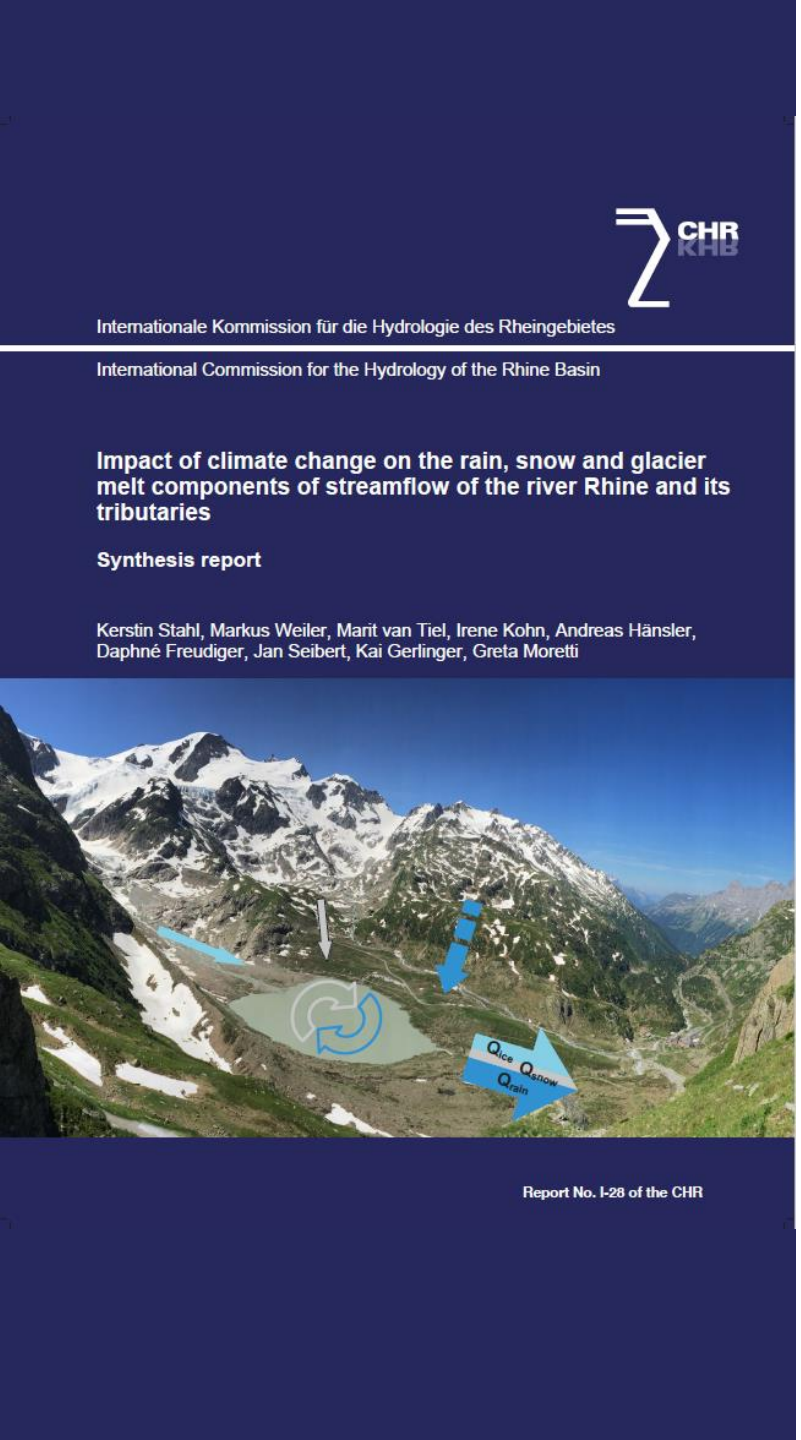

CHR KHB

Internationale Kommission für die Hydrologie des Rheingebietes

International Commission for the Hydrology of the Rhine Basin

Impact of climate change on the rain, snow and glacier melt components of streamflow of the river Rhine and its tributaries

Synthesis report

Kerstin Stahl, Markus Weiler, Marit van Tiel, Irene Kohn, Andreas Hänsler, Daphné Freudiger, Jan Seibert, Kai Gerlinger, Greta Moretti

Report No. I-28 of the CHR

ASG Qice, Qsnow, Qrain:

Modelling future streamflow components along the Rhine with LARSIM

Kai Gerlinger, Greta Moretti

ASG Team University Freiburg

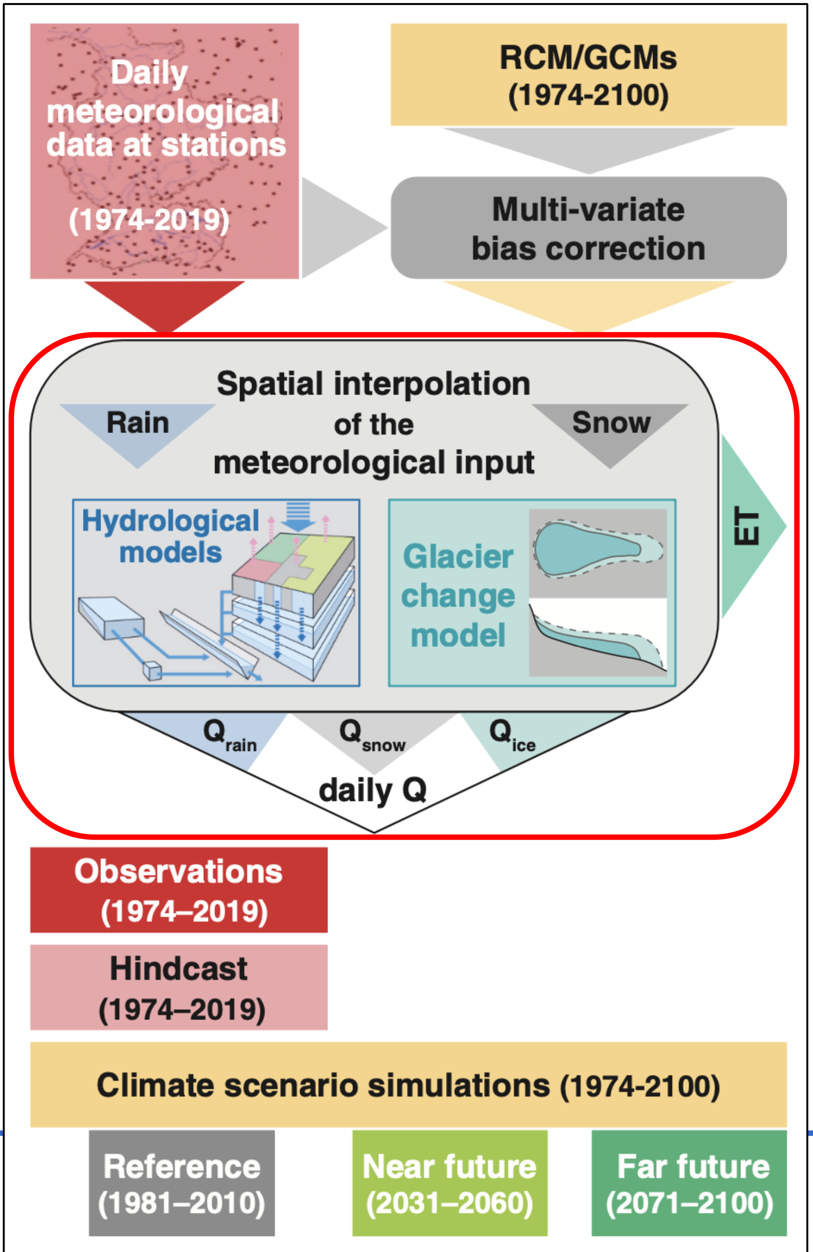
CHR Symposium 1.+ 2. June 2022 in Olten, Switzerland

Universität Zürich UZH

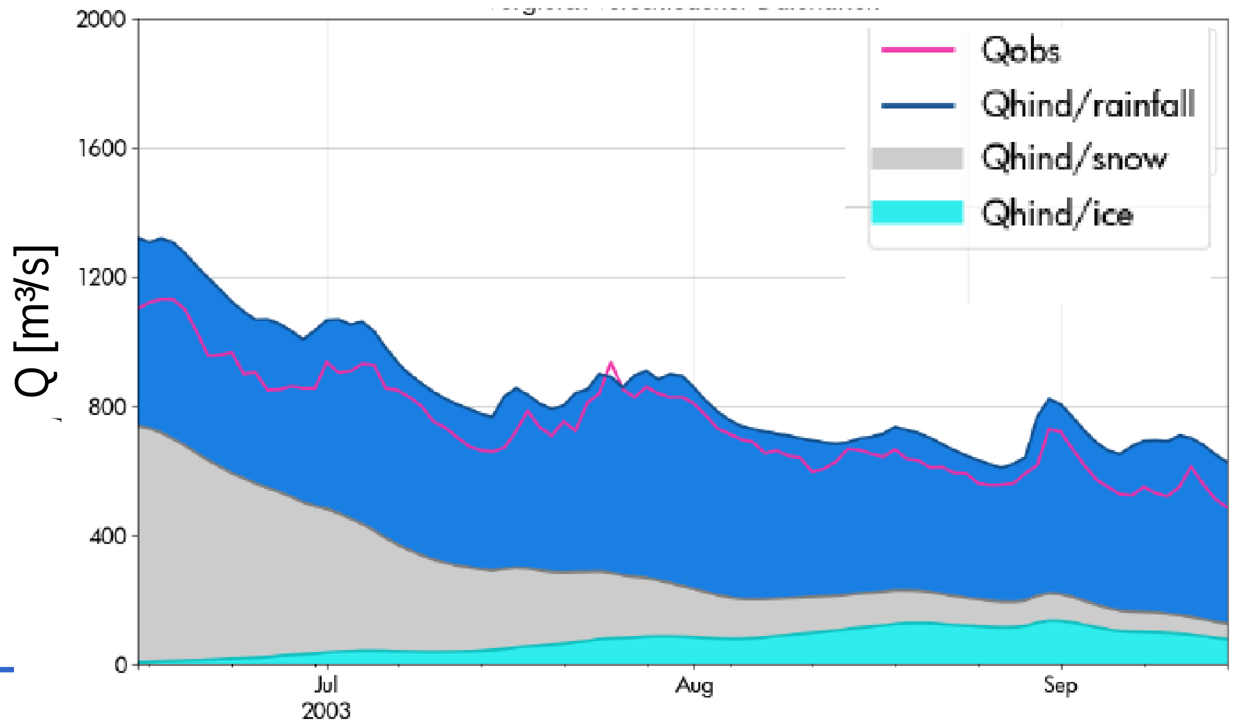
HYDRON UMWELT und WASSERWIRTSCHAFT

UNI FREIBURG

The model approach



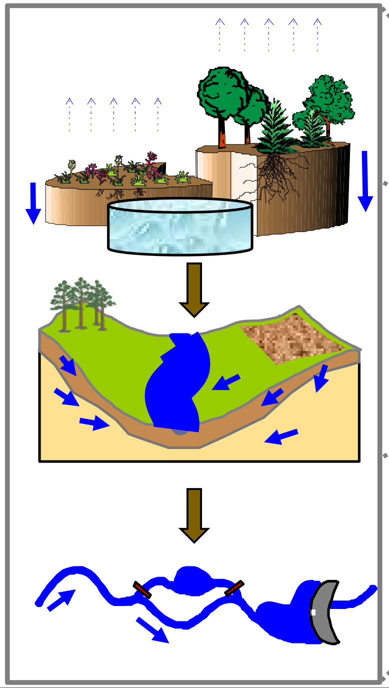
- RCP8.5
- 7-member ensemble (5 GCMs, 2 RCMs)
- Glacierized headwater catchments simulated by the conceptual hydrological HBV-Light model
- Remaining parts of the Rhine basin simulated by the water balance model LARSIM

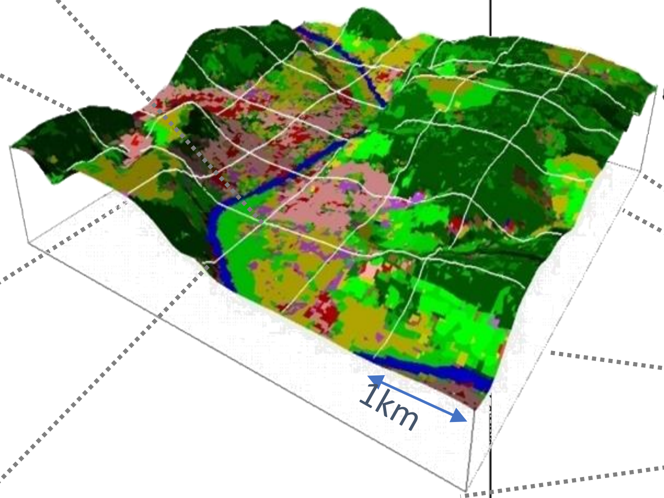


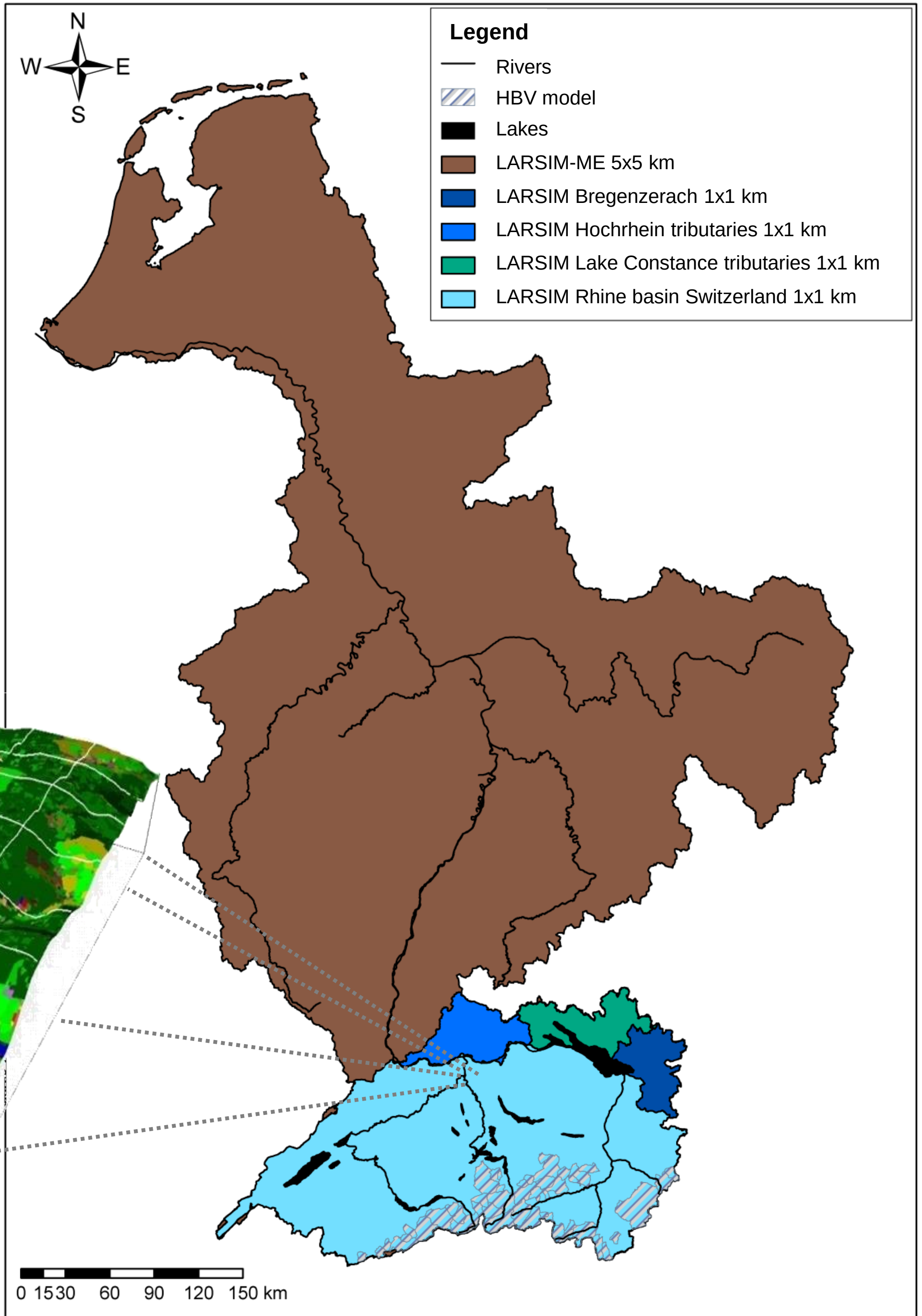
Discharge at Basel/Rhine (hindcast simulation 2003)

The model approach

- Water balance models with LARSIM: model resolution of 1x1km² upstream of Basel and 5x5km² downstream of Basel.
- Consideration of reservoir storage as well as lake regulations (based on how they are currently operating).







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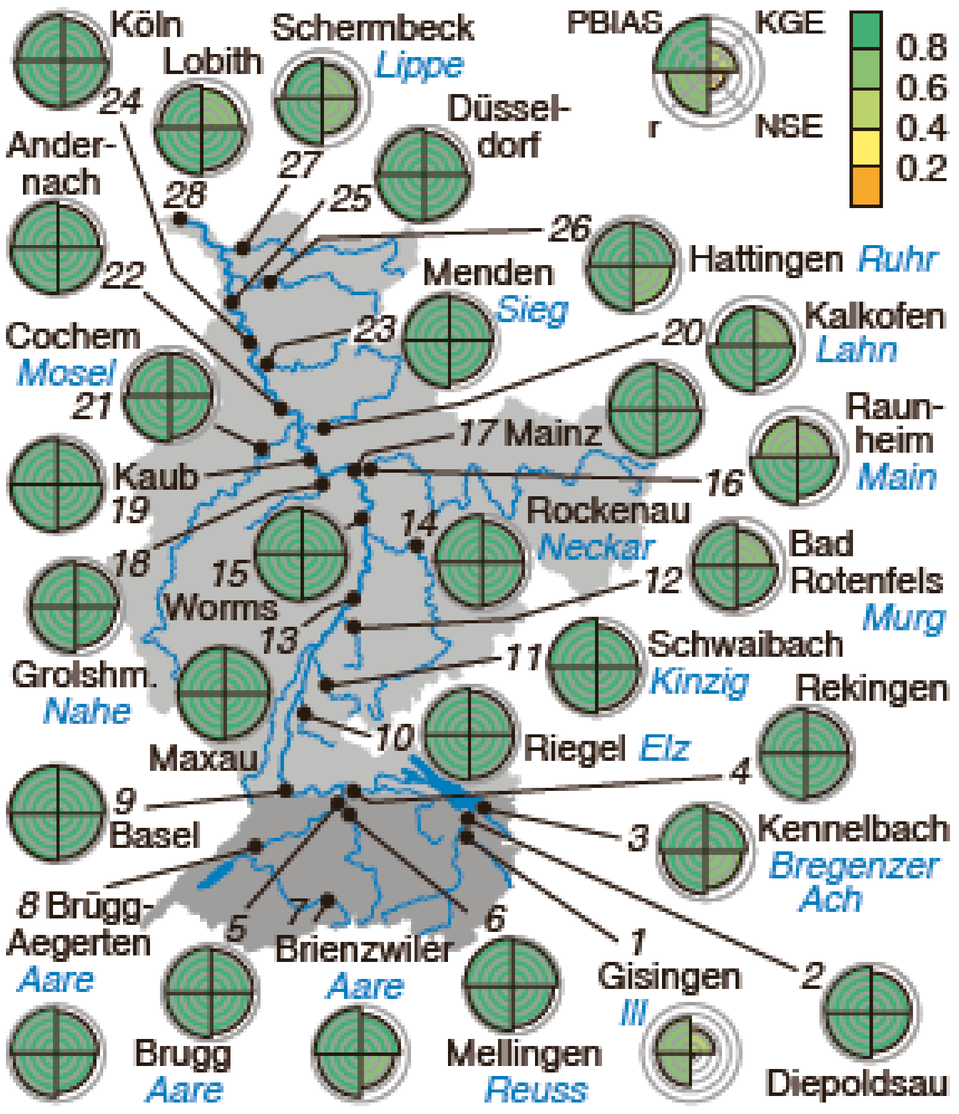
The model approach

- The LARSIM models, versions of which are used as operational hydrological models, were not recalibrated for this project.
- Most of the gauges show a good model performance.



Model performance measures for streamflow in the period 1981–2010 at selected gauges:

- *Kling-Gupta-Model efficiency (KGE): for overall performance*
- *Nash-Sutcliffe efficiency of the logarithm of streamflow (NSE): for low flow representation*
- *Correlation coefficient (r): for agreement of relative variations*
- *Normalized bias measure (PBIAS): for overall deviation*

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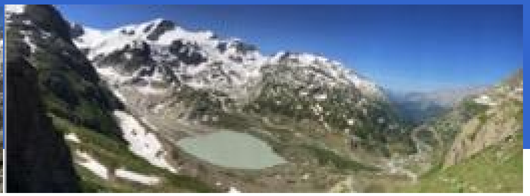
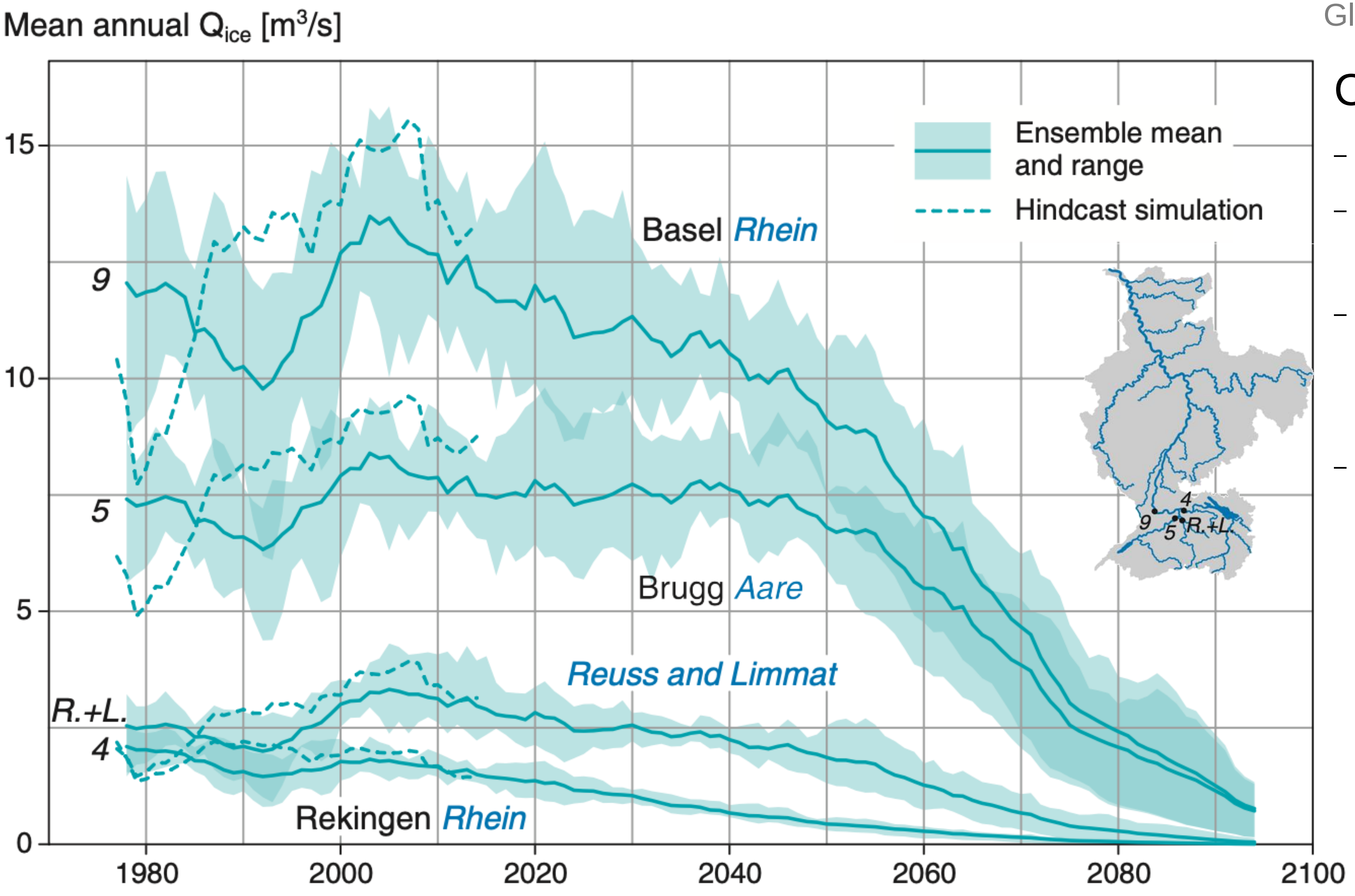
Modelled transient change in Qice

Glaciated headwaters



Deglaciating landscape



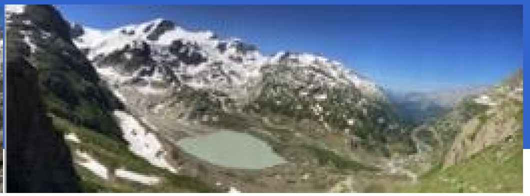
Changes of the ice component Qice:

- Qice far future: > 80% reduced.
- Qice in the Rhine at Basel has already passed its peak (“glacier peak water”).
- For the Rhine at Basel and the tributaries Reuss and Limmat: decline already started end of the reference period.
- For the Aare river: consistent Qice contribution until 2040 (Aare headwaters have the largest glaciers)

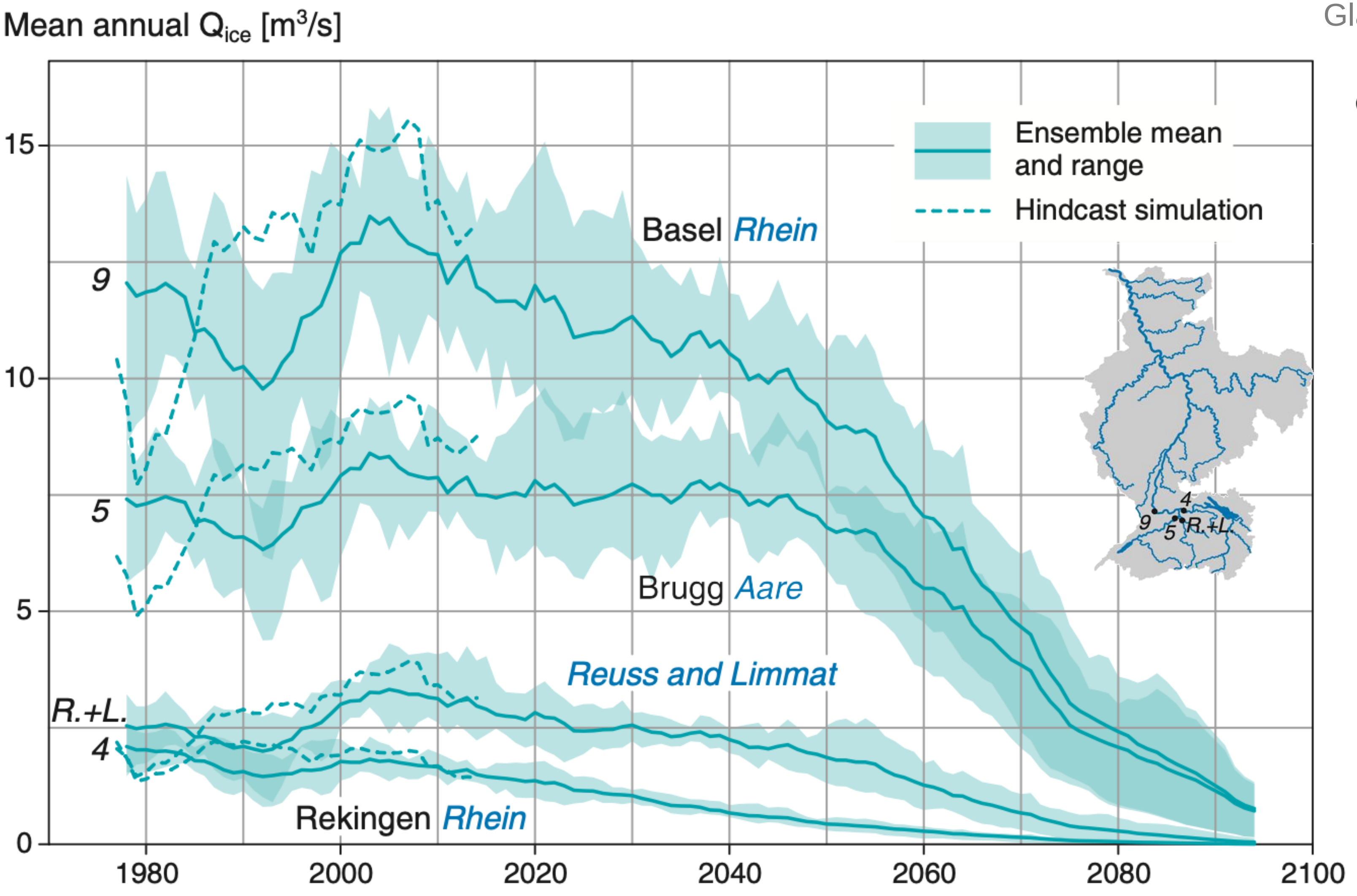
11-year moving averages of hindcast and climate scenario simulations of mean annual Qice

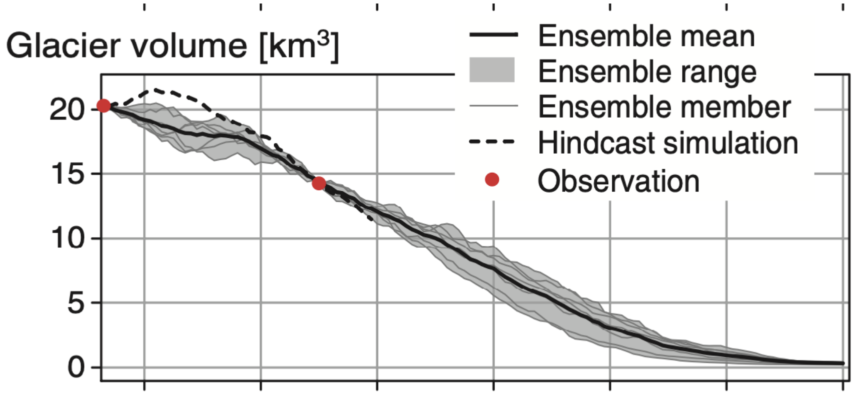
Modelled transient change in Qice

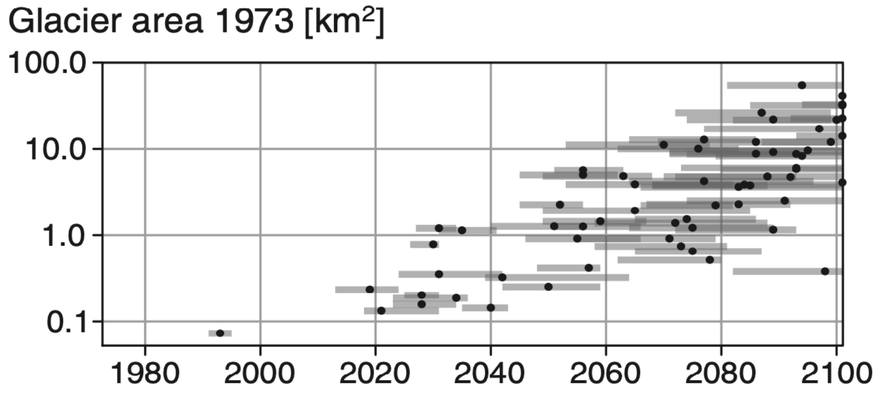
Glaciated headwaters



Deglaciating landscape







Total glacier volume and year of glacier disappearence

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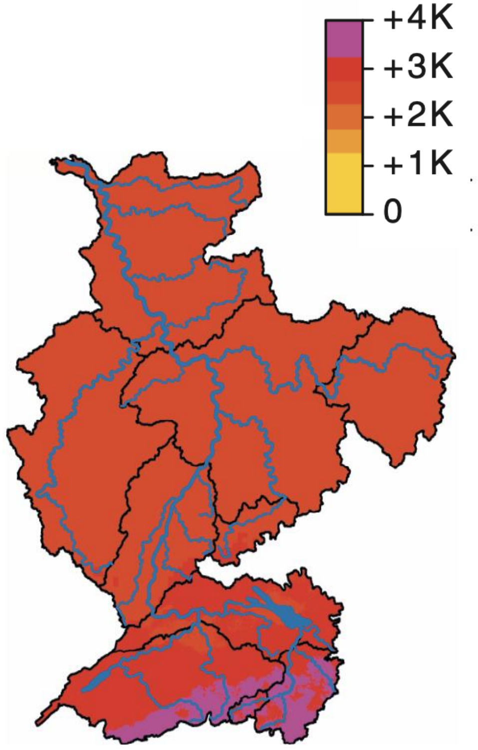
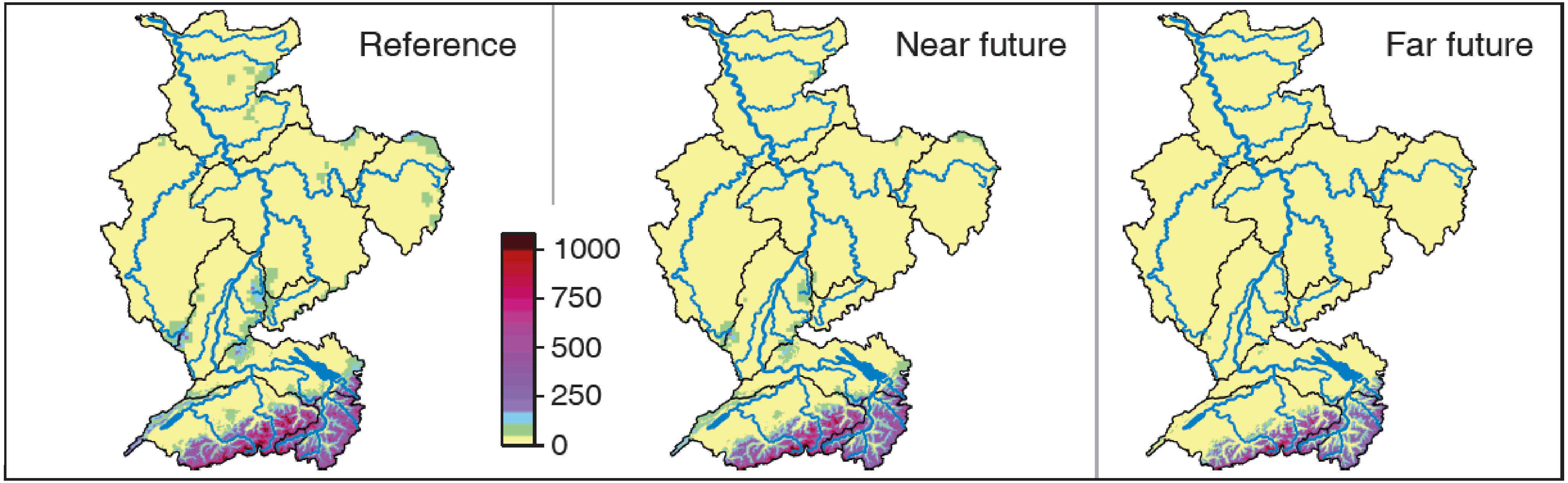
11-year moving averages of hindcast and climate scenario simulations of mean annual Qice

Modelled transient change in Qsnow

- Areas with seasonal snowpacks will decrease in the Alps.
- Snowfall will still occur in the central European upland regions but towards the end of the century there will be no substantial accumulation of snow anymore in those regions.

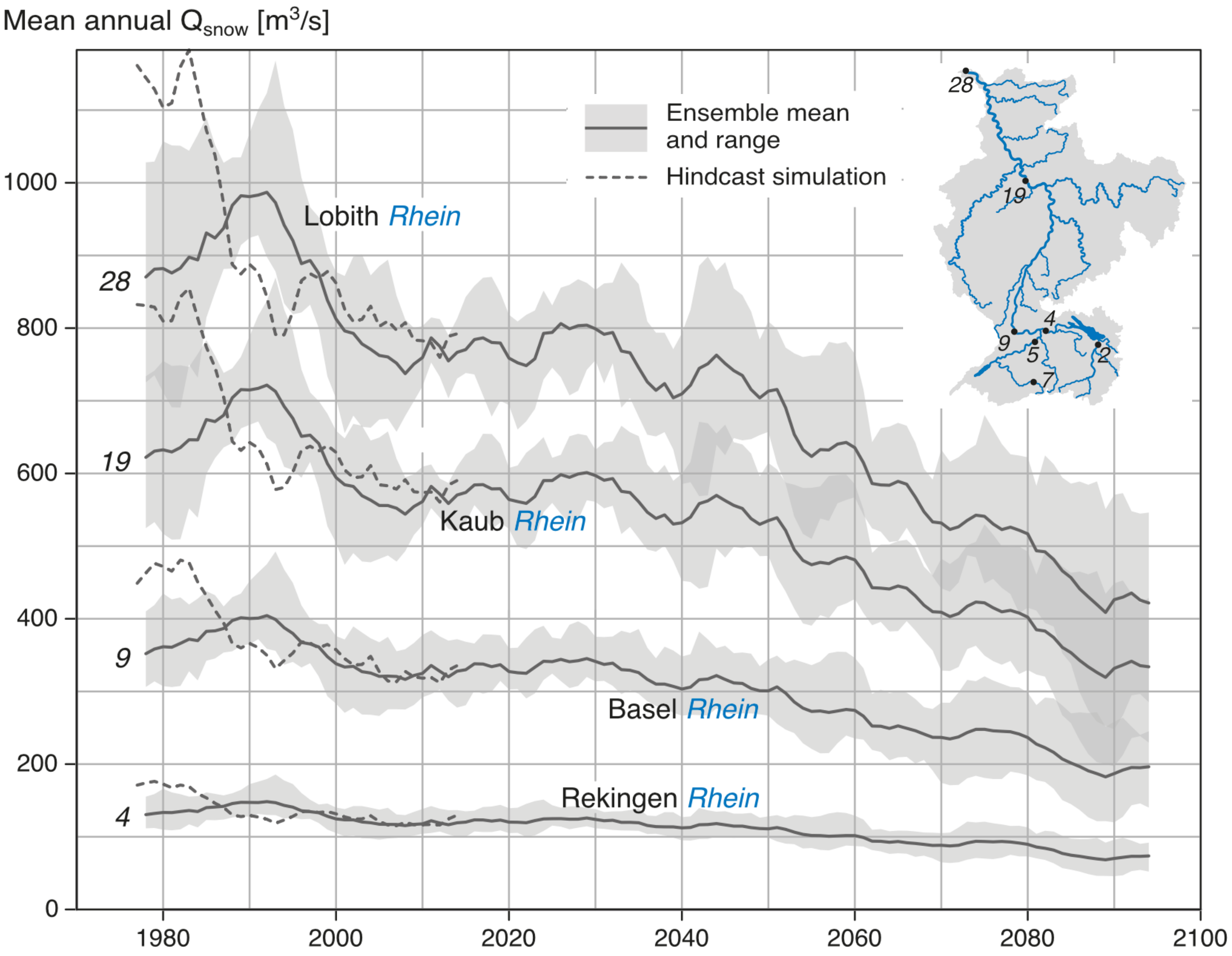
Temperature change: Far future relative to the reference period (ensemble means)





Ensemble mean of the maximum monthly snow water equivalent (SWE in mm)

Modelled transient change in Qsnow

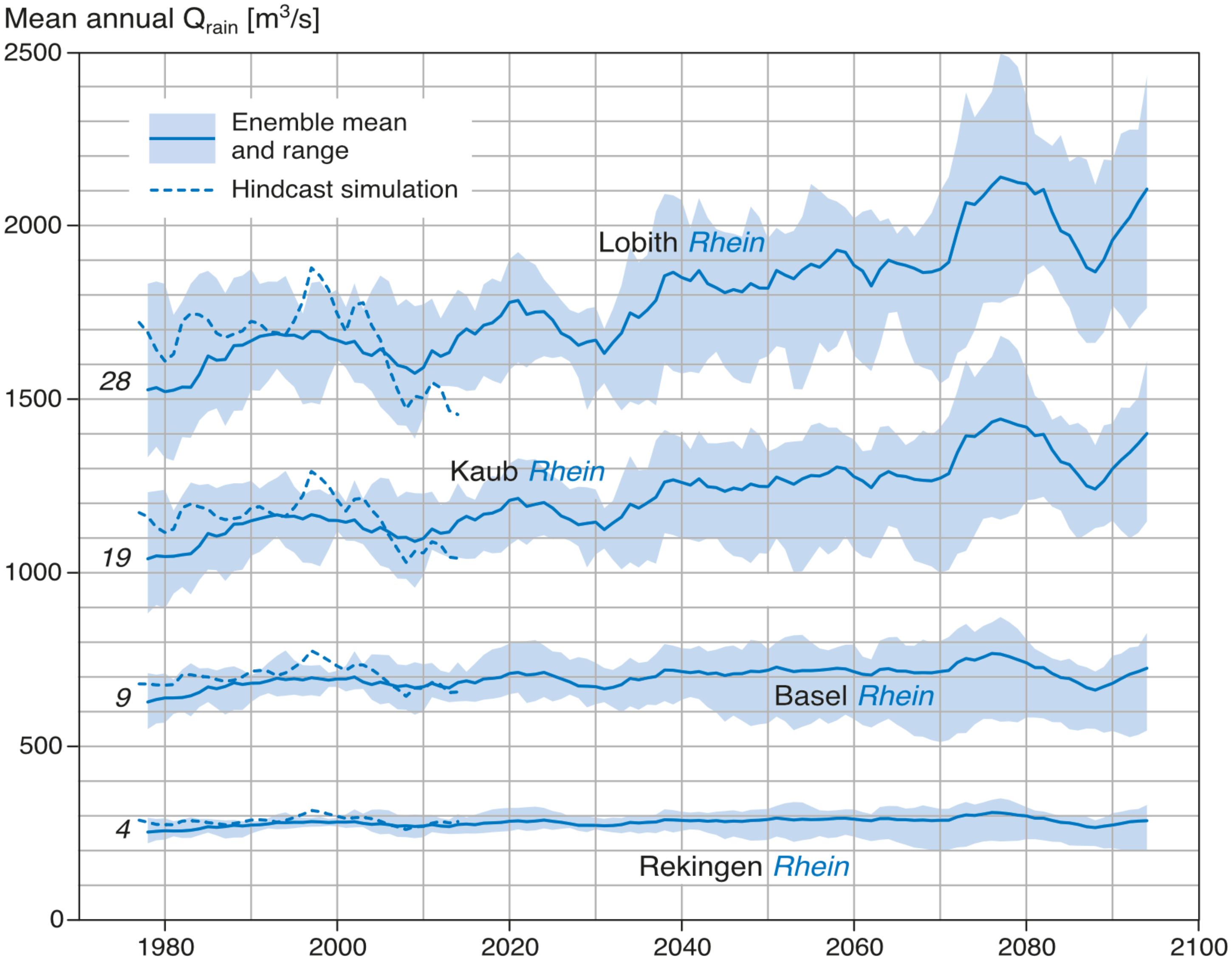


Changes of the snow component Qsnow:

- Qsnow will decrease in all tributaries and in the River Rhine.
- Decrease during the reference period, then small additional change until about 2030, then increased decline.
- At Lobith, the simulated Qsnow decreases from 800 - 900 m³/s to about half by 2100.
- Relative fractions of snow from upstream and downstream of Basel don't change substantially in the future.
- Various regions will continue to contribute Qsnow in the future.

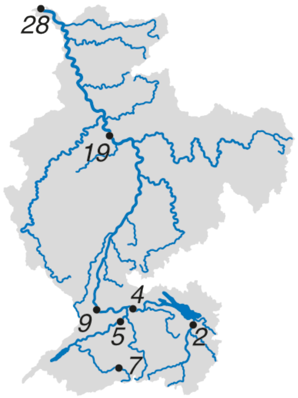
11-year moving averages of hindcast and climate scenario simulations of mean annual Qsnow

Modelled transient change in Qrain



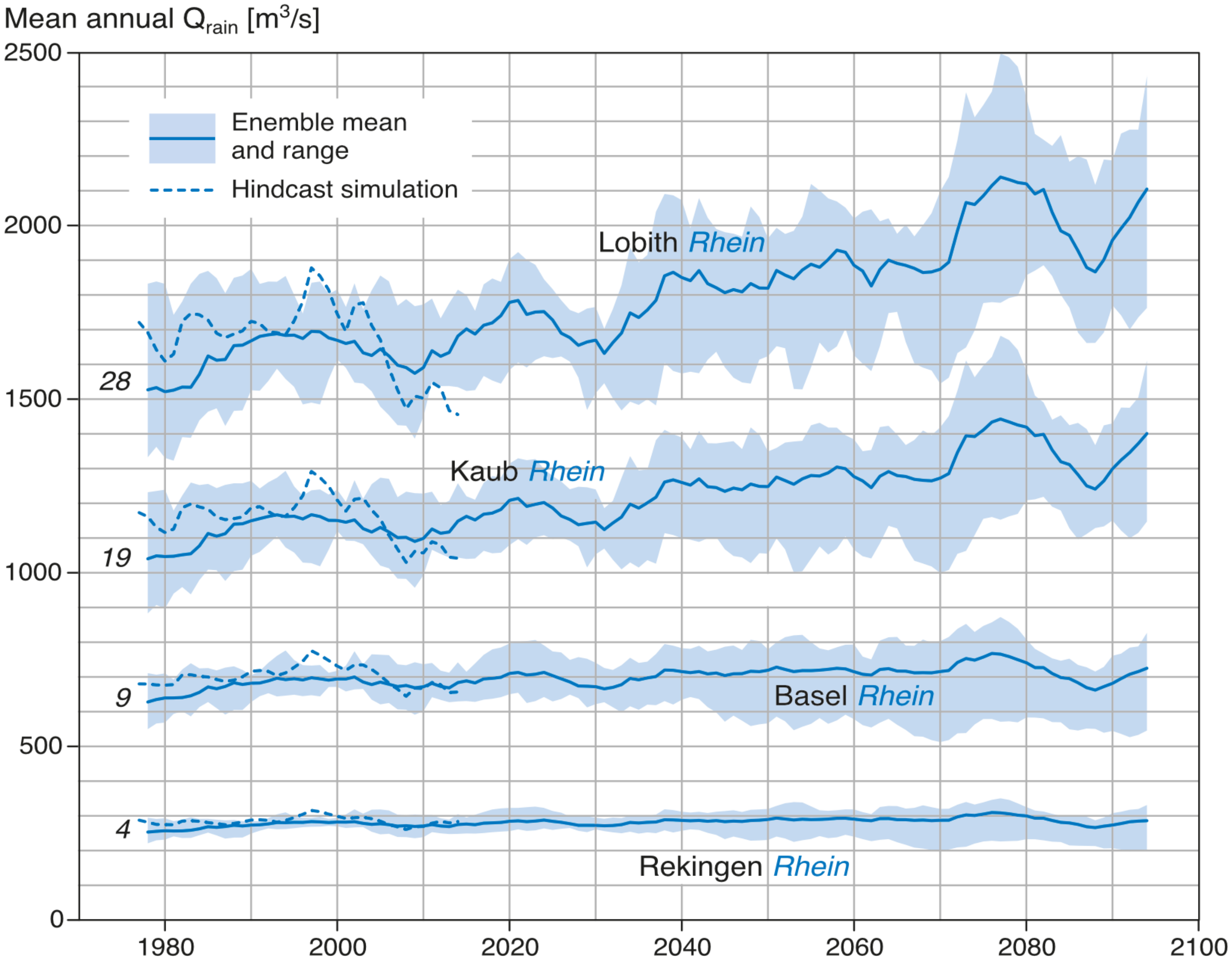
Changes of the rain component Qrain:

- In the Rhine at Basel and Rekingen, changes in Qrain are small with a decrease in the lower ensemble range.
- Qrain will increase stronger later in the century and larger in the downstream reaches.



11-year moving averages of hindcast and climate scenario simulations of mean annual Qrain

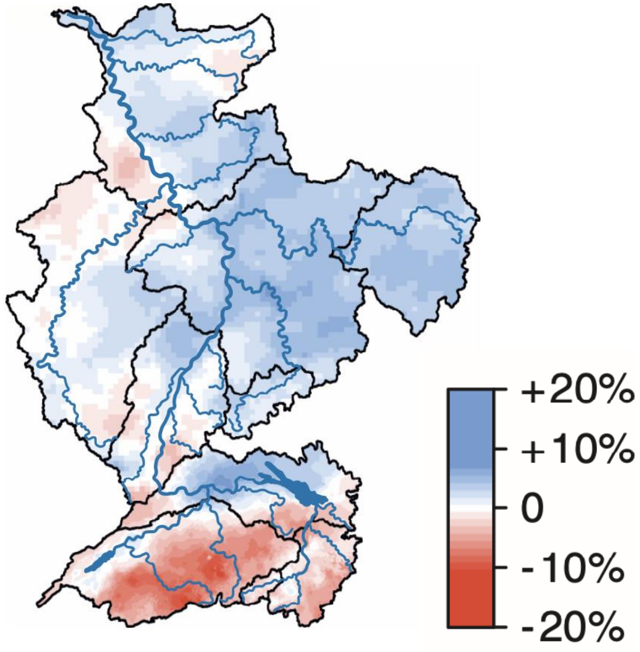
Modelled transient change in Qrain



Precipitation changes:

- Upstream of Basel: annual precipitation decreases (no compensation of summer decrease by increasing winter precipitation).
- Downstream of Basel: annual precipitation increases (compensation of summer decrease by increasing winter precipitation).

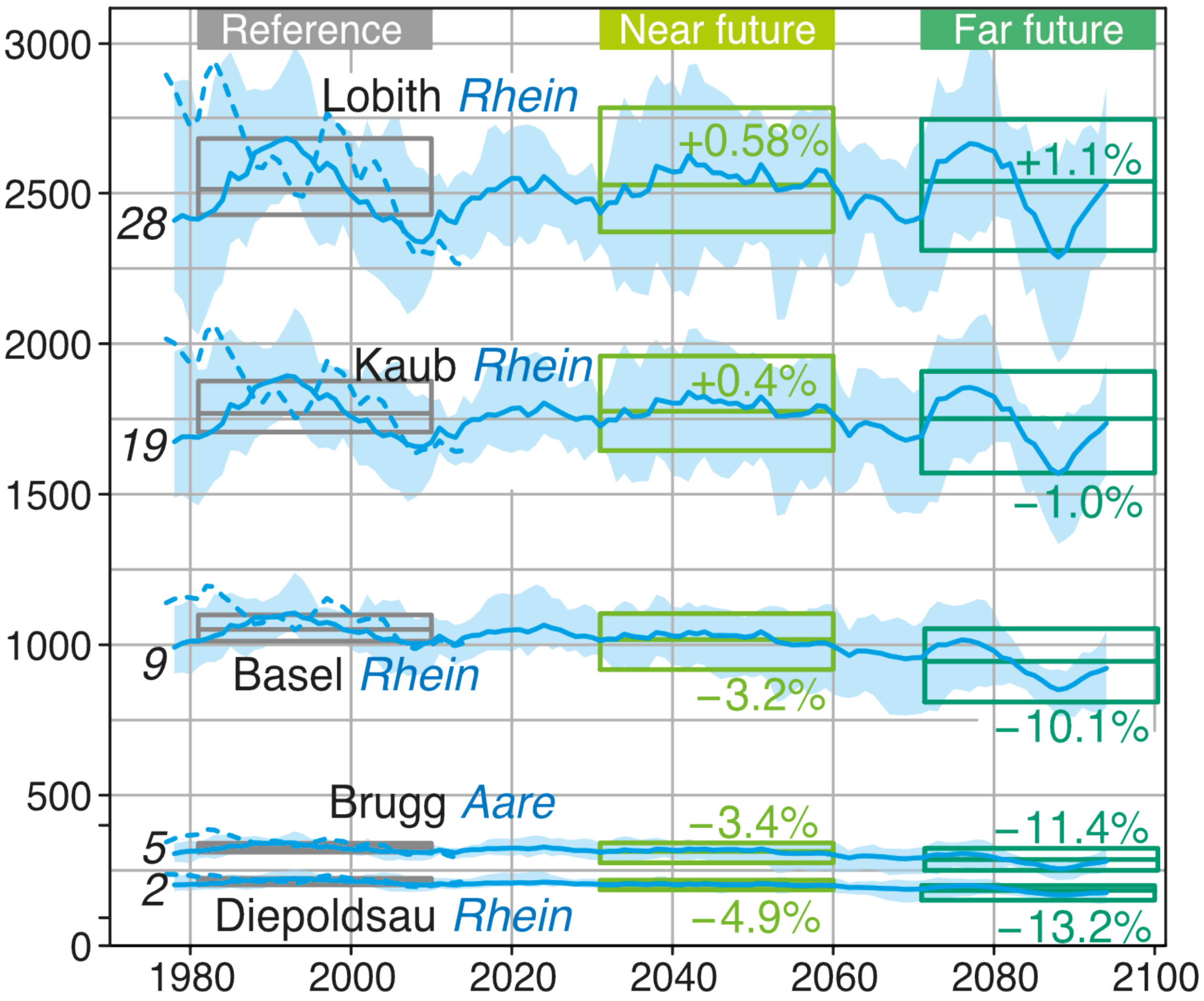
Annual precipitation change: Far future relative to the reference period



11-year moving averages of hindcast and climate scenario simulations of mean annual Qrain

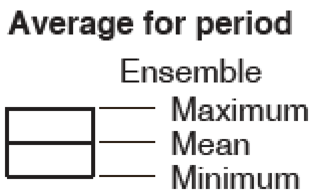
Modelled transient change in total Q

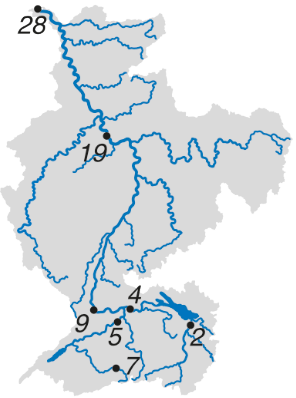
Mean annual streamflow [m³/s]



Changes in annual stream flow:

- Decreasing streamflow in the alpine tributaries (e.g. Aare, Rhine at Diepoldsau and Basel) reflects the changes in precipitation.

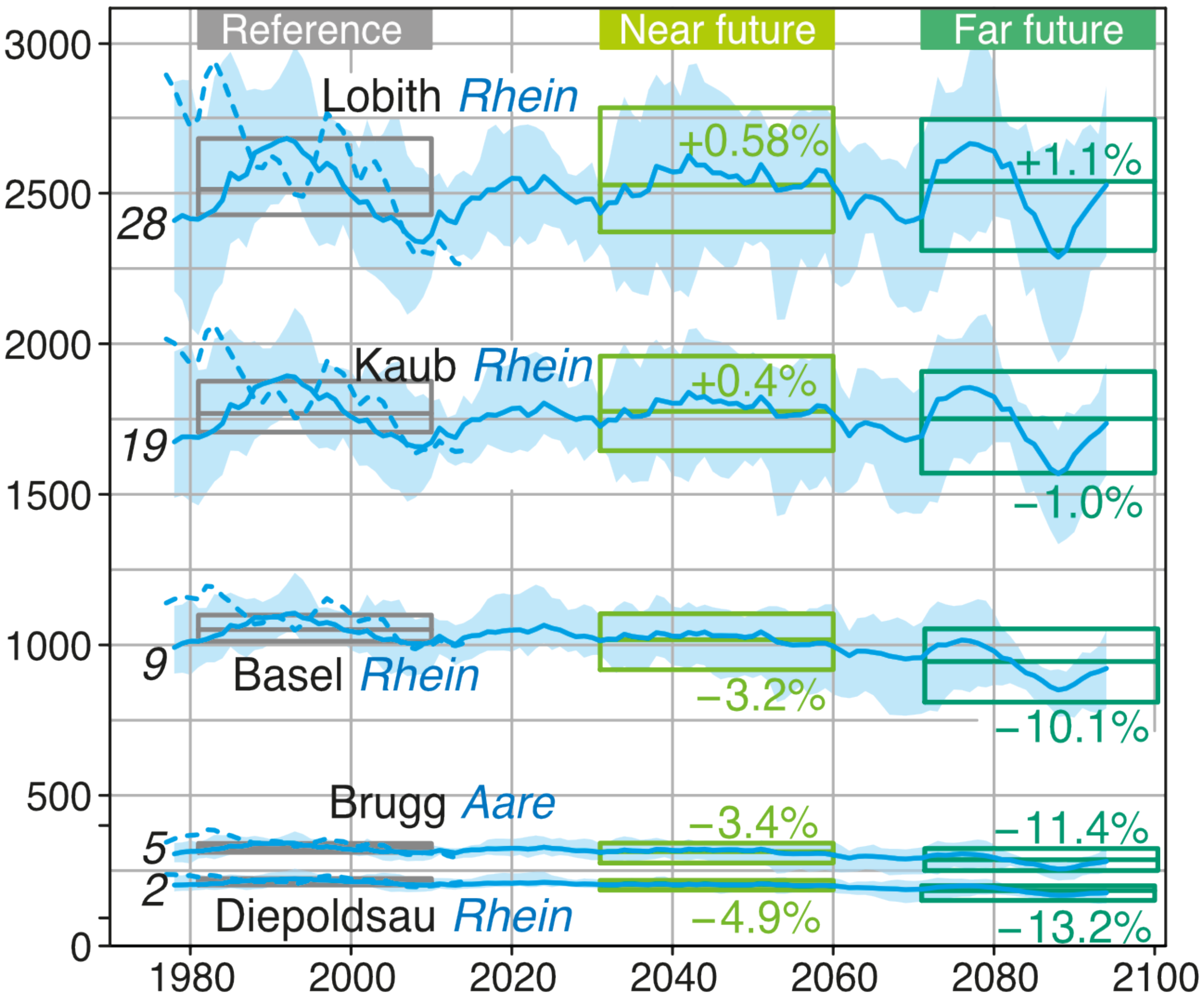




11-year moving averages of hindcast and climate scenario simulations of mean annual streamflow

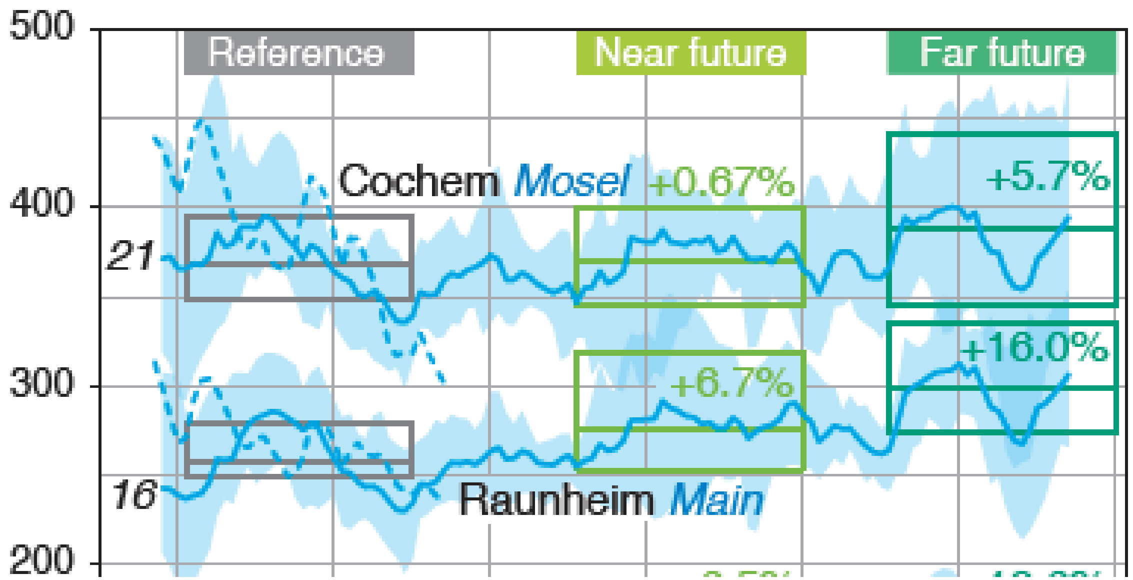
Modelled transient change in total Q

Mean annual streamflow [m³/s]



Changes in annual stream flow:

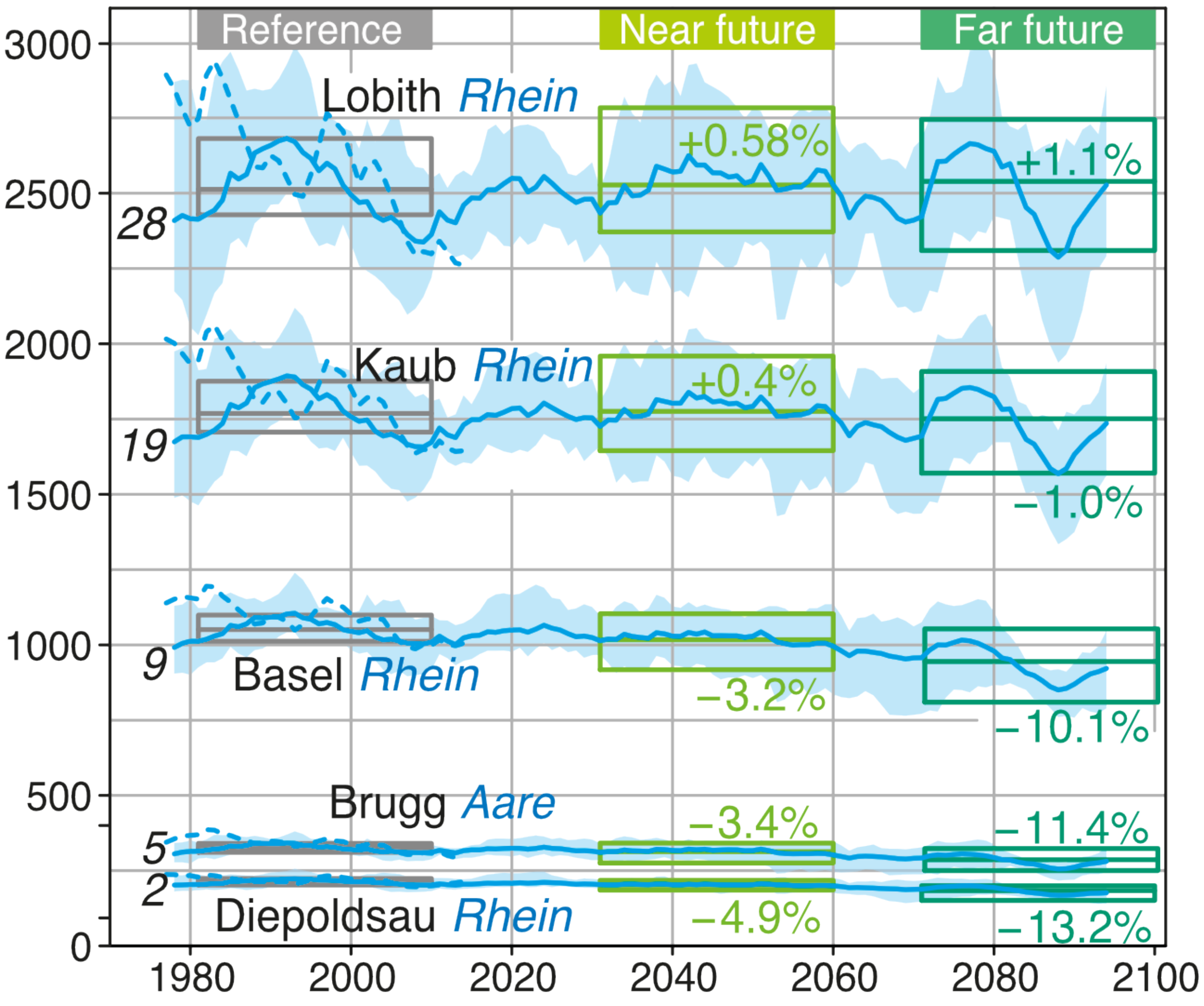
- Decreasing streamflow in the alpine tributaries (e.g. Aare, Rhine at Diepoldsau and Basel) reflects the changes in precipitation.
- The northern tributaries (e.g. Neckar, Main, Moselle) reflect the increasing precipitation of the climate scenario.

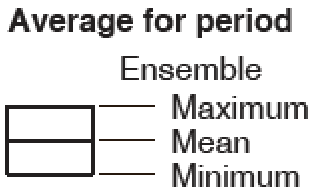


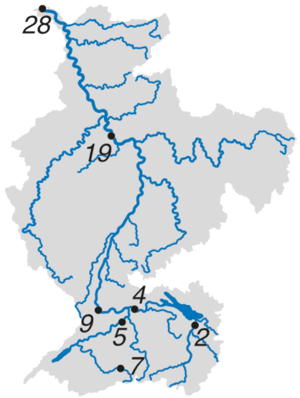
11-year moving averages of hindcast and climate scenario simulations of mean annual streamflow

Modelled transient change in total Q

Mean annual streamflow [m³/s]







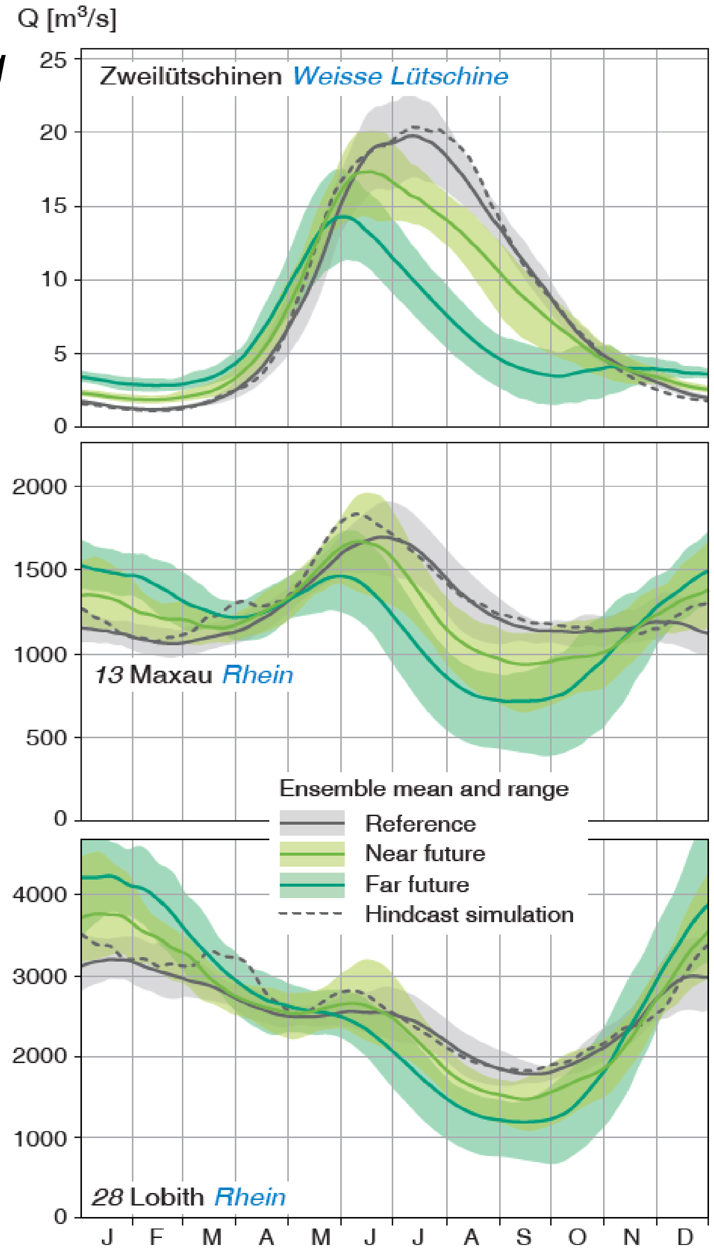
11-year moving averages of hindcast and climate scenario simulations of mean annual streamflow

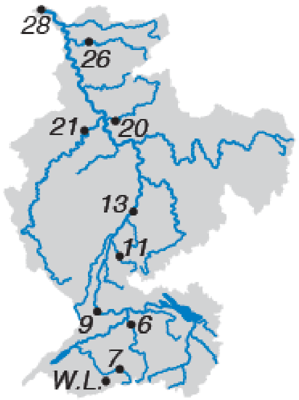
Changes in annual stream flow:

- Decreasing streamflow in the alpine tributaries (e.g. Aare, Rhine at Diepoldsau and Basel) reflects the changes in precipitation.
- The northern tributaries (e.g. Neckar, Main, Moselle) reflect the increasing precipitation of the climate scenario.
- In the main river Rhine, changes in the ensemble mean of streamflow appear to balance out (Rhine at Maxau, Kaub, and Lobith).
- The lower end of the range of the ensemble, however, suggests a decreasing future mean flow.

Changing seasonality of streamflow

30-day moving average of simulated mean daily streamflow





- Seasonal variation of streamflow (hydrological regime) changes upstream to downstream along the Rhine from:
  - a glacier and snowmelt dominated regime with an annual peak in spring and summer to
  - a complex regime with two maxima to
  - a rainfall dominated regime in the downstream regions with a maximum peak in the winter.
- These contrasting regimes will gradually change in the future: spring-summer maxima in the simulations decreases and pluvial winter maxima increases.
- Downstream low flows decrease and their timing shifts to earlier in the autumn

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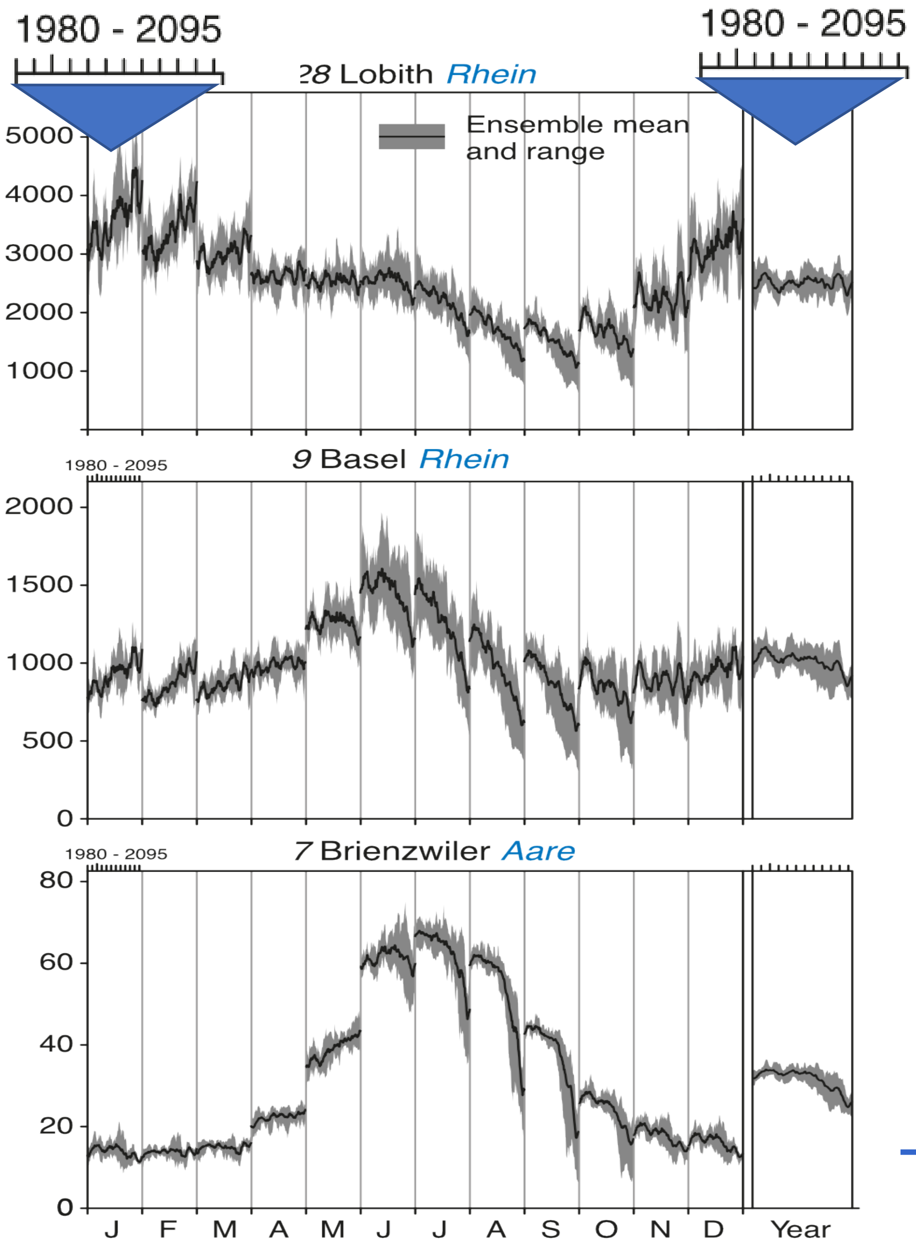
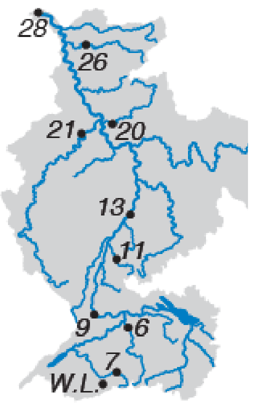
Changing seasonality of streamflow

Modeled streamflow for each month and year (11-year moving averages from 1980 - 2095).





- Decreasing trends dominate the simulated streamflow changes for the summer months at all gauges.
- The alpine tributaries' snow and ice melt-dominated regimes (e.g., Aare and Reuss) show the largest changes from May to October (in the season with the highest streamflow).
- Streamflow decreases from July to September are most notable.
- Downstream most winter months show increasing streamflow trends.

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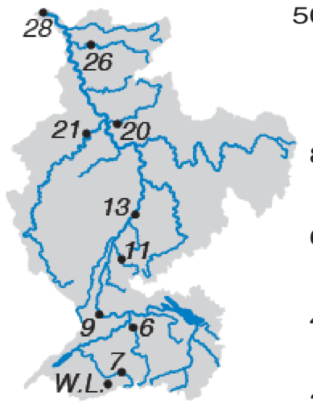
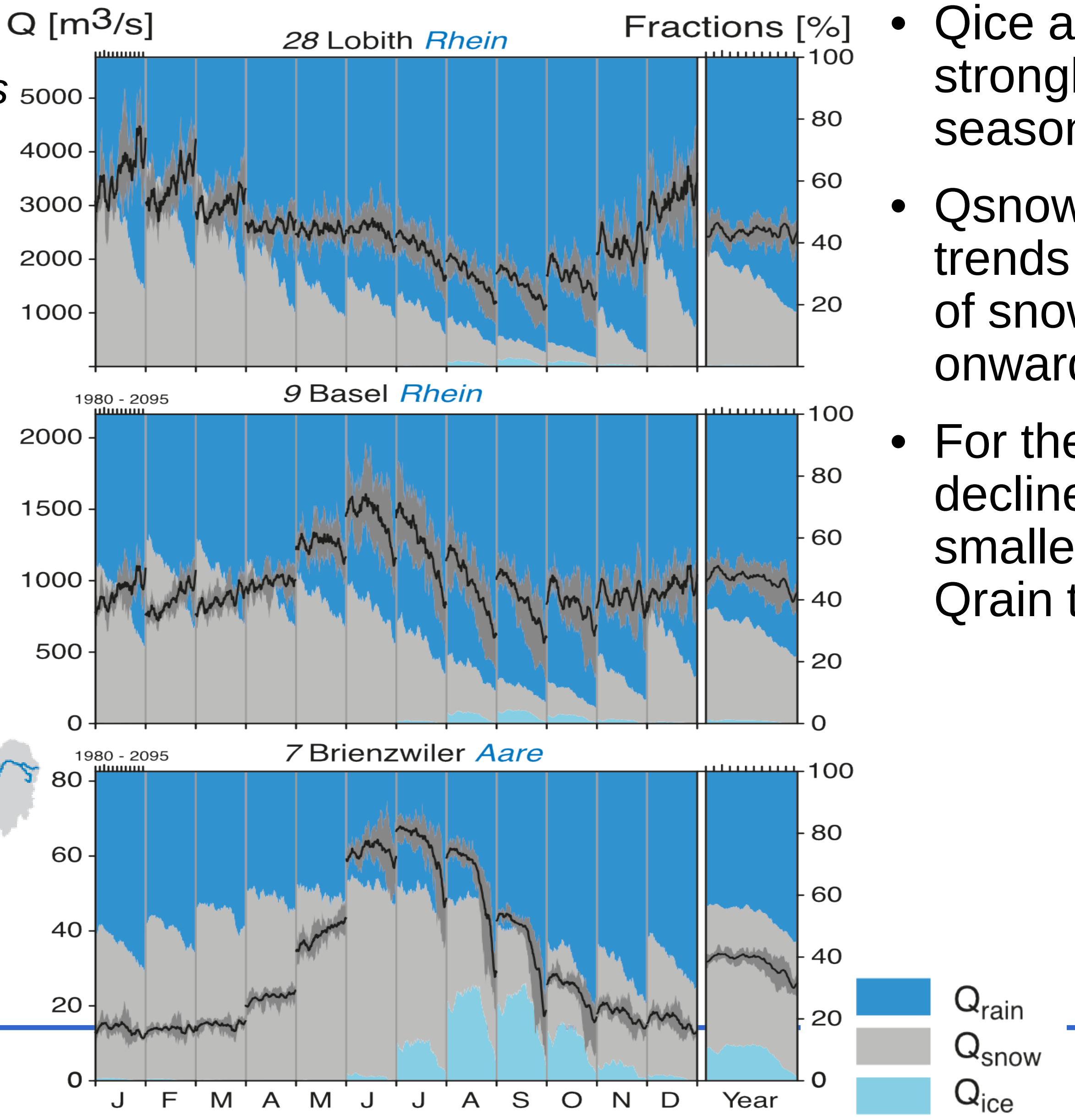
Changing seasonality of streamflow

Modeled percentages of the com-ponents for each month and year (11-year moving averages from 1980 - 2095).





- Qice at Brienzwiler/Aare will start to decline strongly in the near future with a mostly local and seasonally relevant effect.
- Qsnow at Basel/Rhine shows strong declining trends in early summer (during and after the time of snowmelt). Streamflow decreases from June onwards.
- For the Rhine in summary: Qsnow and Qice decline but their net effect on total streamflow is smaller further downstream, due to an increase in Qrain there.

Conclusions

Icemelt:

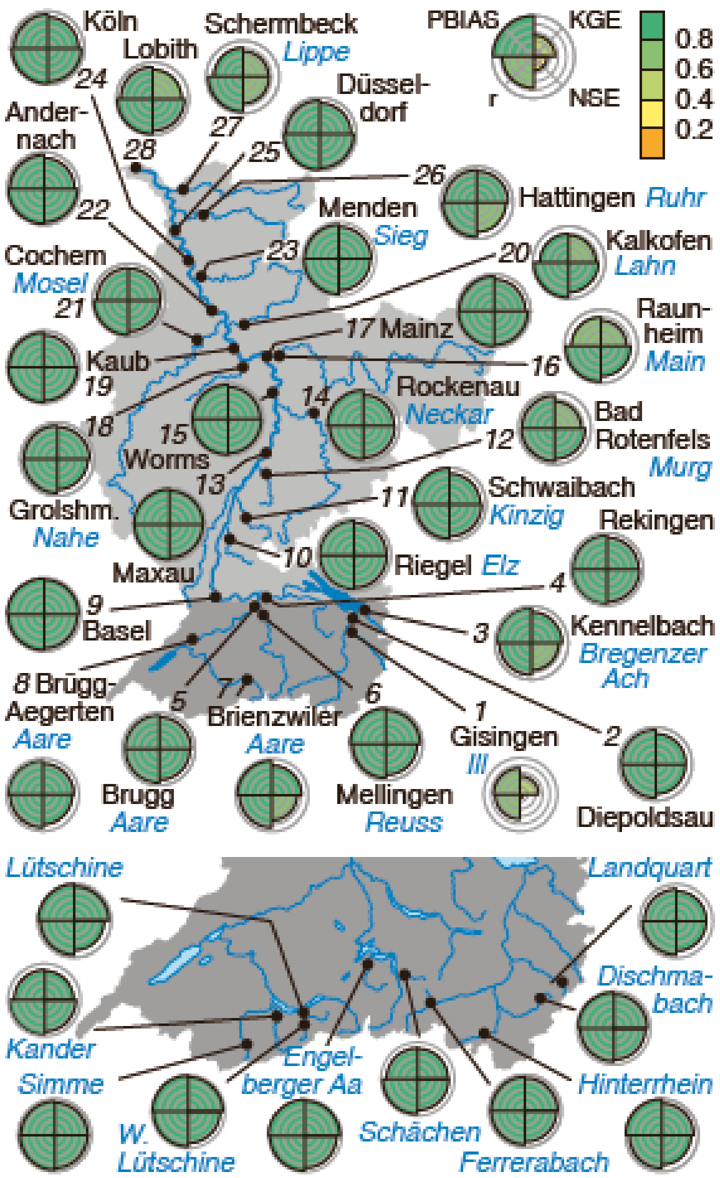
- The already-reduced fraction of ice melt in streamflow will rapidly become even smaller. This change will affect the Rhine and its alpine tributaries mainly.
- For the river Aare a relatively constant glacier ice melt component is expected until about 2040.
- Other tributaries' ice melt components have already been declining and will continue to do so.
- Ice melt, which has sustained recent extreme low flow situations (e.g. with up to a tenth of the flow at Basel), will soon become negligible in the downstream reaches.

Snowmelt:

- The snowmelt component exerts the largest changes to streamflow along the entire Rhine.
- Projected increase in winter precipitation is unlikely to compensate for the expected future reduction of the spring-summer snowmelt component in the Rhine upstream of Basel.
- Downstream, where the rainfall component increases more, some compensation is projected for the annual streamflow, despite seasonally increased variability.
- Snowmelt changes will affect the seasonality most clearly and will no longer provide a considerable contribution even to those low flow events that occur in early summer.

Thank you for your attention!

Evaluating hydrological model performance

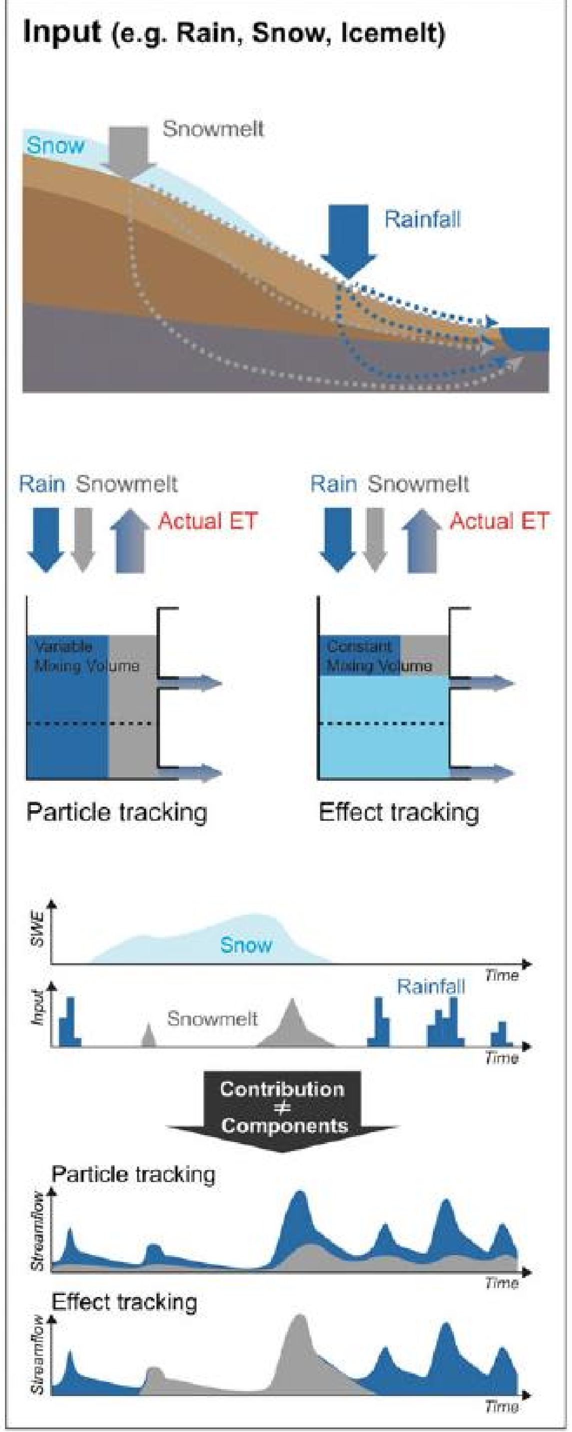


Model performance measures for streamflow in the period 1981–2010 at selected gauges:

- Kling-Gupta-Model efficiency (KGE) for overall performance
- Nash-Sutcliffe efficiency of the logarithm of streamflow (NSE) for low flow representation
- correlation coefficient (r) for agreement of relative variations
- normalized bias measure (PBIAS) for overall deviation.

Evaluating hydrological model performance

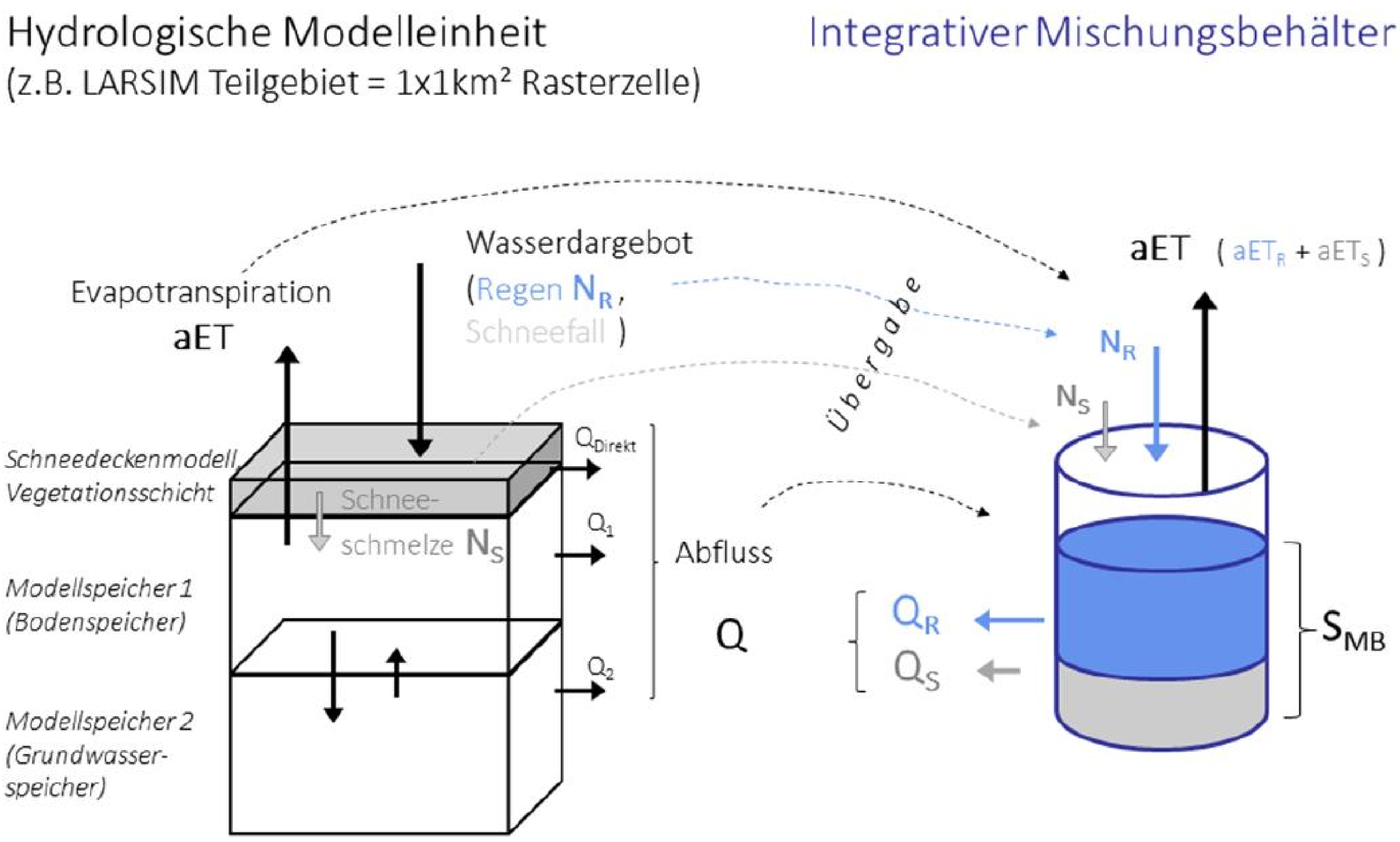
- Hydrological models can only be validated for the past. When assessing future projections, the fact that conceptualizations of hydrological processes in the models contain empirically derived or calibrated parameterizations must be taken into account.
- In this frequently used modeling approach, the assumption is that these will remain constant in the future.
- Limitations include landcover change, for example: in this study only glacier retreat was taken into account, but not changes in vegetation.
- Also, storage and outflow rules from lakes and reservoirs, as well as other regulations were kept constant in addition to the general model parameters.



Tracking the input contributions through a entire system:

- Particle tracking:
  - quantifying the actual water particles from the different input sources
  - depending on the water travel times and hence the particle velocity.
- Effect tracking:
  - quantifying their relative fraction to the discharge
  - depending on the response time and the speed of the propagating wave (celerity) through the hydrologic system.

Discharge component modelling



Discharge component modelling

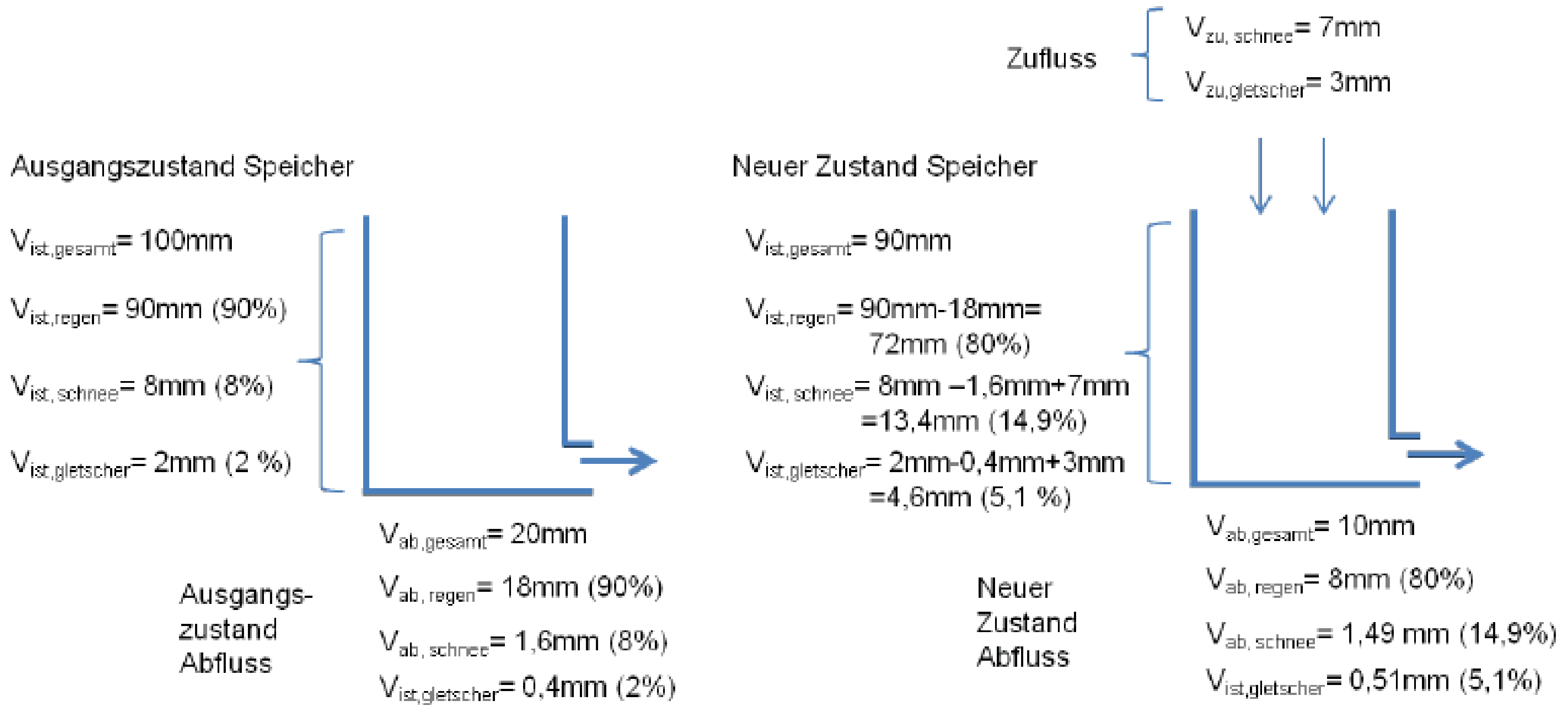


Abb. 1: Beispielhafte Darstellung des Mischungsreaktors: Veränderung der Speicherinhalte nach Abfluss (links unten) und Zufluss (rechts oben). Die prozentualen Anteile der Abflusskomponenten innerhalb des Mischungsreaktors sind im berechneten Abfluss (hier auf 20 bzw. 10 mm gesetzt) zu erkennen.

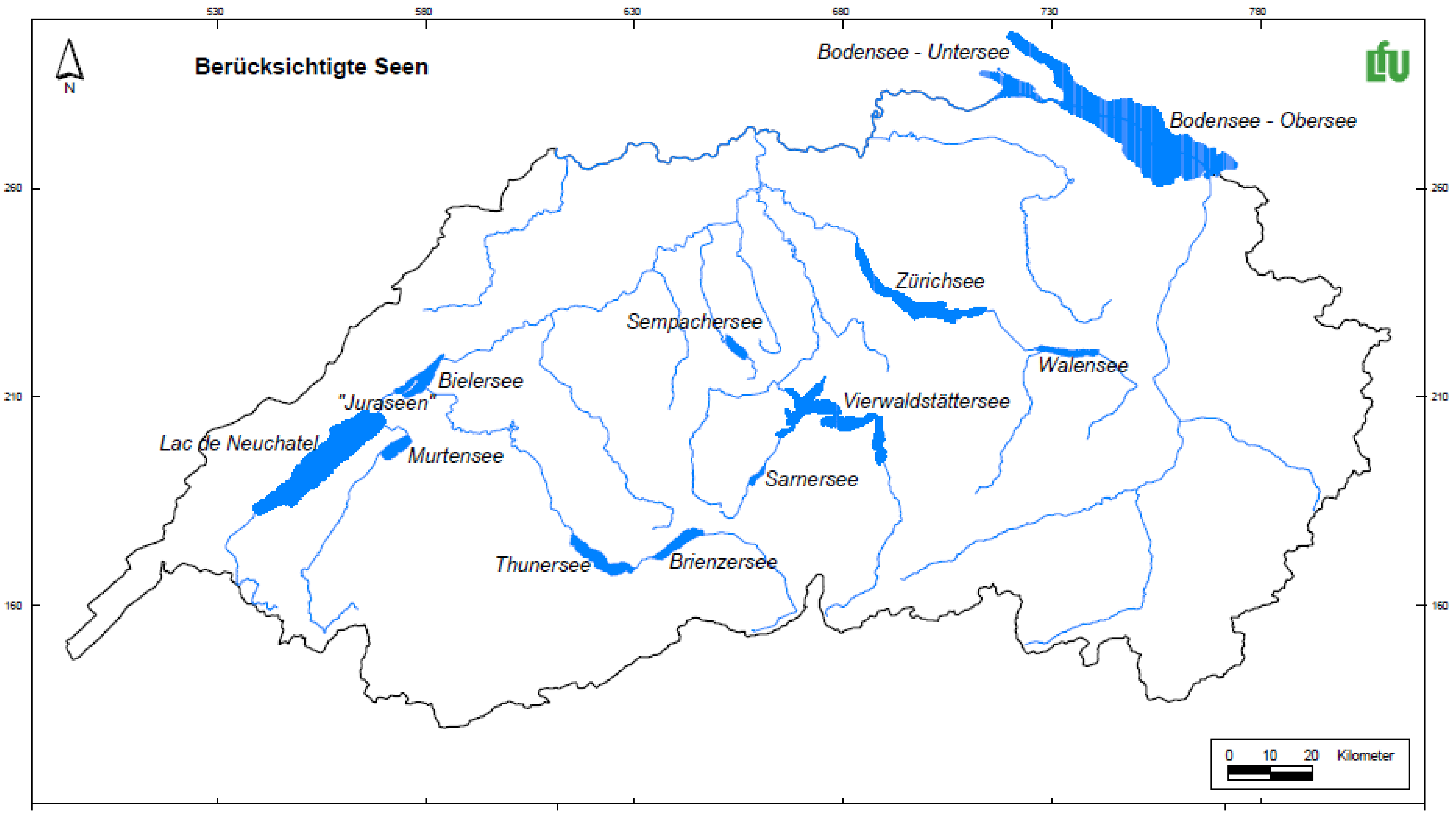
LARSIM water balance model Hochrhein-Switzerland

Calibrated gauges in the LARSIM water balance model Hochrhein Switzerland

LARSIM water balance model Hochrhein-Switzerland

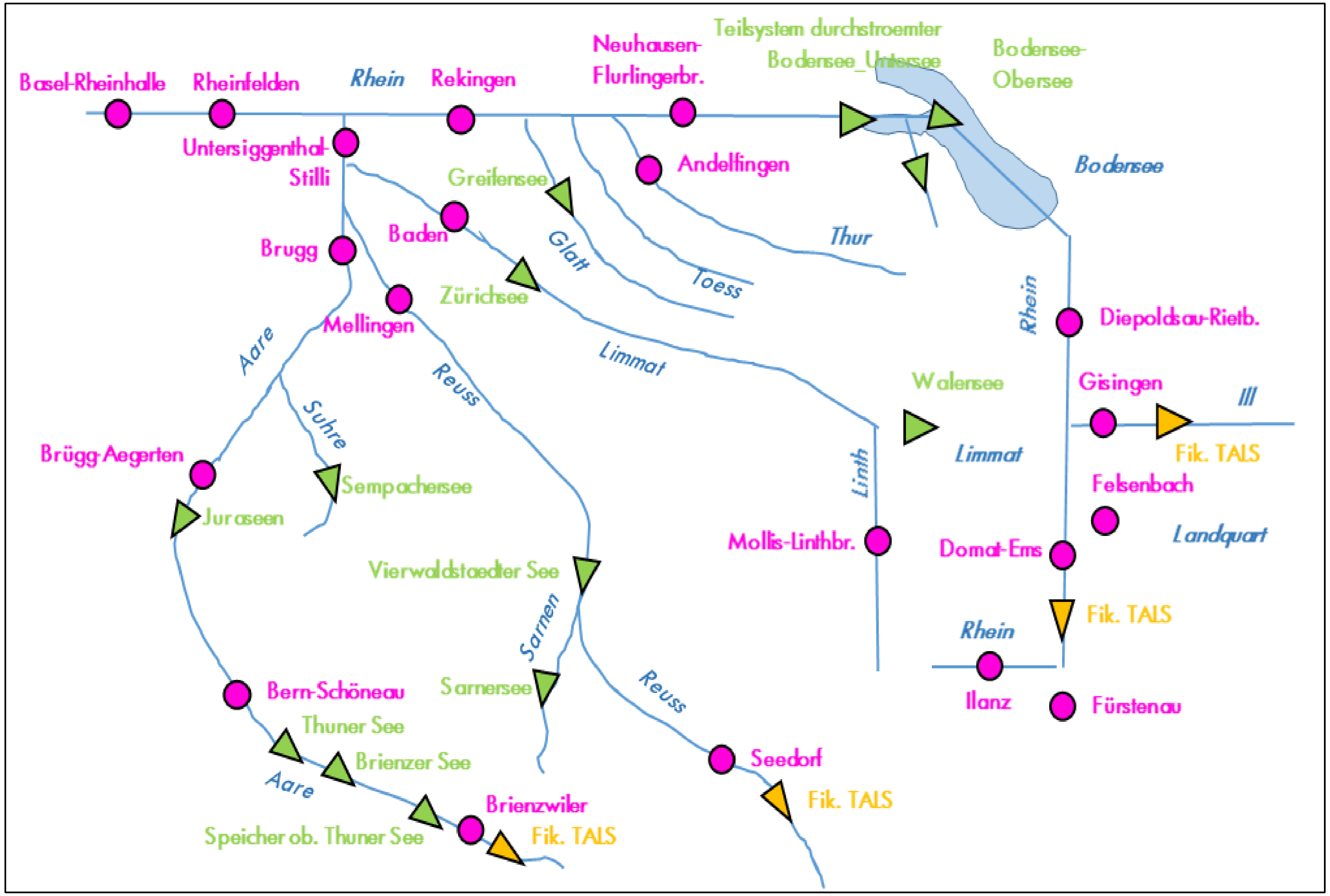
- In the WBM Hochrhein consideration of 10 lakes as regulated/unregulated lakes according to regulation rules

Lake	Regulation
Bodensee (Obersee)	Not regulated
Bodensee (Untersee)	Not regulated
Brienzersee	Regulation rules integrated
Neuenburger-/Bieler-/Murtensee	Regulation rules integrated
Sarnersee	Not regulated
Sempachersee	Not regulated
Thunersee	Regulation rules integrated
Vierwaldstättersee	Regulaton rules derived
Walensee	Not regulated
Zürichsee	Regulation rules integrated



LARSIM water balance model Hochrhein-Switzerland

- 4 cumulative reservoirs built into the WBM Hochrhein as dams:
  - Alpenrhein (above Chur)
  - Ill-Vorarlberg (near the mouth)
  - Aare (above Lake Brienz)
  - Reuss (above Lake Lucerne)



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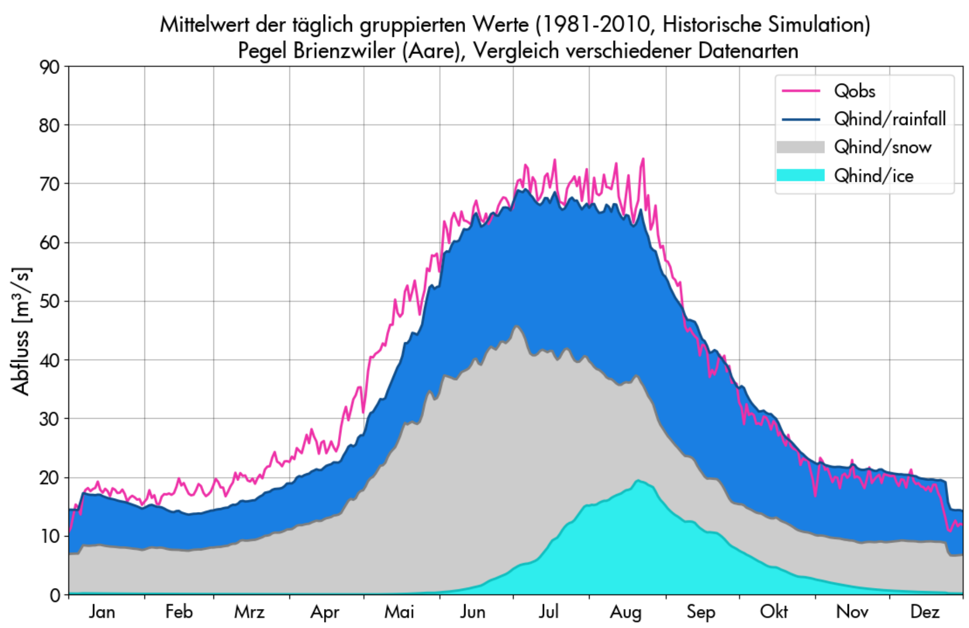
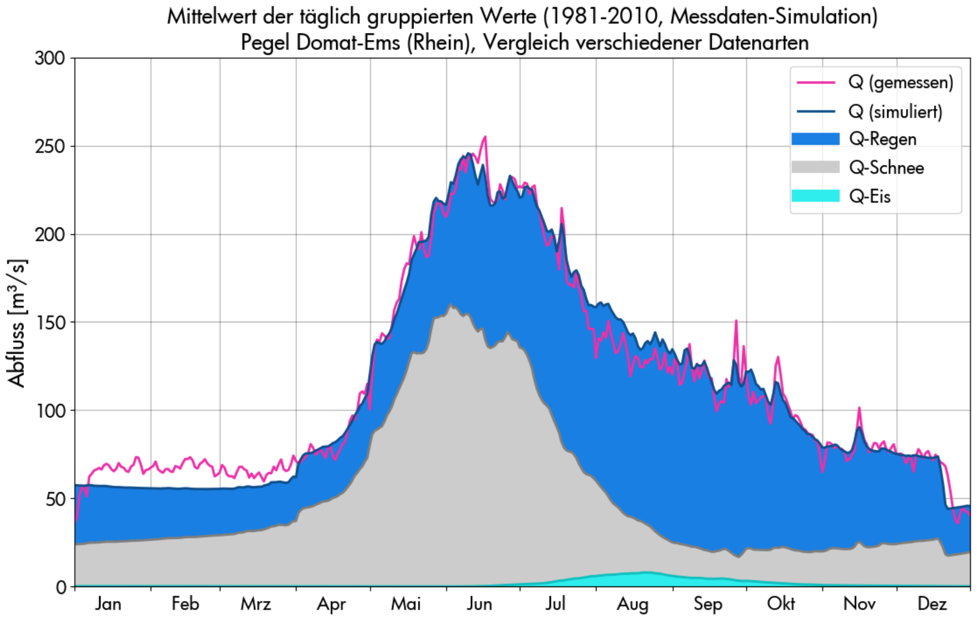
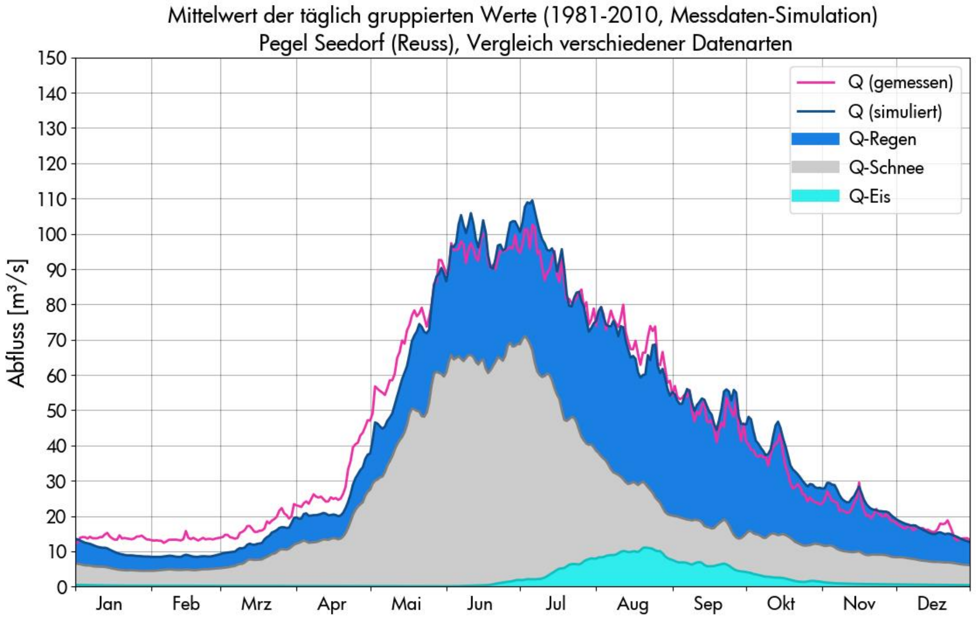
LARSIM water balance model H

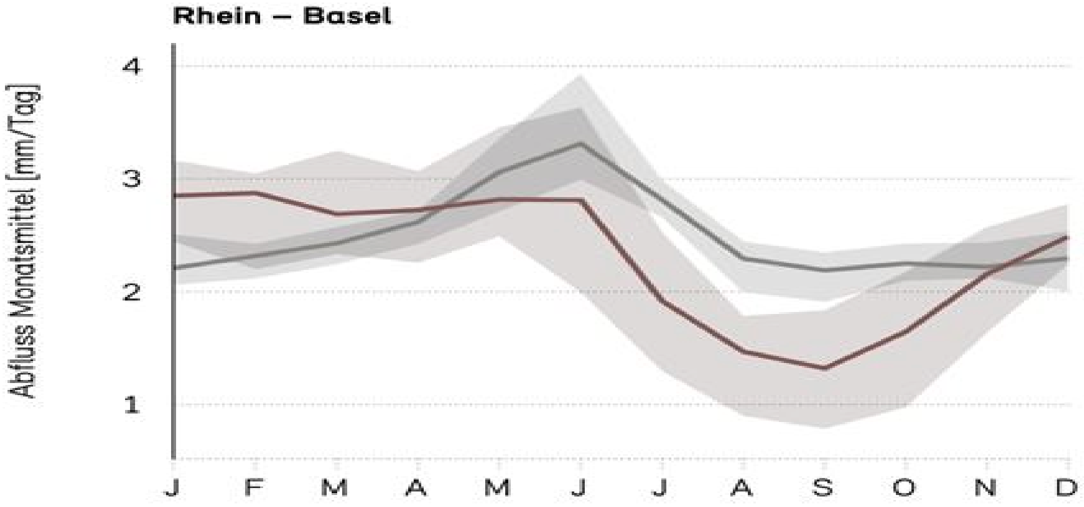
- 4 cumulative reservoirs built into the WBM Hochrhein as dams



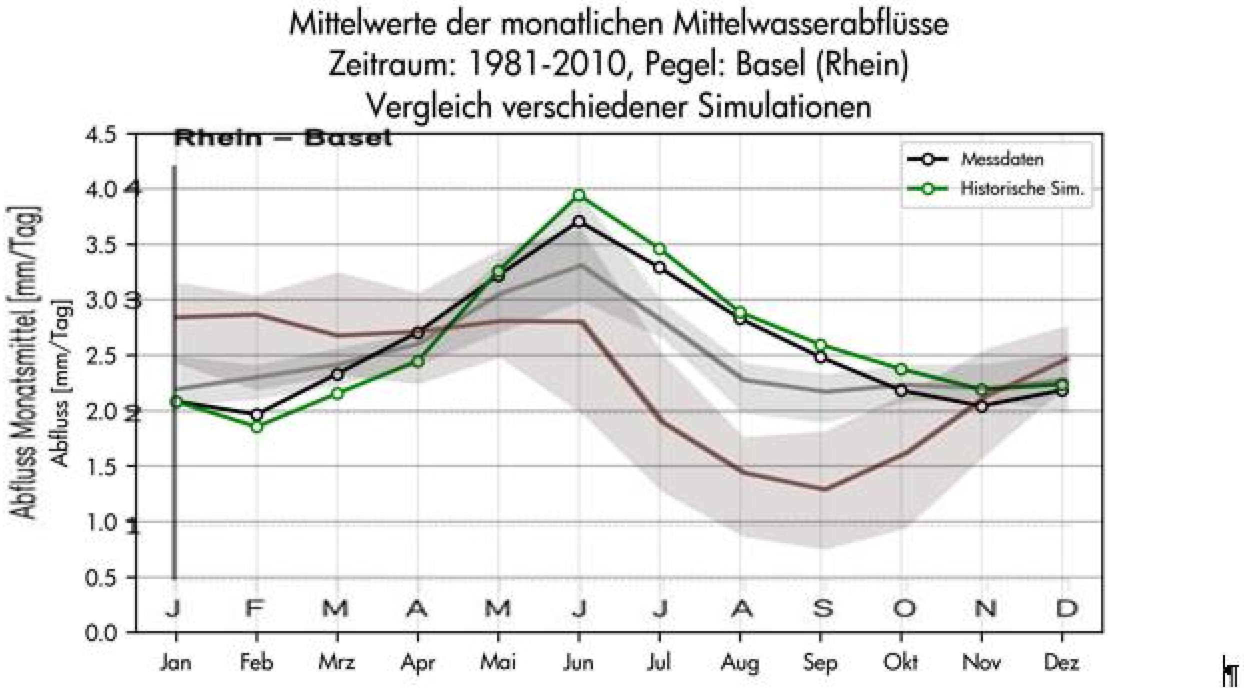




Comparison CH2018 and AGS



Comparison CH2018 and AGS



Bild·1.2: → Mittelwert·der·monatlichen·Mittelwasserabflüsse·am·Pegel·Basel-Rheinhalle/Rhein.· Graue· Linie:· CH2018-Referenzperiode· (1981-2010)· (vgl.· Bild· 1.1);· schwarze· Linie:· ASG· Messdaten· (1981-2010);· grüne· Linie:· ASG· historische· Simulation· (1981-2010).¶

Comparison CH2018 and AGS

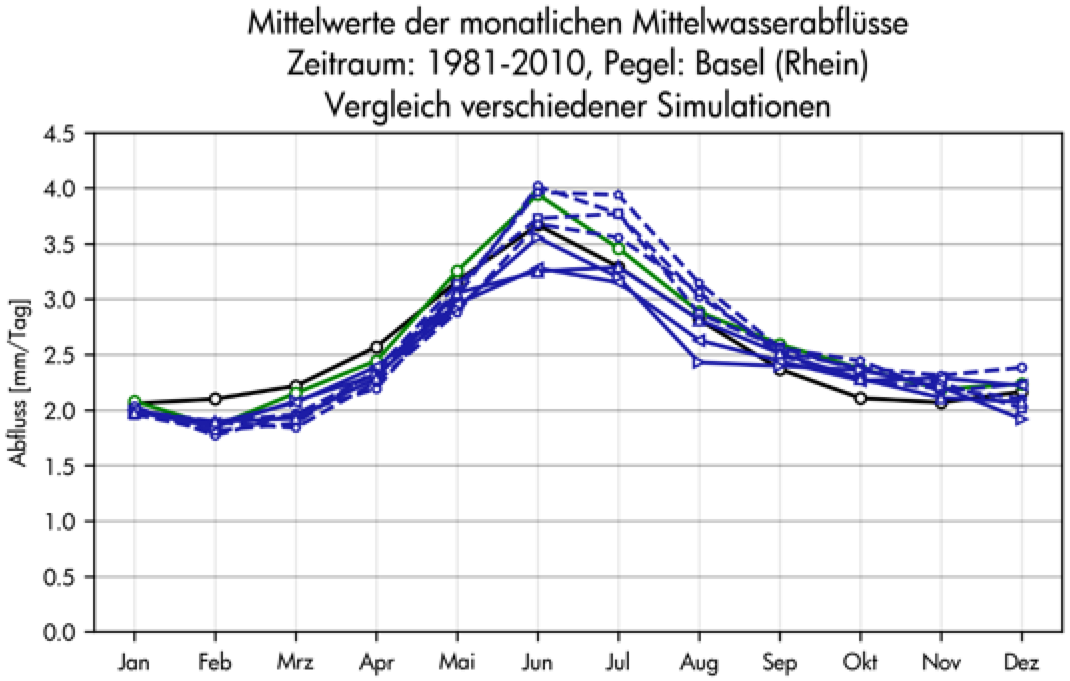


Bild 1.3: Mittelwert der monatlichen Mittelwasserabflüsse am Pegel Basel-Rheinhalle/Rhein. Schwarze Linie: ASG Messdaten (1981-2010); grüne Linie: ASG historische Simulation (1981-2010); blaue Linien: ASG Ist-Zustand Ensemble (1981-2010).

Comparison CH2018 and AGS

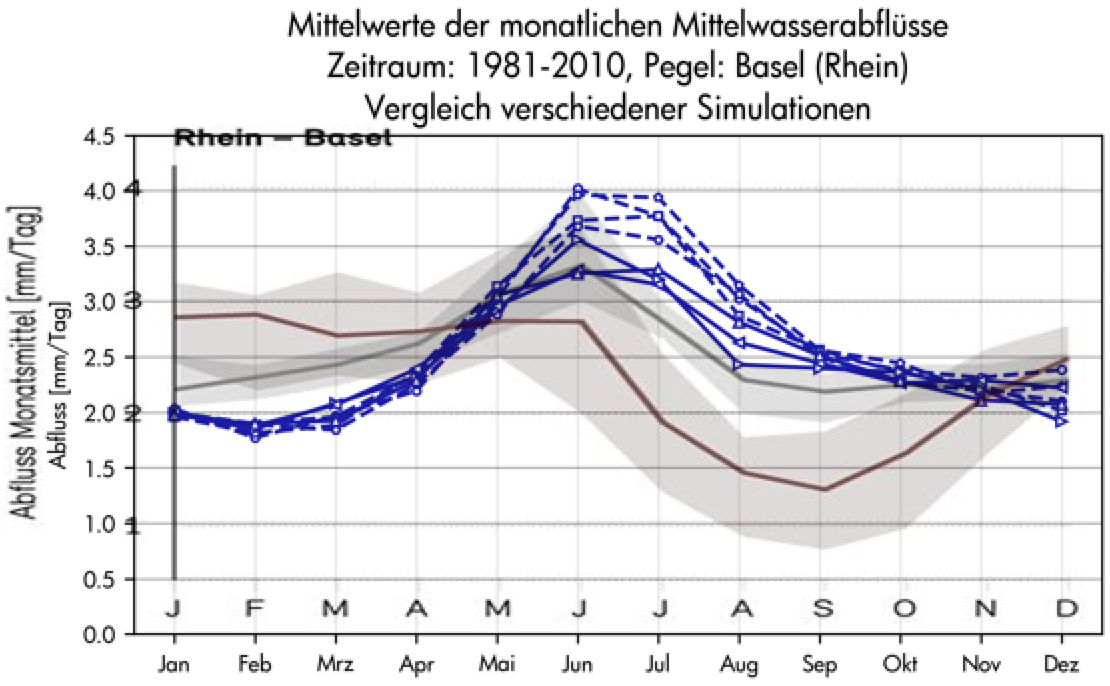


Bild 1.4: Mittelwert der monatlichen Mittelwasserabflüsse am Pegel Basel-Rheinhalle/Rhein. Graue Linie: CH2018-Referenzperiode (1981-2010) (vgl. Bild 1.1); dunkelrote Linie: CH2018-Szenarien ohne Klimaschutz für Ende Jahrhundert; blaue Linien: ASG Ist-Zustand Ensemble (1981-2010).

HYDRON UMWELT und WASSERWIRTSCHAFT

Comparison CH2018 and AGS

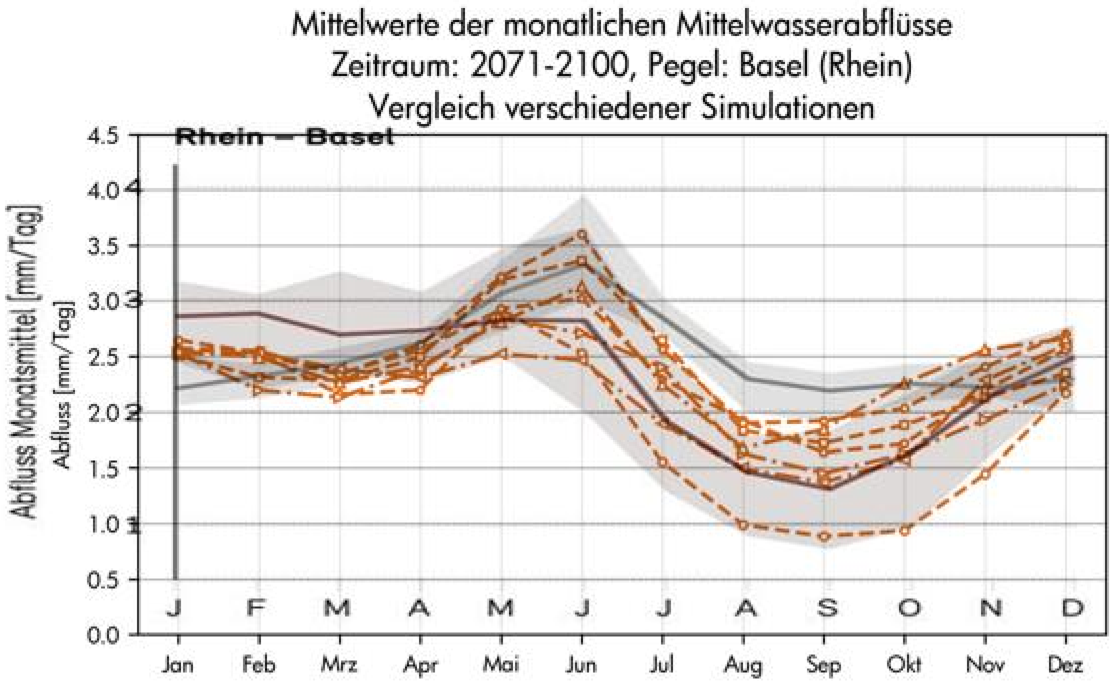


Bild 1.5: Mittelwert der monatlichen Mittelwasserabflüsse am Pegel Basel-Rheinhalle/Rhein. Graue Linie: CH2018-Referenzperiode (1981-2010) (vgl. Bild 1.1); dunkelrote Linie: CH2018-Szenarien ohne Klimaschutz für Ende Jahrhundert; orangene Linien: ASG Zukunft Ensemble (ferne Zukunft: 2071-2100).

Comparison CH2018 and AGS

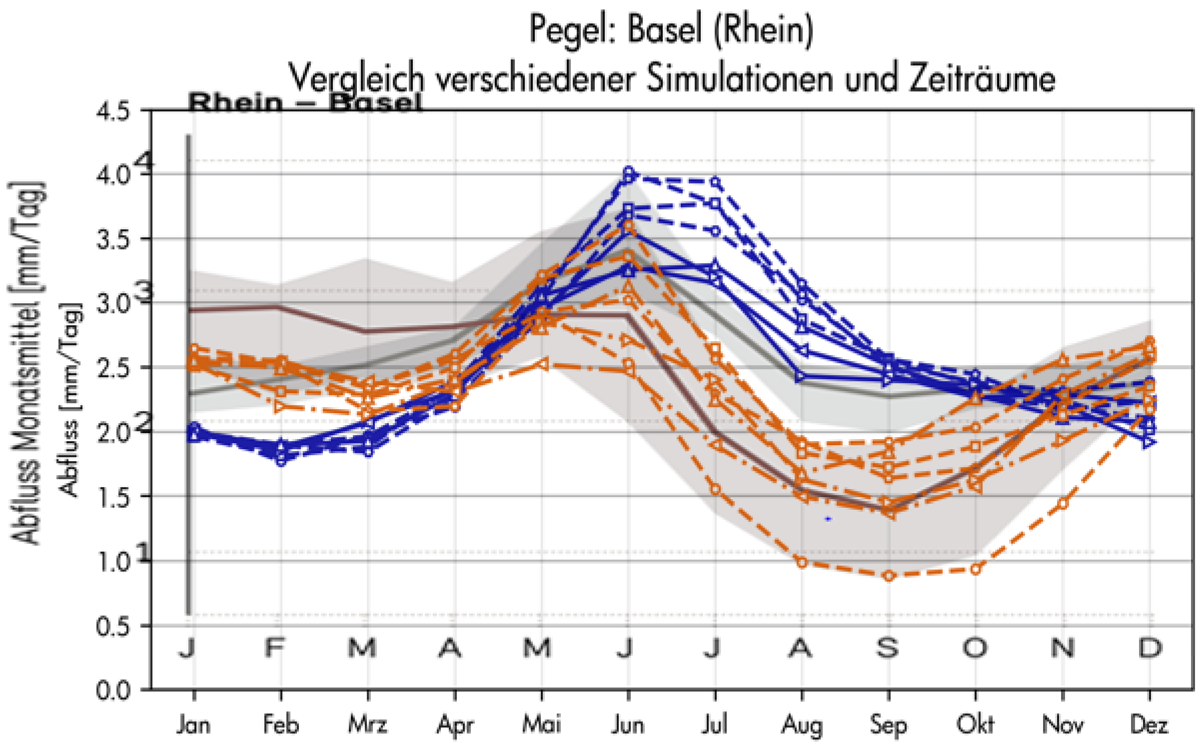


Bild 1.6: Mittelwert der monatlichen Mittelwasserabflüsse am Pegel Basel-Rheinhalle/Rhein. Oben und unten: blaue Linien: ASG Ist-Zustand Ensemble (1981-2010); orangene Linien: ASG Zukunft Ensemble (ferne Zukunft: 2071-2100). Unten: graue Linie: CH2018-Referenzperiode (1981-2010) (vgl. Bild 1.1); dunkelrote Linie: CH2018-Szenarien ohne Klimaschutz für Ende Jahrhundert.