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International Commission for the Hydrology of the Rhine Basin

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Synthesis report

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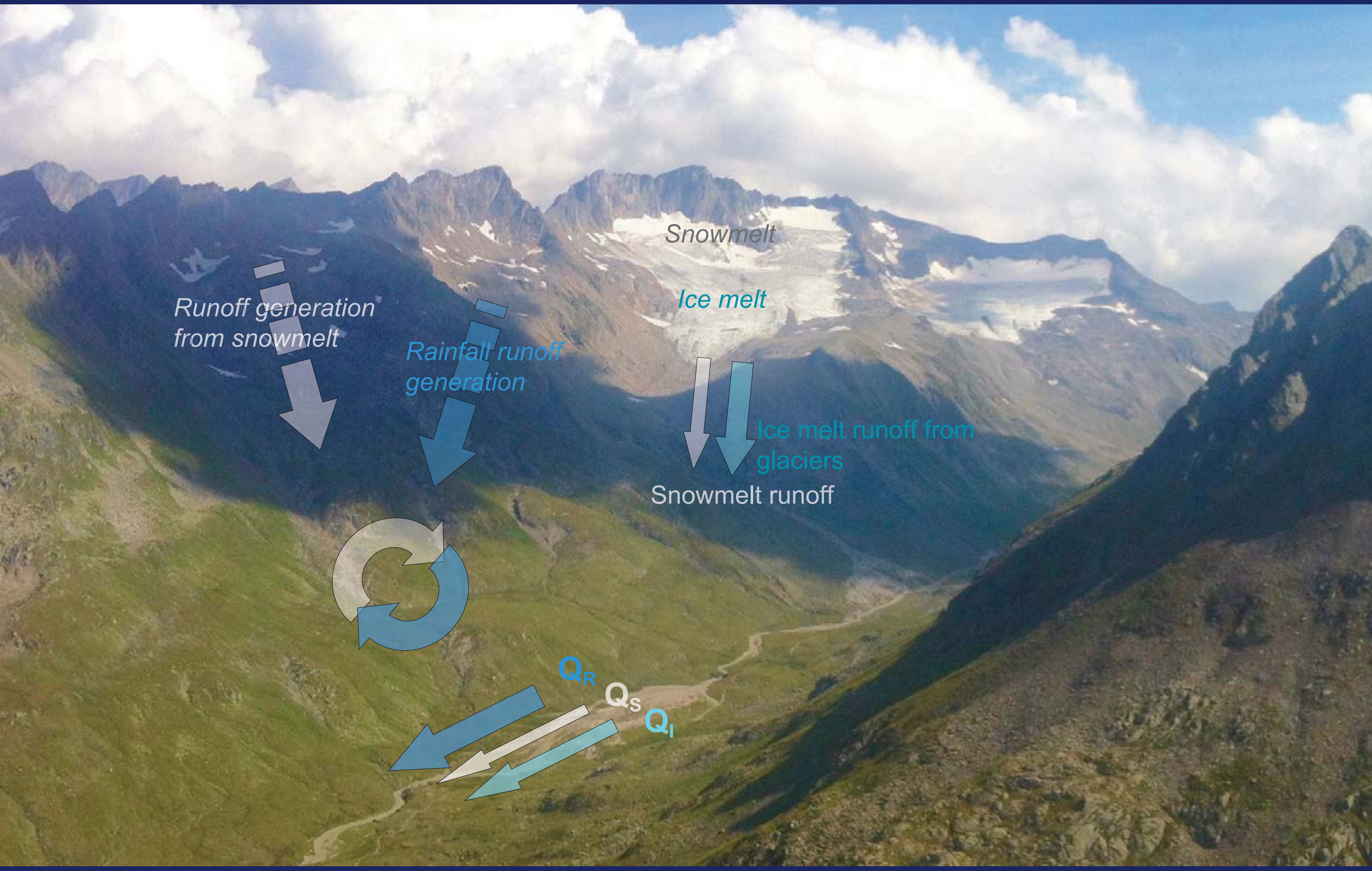

Report No. I-25 of the CHR

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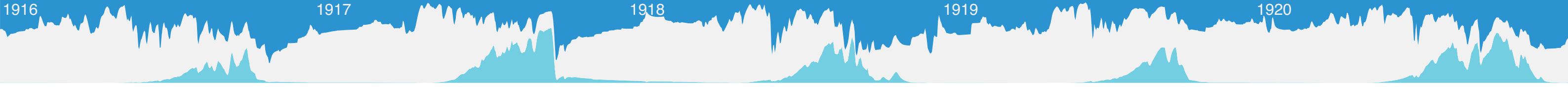

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Conventions	Place names are used in their local versions.

Preface

The need for international cooperation in general, and in particular in the field of hydrology, is not a brand-new insight: rivers do not stop at national borders and groundwater does not recognize the territorial jurisdiction of administrative authorities. At an expert level, at least, approaching hydrological questions and issues on a cross-border level should be a matter of course. But even today, in times of EU-wide cooperation, collecting basic data for large-scale scientific work continues to be a challenge in almost every respect. For decades, and on behalf of the national states (however, without any political leverage), the International Commission for the Hydrology of the Rhine Basin (CHR/KHR) has been addressing vital questions with regard to the international hydrology of the Rhine. Practical experiences gained so far, in decades of cooperation, prove that the assumptions leading to the establishment of the CHR were correct. Namely, that a panel of selected experts from all Rhine riparian states will share findings and make knowledge and information resources accessible, which would otherwise – seen from a purely national perspective – not be available.

Beginning with the large Rhine monograph of 1978, numerous CHR publications on the hydrology of the Rhine and its tributaries have been made available since the 1970ies. Findings thereof have been incorporated into administrative actions and political governance. For almost two decades, the CHR has been devoting special attention to the long-term evolution of discharge patterns and climate change and its impact on the hydrology of the Rhine basin.

In the course of the work on CHR-projects such as the "Discharge Regime of the Rhine and its Tributaries in the 20th Century" (CHR report I-22), with its retrospective approach in investigating the hydrological regime structure and the forward-looking “RheinBlick 2050 /Assessment of Climate Change Impacts on Discharge in the Rhine River Basin "(CHR report I-23), it became also evident that any reliable quantification of the snow and glacial melt fraction of the total streamflow along the Rhine has been lacking so far. This knowledge gap is or was in strong contrast to the offensive way in which the consequences of melting glaciers in the Alps were portrayed by both media and popular science. Retrospectively, this gap in knowledge has been closed at least for the period from 1901 to 2006 with the completion of the CHR project "ASG-Rhine I/ The snow and glacier melt components of streamflow of the river Rhine and its tributaries considering the influence of climate change". Hence, there is nothing standing in the way of a respectable, scientifically proven approach to this subject - for the first time worldwide with respect to such an important river basin.

In view of the methods developed and the insights gained in the course of the project, the CHR is planning a continuation of ASG-Rhine with a prospective approach. This is intended to answer any open questions about the future scope of melting water contribution to the Rhine discharge over the coming decades.

The Commission would like to express its gratitude and appreciation to the participating scientists, to the universities of Freiburg and Zurich for making the project team available, to HYDRON GmbH for providing their project team, and to the project-accompanying active supervisory group, for the work they have accomplished.

Jörg Uwe Belz

Federal Institute of Hydrology, Germany

Project Manager

Climate Change Influences on the Streamflow of the River Rhine

The Rhine is one of the largest rivers in Europe and its flow is crucial for a number of water uses such as energy production, water-borne transportation, water supply for irrigation, industry, and as drinking water. With its headwaters in the Alps and several major tributaries from other central European mountain ranges on its course to the North Sea (Fig. 1), the hydrological regime of the Rhine is influenced by meltwater during spring and summer. The highest elevation areas of the river basin in the Swiss and Austrian Alps are partially glacierized. These glaciers have retreated considerably as air temperatures have warmed, particularly in recent decades (Fig.1). As a result, snowmelt and glacier ice melt have undergone changes as well. Hence, it can be expected that the contributions of rain, snowmelt, and glacier ice melt that comprise the river's streamflow have also changed during that time. The project investigated these streamflow components in more detail.

The influence of climate change is visible particularly in the temporal shifts of seasonal minima and maxima of the hydrological regimes of snow and glacier melt dominated alpine headwater catchments. Regime changes have already been shown based on observed streamflow time series in the Rhine basin (Belz et al., 2007). Furthermore, future projections of climate change (Görgen et al., 2010; BAFU, 2012) suggest they are among the most important changes expected to influence water use and resources management in the future. In this context a correct quantification of the contribution of snow and glacier melt runoff in the Rhine basin to the streamflow along the river becomes an important task. The different runoff contributions control the hydrological regimes through the runoff generation processes and thus determine spatial differences in the evolution of the streamflow and its availability for different water uses.

The quantities of the streamflow components of the river Rhine are particularly interesting during summer low flow situations in the downstream reaches of the Rhine when natural catchment storages feeding lows flows have been depleted due to a long dry weather period. In those situations, the glacier melt water component from the Alps becomes particularly important. In the past, such extreme summer low flow situations occurred in 1921, several times in the 1940s and 1950s, and more recently in 2003, as can be seen in the examples of observed streamflow time series at the gauging stations in Basel and Köln (Fig. 1). In light of this issue, model-based studies have previously calculated the contribution of glacier melt runoff to the downstream streamflow at various gauging stations of the Rhine, including the drought of 2003, and its changes over time (e.g., Huss, 2011). These studies mostly computed the contributing glacier melt runoff on a monthly, seasonal, or annual basis and did not consider the temporal delay due to the channel routing, lake retention, and the mixing of the glacier runoff contribution with the rain and snowmelt runoff from the non-glacierized parts of the basin in great detail. However, for the economy and ecology during low flow events, the influence of glacier melt augmentation of flow may also matter at shorter time scales.

The ASG-Rhine project's aim was therefore to analyse and simulate the changes in the streamflow components of the Rhine from glacierized and non-glacierized parts of the basins together for the first time. Specifically, the project aimed at the determination of the streamflow components from rain, snowmelt, and ice melt at a daily resolution over the long period from 1901–2006. Modelling at a daily resolution allows the studying of the different contributions to extreme events, in particular low flows. The analysis of the long time period allows the investigation of trends and changes, in particular those related to the retreat of glaciers. Throughout the study, a detailed consideration and analysis of observational data supported the largely model-based results.

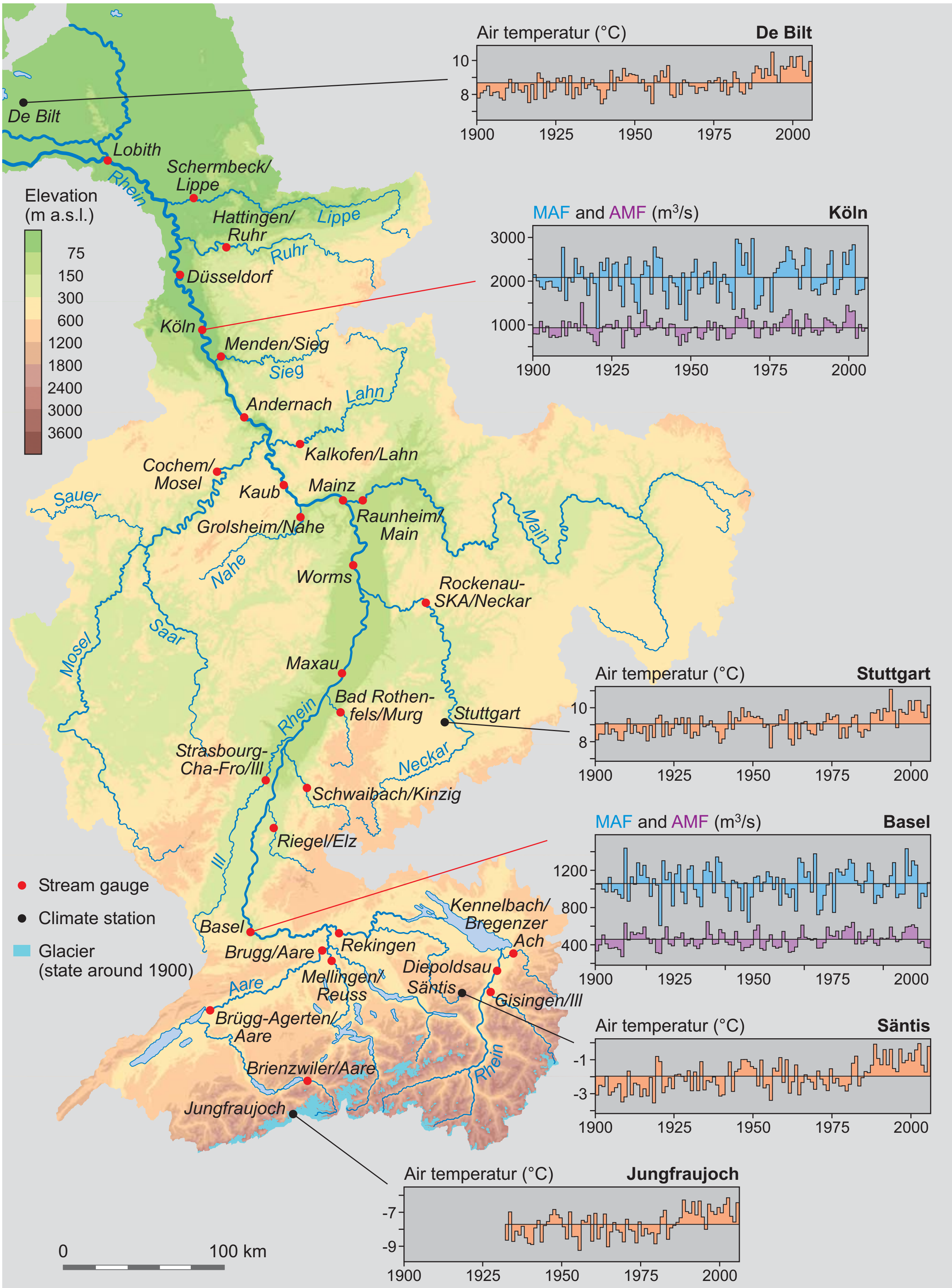


Figure 1: The Rhine basin with time series of values of the mean annual air temperature, mean annual streamflow (MAF) and annual minimum flow (AMF) at selected climate and gauging stations. Data sources: DWD/BfG, MeteoSwiss and European Climate Assessment & Dataset ECA&D.

Data and General Approach

For the calculation of the three streamflow components, the ASG-Rhine project combined a number of datasets, data analyses, and simulation models (Fig. 2). A comprehensive data collection was assembled for the project that consists of long-term observational time series of the water cycle, including station data as well as gridded data products for large areas. One grid product covering the entire Rhine basin is the HYRAS data of the German Weather Service and the Federal Institute of Hydrology in Germany. The interpolated climate variables in HYRAS (precipitation, air temperature, and relative humidity) provide suitable meteorological input to hydrological models (Rauthe et al., 2013; Frick et al., 2014).

As these data only start in the year 1951, one of the first steps in the project's workflow was the reconstruction of meteorological data at daily resolution for the same grid for the earlier period 1901–1950. For consistency of the spatial structure and resolution as model input over the entire time period 1901–2006, a method based on weather analogues was developed that resampled the early part of the period (HYRAS-REC) from the daily grids of the later part of the period. The analogue method is based on information from all available long-term series of climate variable observations in the Rhine basin.

The project database also assembled streamflow records, in particular all available data from the glacierized headwater catchments, even if only a few years of record were available in the past. The long series then served as a basis to empirically analyse the climate sensitivity of streamflow in headwater catchments (see Box 1). All records also provided important benchmarks to improve process representation and to constrain the calibration and validation of the HBV-Light model for the glacierized headwaters (see Box 2).

Further benchmarks were derived from various data on the cryosphere. Through the collaboration with external partners, data on the seasonal evolution of the snow cover and on the long-term changes of the glaciers could be considered. The latter includes glacier length, glacier area and glacier thickness information at several times in the past that could be integrated as benchmarks into analyses and modelling. The glacier extents at the beginning of the 20th Century were digitized from historical Swiss maps, the "Siegfriedkarten", and provided the initial conditions for the models (see Box 3).

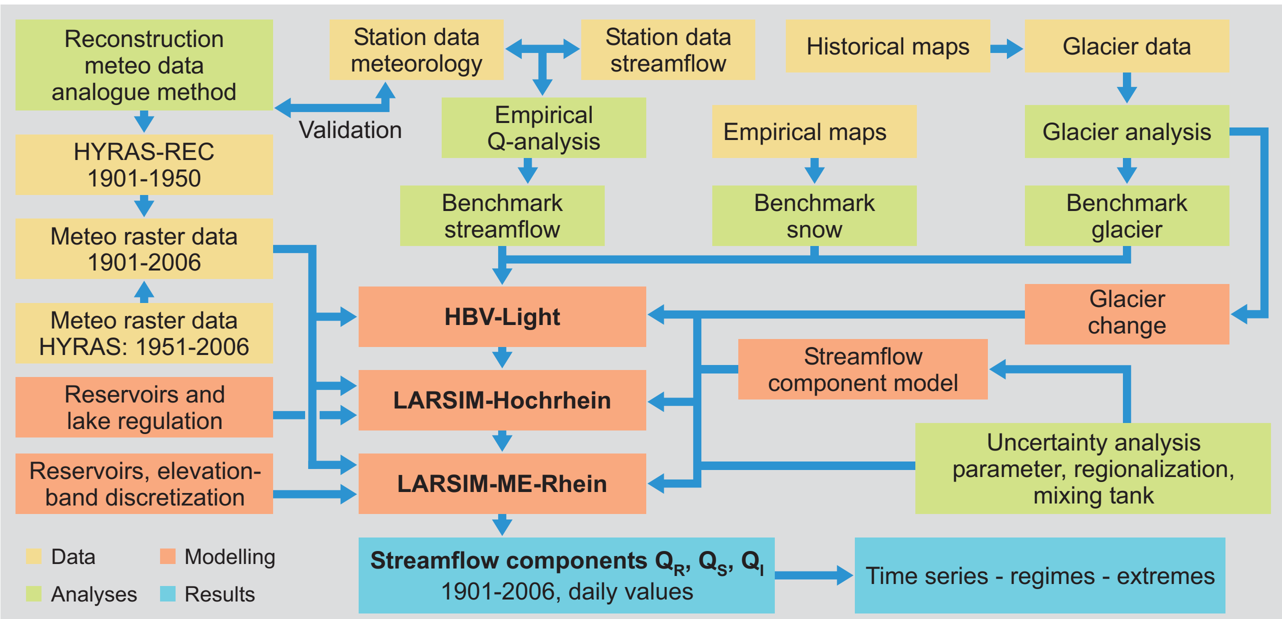


Figure 2: Project scheme. Abbreviations: SLF WSL-Institute for Snow and Avalanche Research, Davos; SWE snow water equivalent, Q streamflow; Q_R modelled rain component of streamflow; Q_S modelled snowmelt component of streamflow; Q_I modelled glacier ice melt component of streamflow.

Box 1:
Climate Sensitivity of Catchment Runoff: Data Analysis

The work in the ASG-Rhine project included an empirical analysis of the climate sensitivity of the streamflow of alpine headwater catchments. The project dataset contains 25 observational streamflow time series from smaller catchments in alpine and pre-alpine regions of Switzerland. These are climate-sensitive series of catchments with relatively little human influence on streamflow through regulation. Based on linear regression for each catchment, the contribution of temperature and precipitation to the explained variance of streamflow (converted to catchment runoff) was estimated for each calendar week. The regression coefficients thus describe the sensitivity of catchment runoff to climate variability, i.e. its estimated change per change in temperature or per change in precipitation. The selection of catchments includes many partially glacierized catchments as well as some reference catchments with no glacier coverage. This variety allowed the calculation of systematic gradients of the obtained climate sensitivities with the catchment characteristics „mean catchment elevation“ and „glacier coverage“, the latter based on the glacier inventory for the year of 2003.

The dependence of relative runoff sensitivity to temperature over the year on elevation in Fig. B1 illustrates the temperature controls of the hydrological regime. Positive sensitivities to temperature hereby describe a runoff increase with increasing temperature due to the seasonal snowmelt timing variation with elevation. The temperature sensitivity increases with elevation in spring and from May onward decreases again depending on elevation. Negative sensitivities to temperature indicate the opposite effect of runoff reduction with increasing temperatures. Due to seasonal evapotranspiration effects, this is the case in the lower elevation catchments. Under the assumption of no glacier coverage the negative temperature sensitivity in the summer extends to high elevation catchments (Fig. B1 top). Under the assumption of an elevation-dependent glacier cover (derived from the catchment characteristics of the dataset) the positive temperature sensitivity of streamflow spans the entire summer due to the ice melt effects following the snowmelt period for catchment elevations above 2000 m a.s.l. (Fig. B1 middle)

The derived regional gradients of the runoff sensitivity were finally employed to regionalize potential runoff changes for the Swiss basins. The map in Fig. B1 shows relative runoff changes for the summer season (July-Oct) as a response to a hypothetical temperature change of +2 °C. The map shows that in most areas the evaporation effect dominates and causes a reduction of runoff. In strongly glacierized basins ice melt causes a runoff increase.

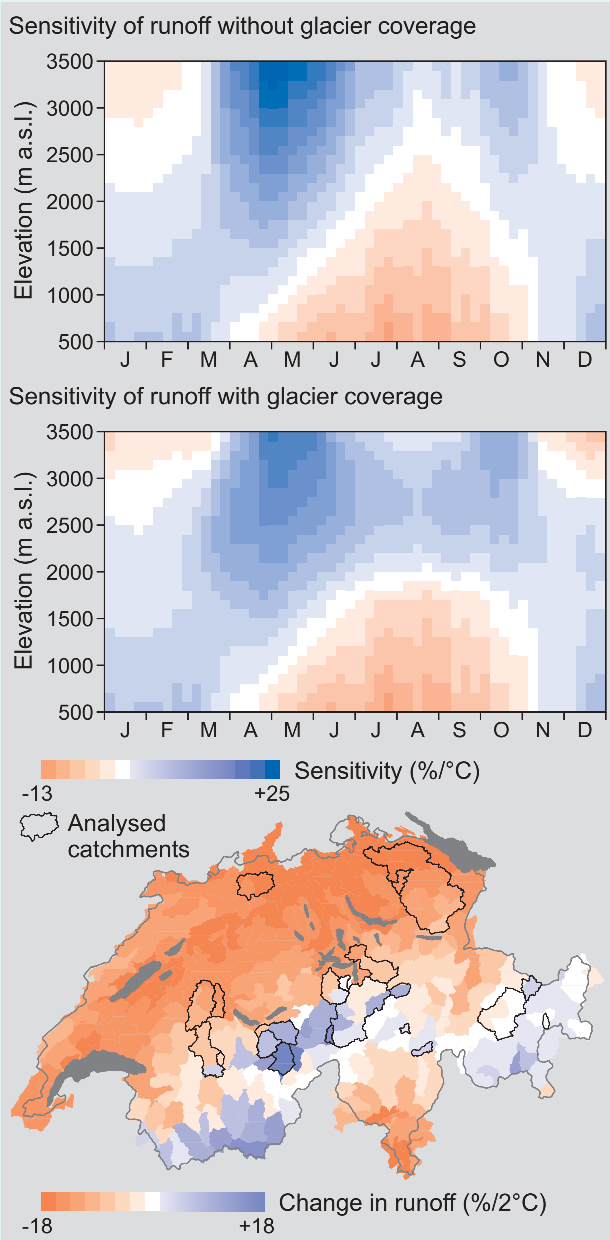


Figure B1: Weekly relative temperature sensitivity of catchment runoff depending on mean catchment elevation (upper) and regionalization of summer runoff changes based on the application of the sensitivity estimates to a hypothetical temperature increase of +2 °C.

Models for the Simulation of Streamflow Components of the River Rhine

A model chain was developed to model the streamflow components in the Rhine and its tributaries. From upstream to downstream, this model chain works in the following way (Fig. 3):

The **HBV-Light model** simulates all glacierized headwater catchments separately at the hydrological mesoscale. This semi-distributed conceptual hydrological model includes a snow and glacier routine. For the glacierized headwater catchments it was important to model the long-term glacier change and the streamflow evolution similarly well. To achieve this, a new snow distribution approach was developed for the model that accumulates snow over multiple years at high altitudes only on the accumulation areas of glaciers. The glacier adaptation routine according to the "δh method" (Huss et al., 2010) was developed further to allow not only glacier retreat but also transient glacier advances during the long simulation period.

The **Water Balance model LARSIM** simulates the remaining parts of the Rhine basin down to Lobith at the Dutch–German border. Two different grid based versions of LARSIM were used that differ in the spatial resolution of the model grid and in some of the conceptual representation of the hydrological processes. A 1x1km² model was used in the "LARSIM-Hochrhein" for the basin upstream of Basel, and a 5x5km² version was used for "LARSIM-ME-Rhein" for the basin downstream of Basel. In both LARSIM model versions, the snow routine was adapted and evaluated for the project and in the lower resolution LARSIM-ME-Rhein, a new elevation-band discretization per grid cell was introduced (Fig. 3). In addition, the development of river regulation in the Rhine basin had to be considered. In particular, the successive increase in reservoir storage for hydropower production over the modelling period was accounted for. In the alpine part of the Rhine basin, a simplified scheme with four reservoirs that conceptually summarize the increasing storage of many small reservoirs in the Alps throughout the 20th Century was implemented. Furthermore, 17 reservoirs in the mid- and lower reaches of the Rhine basin were implemented directly in the river network. The models also include regulation schemes for the large pre-alpine lakes.

As a **special feature** of the ASG-Rhine project all models in the model chain track the **rainfall component of streamflow (Q_R), snowmelt component of streamflow (Q_S), and glacier ice melt component of streamflow (Q_I)** from their respective runoff generation through runoff concentration in the sub-catchments through lakes and along the tributaries and in the main river. To provide quantitative estimates of the three components on their way through the model system, a method was developed that calculates the fractions of the three components in a system of ,virtual mixing tanks' that runs parallel to the system of storages and fluxes of the actual hydrological model. In each spatial model element, for each time step, the generated and already stored components are completely mixed according to the local water balance of fluxes in and out the mixing tank. Water is then released to the next model element with the resulting new composition of the three components.

As opposed to the calibrated model storages, however, the mixing tanks' capacities needed to be limited. If they had a similarly large capacity as the real groundwater and lake storages, the assumption of a complete mixing would result in a released flux with a constant ratio of components year-round. Limiting the mixing tank capacity instead allows estimating the direct response of streamflow components to the three different incoming runoff generation components and their runoff concentration. This addition to the models and their routing along the river network thus allows the simulation of the individual streamflow components in every model element for every day during the simulation period of 1901–2006.

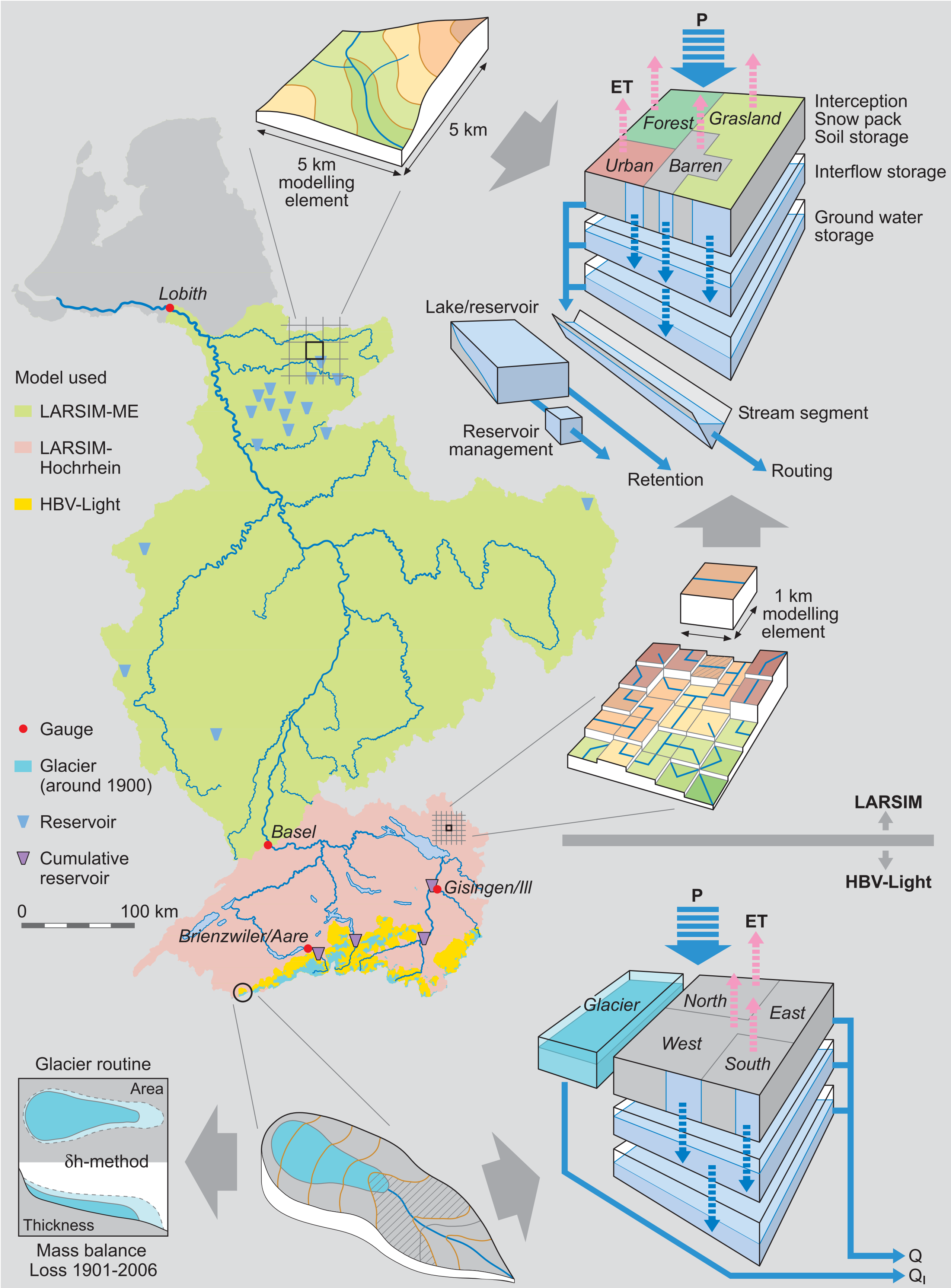


Figure 3: Scheme of the model chain and particularities of the models employed in the ASG-Rhine project. For general details on the HBV-Light model see Seibert & Vis (2012) for the LARSIM model see Ludwig & Bremicker (2006).

Box 2:
Model Calibration, Validation and Uncertainty

The model application of HBV-Light for the 49 glacierized headwater catchments had to represent the hydrological processes of high mountain hydrology. Particular attention was paid to an adequate representation of the glacier change. Although the streamflow component Q_I is generated from glacier ice melt in a comparatively small area of the entire basin, it is important with regard to the different phases with pronounced climate variation covered by the long-term simulation (see Box 3). Therefore, the modelling was supported by observational data that are available in as many catchments as possible. The employed multi-criteria calibration optimized six different criteria simultaneously during model calibration. A specifically designed objective function weighs these six criteria. Based on that, ten calibration runs consisting of about 3000 model runs with different parameter combinations, compare observed and simulated variables for each catchment. Fig. B2 shows the agreement of individual criteria for the ten best parameter sets for one exemplary catchment. The criteria (and their weights in the objective function) are:

Streamflow dynamics (50%): three calibration criteria were the general dynamic and the volume error according to the Lindstrom measure, the Nash-Sutcliffe model efficiency of the logarithmic flow data to consider the winter low flows and the Nash-Sutcliffe efficiency for the summer season to consider the melt period. Streamflow data were available for 24 of the 49 modelled headwater catchments for different periods.

Snow (25%): two calibration criteria were the snow cover area (SCA) and the mean snow water equivalent (SWE) in the elevation range of 2000–2500 m a.s.l.. Daily SWE values interpolated to a 1km grid from the SLF SWE map product, were available during the winter months Nov–May for the period 1971–2006 for parts of the Rhine basin in Switzerland and Austria.

Glacier volume change (25%): one calibration criterion was the aggregated catchment glacier volume 1940, 1973 & 2003 for each catchment. Estimates of the glacier volumes were based on glacier volume-area scaling applied to data from different sources (area 1940: Siegfried maps; area 1973: Müller et al. (1976); thickness 1973: Matthias Huss; area 2003: Paul et al. (2003)).

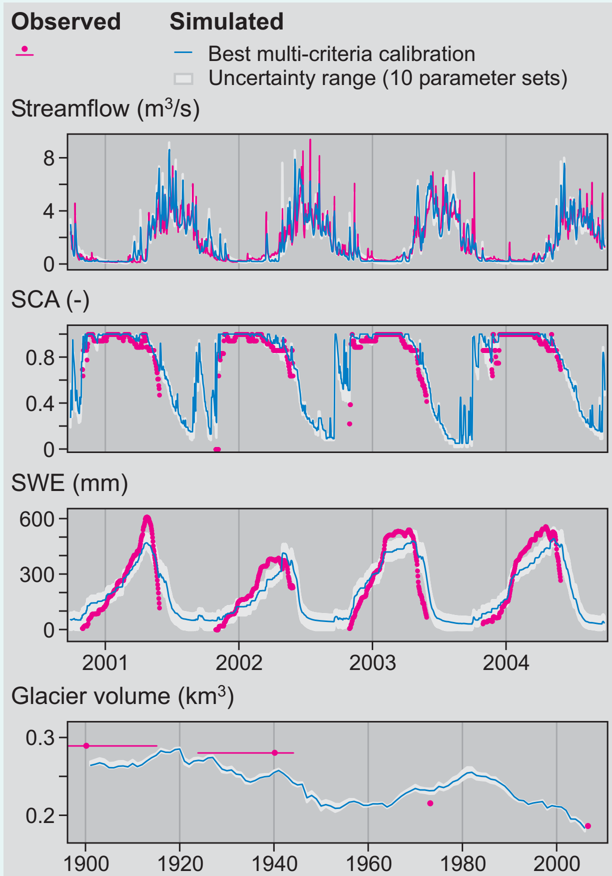


Figure B2: HBV-Light simulation results for the Alpbach catchment for daily data of streamflow, snow cover area (SCA), and mean snow water equivalent (SWE) for the elevation range 2000–2500 m a.s.l. and annual glacier volume compared to different observation-based datasets.

The use of snow and glacier data also allowed an adequate parameter optimization for those HBV-Light catchments where no streamflow record was available. The multi-criteria calibration succeeded in obtaining an acceptable agreement of simulated and observed data of streamflow, snow and glaciers over the 106-year simulation. The resulting parameter ensembles also enabled an assessment of the uncertainty in the derived fractions of the three streamflow components. The simulated daily components from the overall best parameter set in each glacierized headwater catchment were then fed into the respective model cell of the LARSIM-Hochrhein model.

Streamflow Components: the Long-term Averages

The **modelled time series of the annual streamflow components** at gauges along the Rhine illustrate the different magnitudes as well as the variability of the components from year to year (Fig. 4). On average over the study period 1901-2006 the ice melt component Q_I comprises the smallest fraction of the streamflow components at all stations shown on the map.

In the Rhine basin upstream of Basel, the Aare river contributes the largest Q_I. At the gauging station Brienzwiler Q_I is on average close to ten percent of the annual streamflow. In the Reuss river and the Alpine Rhine, where the basins' headwaters are less glacierized Q_I plays a less important role. The snowmelt component Q_S comprises the highest fractions of annual streamflow in the alpine headwaters. Downstream of the tributaries Aare, Reuss, and Alpine Rhine to the ‚High Rhine', however, the rain component Q_R dominates the streamflow composition. At the gauging station Basel, Q_R comprises close to 60% of the annual flow.

Downstream of Basel along the Rhine, the relative fractions of the ice melt and snowmelt components decline further, while the fraction of the rain component increases. On average during the study period 1901–2006 the fractions of Q_I downstream of Basel amount to less than 2% with 0.8% at Lobith. The average fraction of the snowmelt component Q_S amounts to 39% in Basel and 34% in Lobith. For the larger tributaries that have their headwaters in the various central European mountain ranges Q_S fractions around 20–45% were estimated.

Visually, it is difficult to detect uniform long-term changes governing the entire Rhine basin. The inter-annual variability of the annual mean values of the streamflow components is high. High streamflow years generally reflect wet years with large rain and snowmelt components. Low streamflow years, on the other hand, reflect years with small rain and snowmelt components. The inter-annual variability of both components amounts to about 25% of the annual flow for the river reaches downstream of Basel.

The **hydrological regimes** can also be divided into the three streamflow components based on the modelled time series. Fig. 5 shows the results for some examples: the snow and glacier melt dominated regimes of the Weisse Lütschine, one of the heavily glacierized catchments modelled with HBV, as well as the Aare river at the gauging station Brienzwiler, and the Rhine at Basel. The rain-dominated regime can be seen for the Mosel at Cochem and the complex regime of the middle and lower Rhine river. The seasonal variation of the three components directly illustrates the main controls on the hydrological regimes. The component Q_I contributes only seasonally to streamflow and peaks in August and September in the glacierized headwaters and in the Aare. From November to June, however, fractions of Q_I are negligible everywhere. In the Mosel, the snow component is present only seasonally from November to May/June. On the contrary, in the Rhine, Q_S was modelled to contribute to streamflow throughout the year. In the headwaters of the Alps QS generally peaks in June, further downstream, the largest fractions of Q_S are modelled to occur considerably earlier in the year.

At the gauge in Basel, the percentage of Q_I was modelled to amount to 4.5% in August and approx. 6% in September while at Lobith it is 2.6% in August and 4.2% in September. Thus the relative values are higher in September. The reason is that the streamflow in September is generally lower than in August, while the ice melt component still remains high and its relative percentage hence increases in September. In addition, the modelled retention of streamflow in the reservoirs and lakes and in the river network causes the occurrence of the maximum fraction of the ice melt component of streamflow in September.

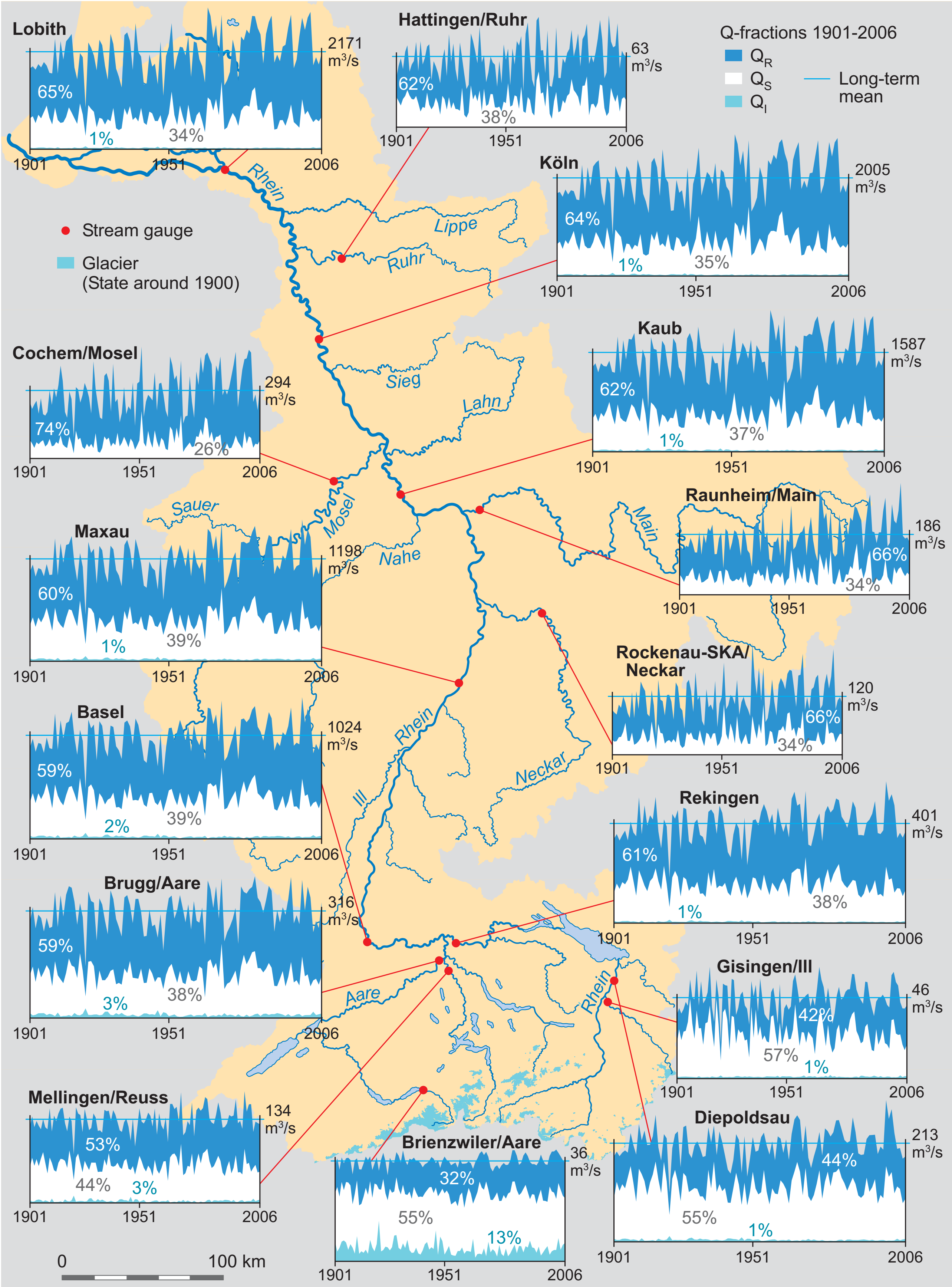


Figure 4: Modelled annual means of the streamflow components and their relative fractions of total annual streamflow from 1901–2006 for various gauges in the Rhine basin.

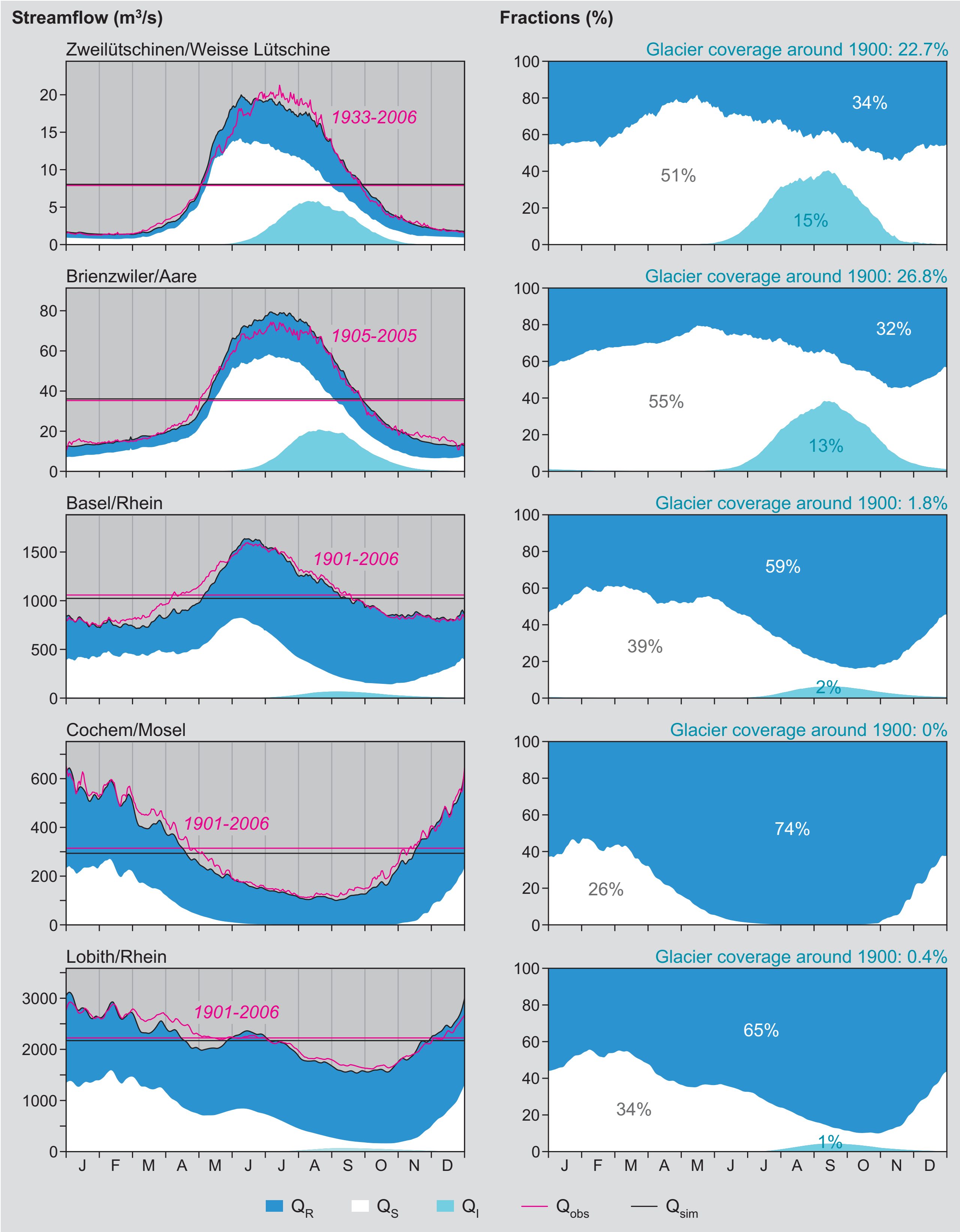


Figure 5: Hydrological regimes with modelled streamflow components of rain, snowmelt, ice melt at the selected gauges in the Rhine basin (left: absolute values with the long-term mean as a line; right: relative fractions).

Box 3:
Changes in the Ice Melt Component in the 20th Century

Despite the glacier retreat the modelled ice melt component of the streamflow in the Rhine does not show a strong long-term trend over the entire study period, i.e. a systematic decline or increase of this component. The detailed results of the modelling suggest that an increased ice melt due to increased temperature may have been compensated by the reduction in glacier area.

Fig. B3 illustrates the compensation based on the loss of glacier area and modelled mass balances. Over the entire period, about half the glacier area was lost. The simulation shows the losses during the known sub-periods with negative mass balances in the 20th Century: in the first half mainly in the 1940s and in the second half since the 1980s. The simulated ice melt component from the entire basin was higher in those periods and more so in the first compared to the second period.

In the mid- and downstream reaches the relative fractions of the simulated ice melt components also show higher decadal means during the first part of the century. During the study period no typical evolution with a maximum of the ice melt runoff contribution (peak water) was found for the Rhine. It has to be noted that the ice melt component results from a constellation of many individual glaciers with different sizes and locations. The contributions of each glacier individually may still be rising or already be declining. Nevertheless, with the model simulation it could be calculated that the generation of the same amount of the ice melt component of streamflow requires nearly twice the per-unit glacier melt at the end of the study period than in the beginning. However, the most recent years of the simulation, ca. 2000–2006, have shown a tendency to a renewed increase in the ice melt component. The question when the ice melt component of the streamflow of the Rhine will finally decline has yet to be answered.

In a separate model run, performed as a comparative experiment, the glacier area and volume was not rescaled according to the modelled mass balance. Thus, in this experiment, the glaciers still had the same extent at the end of the study period as in the beginning of the simulation in the year 1901. This simulation with constant glacier area shows a strong increase of the ice melt component of streamflow and an increasing trend over the simulation period and particularly since 1980.

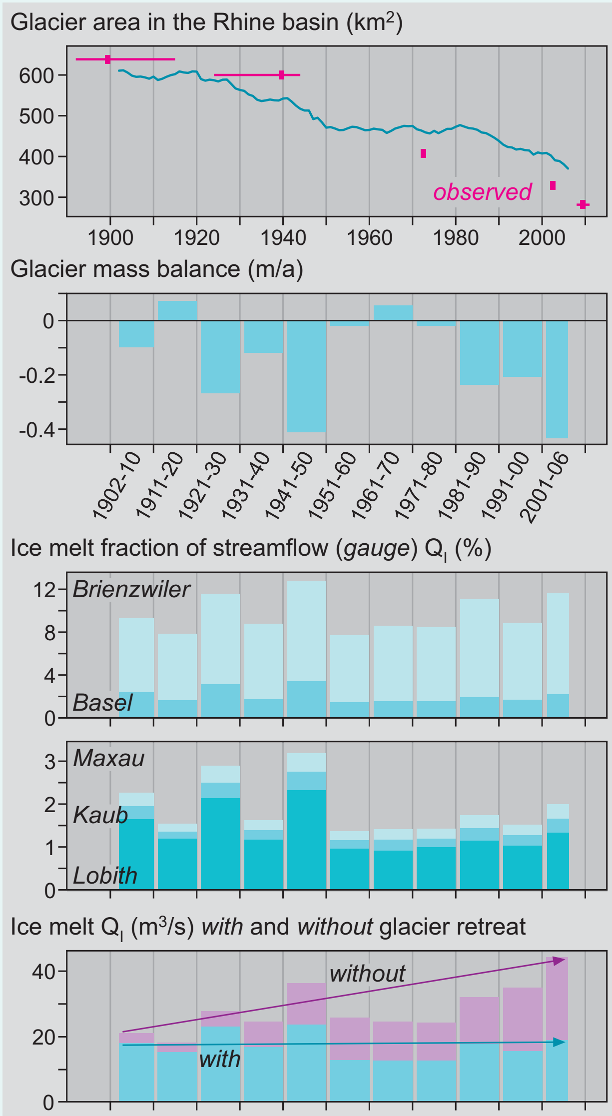


Figure B3: Simulated and observed long-term changes of the entire glacier area and simulated glacier mass balance in the Rhine basin (upper), relative fractionso of Q_I for selected downstream gauges along the Rhine (middle), and generated ice melt component in a comparative model experiment with constant glacier area (lower).

Streamflow Components During Low Flow Situations

Extended summer dry weather periods in central Europe can cause notable low flow situations even in large rivers. In the Rhine extreme low flow situations have occurred in the years 1921, 1947, 1976, and 2003. Fig.6 shows the modelled streamflow components during the year 2003 for an example of a glacierized headwater catchment, the Weisse Lütschine, as well as for the Rhine at Basel and Lobith. Following an early termination of snowmelt in the Alps, low rainfall amounts and high temperatures caused an unusually high contribution of ice melt in the headwaters. In the Weisse Lütschine daily maxima of the relative fraction of Q_I reached over 70% and Q_I comprised a quarter of the annual flow that year. In the Rhine at Basel streamflow in 2003 barely showed a spring peak of Q_S compared to that of the average hydrological regime (Fig. 5). Between June and September flow recession was only briefly interrupted. The hydrograph at Lobith illustrates the severe low flow conditions that dominated the mid and lower reaches of the Rhine in 2003.

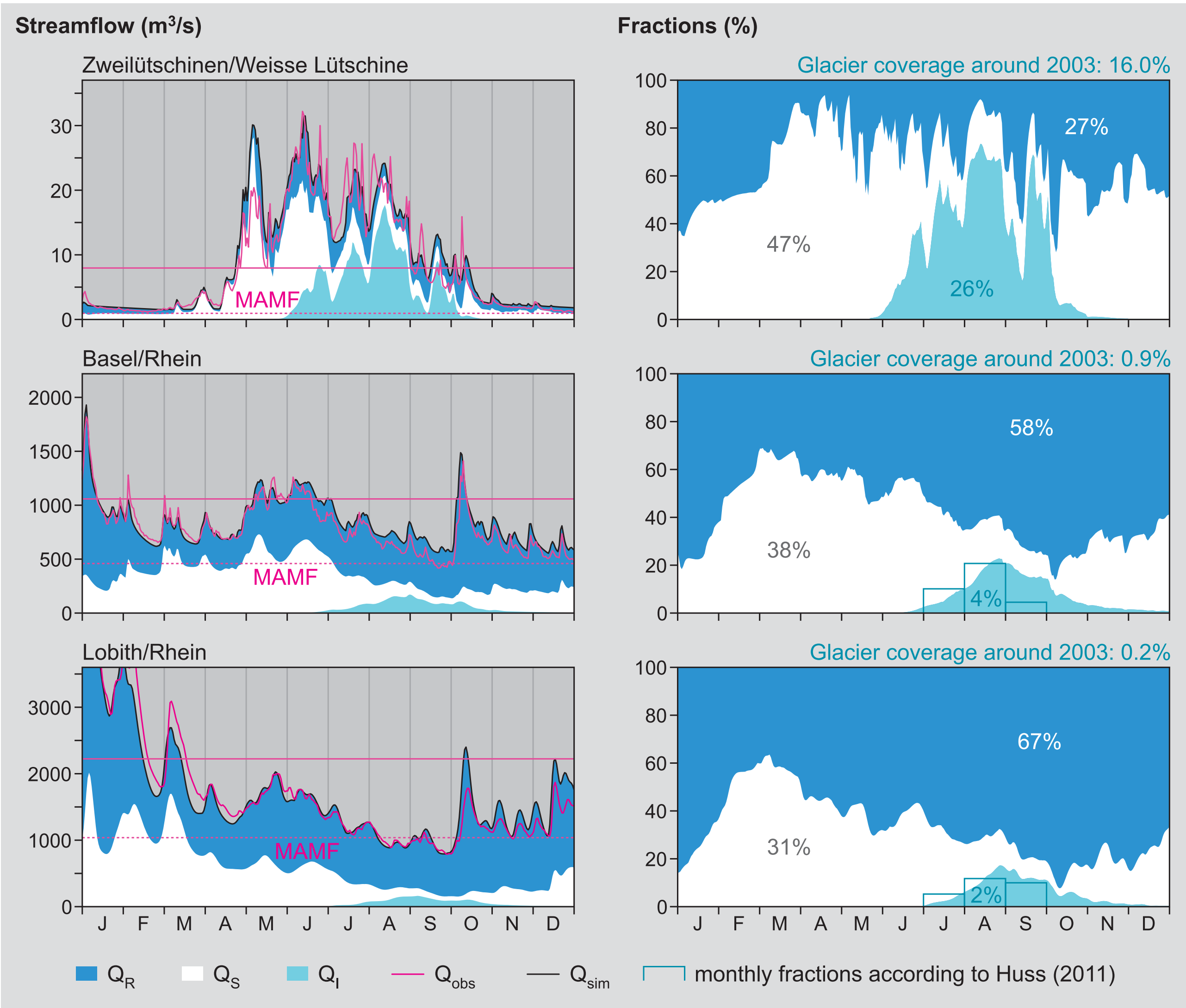


Figure 6: Observed and simulated hydrographs during the low flow year 2003 with the line of mean annual minimum flow (MAMF). With modelled daily values of the rain, snowmelt, and ice melt components of streamflow at selected gauges and compared to a previous study by Huss (2011).

Table 1: The streamflow component Q_I during the low flow year 2003.

Gauge	Minimum Q_{sim} (in 2003)				Max. absolute Q_I-component				Max. relative Q_I-fraction			
	Day	Q_{sim} (m³/s)	Q_{obs} (m³/s)	Q_I (%)	Day	Q_I (m³/s)	(%)	Q_I/Q_{obs} (%)	Day	Q_I (%)	(m³/s)	Q_I/Q_{obs} (%)
Brienzwiler	31 Dec	14	7	1	13 Aug	53	74	74	13 Aug	74	53	74
Basel	12 Dec	555	507	1	31 Aug	171	20	24	27 Aug	23	147	27
Maxau	22 Sep	586	421	14	2 Sep	167	20	23	27 Aug	22	148	26
Worms	22 Sep	610	511	14	2 Sep	166	18	20	27 Aug	21	149	24
Mainz	22 Sep	660	619	13	3 Sep	165	18	19	27 Aug	20	150	22
Kaub	23 Sep	668	621	13	3 Sep	164	17	18	27 Aug	20	151	21
Andernach	23 Sep	726	716	12	4 Sep	164	16	17	27 Aug	19	151	19
Köln	23 Sep	742	738	12	4 Sep	163	16	17	28 Aug	18	151	19
Düsseldorf	24 Sep	751	730	11	5 Sep	163	16	17	28 Aug	18	152	19
Lobith	23 Sep	794	820	11	6 Sep	162	16	16	28 Aug	17	153	17

During the low flow year 2003 high values of the ice melt component were modelled. Any interpretation of its temporal evolution has to distinguish between the absolute amount of Q_I and its relative fraction (Table 1 and Fig. 7). In many of the tributaries upstream of Basel the lowest flows in 2003 occurred late in the year, in December. At that time, the ice melt component did not play a role for low flow augmentation. Downstream of Basel, however, the lowest flows occurred in September 2003. At that time of the year, the ice melt component is more important with about 10–15% of the streamflow. Maximum daily values of Q_I were modelled between mid-August (Aare) and end of August (Rhine at Lobith). The modelled maximum daily relative contributions in percent of total flow downstream of Basel, where the Rhine was affected by low flow, was 27–17% and occurred in the beginning of September (Table 1).

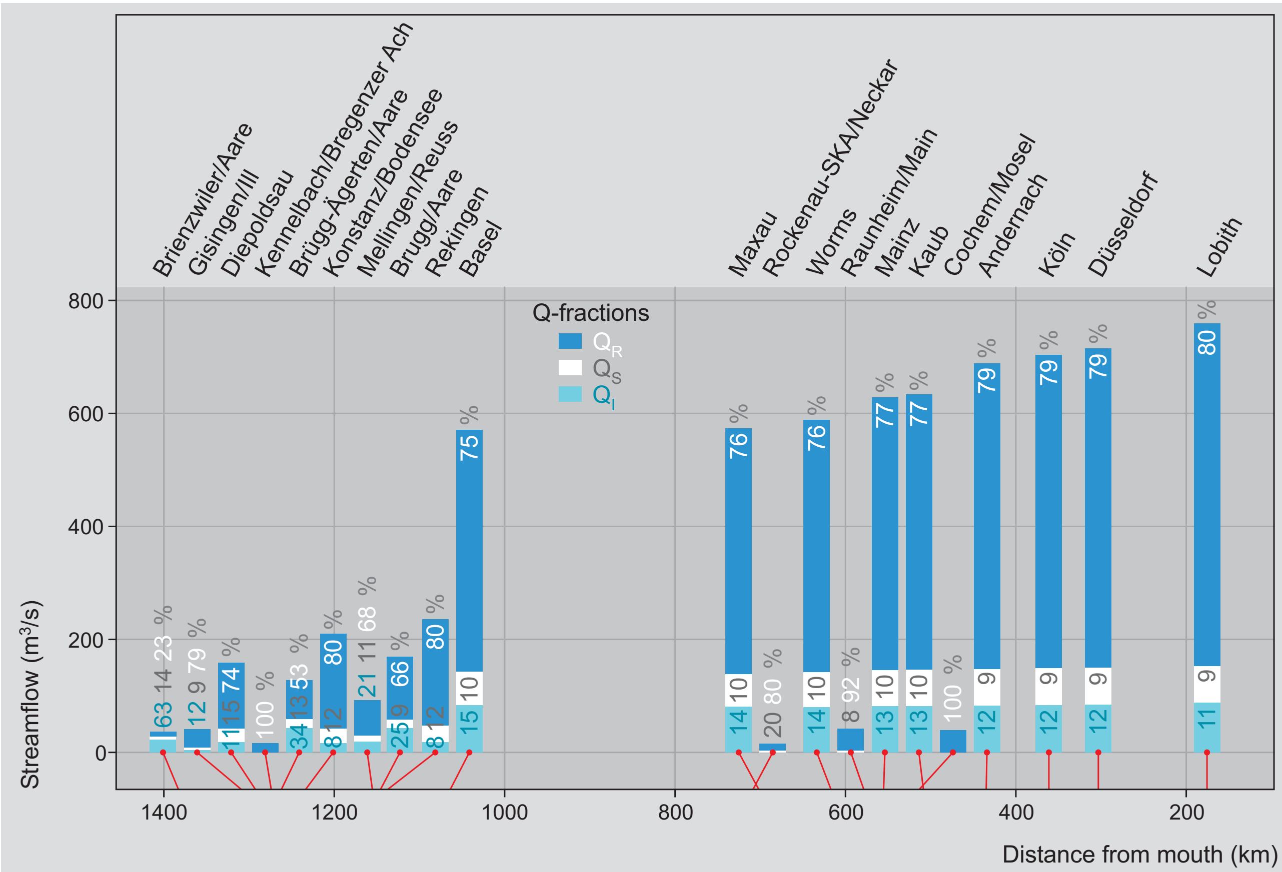


Figure 7: Longitudinal profile of the modelled streamflow components of the Rhine and its tributaries on the 23.09.2003.

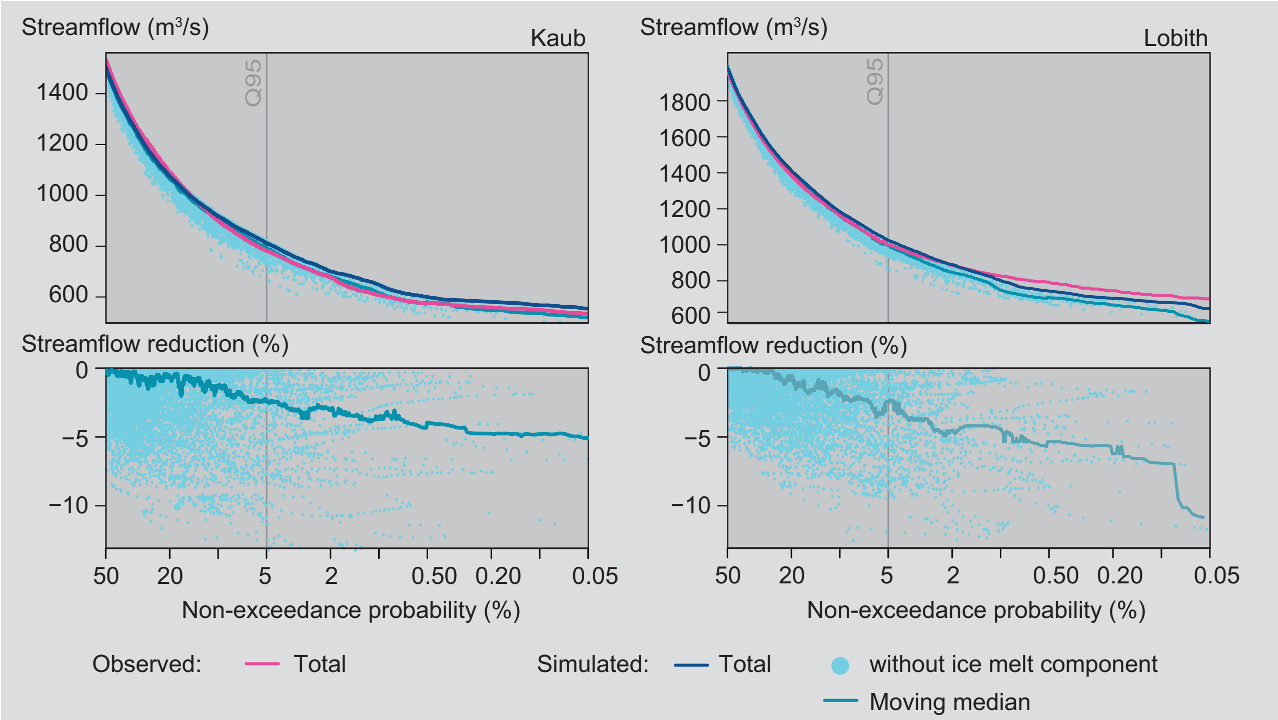


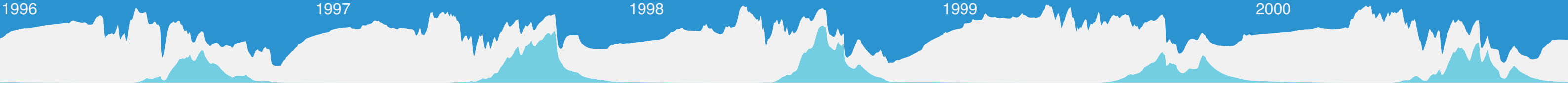
Figure 8: Distribution of the daily streamflow values during the period 1951–2006 with substracted ice melt component of the corresponding day (Qsim–QE) (upper) and derived flow reduction (lower).

The longitudinal profile along the Rhine in Fig. 7 allows a direct comparison of the fractions of the streamflow components on a particular day, the 23 September 2003, which is the day of the annual minimum flow in the Rhine at Kaub, Andernach, and Köln. The profile also shows that at the time of low flow recession, the tributaries Neckar, Mosel, Main, and others could not substantially help to decrease the fraction and thus the reliance on Q_I.

This relevance can also be illustrated by the distribution of daily flows. Fig. 8 shows the non-exceedance probabilities of the daily flow values below the median (50%) at the gauging stations Kaub (Middle Rhine) und Lobith (Lower Rhine). The comparison of modelled and observed values shows how difficult it is for the models to correctly represent the extreme low flow range, i.e. the lowest 5% (what is also known as below „Q95“ or „Q347“). Gauged streamflow in this range is also known to be subject to considerable uncertainty. The low flow range of the flow duration curve without the ice melt component can be estimated through the difference of Q_{sim} und Q_I of each daily value. The resulting curve thus corresponds to the flow if there had not been any Q_I on that day, which may correspond to a scenario for the long-range future with nearly deglaciated Alps.

Moving medians of the Q_{sim}–Q_I -values show that indeed the flows with the lowest non-exceedance probabilities show the relatively strongest reduction at those reaches of the mid and lower Rhine, where the seasonal minimum of the rain-dominated regime occurs in late summer and autumn.

Whereas on average over the simulation period 1901–2006, Q_I amounts to only 5–7% at Basel and 3–5% at Lobith during the months of August and September the maximum monthly and particularly the maximum daily fractions of Q_I can be much higher. In fact, the maximum absolute and relative fractions of Q_I were modelled during the years 1921 and 1947. The event of 2003 was one in the more recent past. Due to wide-ranging negative economic and environmental impacts of the drought and low flows this event has already been studied widely and was hence analysed in more detail in this project as well. The debate over the relevance of glacier ice melt for the low flow along the Rhine in 2003 was also one of the reasons for initiating the project. The modelled streamflow components confirm that relevance.



Conclusions

For the first time, the ASG-Rhine project quantified the daily fractions of the rain, snowmelt, and glacier ice melt components of streamflow over the long period from 1901–2006 for the entire Rhine basin. As with every model simulation, the results contain a number of uncertainties due to uncertainties in the underlying data, the simplified process representation by the models, and model parameterization. The project carried out a number of analyses to improve the understanding of these uncertainties. Overall, the conclusion is that they do not affect the principal findings, which is owed in particular to the detailed consideration of observation-based data of glacier change as well as of the dynamics of snow and runoff generation processes in the models. The elaborate model chain adapted for this project, which allows the tracking and analysis of the three streamflow components through the system, also offers a new tool for the analysis of climate and regulation scenarios.

Three results appear to be particularly important with regard to climate change and the expectation that summers will get warmer and drier in the future:

The **considerable fraction of the snowmelt component** of streamflow along the entire Rhine over the whole year highlights the relevance of further research especially on this component. For the hydrological regime and the seasonal water balance one question is whether the projected increased winter precipitation can compensate for the expected future reduction of the snowmelt component. Considering the relevance of the snowmelt component for streamflow, in particular an improved analysis and integration of observation data into the models will be important.

The only minor **change in the glacier ice melt component** of streamflow over the long time period 1901–2006 can be attributed to the process of an increasing ice melt compensated by a simultaneous glacier retreat. Due to data availability, the modelling period ended in 2006. Since then, however, several exceptionally warm summers with high glacier melt rates have occurred. With respect to climate change, the question of when the ice melt component at the scale of the entire Rhine basin will definitely start to decline is thus still unresolved. Nevertheless, the modelling suggests that at the end of the study period a runoff generation nearly twice as high as in the beginning was needed per unit area of glacier to generate the same amount of ice melt in the basin as in the early 20th Century.

Currently, the **glacier ice melt component** still plays an important role for the **sustenance of low flows** along the mid and lower reaches of the Rhine, where extreme low flows often occur in late summer. The results of the daily modelling suggest that during extreme situations as in 1921, 1947, and 2003 for example, low flows in August and September had high maximum daily fractions of ice melt that amounted to a third of the total streamflow at Basel and a fifth of the flow at Lobith. The modelling confirmed that the drought and heat wave in 2003 might have caused a considerably less severe low flow situation, had it occurred earlier in the study period, when glaciers were still larger and would have generated more melt water.

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