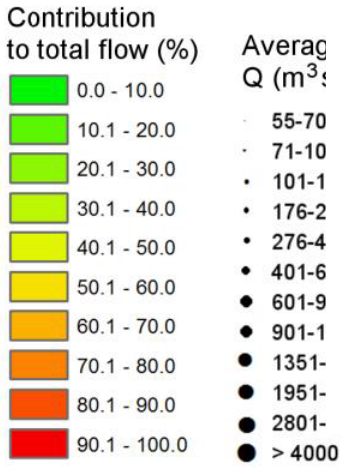
- With expected climate change impacts (e.g. glacier retreat, decreasing snow) there is an **increasing concern** about water supply security in mountain ranges
- The impact of future glacier changes on runoff is discussed with controversy and obtains widespread **public interest**

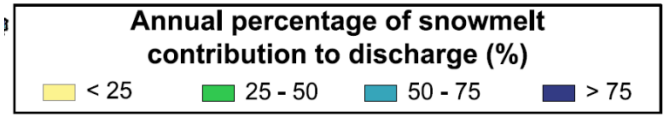
Important question:

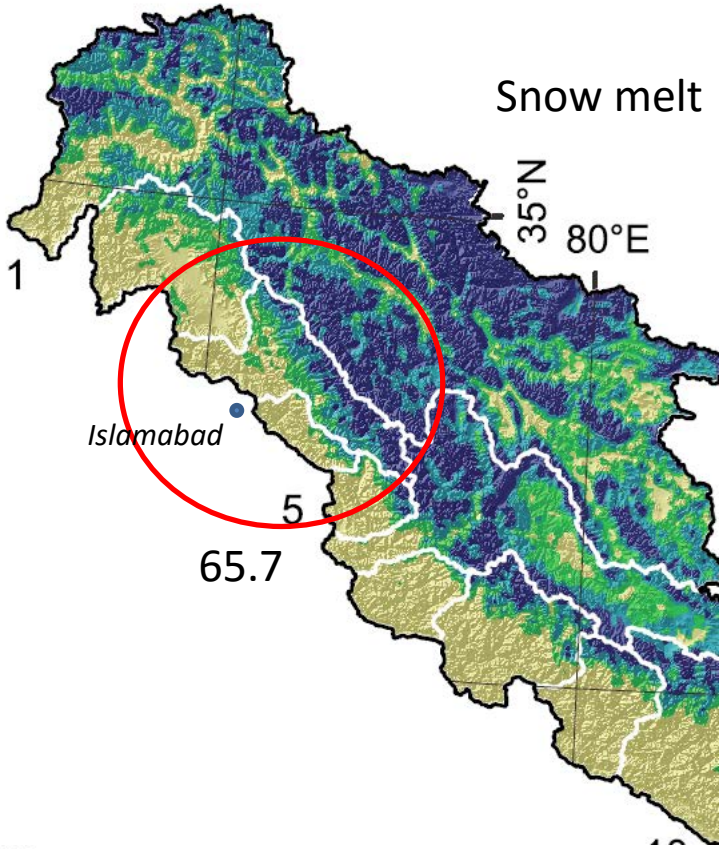
- How can we quantify the contribution of glaciers to runoff?

Exercise


A)
Glacier melt
Islamabad
B)
Snow melt
C)
Rainfall


Contribution
to total flow (%)
0.0 - 10.0
10.1 - 20.0
20.1 - 30.0
30.1 - 40.0
40.1 - 50.0
50.1 - 60.0
60.1 - 70.0
70.1 - 80.0
80.1 - 90.0
90.1 - 100.0


Annual percentage of snowmelt
contribution to discharge (%)
< 25
25 - 50
50 - 75
> 75

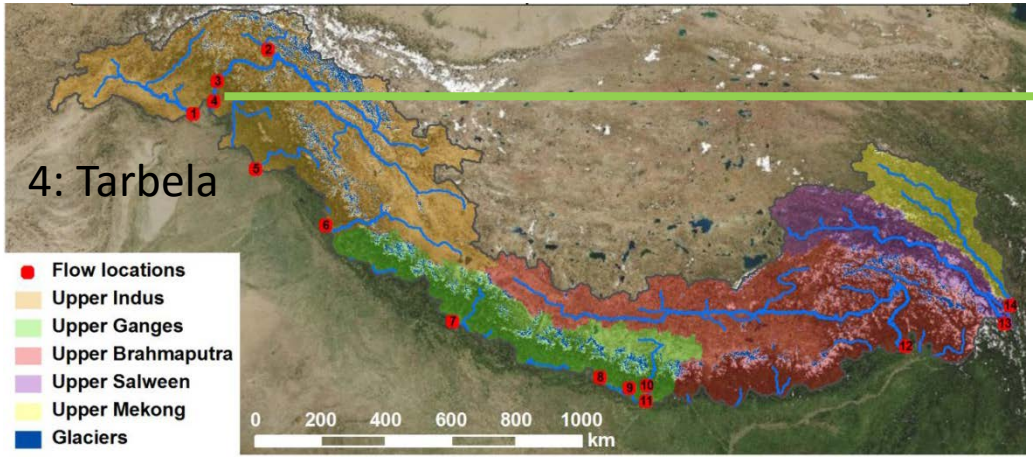

Snow melt
35°N
80°E
1
Islamabad
5
65.7

Exercise

	Indus at Tarbela (Lutz and Immerzeel 2013)	Indus at Tarbela (Bookhagen and Burbank 2010)
Glacier melt (%)	28	65.7 no distinction between snow and ice
Snow melt (%)	55	
Rainfall (%)	13	100 - 65.7 = 34.3
Baseflow (%)	5	not considered
Evapotranspiration (%) (negative contribution)	considered, but no information in the publication	2.2
Annual precipitation (mm)	(346 in upper Indus, gridded APHRODITE)	300 (TRMM PR)
Area	203'142	205'536
Annual runoff	2307 m^3/s = 358 mm (simulated)	4200 m^3/s = 644 mm (simulated)

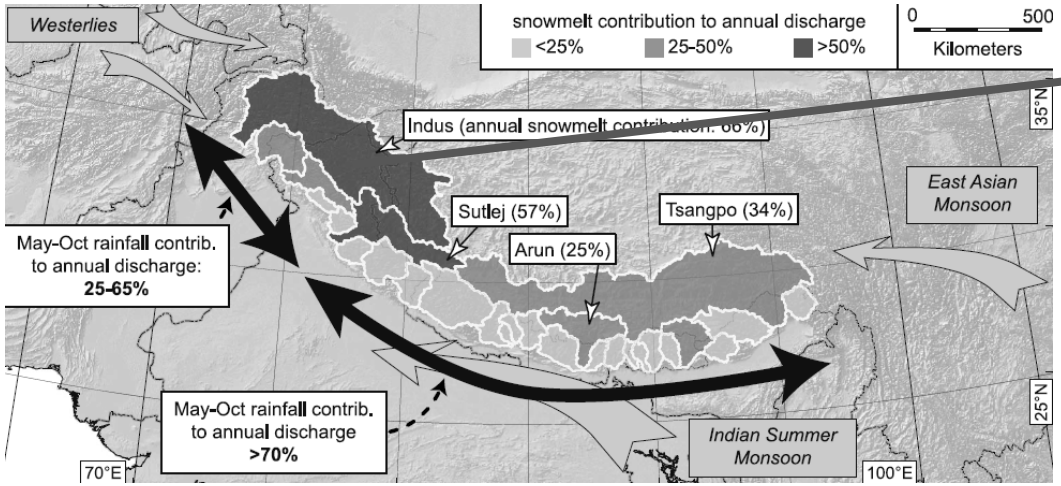
Exercise

- Explain the differences



(Lutz and Immerzeel 2013)

83% snow and ice melt contribution



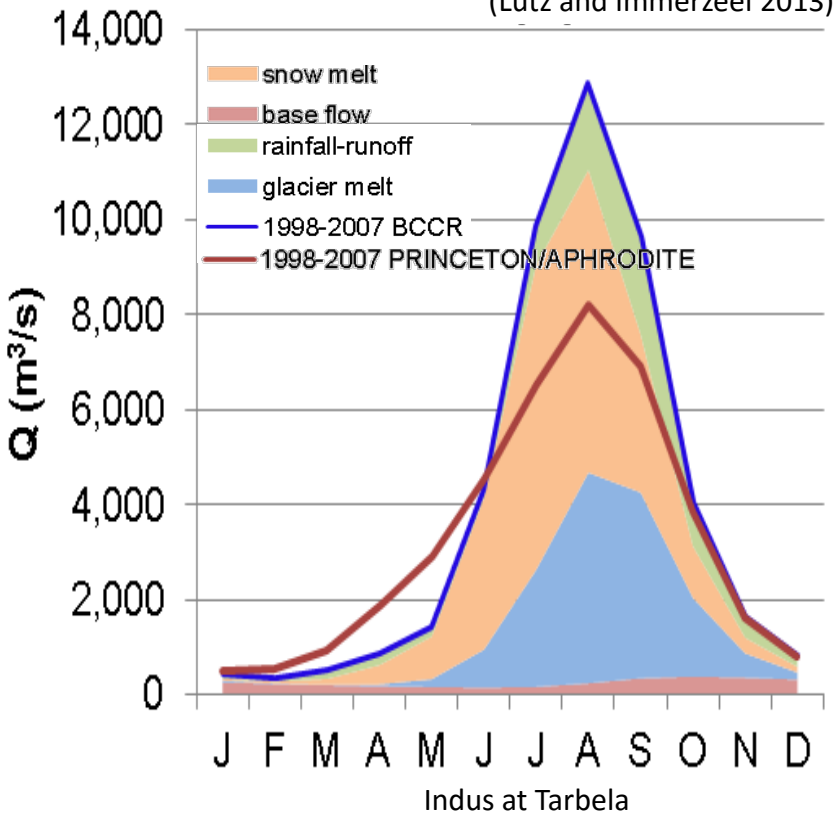
(Bookhagen and Burbank 2010)

65.7% snow and ice melt contribution

Exercise

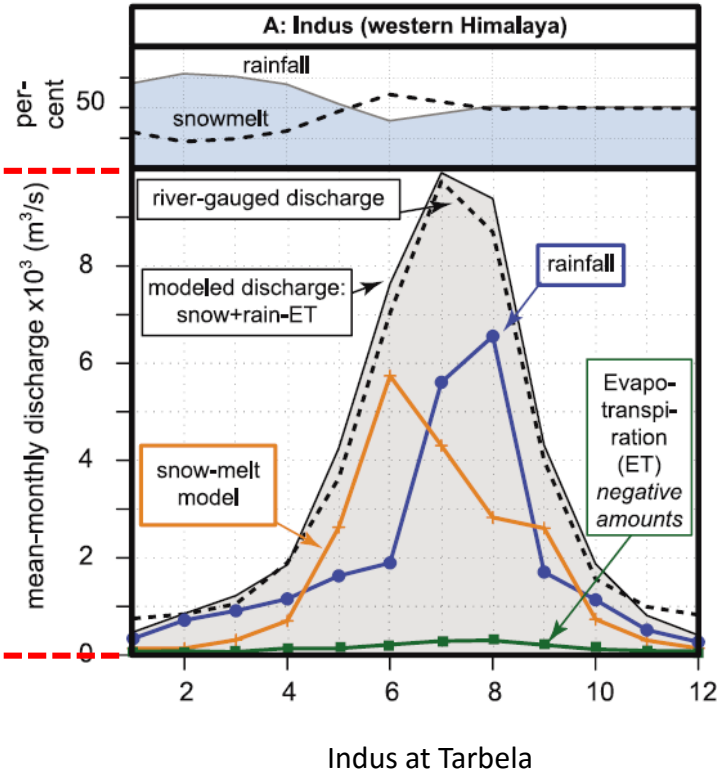
Annual hydrograph 1998-2007

(Lutz and Immerzeel 2013)



Annual hydrograph

(Bookhagen and Burbank 2010)

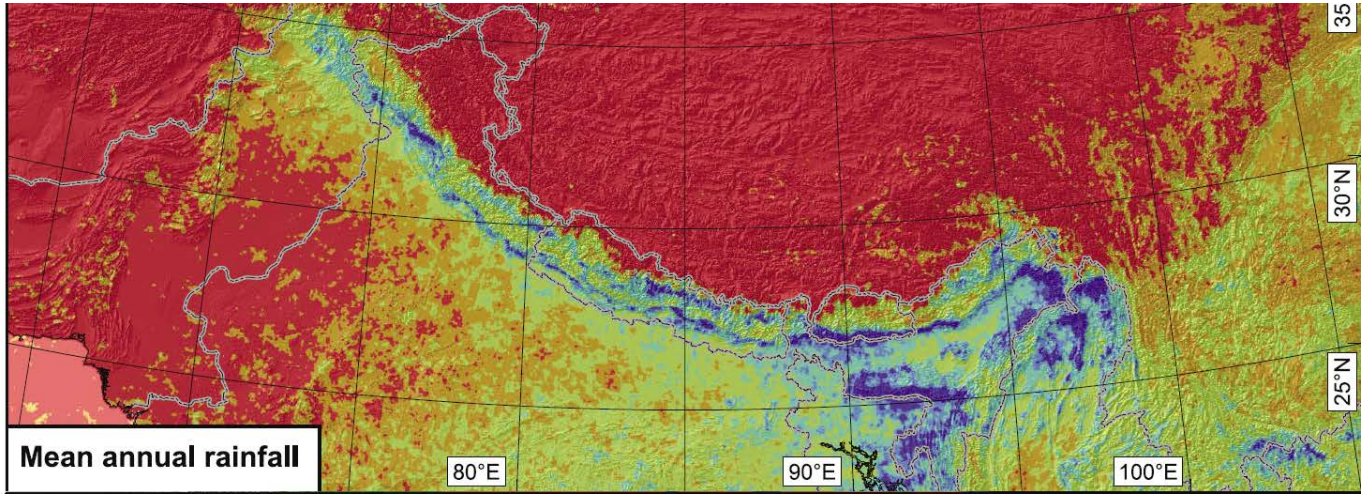


- Describe and discuss the main differences between the two annual hydrographs

Exercise

Input for rainfall in Bookhagen and Burbank 2010

- Mean annual rainfall
- based on calibrated TRMM 2B31 data
- averaged over 10 years from 1998 to 2007



(Bookhagen and Burbank 2010)

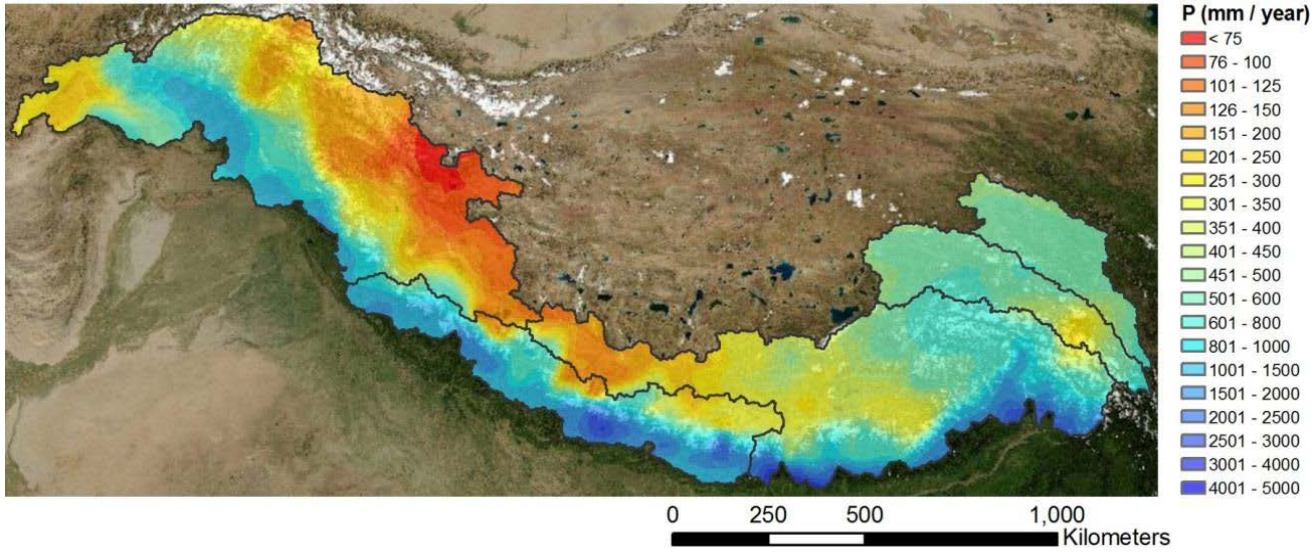
Exercise

Input for rainfall in Lutz and Immerzeel 2013

- daily precipitation data are taken from the gridded APHRODITE product for daily precipitation input
- For the reference period (1998-2007)

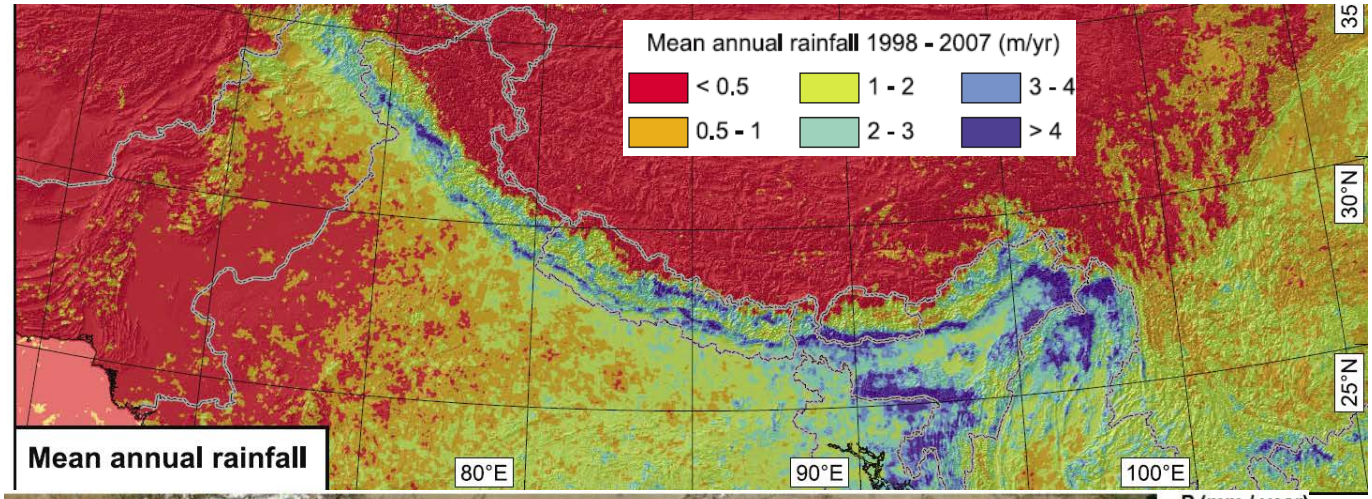
APHRODITE is based on rain gauge data and is available at 0.25 x 0.25° spatial resolution and daily temporal resolution.

(Lutz and Immerzeel 2013)

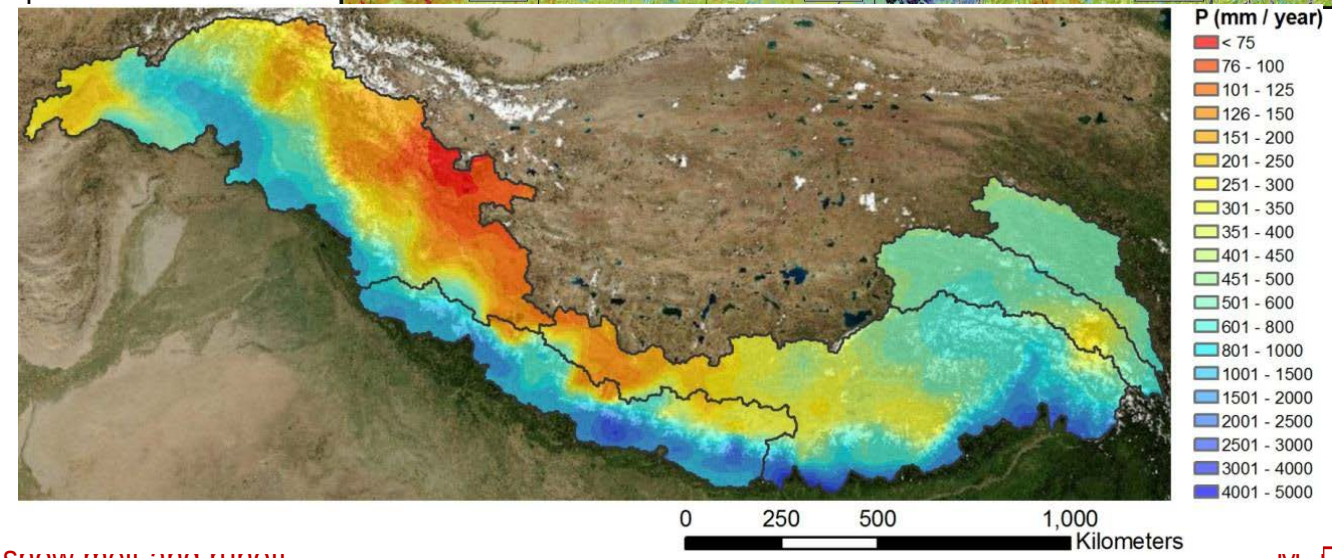


Exercise

- Compare the maps of mean annual precipitation derived by TRMM PR and APHRODITE (Resolution, pattern, maximum values, etc.)



(Bookhagen and Burbank 2010)



(Lutz and Immerzeel 2013)