Climate change induced discharge scenarios for the Rhine basin

Update of the discharge scenarios for the Rhine basin using latest climate change findings

International Commission for the Protection of the Rhine

Technical report no. 297

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1. *When using data or information, the number and year of the ICPR report (ICPR Technical Report No. 297, 2024) and, if applicable, the name of the national climate service (see details under 3) must be indicated.*
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3. *Further detailed data (e.g. for other gauges and hydrological indicators) that was not used in the report can be provided on request by the ICPR Secretariat (sekretariat@iksr.de). In this case, the Secretariat will forward the request to the responsible members of the EC HCLIM and/or will refer to the research groups and national climate services mentioned in the report.*

Climate change induced discharge scenarios for the Rhine basin

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Management Summary

1. *The present report is an **update of the ICPR Technical Report No. 188 on discharge scenarios from 2011**. The report is in line with the IPCC's 5th Assessment Report (previously: 4th IPCC Report). Regional climate data based on the latest 6th IPCC report was not yet available at the time of the report in the necessary degree of detail and extent. Findings and data from the 6th IPPC report may form the basis for future updates of the discharge scenarios.*
2. *The present ICPR report refers to a **high emission scenario (RCP8.5)** for risk assessment and for evaluating needs to build up resilience in the Rhine catchment.*
3. *In summary, the evaluation of long-term changes in the past (observations) and the future (projections of RCP8.5) support the pre-existing picture of a change towards **more rain-fed flow[1] regimes** to the disadvantage of snow- and glacier-fed flow regimes in the Rhine catchment. This leads to **decreasing summer flows**, **increasing winter flows**, whereas the annual flow hardly changes.*
4. *The sequence of years with extremely low discharges over the last ten years only partially fits into the aforementioned picture, as the most recent low water events did not only occur in summer, but also in other seasons. The **recent series of dry years** is **exceptional** compared to the long-term changes observed in the past and projected for the future.*
5. *The scenarios presented here are based on further developed **climate and hydrological models** and have provided new information on changes in some cases. These new insights show that it is necessary to **update** the **ICPR climate change adaptation strategy** and its contributing reports (ICPR working and expert groups B, S, H, STEMP, LW …).*
6. *The ICPR expert group HCLIM has outlined specific topics to be part of **future research projects**; these are a) the development of a standardised method that enables the integration of discharge projections from the participating countries and institutions, b) the review of methods with the aim of improving extreme value statistics based on projections and, if necessary, the development of standardised extreme value statistics, c) projections of sub-daily precipitation and flash flood events, and d) in-depth analysis of the combined effects of climate change (drought/sea level rise, climate and socio-hydrological change).*

[1] Note: In this report, the English terms ‘discharge’ and ‘flow’ are used synonymously and are therefore interchangeable.

Extended summary

As part of its **Programme Rhine 2040** entitled 'The Rhine and its Catchment - Sustainably Managed and Climate-resilient' (ICPR, 2020), the ICPR mandated its climate expert group (formerly EG KLIMA, now EG HCLIM) with an **update of the ICPR climate scenarios** by 2024. While the previous ICPR scenarios, published in 2011, were based on information of the 4th assessment report of the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2007), this update generally relies on the 5th IPCC assessment report (IPCC, 2014). Regional climate data based on the latest 6th IPCC report (IPCC, 2021) was not yet available at the time of the report in the necessary degree of detail and extent.

As in the previous version, the new ICPR discharge scenarios combine currently existing knowledge and data from the riparian countries on the consequences of climate change on the hydrology of the Rhine. The current update is essentially based on data from Switzerland, Germany, France, the Netherlands, and the research network of the International Commission on the Hydrology of the Rhine basin (CHR). Unlike the previous version, the data acquisition and integration were not done within the research network but had to be done by the expert group HCLIM. This was possible thanks to the technical support of a climate service run by one of the participating institutions.

In line with many national climate impact assessments, HCLIM selected a high emission scenario (RCP8.5) because this scenario is regarded as more relevant for ICPR management questions than more moderate or optimistic scenarios. Many water management questions relate to risks of detrimental situations triggered by climate change and the development of resilience of the various functions of the Rhine River against those situations. These aspects will be covered by an ICPR **overarching climate change adaptation strategy in 2025**.

This report is based on observations and on five hydrological simulation data sets compiled as part of **various national and regional studies** which differ in models and methods applied. In order to compare these studies, decisions have been made with respect to **time periods (reference 1981-2010; present 1991-2020; near future 2031-2060; distant future 2071-2100), indicators (mean, low and high flow)**, and **gauging stations** or sub-catchments. Guiding principles for these decisions were a) comparability with the previous scenario report on the discharge scenarios of the Rhine (ICPR, 2011) as well as b) the best possible comparability between the data pools provided by the different participants. Despite this effort, a certain level of heterogeneity between data from the different sources remains. This results in an overall higher spread of results compared to the previous report, and somewhat limited comparability between individual gauging stations.

Global climate change interferes with the hydrological system of the Rhine River through changes in precipitation, air temperature, and other variables that determine changes in evapotranspiration and snow regimes. The main results of these **hydro-meteorological changes in the Rhine catchment** as a whole are:

a) **Air temperature has already increased significantly** in the entire Rhine basin since the middle of the 20th century (0.7 to 1 degrees Celsius, depending on the season) and **will continue to do so** in all meteorological seasons by about 1 to 2.5 degrees Celsius until the mid of the 21st century (2031-2060) and 3 to 5 degrees until the end of the 21st century (2071-2100) with the strongest increase in summer and fall (between June and November). Accordingly, the **number of hot days** (>30°C) will increase while the number of frost and ice days will decrease.

b) Both observations and projections show that climate change causes **precipitation levels** to **shift** between the meteorological seasons, with **increases in winter and spring and decreases in summer**. This results in **moderate increases in annual precipitation amounts**. The changes progress over the course of the 21st century and reach increases or decreases of up to over 20% towards the end of the 21st century.

c) The **projections** show a **general trend** towards an increa**se in extreme precipitation events**. This is not yet clearly evident in the **observations**. It is assumed that **heavy precipitation will increase as will the number of dry days**. In addition, an **increase in the duration of dry periods** is expected, even if this signal is not quite as clear as the previously mentioned signals.

These hydro-meteorological changes affect a. o. the seasonal distribution of discharges in the different reaches (stretches) of the Rhine River. These **flow regimes** can be summarised as follows:

d) In the **past** (1981-2010 compared to 1951-1980), all flow regimes (snow fed, rain fed, combined) showed **increasing winter flows and decreasing summer flows**, indicating a general tendency towards more **rainfed regimes**.

e) The general **future** picture is that **observed changes and trends** will become much more pronounced for the future periods, in particular for the period at the end of the 21st century (2071-2100 compared to 1981-2010) as opposed to the mid of the century (2031-2060 compared to 1981-2010).

f) It should be noted, however, that the different ensembles (i.e. data pools) - although showing the same direction of change - **differ with regard to the projections** for some months, seasons, half years and river stretches, in particular with respect to the summer flow decrease projected for the end of the 21st century in the upper reaches.

The changes in the **flow regimes** are associated with changes of **high, mean and low flow** statistics.

g) Compared to the **reference period (1981-2010)**, the **recent past (1991-2020)** and in particular the period after 2010 was characterised by **many drought years**. Although severe river floods were recorded in some sections of the Rhine (e.g. flood event with an exceedance probability of less than once in a hundred years at the Basel gauge in May 1999 and in August 2007), this was not the case for the entire Rhine.

h) As a consequence, all **flow indicators** (low and high, seasonal and annual) show **decreases** of a few percent at most gauges. This picture (flow decrease in summer and winter) differs from the developments in the 20th century, which, for example, show increasing winter flows. These recent changes, which occurred over a period of 10 years, are also visible in the long-term parameters (30 years).

i) The discharge changes **get more pronounced with increasing distance from the Alps** due to the larger influence of the tributaries from the mid-mountain ranges (Main, Moselle) which show the highest relative changes.

j) In the **middle of the 21st century (2031-2060)** the overall view of all results repeats the picture already known from earlier climate impact analyses for the Rhine. On average, decreasing summer discharges (MQ_{Summer}, $NM7Q_{Summer}$) are contrasted by winter increases (MQ_{Winter}) with the consequence of only **slightly changed annual discharges** (MQ).

k) These changes are associated with an **increase of discharges** in the upper (MHQ, HQT) as well as in the lower discharge range (MNQ).

l) It is noticeable that the **increases** apparent in the **ensemble projections for winter (MQ) differ from the developments currently observed**. Observations currently show a decrease during the winter months.

m) By the **end of the 21st century (2071-2100)**, the aforementioned changes essentially persist with an intensification in the second half of the 21st century.

n) On average, **discharges** will continue to **decrease in summer** (MQ_{Summer}, $NM7Q_{Summer}$) and **increase in winter** (MQ_{Winter}) until the end of the 21st century. As these opposing signals largely balance each other out, there are only **minor changes in the mean annual discharge (MQ)**.

o) An **intensification of extreme discharges** is visible both in the high flow indicators (MHQ, HQT) and in the low flow indicators (MNQ). Also, for winter low flows ($NM7Q_{Winter}$) there are trends towards a decrease at some gauges.

In summary, the evaluation of long-term changes in the past (observations) and the future (projections of RCP8.5) largely support the pre-existing picture of a change towards **more rain-fed flow regimes** rather than snow- and glacier-fed flow regimes in the Rhine catchment. **This leads to decreasing summer flows, increasing winter flows, almost unchanged annual flows**, and - in many river sections and tributaries - an intensification of low and high flow extremes. The sequence of extreme low flow years after 2010 does not fit into this picture, because it shows decreases in all indicators (high and low flow) and seasons (including winter).

Due to the updated scenarios, the continuously improved capabilities of climate and hydrological models, and the new span of change signals for the analysed parameters, **HCLIM recommends re-evaluating the ICPR climate change adaptation strategy and its corresponding reports** (e.g. Water temperature) based on the new discharge scenarios.

Glaciers are still important water sources during long lasting dry weather situations. Research projects focusing on snow- and ice-related river flow components show that the low flow support from glaciers in the Rhine at Basel has passed its peak already (known as 'glacier peak water') decreasing to almost zero by the end of the century under a high emission scenario (RCP8.5).

The **large lakes** in the upper reach of the Rhine catchment generally follow the aforementioned seasonal effects of climate change (higher levels in winter, lower levels in summer and fall) due to the changes of inflow. Current reservoir management in the upstream parts of the catchment, determined by the energy market, amplifies these climate change effects by retaining water in summer and releasing water in winter.

In the **delta region**, the compounded effects of hydrological change and **sea level rise** have to be taken into account. Both aspects will affect drainage opportunities, flood risk management, as well as fresh water supply and salinity. Also here, current management practices and targets may come to their limits within the context of climate change.

Compared to the changes projected by **previous scenarios** (Special Report on Emissions Scenarios - SRES A1B), the changes projected with the RCP8.5 scenario fundamentally point in the same direction. The spread of results is, however, higher because more - and in part heterogenous - data pools were used. This report is a first attempt to **compare national studies based on the 5th IPCC report**. Within the framework of HCLIM it was not possible to explore and possibly eliminate the differences between the modelling and data treatment procedures of the contributing research teams. This should become part of future projects in the research network. Furthermore, more **research and insights are needed** with respect to (a) an inventory of available methods for extreme value statistics including projected flow series, (b) sub-daily extreme phenomena such as convective precipitation and resulting flash flood-like events, and (c) compound effects of climate change, e.g. due to combined effects of hydrological change and sea level rise, and future water uses and water management in the entire catchment.

The **next generation** of climate scenarios as published in the 6th IPCC assessment report from 2021 on (AR 6) (IPCC, 2021 and 2023) are not available in enough detail to allow a regional impact assessment for the Rhine and its sub-catchments. A global comparison based on the new high emission scenario (Shared Socioeconomic Pathways - SSP5-8.5) points towards higher global temperature changes (with large uncertainty) than in the 5th IPCC report underlying this report. The KNMI'23 climate scenarios are already based on a selected set of global climate models, the regional-mean climate change response is determined by a selected set of global climate models (Coupled Model Intercomparison Projects - CMIP6). Generally speaking, the mean spring and summer climate will become drier.

The next **update of this scenario report** is scheduled in connection with or ahead of the ICPR climate change adaptation strategy updates scheduled every 10 years (next update 2035).

1 Context of the present study

The Conference of Rhine Ministers in 2007 stated that the effects of climate change in the water sector are clearly visible and instructed the ICPR to take measures to adapt to these effects. Therefore the ICPR published the 'Study of Scenarios for the Discharge Regime of the Rhine' in 2011 (ICPR report no. 188, 2011), including information from the International Commission for the Hydrology of the Rhine basin (CHR; project 'Rheinblick2050' - CHR I-23, report 2010). As a result, the first ICPR strategy on climate change adaptation for the Rhine basin was published in 2015 (ICPR 2015).

At the 16th Conference of Rhine Ministers (2020), the next important step towards appropriate measures against climate change in the Rhine catchment was undertaken, namely the launch of the Rhine 2040 Programme called 'The Rhine and its Catchment: Sustainably Managed and Climate-resilient' (ICPR 2020). One of the main objectives of Rhine 2040 is to update the ICPR climate change adaptation strategy by 2025.

The Working Group 'Flood and Low Water' (WG H) has tasked the ICPR Expert Group HCLIM (EG HCLIM) with updating the strategy by updating the report no. 188, including the new discharge scenarios. This report will be the basis for an updated climate change adaptation strategy (2025) and feeds into activities of the other ICPR groups as well as in the interim report of Rhine 2040 to be published in 2027. Also, the report and results can be used - e.g. in the frame of the relevant EU directives - for studying the consequences of climate change by the organisations of the Rhine basin states (government, research institutes, universities and consultancy companies) and by any other organisation outside the Rhine basin.

2 Data and methods

Climate change is one of the central challenges for human society and its environment. Since the publication of the ICPR report no. 188 (2011), various extreme events in the Rhine catchment and others have taken place. This has led to a lot of attention on climate impact studies and climate adaptation strategies. Also, the relevant data and literature base has grown considerably. This report will only mention a few essential works that are directly related to the activities of the EG HCLIM.

The Coupled Model Intercomparison Projects (CMIP) of the World Climate Research Programme (WCRP) provide projections of future climate on a global scale and insights on climate change in the form of a multi-model ensemble of global climate models. These model outputs contribute to the physical science basis of the Intergovernmental Panel on Climate Change (IPCC) reports (Mehl et al., 2011; Eyring et al., 2016). For a regional analysis (e.g. for the Rhine basin), the global climate models (e.g. EC-Earth) are downscaled to a regional level within the framework of EU-funded and national programmes (e.g. EURO-CORDEX) (e.g. Jacob et al., 2014). These regional models form the basis for climate impact modelling and hydrological analysis including discharge projections through hydrological modelling. In this report, we use regional studies focusing specifically on the Rhine catchment as a whole or its sub-catchments.

So-called 'climate services' have developed rapidly in the past 10 years. Information on the hydrological effects of climate change is offered through both national portals and the European Copernicus Climate Change Service (Berg et al., 2021; EU-Copernicus, 2024). In this context, 'information' means access to data and, in some cases, advice on specific issues, including user-specific evaluations. Various guidelines that have been developed or updated in recent years provide information and guidance on how to deal with the topic of climate change in the water management sector. This includes the European level, e.g. in the form of the EU guidance document number 24 (EU-CIS 2009, 2024).

2.1 Data providing research institutions and research teams

The objective of the present report is to evaluate and update the existing ICPR river flow scenarios (ICPR, 2011). For reasons of comparability, the evaluation scheme of the 2011 scenario study is basically retained. New and more data sources are used, which are currently the basis for adaptation strategies in the riparian states. The states of the Rhine basin have conducted recent or ongoing studies on the effects of climate change on the water regime in the Rhine catchment. A short description of the studies and research teams that contributed data to this report is given below. Summary information on the data sources and on the technical-methodological framework (scenarios, climate simulations, and hydrological models used) can be found in section 2.3 and in the technical appendix A.

The **International Commission for the Hydrology of the Rhine basin** (**CHR**) launched the project: 'The snow and glacier melt components of streamflow of the river Rhine and its tributaries considering the influence of climate change' (CHR, 2016 and 2022). It examined how the streamflow components of the Rhine have changed, as well as how they will change in the future, as a result of climate change, retreating glaciers and decreasing snowpacks in the mountains. This project quantified the daily fractions of the rain, snowmelt, and glacier ice melt components for a specific future climate scenario (RCP8.5) for major tributaries and along the main river Rhine based on an ensemble of 7 projections until 2100 (label '**ASG2**').

In **Switzerland** the Federal Council commissioned the Federal Office for the Environment to prepare reliable hydrological bases for the adaptation measures. To this purpose the priority theme 'Hydrological principles of climate change' of the National Centre for Climate Services (NCCS) - **Hydro-CH2018** for short - analysed the effects of climate change on the water balance, water bodies and water management. The work is based on the CH2018 climate scenarios that projected - among others - RCP8.5 for Switzerland (NCCS, 2018). Various hydrological models tailored to the specific research questions (models for groundwater, water temperature, vegetation and agriculture) were used in the Hydro-CH2018 project (Federal Office for the Environment - FOEN, 2021). This resulted in the hydrological scenarios indicating the future developments in the Swiss water bodies. The results are openly accessible in various publications and on the NCCS website (Hydro-CH2018 hydrological scenarios) and the Hydrological Atlas of Switzerland (HADES, HYDROmapsCC).

In **Germany**, expertise, models and methods are continuously developed within the Länder institutional networks (e.g. within the KLIWA cooperation) and within research projects and programmes (e.g. BMDV network of experts; NILSON et al. 2020). The provision of data is carried out by permanently established climate services (e.g. the 'DAS Basisdienst Klima und Wasser') or advisory services of the Länder supporting national and regional climate adaptation strategies (e.g. the 'German Adaptation Strategy', DAS). In total, Germany contributes two daily discharge data sets that are being used in this report, based on the high-emission scenario RCP8.5 on one hand and using the spatially distributed process-oriented water balance model LARSIM on the other hand (Bremicker 2000; Nilson et al. 2020). They cover the period up to 2100. The projection ensemble provided by the Federal Institute of Hydrology (BfG) via the DAS basic service 'Climate and Water' uses an ensemble of 16 projections for the international catchment and was produced with the water balance model LARSIM-ME (horizontal resolution of 5 km, label '**DAS**'). Another ensemble of 9 projections covering the catchment upstream of gauge Cologne and simulated with the water balance model LARSIM (horizontal resolution of 1 km) and a so-called synoptic-model for the Rhine channel was contributed by the KLIWA cooperation (label '**KLIWA**').

France contributed data produced in the MOSARH21 project (Moselle-Sarre-Rhin au 21e siècle - MOSARH21) (Thirel et al., 2018). The project was completed in 2017, funded by the Rhine-Meuse Water Agency (Agence de l'Eau Rhin-Meuse) and IRSTEA (now INRAE), led by IRSTEA in association with Laboratoire LOTERR (Université de Lorraine), HYDRON and DREAL Grand Est. It aimed to evaluate over the 21st century the future impacts of climate change on river discharge for the **French tributaries** such as Moselle, Sarre and others. The study was performed following a multi-model approach (using two hydrological models - GRSD and LARSIM - and several parameter sets) in conjunction with an ensemble of downscaled climate projections (based on the IPCC AR5 emission scenarios) (label '**MOSARH21**').

In the **Netherlands** the Royal Netherlands Meteorological Institute (KNMI) produces climate scenarios and data on a regular basis. The **KNMI'23** scenarios are the most up-to-date scenarios, based on the AR6 report of the IPCC. The climate scenarios are input for the discharge projections which are processed by Deltares in collaboration with KNMI and Rijkswaterstaat, the river management authority on large water bodies. As the KNMI'23 discharge projections were still in development when this report was written, other data sets based on the AR5 report had to be used (label '**KNMI'14**'). First results of KNMI'23 on the meteorological changes are mentioned in section 6.1. The discharge projections selected in this study (label: KNMI'14) use the hydrological model HBV and are based on the high emission scenario RCP8.5, among others. The Dutch dataset differs from the other datasets in terms of data processing and approach. Details can be found in the technical appendix A and the project reports cited there.

Although some of the riparian states have carried out general studies on the effects of climate change on the Rhine catchment, the information was not available in sufficient depth to serve as a data basis for the evaluations presented here. Information is available here as well, as some of the aforementioned data pools cover larger sections of the Rhine catchment area. **Liechtenstein** is covered e.g. by the data from Switzerland and the CHR. The CHR data also covers **Austria**. **Luxembourg and Belgium (Wallonia)** are covered by the CHR, KLIWA and DAS data.

In summary, the whole Rhine catchment is covered with data, but data sources and processing procedures differ, resulting in a variety of model results for each sub-catchment and gauging station.

2.2 Data integration and analysis scheme

There is currently no unequivocally and generally accepted 'best practice' in hydrological climate impact assessments. Indeed, modelling discharge projections is still a challenge with several uncertainties. This means that the contributing research teams that supplied data to this study (see section 2.1) have independently chosen their own approaches and models. An overview of similarities (green) and differences (orange) between the studies contributing to HCLIM is shown in table 1.

Table 1: Overview of the similarities (green) and differences (orange) of the supplied data sets in this study

Country, contributing research team	**CHR**	**NL**	**CH**	**DE**	**DE (federal states)**	**FR**
Contributed activity	**CHR-ASGII**	**KNMI'14**	**Hydro-CH2018**	**DAS (2021)**	**KLIWA**	**MOSARH21**
Previous activity	CHR-Rheinblick (2010)	KNMI'06	Hydro-CH2011	KLIWAS, DAS (2015)	KLIWA	EXPLORE 2070
Spatial coverage	Rhine (complete)	Rhine (complete)	Rhine (CH)	Rhine (complete)	Rhine (Cologne)	Rhein (FR)
Temporal coverage	1973-2100	1951-2100 (slices[2])	1981-2100	1971-2100	1971-2100	1971-2100 (slices)
IPCC report	AR5	AR5	AR5	AR5	AR5	AR5
Scenario	RCP8.5	RCP8.5, ...	RCP8.5, ...	RCP8.5, ...	RCP8.5	RCP8.5, ...
Climate models	CORDEX	CMIP5, RACMO	CORDEX	CORDEX	CORDEX	CMIP5, CORDEX
Climate data processing	Bias correction	Delta change	Bias correction	Bias correction	Bias correction	Delta change
Ensemble size	7	3[3]	20	16	9	4[4]
Hydrological model	HBV-light, LARSIM	HBV	HBV-light, PREVAH	LARSIM	LARSIM	GRSD, LARSIM
Reference period	1981-2010	1951-2006	1981-2010	1971-2000	1971-2000	1971-2000 (2005)
'near' future (future 2)	2031-2060		2020-2049 (2045-2074)	2031-2060	2021-2050 (2041-2070)	2021-2050
'distant' future	2071-2100	2071-2100	2071-2100	2071-2100	2071-2100	2071-2100
Successor activity	CHR-Rheinblick (2027)	KNMI'23	Hydro-CH2025	DAS (2027)	KLIWA ...	Explore2

[2] Explanation of 'slices': For discharge scenarios, the KNMI'14 and MOSARH21 models do not calculate continuous periods (daily time series extending from 1971 to 2100) like the other models, but periods limited to a few decades (called 'slices' in this report).
[3] W_L, W_H, W_{Hdry}; the scenarios G_L and G_H were not taken into account because they are not based on RCP8.5. See related explanations and definitions in section 2.1.
[4] 2x LARSIM, 2x GRSD

The expert group provided a technical integration within the limitations of the raw data (daily time series) of the different contributions and data sources following the definitions summarised in the following paragraphs.

The data processing and analysis for this report was carried out by the German Federal Institute of Hydrology (Bundesanstalt für Gewässerkunde - BfG) within the framework of the DAS-Basisdienst 'Klima und Wasser'. The results of the analyses were discussed by expert group HCLIM. Decisions on the integration of the data and the analysis steps were taken jointly by the group. The analysis scheme that was applied to all data and led to the results presented in section 3 is outlined below. Additional background information is given in the technical appendix (appendix A).

2.2.1 Time periods

Input data (observations, projections) were provided as daily time series extending from 1971 to 2100[5] (or similar, see table 1). The decision was made to base the time periods on the available data and the partial consistency with underlying studies. The report evaluates changes in the periods **2031-2060** ('near future', 'mid of the 21st century') and **2071-2100** ('far/distant future', 'end of the 21st century') with the period **1981-2010** as a reference climate. In addition, the period **1991-2020** ('present') was added to capture hydrological changes in the recent past.

2.2.2 Scenario

Although several groups used more than one scenario, it was decided to limit evaluation to the high emission scenario **RCP8.5**. In addition, it was decided to only run the climate model runs consistent with the **5th IPCC assessment report**.

First, the decision was taken for pragmatic reasons because RCP8.5 is the only scenario that was used in *all* underlying studies. Second, HCLIM decided to follow a *precautionary* approach. The assumption was made that for risk management other ICPR working groups will focus on and are in preparation of adverse conditions (presumably linked with high emission scenarios) rather than more moderate conditions. It is, however, important to note that all scenarios (i.e. also RCP8.5) have to be regarded as *possible* pathways to the future, depending on the mitigation decisions and measures as well as success in the upcoming years. Taking other RCP scenarios (2.6 or 4.5) leads to different results.

The limitation to the scenarios and global data bases of the IPCC's 5th Assessment Report is based on the fact that more recent scenarios and data that are consistent with the most recent 6th Assessment Report are not yet available in the form of runoff projections.

2.2.3 Gauging stations/sub-basins

According to the available projections, climate change is expected to show its effects in several components of the hydrological cycle (snow, rain, groundwater, evaporation etc.). As these components are of different relevance in different regions of the Rhine catchment (e.g. snow in the Alpine parts, rain in the mid mountain ranges), river flow changes will differ in different reaches of the Rhine Basin.

In order to recognise this differentiation in the necessary brevity of this report and to ensure comparability with the earlier scenario report (ICPR, 2011), nine representative gauging stations were selected. These stations give insight into important regional characteristics of river flow change (figure 1). Basel and Maxau represent the Alpine part of the Rhine River (currently strongly snow-influenced). Trier and Raunheim represent the mid-mountain ranges (rain-dominated). Worms, Kaub, Cologne, and Lobith represent combined characteristics of both regions (snow- and rain-influenced regimes). Report No. 188 (ICPR, 2011) uses eight of the stations mentioned here. The Rockenau gauge was included additionally.

Note: The data pool in this report comes from a larger number of gauging stations than shown in figure 1. Further information and evaluation results can be provided on request by the ICPR Secretariat (sekretariat@iksr.de). In this case, the Secretariat will forward the request to the

[5] Note that this is true for all models used except for KNMI'14 and MOSARH21 which feature time slices defined in table 1/section 2.2.

responsible members of the EC HCLIM and/or will refer to the research groups and national climate services mentioned in the report.

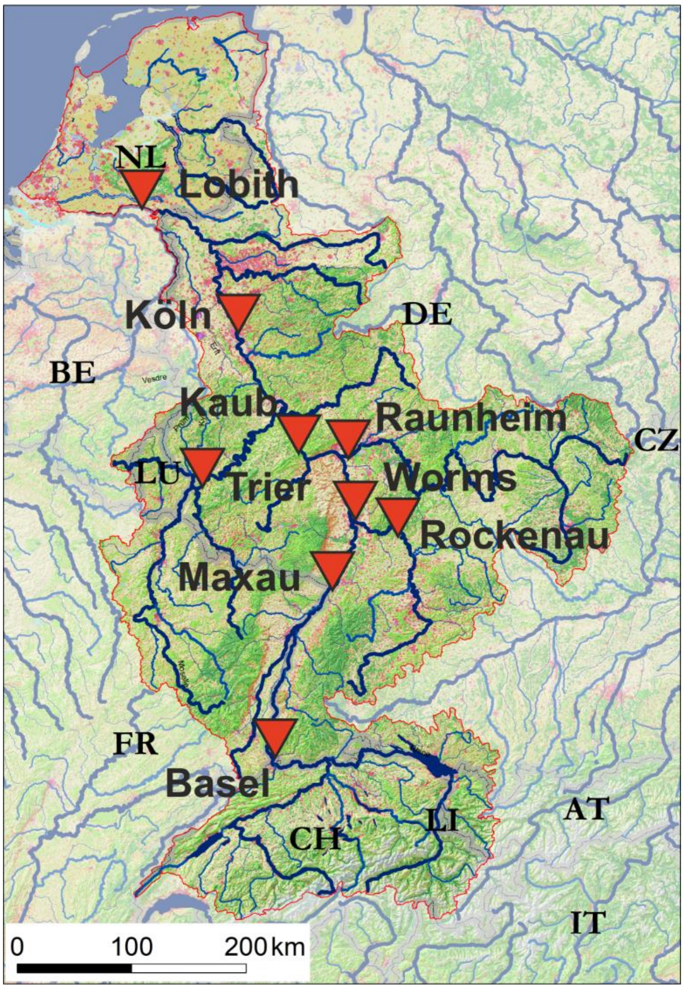

Figure 1: Overview map showing the gauging stations selected for this report

2.2.4 Hydrological statistics and indicators

As in the previous report no. 188 (ICPR, 2011) a selection of hydrological statistics and indicators was chosen to reflect the effects of climate change (table 2). The hydrological indicators were chosen to ensure comparability with the previous report (ICPR, 2011) and to address specific water management aspects such as annual water resource availability, navigation, ecological aspects and flood risk management. To keep the report compact, it was not possible to cover all possible indicators and hydrological aspects. Further indicators can be generated on request. The ICPR Secretariat is responsible for this.

Table 2: Overview of hydrological indicators applied in the report

(Note: On request, the ICPR Secretariat can provide information on further indicators and hydrological parameters. In this case, the Secretariat will forward the request to the responsible members of the EC HCLIM and/or will refer to the research groups and national climate services mentioned in the report.)

Annual indicators (hydrological years: Nov-Oct)		Possible relevance
Annual mean flow	MQ	indicator of general water resource availability
Annual lowest flow	MNQ	indicator of annual low flows, e.g. relevant for navigation, water quality and ecology
Annual highest flow	MHQ	indicator of annual high flows (not extreme high flow), e.g. relevant for floodplain ecology and environment
Seasonal indicators (hydrological seasons summer (May-Oct) and winter (Nov-Apr))		**Possible relevance**
Summer and winter mean flow	MQS and MQW	indicators of changes in flow seasonality (flow regime) and changes in water resource availability
Summer lowest flow (7-day mean)	NM7QS	indicator of stress due to low flow in the warm season (ecology, e.g. for fish populations in connection with too high water temperatures)
Winter lowest flow (7-day mean)	NM7QW	Indicator of low-water stress in the cold season (ecology, e.g. for fish populations in connection with too low water temperatures)
High flows linked to flood risk management plans		**Possible relevance**
frequent flood	HQ10	linked to high-probability scenario according to EU floods directive (maps and plans)[6]
medium flood	HQ100	linked to high-probability scenario according to EU floods directive (maps and plans)[6]
extreme flood	HQ1000	linked to extreme scenario according to EU floods directive (maps and plans)[6]

[6] The absolute reference values of the discharge used to calculate the change information are based on the database underlying this report. They do not necessarily correspond to the officially agreed values (e.g. as part of the national implementation of the EU Floods Directive). To avoid confusion, no absolute values are given.

All indicators were calculated for the gauges mentioned above, using the available data from observation and projections. For the discharge-related indicators, annual indicators refer to hydrological years (Nov-Oct), seasonal indicators refer to the hydrological seasons summer (May-Oct), and winter (Nov-Apr). Annual HQ-series underlying the extreme value statistics refer to hydrological years. Further information on extreme value statistical flood analyses can be found in technical appendix A.

Note: The hydro-meteorological indicators are based on meteorological practices and have different annual and seasonal references (see Section 3.1 and table 6).

All change signals are rounded to full percent values.

2.2.5 Aggregation and integration

From the annual and seasonal series, multi-annual change signals between the future and the reference period (1981-2010) were calculated as 30 year running means (figure 2).

In a second step, the range of change signals between the reference period (1981-2010) and the defined future time periods (2031-2060, 2071-2100) was determined separately for each of the datasets (discharge projections from CHR, Hydro-CH2018, KLIWA, DAS, KNMI'14) (vertical columns in figure 2, left part in figure 3). The range results from the dispersion of the various projections and gives an impression of the range of possible developments.

Third, to come to an integrated view of all results, the overall spread of all projections was determined (minimum to maximum) and - if available - the intersection of the data pools was determined (right part in figure 3). This information is also shown in the tables in section 3.3.

This procedure was applied to all hydrological indicators (table 2 and the selected gauges (figure 1), except for the extreme values HQ10, HQ100 and HQ1000 (see separate text below).

It should be noted that this form of data integration is highly simplified, but pragmatism was required in view of the resources and mandate of the group, as well as the data availability. Due to the large differences and imbalances between the various datasets (see table 1 and technical appendix A, section 2) no complete statistical integration (e.g. determination of percentiles of the total ensemble) was carried out. Furthermore, there was no assessment of the advantages and disadvantages of the models and methods used. Against this background, a certain degree of caution is required when interpreting the ‘integrated’ overview in section 3.3 and the graphic appendices.

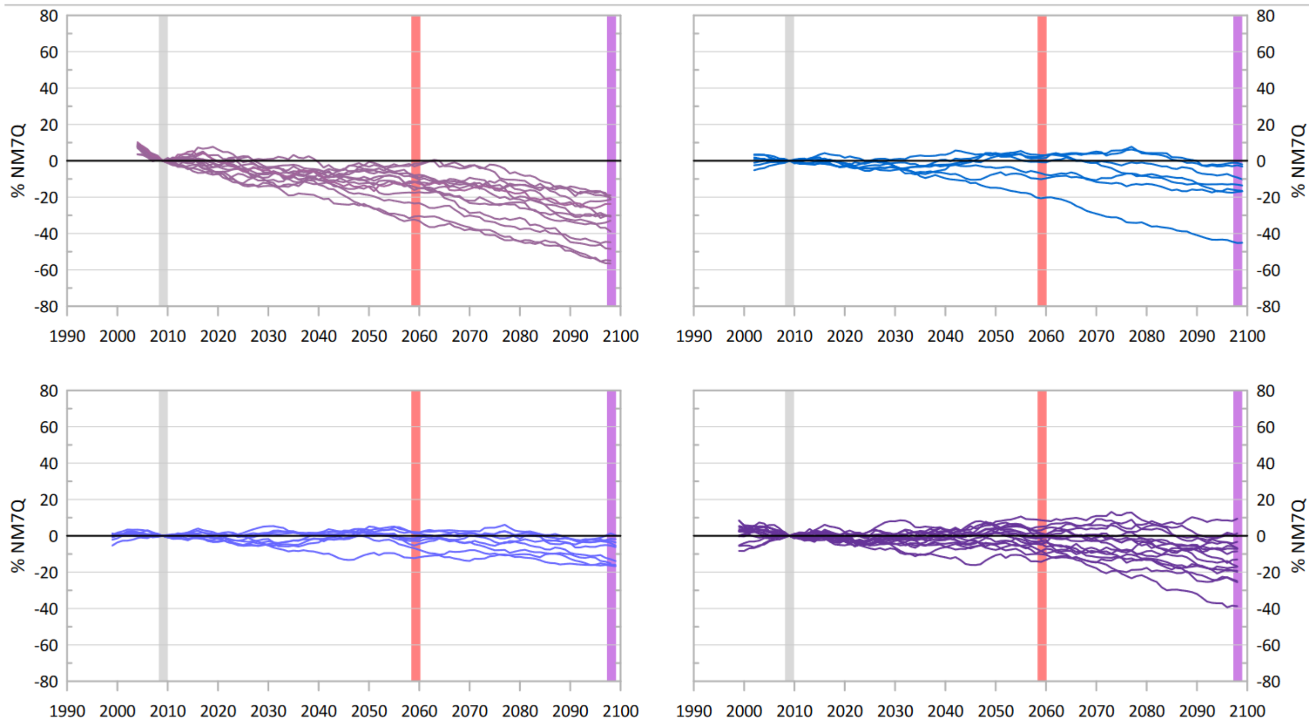

Figure 2: Example working graph illustrating the ensemble spread of different data pools (from top left to bottom right: Hydro-CH2018, ASGII, KLIWA, DAS). Exemplary graph for the annual low flow (NM7Q) at the Basel gauge, change in 30-year running mean values compared to the reference period. The vertical columns mark the reference period (1981-2010) and the future periods defined in this report (2031-2060 and 2071-2100; see figure 3). All diagrams are available on the CHR-Website. The KNMI'14 dataset cannot be shown here as it does not contain any continuous time series (see section 4.2.2).

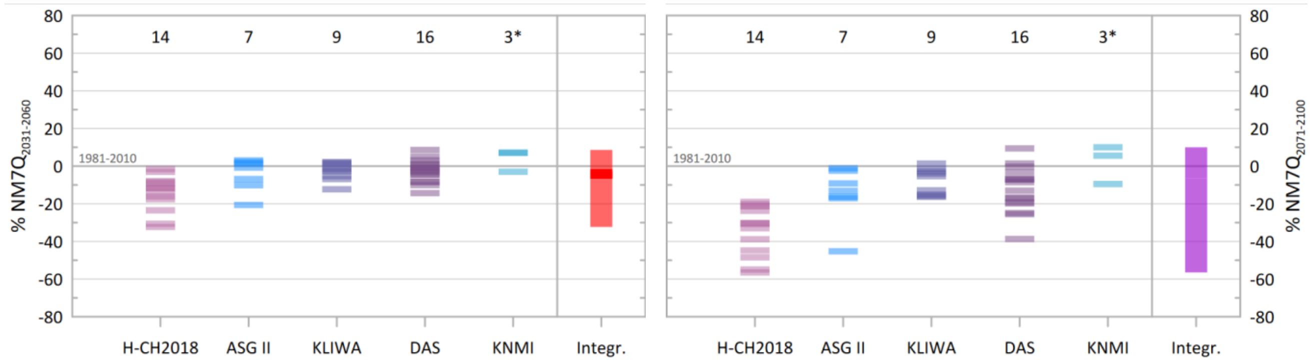

Figure 3: Example working graph illustrating the ensemble spread of different data pools for two future time slices selected in this report. The integrated pictures show the range between the lowest and highest projected values of all ensembles (Note: some of the lines in the diagram overlap, which is why there are lines of different thicknesses).

2.2.6 Flood indicators (or flood scenarios according to flood risk management plan: HQ10, HQ100, HQ1000)

The aforementioned procedure could not be maintained for flood parameters that are relevant according to the EU Floods Directive. The reason for this is that very long time series are required for reliable extreme value statistics. Except for the Netherlands, which have developed a method for this[7] (see explanations below), the approximation of a flood event with a statistical return period of once in a 1000 years (HQ1000) is almost impossible with the above-mentioned periods covering only 30 years of observations and is also very uncertain for a return period of once in a 100 years (HQ100). This (too) short time series length was addressed in different ways by the research groups contributing to this report.

Following Rauthe et al. (2020), the projections of the 'Hydro-CH2018', 'ASGII' and 'DAS' ensembles were treated as so-called 'grand samples' or 'unified series'. This approach is based on the assumption that all projections of an ensemble are based on the same population. This assumes that (a) all climate simulations were generated using the same emission scenario, (b) a bias correction was made for observations in a similar climate period (1971-2000 or 1981-2010) and (c) all hydrological simulations were carried out using the same hydrological model. These conditions are met for each of the three data sets mentioned. As a result, the amount of data available for the extreme value statistics is expanded (table 3). For example, the return periods (HQ10, HQ100, HQ1000) from the ASGII ensemble are calculated based on 7x30 years (210 years) instead of 1x30 years[8]. On the one hand, this approach enables more robust statistics and the adherence to the above-mentioned evaluation periods; on the other hand, bandwidths of possible developments can no longer be specified (i.e. only one change value per ensemble, period and parameter).

The database for the extreme value statistics was also expanded for the 'KLIWA' ensemble, following the consideration that extreme flood events in particular are almost random phenomena over time. Therefore for the extreme value statistics 'one' future period was considered, which includes all years from 2031-2100. Each of the nine KLIWA projections was analysed separately on the basis of these 70 years. By using this method, it is possible both to map the range of projected developments and to base the extreme value statistics on a longer evaluation period (70 projection years instead of 30 projection years). In return, no period-specific change information can be given for the middle and end of the century (i.e. the same range for both future periods for each parameter).

In order to generate long synthetic time series from which extreme floods/annualities can be extrapolated, 'KNMI'14' has used a precipitation generator to simulate 50,000 years for today's climate. The precipitation generator uses the resampling method, which generates new synthetic precipitation series for today's climate with the same characteristics as the observations of daily precipitation with different temporal patterns (Deltares, 2014). For the synthetic time series for today's climate, hereafter referred to as the reference, a transformation of the time series is being performed using a transformation that depends, among other things, on the climate scenario and the desired time horizon. The time series transformation thus generates localised temperature and precipitation time series (and potential evapotranspiration - PET). The high annualities are ultimately derived from these synthetic series with the aid of hydrological and hydraulic instruments. The synthetic series can provide new, higher multi-day precipitation totals, but are limited in terms of change in persistence (consecutive wet or dry days).

With regard to the Dutch 'KNMI'14' database, considerable effort was invested, particularly for the extreme value statistics at the Lobith gauge, in order to obtain reliable change information for flood extremes. The method was designed for annual periods of up to 50,000 years and includes different climate scenarios as well as different assumptions for flooding upstream of the Dutch border.

The 'MOSARH21' database (France) was not taken into account in the analysis as it does not contain any of the chosen gauges.

[7] In the Netherlands, data series are artificially extended using a precipitation generator and hydrological and hydraulic models, e.g. to generate extreme annualities. Its disadvantage, however, is that no change in persistence can be recognised and uncertainties must be taken into account.
[8] Hydro-CH2018 14x30 = 420 years; DAS 13x30 = 390 years

Table 3 summarises the main features of the aforementioned methods.

Table 3: Characterisation of the various data sources and methods used to determine the flood parameters HQ10, HQ100 and HQ1000

Source	Number of years for determination of HQT	Method	Differentiation in Table 9		
			Bandwiths	Time periods	Parameters
ASGII	210	Grand Sample	no	yes	yes
Hydro-CH2018	420	Grand Sample	no	yes	yes
KLIWA	70	Individual projections	yes	no	yes
DAS	390	Grand Sample	no	yes	yes
KNMI	56	Individual projections	yes	yes	yes

It has become evident how challenging it is to determine climate change-induced changes in the occurrence and intensity of rare extreme events and that there is a wide range of possible developments. In addition to the wide range of projected extreme precipitation developments, the uncertainties in hydrological modelling and also in statistical evaluation increase with annuality. It should be noted that in hydrological modelling in most studies (except KNMI'14), the hydraulic capacity of the channel is not limited and retention measures such as polders were not taken into account. In reality, the (hypothetical) extreme flood events determined this way would in some cases lead to dam overflows and breaches in the upper reaches. This means that the extreme flood discharges tend to be overestimated in the present modelling.

Just like for other hydrological indicators, the 'integrated view' shown in table 9 for the illustration of the flood parameters HQ10, HQ100 and HQ1000 (or HQ 'frequent', HQ 'medium', HQ 'extreme') is determined by the highest and lowest development available in the current overall dataset. Results for the individual datasets can be found in the online graphic appendix (CHR website).

In contrast to the other hydrological indicators, the analyses for HQ10, HQ100 and HQ1000 do not include observed values ('reference' and 'present'). This is also due to issues of data homogeneity. Corresponding official discharge values can be found, for example, in the ICPR report on the second cycle of the EU Floods Directive 'Updating the flood hazard and flood risk maps in the IRBD 'Rhine'' (Annex 3) (ICPR, 2019).

2.2.7 Additional indicators

In addition to the hydrological indicators, **selected hydro-meteorological indicators** were calculated to provide information on **changes in air temperature and precipitation** in the Rhine basin (entire catchment as far as the Lobith gauging station; section 3.1). Moreover, an indicator for **changes in the discharge regime** (long-term mean monthly discharge) was calculated for selected gauging stations (section 3.2), in order to better explain the hydrological changes (table 2).

2.3 Remarks on the heterogeneity of the input data

Unlike the previous report no. 188 (ICPR, 2011) the expert group HCLIM could not build its work on one consolidated data set but had to work with several, in part heterogeneous data sets (see section 2.2 and details in technical annex A). Combining the results from these data sets leads to a larger total spread of results than the spread communicated by each single contributing research team, and to a larger spread of results as compared to the earlier report.

Moreover, this heterogeneity results in different data bases for the gauging stations representing various river stretches and tributaries. This is due to the fact that some data sets only cover parts of the Rhine catchment. Table 4 gives an overview of the research groups that contributed data for the individual gauging stations.

Particular aspects arise in relation to the indicators for flood extremes (HQ10, HQ100 and HQ1000); see separate text in section 2 under 'Aggregation'.

Table 4: Overview of contributing research teams by gauging station[9]

Station	River	Countries (in catchment)	Hydro-CH2018 (CH)	ASGII (CHR)	KLIWA (DE)	DAS-BfG (DE)	KNMI'14 (NL)	Total
Basel	Rhine	CH	x	x	x	x	x	5
Maxau	Rhine	CH-FR-DE		x	x	x	x	4
Worms	Rhine	CH-FR-DE		x	x	x	x	4
Kaub	Rhine	CH-FR-DE		x	x	x	x	4
Cologne	Rhine	CH-FR-BE-LUX-DE		x	x	x	x	4
Lobith	Rhine	CH-FR-BE-LUX-DE-NL		x		x	x	3
Rockenau	Neckar	DE		x	x	x		3
Raunheim	Main	DE		x	x	x	x	4
Trier	Moselle	FR-LUX-DE-BE		x	x	x	x	4

[9] The 'MOSARH21' database (France) was not taken into account in the analysis as it does not contain any of the chosen gauges. Note: The complete data set contains further gauges. These can be obtained via the CHR Website.

3 Results

This section shows results on hydro-meteorological changes (entire Rhine basin, section 3.1), flow regime changes (three gauges, section 3.2), and - as a key finding of this report - changes in selected high, mean, and low flow indicators (nine gauges, section 3.3). The tables show changes in the present (1991-2020), the near future (2031-2060) and the distant future (2071-2100), in each case compared with the reference period (here: 1981-2010).

The result ranges shown in tables 7 and 8 represent the total range of all data sets supplied for each of the discharge indicators ('integrated overview', see section 2.2) and (in brackets) the intersections between all data sets. The tables resemble the result tables of the previous report 188 (ICPR, 2011). Table 5 explains the colouring scheme used in this report (for tables 6 to 9 and appendix B).

Table 9 follows a different methodology (see section 2.2 'Indicators for flood extremes'), but maintains the colouring scheme described hereafter.

Table 5: Colouring scheme for tables 5 to 8

Colour Code	Meaning	Explanation
Orange	change towards hot/dry conditions	more than 2/3 of the total span shows the respective change
Blue	change towards cold/wet conditions	more than 2/3 of the total span shows the respective change
Grey	indifferent signal	otherwise

Please refer to sections 2.2 and the technical appendix A for indications on the analysis and interpretation of the data.

Annex B compares the results of the present report with those of ICPR Report No. 188 (ICPR, 2011) in tabular form.

Plots as displayed for example in figure 2 and figure 3 for all indicators and gauges can be accessed via the CHR-website.

3.1 Change of hydro-meteorological conditions

Hydro-meteorological changes are driving hydrological changes in many ways. Precipitation change will directly affect the spatial and seasonal distribution of water. Temperature change will lead to changes in evaporation (e.g. snow and ice melt) and precipitation (e.g. snowfall, rain).

Table 6 describes the general changes of hydro-meteorological conditions in the international Rhine catchment upstream of the Lobith gauge based on a set of temperature and precipitation indicators. Long-term mean values for the past (1951-1980) and the reference period (1981-2010), derived from observations, are shown. The projected signals of change refer to a 19-member ensemble of regional climate models[10] forced by the high emission scenario RCP8.5. Although discharge projections are based on different ensembles of climate projections (see table 1, appendix A), the overall direction and magnitude of hydro-meteorological change is similar for all ensembles.

Summarizing the results (table 6) the following changes of hydro-meteorological conditions in the international Rhine catchment upstream of Lobith can be seen:

a) Air temperatures have already risen significantly since the middle of the 20th century (0.7 to 1 degrees Celsius, depending on the season) and will continue to do so in all meteorological seasons by another 1 to 2.5 degrees Celsius until the middle of the 21st century (2031-2060) and by 3 to 5 degrees until the end of the 21st century (2071-2100) with the strongest increase in the summer and fall (between June and November). Accordingly, the number of hot days (>30°C[11]) will increase while the number of frost and ice days (minus temperatures) will decrease.

b) Both observations and projections show that climate change causes precipitation amounts to shift between the meteorological seasons with increases in winter and spring (December to May) and decreases in the summer (June to August), resulting in moderate increases in the annual precipitation sum. Changes continue over the course of the 21st century and reach increases or decreases of up to over 20% towards the end of the 21st century.

c) Projections show a general tendency towards more extreme precipitation situations. This is not yet apparent in the observations. The number of days with heavy precipitation is projected to increase as is the number of dry days. Also, the duration of dry spells is projected to increase, though this signal is not as clear as the aforementioned signals.

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[10] Same members as 'DAS' plus three additional runs (cf. table 10 in appendix A).
[11] Note: In the Netherlands (KNMI'14), they are defined as > 25 degrees Celsius. This is not part of Table 6.

Table 1: Overview of hydro-meteorological changes in the whole international Rhine Catchment up to the gauge Lobith in the near and distant future relative to the period 1981-2010. *Note: The calendar references in the table are based on meteorological conventions: 'Winter' from December to February, 'Spring' from March to May, 'Summer' from June to August and 'Autumn' from September to November. The 'year' here corresponds to the calendar year from January to December.*

Data source: DWD as part of DAS-Basisdienst[12]

Rhine catchment up to gauge Lobith	Observed values		Projected change	
	Past 1951-1980	Reference 1981-2010	Near future 2031-2060	Distant future 2071-2100
Mean air temperature (year)	7,9 °C	8,6 °C	1,5 to 2,3 °C	3,1 to 4,9 °C
Mean air temperature (winter)	0,1 °C	0,8 °C	1,2 to 2,6 °C	3,4 to 4,6 °C
Mean air temperature (spring)	7,4 °C	8,2 °C	1,1 to 1,9 °C	2,3 to 3,6 °C
Mean air temperature (summer)	15,7 °C	16,7 °C	1,6 to 2,4 °C	3,5 to 5,4 °C
Mean air temperature (fall)	8,3 °C	8,8 °C	1,5 to 2,7 °C	3,3 to 5,7 °C
Precipitation sum (year)	940 mm	994 mm	-1,9 to 8,6 %	-3,8 to 13 %
Precipitation sum (winter)	219 mm	238 mm	-0,1 to 22,9 %	7,0 to 30,1 %
Precipitation sum (spring)	210 mm	235 mm	1,5 to 16,6 %	1,2 to 24,4 %
Precipitation sum (summer)	291 mm	274 mm	-12,5 to 5,8 %	-24,5 to 0,7 %
Precipitation sum (fall)	217 mm	245 mm	-7,7 to 9,4 %	-13,7 to 15,4 %
Number of hot days (year, Tmax > 30 degrees)	4 days	6 days	+6 to +12 days	+16 to +33 days
Number of ice days (year, Tmax <0 degrees)	27 days	24 days	-15 to -7 days	-21 to -15 days
Number of frost days (year, Tmin <0 degrees)	103 days	93 days	-38 to -22 days	-67 to -45 days
Number of days with heavy precipitation (year, sum > 20 mm)	7 days	8 days	0 to +2 days	+1 to +3 days
Number of dry days (year)	230 days	228 days	-2 to +14 days	+1 to +23 days
Max duration of dry period (year)	42 days	37 days	-7 to +14 days	-6 to +16 days

[12] The indicators have been provided by the Deutsche Wetterdienst as contribution of the DAS-Basisdienst 'Klima und Wasser'. Observed conditions are based on the international HYRAS product (5 km daily grids of hydro-meteorological variables since 1951; Rauthe et al., 2013), projected changes are based on a Global Climate Model-Regional Climate Model (GCM-RCM) ensemble with 19 members (CMIP5-CORDEX/REKLIES/ReKliEs; Sperna-Weiland et al., 2021; HLNUG, 2024) forced by RCP8.5.

3.2 Change of flow regimes

The spatio-temporal distribution and interplay of rain and snow (ice) lead to distinct flow regimes that can be linked to different parts of the Rhine catchment. Today, and in the recent past, ice and snow processes dominate the upper reaches close to the Alps, leading to relatively low flows in winter and meltwater-driven high flows in summer. In figure 4 this ice- and snowfed ('nivo-glacial') regime is represented by the gauge Basel/Rhine. However, the tributaries draining the mid-mountain ranges show a rainfed regime that is usually associated with relatively high flows in winter and low flows in late summer. This rainfed ('pluvial') regime is highlighted by the gauge Trier/Moselle in figure 4. Where the glacier-, snow- and rainfed regimes join (i.e. in the middle and lower reaches of the Rhine) a combined regime (complex) emerges as represented by the gauge Lobith/Rhine.

Figure 4 shows flow regime changes in the past by comparison of the periods 1951-1980 and 1981-2010 (grey and black lines, observations), and in future periods 2031-2060 and 2071-2100. Projections of the future or the periods 2031-2060 and 2071-2100 are based on different scenario studies. The spread of the different ensembles is marked as floating bars. As explained in section 2.2 and figure 2, these bars illustrate the respective spread of the various discharge projections[13]. Long-term mean values of the monthly discharge are shown[14].

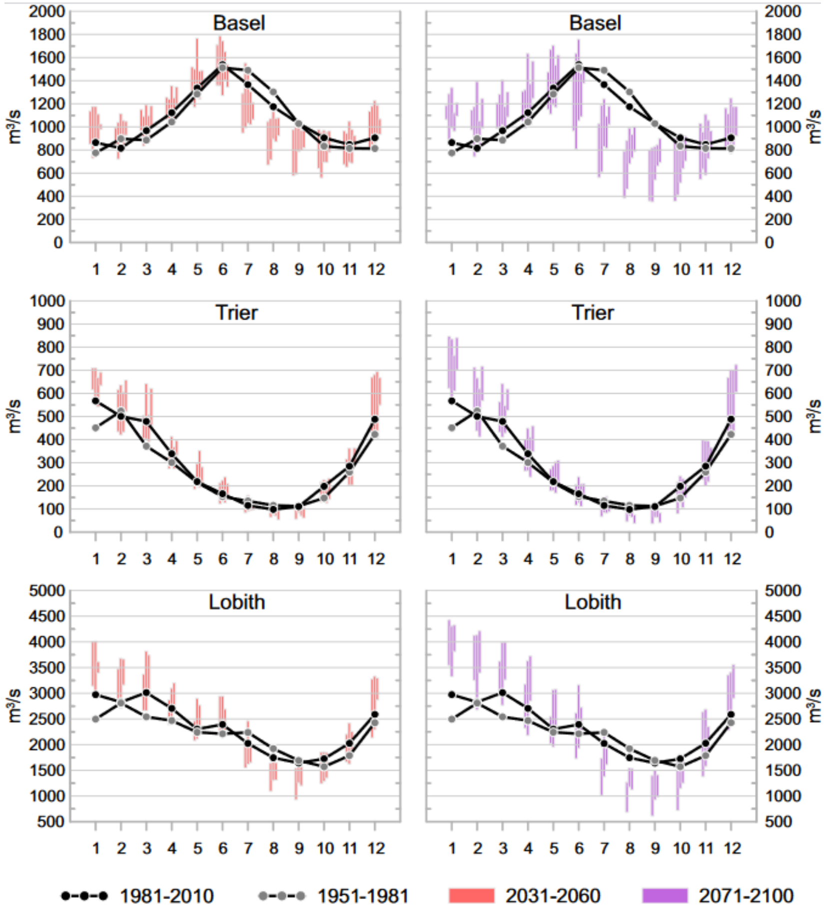

Figure 4: Multiannual mean monthly river flow for three gauges representing the main flow regimes currently observed at the Rhine river (black lines, period 1981-2010): glacier-/snowfed regime (Basel), rainfed regime (Trier), combined regime (Lobith). Furthermore, the situation in the past (grey line, 1951-1980), and the future (2031-2060, red/left; 2071-2100, purple/right) is displayed. Projections of the future are based on different scenario studies (see text).

[13] Basel (ASGII, Hydro-CH2018, DAS, KLIWA, KNMI'14); Trier (ASGII, DAS, KLIWA, KNMI'14); Lobith (ASGII, DAS, KNMI'14)

[14] The monthly values were determined by calculating the percentage change in the respective future period (2031-2060 or 2071-2100) compared to the simulated reference period (1981-2010) for each month and each projection and increasing or decreasing the observed value of the reference period (1981-2010) by the corresponding percentage value.

Already in the observations (comparison 1951-1980 and 1981-2010), all three regimes mainly show increasing winter and early spring flows (December, January, March) and decreasing summer flows (July, August), indicating a general tendency towards more rainfed regimes. This is a result of advancing global warming, associated with a shift in the height of the snow line and the retreat of the glaciers.

In general, already observed changes will be even more pronounced in the future, in particular at the end of the 21st century (2071-2100).

Obvious changes (see figure 4) are the strong decreases in the upper reaches during the summer (Basel) and the strong increases in the lower reaches (Lobith) and tributaries (Trier) in the winter, in particular. Although the different ensembles show the same direction of change, they differ strongly, in particular with respect to the summer decrease projected by the end of the 21st century in the upper reaches (Basel). Furthermore, although changes in absolute values may seem small for summer months in the mid-mountains (here: Trier/Moselle), relative changes are comparatively high given the low flow value (average monthly discharge in some cases only 100 m^3/s).

The changes in the flow regimes give first indications on the changes of high and low flow statistics described in the following sections.

3.3 Change of hydrological indicators

In the following tables and sections information on high, mean, and low flow changes is summarized. The analysis is carried out for a selected set of gauging stations, indicators and time spans (see section 2.2). Tables 7 to 9 contain information on observed changes (present, 1991-2020, section 3.3.1) and on changes projected for the future (2031-2060, section 3.3.2 and 2071-2100, section 3.3.3), in each case compared with the reference period (1981-2010). For interpretation of the data, please take into account the remarks on the heterogeneity and treatment of input data (see section 2.2 and appendix A).

All presented change signals highlight the 'integrated picture' explained in section 2.2. Consequently, the range is determined by the most extreme projections of all data pools, ranging from the worst projected case to the best projected case. Furthermore, the intersection of all data pools (if present) is given in brackets, showing the 'common part' of the results.

This presentation differs from other impact assessments and IPCC practice (e.g. IPCC, 2021: page 62) which do not communicate the total range of all results, but rather the so-called percentiles (e.g. 15th and 85th) and thus fade out extreme individual projections. In the current report, the step of capturing the internal structure of the ensemble was not possible because of the heterogeneity of the input data and the imbalances in the overall ensemble. Annex A (table 11) and the graphic appendix published online (see CHR-website) provide information on this.

3.3.1 Changes up to the present (here: 1991-2020)

The recent past (1991-2020; 'present') was characterised by many drought years. This holds particularly true for the last decade (2011-2020), when extreme low flows were frequent (e.g. 2011, 2015, 2018). Although severe river floods were recorded in some sections of the Rhine (e.g. flood event with an exceedance probability of less than once in a hundred years at the Basel gauge in May 1999 and in August 2007), this was not the case for the entire Rhine. The 2013 flood event on the Rhine is given as having an annuality of < 20 years (BfG, 2014).

When comparing the 'present' (1991-2020) with the reference period (1981-2010; table 7 and table 8), all hydrological indicators show a decrease, i.e. not only in the summer low flow characteristics, but also in the flood parameters during winter months and consequently in the mean annual flow.

The decreases get more pronounced with increasing distance from the Alps due to the larger influence of the rain-fed tributaries from the mid-mountain ranges (Neckar, Main, Moselle) which show the highest relative changes. At first glance the changes do not seem large with a few percent at most gauges. But it must be taken into account that the changes became apparent in a comparatively short period of time - about 10 years - and are even reflected in 30 year mean values.

This recent decrease in winter mean flow is contrary to the regime change determined in the decades before (see section 3.2) which showed an increase in winter flows (comparing the two periods 1951-1980 and 1981-2000). Likewise, the ICPR report no. 188 (ICPR 2011) showed a strong increase in mean winter flows during the 20th century (comparing the two periods 1971-2000 and 1901-1930), resulting in an increase of mean annual flows in this hundred-year perspective (ICPR, 2011).

3.3.2 Changes up to the middle of the 21st century (here: 2031-2060)

The overall results confirm earlier climate impact analyses for the Rhine: on average, summer flow decreases (MQ Summer, NM7Q Summer) whereas winter flow increases (MQ Winter). Consequently, annual flows change only slightly, whereas flood and low water events become more pronounced (increase in MHQ, decrease in MNQ). Deviating from this seasonal pattern, decreases in winter low flows (NM7Q Winter) are projected at some gauges in the mid of the 21st century.

The corridor of projected changes in the mid 21st century (tables 7 and 8) for the main course of the Rhine can be outlined as follows:

a) The main direction of change points to a **decrease** of summer mean flows (**MQ Summer**), summer low flows (**NM7Q Summer**), and annual low flows (**MNQ**). The total span extends from -25% or -36% to +5% or +8%.

b) The main direction of change points to an **increase** of winter mean flows (**MQ Winter**) and annual high flows (**MHQ**). The total span shows values respectively up to 23% and 44% and down to -7% to -10%. The projected increase in mean winter flow (MQ Winter) differs from the recently observed changes (present 1991-2020, section 3.3.1), which show a decrease in mean winter flow.

c) Winter low flows (**NM7Q Winter**) show **no clear direction** of change at the upper and middle Rhine gauges and a **decrease** at the lower Rhine gauges.

d) Annual mean flows (**MQ**) show **no clear direction** of change (-15% to + 13%).

e) With the exception of the Basel gauge, there are increases in the **flood discharges with an annuality of 10, 100 and 1000** (HQ10, HQ100 and HQ1000). The ranges of results and the uncertainties in relation to these parameters are particularly large.

For the tributaries (Neckar, Main, Moselle) the spread of changes indicated in % is generally higher than for the main course of the Rhine, mainly because of the lower absolute discharge values, leading to important relative changes. Some change signals are less pronounced in the aforementioned tributaries; for example, the decrease of summer mean flows (MQ Summer) shows no direction of change, here.

Generally, the intersecting part of the ensembles (in brackets) leads to the same direction of change as the whole spread, which can be taken as a simple indicator of consistency with regard to the substantial change information. However, there are indicators for which the differences between the ensembles are so large that there is no intersection ('-'). This is the case for the low flow indicators MNQ year and NM7Q Summer at the Basel gauge. Exploring the reasons for this should be part of future research (see research impulses in section 6.2).

With respect to enormous ranges of results, it should also be noted that extreme change signals are in some cases supported only by one single projection. For example, the increase in the annual high flow indicator (MHQ) of more than 60% at Rockenau and more than 40% at Kaub is supported only by one single member in one ensemble, while the majority of projections shows increases of less than 30% (Rockenau) or 20% (Kaub). For in-depth analyses of the structure of the data, please refer to the corresponding graphs (see CHR-website).

3.3.3 Changes up to the end of the 21st century (here: 2071-2100)

The changes indicated for the middle of the century intensify in the second half of the 21st century. The seasonal pattern of change is thus preserved: on average, summer flow decreases (MQ Summer, NM7Q Summer) whereas winter flow increases (MQ Winter). These changes level out, when analysing the year as a whole, resulting in relatively minor changes in the annual mean flow (MQ). An intensification is visible in the high flow (MHQ, HQT) and low flow indicators (MNQ). Also for winter low flows (NM7Qwinter) there are some indications pointing to a decrease.

The corridor of projected changes at the end of the 21st century (tables 7 and 8, last column) for gauges on the main course of the Rhine can be outlined as follows:

a) The main direction of change points to a **decrease** of summer mean flows (**MQ Summer**), summer low flows (**NM7Q Summer**), and annual low flows (**MNQ**). The total span gives values of down to -48%, -67%, and -57% (lower end), respectively. The upper end of the span predominantly shows moderate increases of +4% to +9%.

b) The main direction of change points to an **increase** of winter mean flows (**MQ Winter**) and annual high flows (**MHQ**). The total span shows values respectively up to 36% and 38% (upper end) and decreases of up to -17% to -2% (lower end).

c) Winter low flows (**NM7Q Winter**) show **no clear direction** of change at the upper Rhein gauges (-38% to +22%) and a weakly defined **decrease** at the middle and lower Rhine gauges.

d) Annual mean flows (MQ) show **no clear direction** of change at all gauges (-23% to +19%) except Basel with some indication of a decrease (-26 % to +10 %).

e) With the exception of the Basel gauge, there are increases in the flood **discharges of the 10-, 100- and 1000-year annuality periods** (HQ10, HQ100 and HQ1000). The ranges of results and the uncertainties in relation to these indicators are particularly large.

As already mentioned in section 3.3.2, the spread of changes is generally higher for the tributaries (Neckar, Main, Moselle) than for the main course of the Rhine. Unlike the main course of the Rhine, the gauges at the Neckar and Moselle (Rockenau, Trier) show indications of increasing annual mean flows (MQ).

Again, the intersecting part of the ensembles (in brackets) leads to the same direction of change as the whole spread (see section 3.3.2). On the Upper Rhine gauges (Basel, Maxau), the data sets for the summer low flow differ so much that no intersect exists.

The notes on the structure of the ensemble in section 3.3.2 apply analogously here. It should also be noted that the change projections for the distant future (2071-2100) should be interpreted with caution, as some of the quantitative figures are based on extreme individual projections. For example, low flow (NM7Q Summer, MNQ) decreases of -50% and below on some gauges are only represented by one member of one ensemble. All other members show decreases of -30% and less. Therefore, a detailed evaluation of the data structure using the diagrams of the graphical appendix (see CHR-website) is highly recommended.

Table 7: <u>Annual indicators</u> of mean, low, and high flow (MQ, MNQ, MHQ). All changes relative to 1981-2010 (%). Integration of various data sources (section 2 and appendix A).

Note on column 'Projected changes': see table 5 and section 2 for an explanation of the colour code and further information on the illustrated values. Values without brackets represent the complete span of results regarding possible discharge changes in the Rhine basin (minimum to maximum changes of all projections); Values in brackets show the span of results that is common to <u>all</u> research teams that contributed to HCLIM (intersect of the different ensembles. If there is no intersection, this is marked with '-'.)

Indicator	**Gauge**	**Observed values (m³/s)**	**Observed change (%)**	**Projected change (%)**	
		Reference 1981-2010	Present 1991-2020	Near future 2031-2060	Distant future 2071-2100
MQ	Basel	1073	-3	-15 to +11 (-6 to +5)	-26 to +10 (-8 to -2)
	Maxau	1272	-4	-14 to +12 (-7 to +4)	-23 to +12 (-8 to -1)
	Worms	1457	-4	-12 to +13 (-7 to +4)	-19 to +14 (-7 to +2)
	Kaub	1745	-5	-13 to +13 (-5 to +6)	-16 to +17 (-4 to +4)
	Cologne	2203	-6	-12 to +11 (-4 to +7)	-13 to +19 (-3 to +8)
	Lobith	2324	-6	-11 to +11 (-4 to +10)	-12 to +19 (-3 to +13)
	Rockenau (Neckar)	146,2	-8	-13 to +24 (-11 to +16)	-13 to +28 (-2 to +15)
	Raunheim (Main)	223,3	-7	-22 to +23 (+5 to +15)	-44 to +33 (+11 to +15)
	Trier (Moselle)	295,5	-8	-12 to +19 (0 to +10)	-12 to +27 (+7 to +23)
MNQ	Basel	504,0	-1	-32 to +8 (-)	-57 to +9 (-)
	Maxau	618,6	-4	-26 to +7 (-8 to 0)	-48 to +6 (-15 to -6)
	Worms	700,0	-5	-27 to +7 (-11 to 0)	-48 to +3 (-19 to -6)
	Kaub	836,1	-4	-27 to +6 (-15 to -1)	-46 to +1 (-23 to -5)
	Cologne	1001	-6	-29 to +4 (-18 to -2)	-47 to -1 (-27 to -6)
	Lobith	1074	-5	-29 to +4 (-19 to -3)	-48 to -1 (-27 to -6)
	Rockenau (Neckar)	41,53	-6	-28 to +18 (-21 to +7)	-35 to +15 (-22 to +4)
	Raunheim (Main)	70,72	-4	-33 to +16 (-19 to +8)	-42 to +21 (-25 to -3)
	Trier (Moselle)	49,40	-11	-51 to +8 (-26 to -4)	-66 to +16 (-30 to -21)

Table 7: (continued)

MHQ	Basel	2844	-3	-14 to +17 (0 to +10)	-17 to +24 (+5 to +8)
	Maxau	3223	-4	-7 to +30 (+2 to +14)	-3 to +28 (+9 to +14)
	Worms	3599	-5	-3 to +43 (+3 to +16)	-3 to +31 (+12 to +17)
	Kaub	4547	-6	-3 to +44 (+4 to +19)	-8 to +37 (+15 to +21)
	Cologne	6751	-7	-4 to +39 (+5 to +21)	-12 to +38 (+17 to +22)
	Lobith	7043	-8	-7 to +36 (+5 to +21)	-12 to +37 (+16 to +30)
	Rockenau (Neckar)	1108	-7	-9 to + 69 (-3 to +46)	-16 to + 46 (+5 to +35)
	Raunheim (Main)	1036	-12	-20 to +42 (+8 to +28)	-27 to +60 (+24 to +33)
	Trier (Moselle)	2081	-11	-1 to +35 (+6 to +21)	-12 to +49 (+23 to +31)

Table 8: <u>Seasonal indicators</u> of mean and low flow (MQ, NM7Q; hydrological seasons). Change relative to 1981-2010 (%). Integration of various data sources (section 2 and appendix A).

Note on column 'Projected changes': see table 5 and section 2 for an explanation of the colour code and further information on the illustrated values. Values without brackets represent the complete information on possible discharge changes in the Rhine basin (minimum to maximum changes of all projections); Values in brackets show the span of results that is common to <u>all</u> research teams that contributed to HCLIM (intersect of the different ensembles. If there is no intersection, this is marked with '-'.)

Indicator	**Gauge**	**Observed values (m/s^3)**	**Observed change (%)**	**Projected change (%)**	
		Reference 1981-2010	Present 1991-2020	Near future 2031-2060	Distant future 2071-2100
MQ Summer	Basel	1225	-4	-25 to +4 (-16 to -2)	-48 to -4 (-21 to -15)
	Maxau	1352	-5	-24 to +5 (-16 to -1)	-47 to -3 (-21 to -14)
	Worms	1482	-6	-23 to +6 (-16 to 0)	-46 to -1 (-21 to -12)
	Kaub	1671	-6	-21 to +7 (-16 to +1)	-43 to +2 (-20 to -10)
	Cologne	1913	-7	-21 to +6 (-17 to 0)	-42 to +3 (-21 to -8)
	Lobith	1971	-7	-20 to +6 (-17 to +4)	-42 to +4 (-21 to -6)
	Rockenau (Neckar)	103,4	-10	-16 to +24 (-16 to +19)	-37 to +22 (-20 to +6)
	Raunheim (Main)	144,1	-6	-30 to +27 (-10 to +8)	-56 to +27 (-13 to +3)
	Trier (Moselle)	151,1	-14	-26 to +15 (-21 to +6)	-41 to +19 (-25 to +10)
MQ Winter	Basel	919,2	0	-10 to +22 (+6 to +14)	0 to +32 (+10 to +20)
	Maxau	1191	-2	-2 to +21 (+5 to +14)	+4 to +31 (+9 to + 19)
	Worms	1431	-3	-4 to +21 (+4 to +14)	+3 to +32 (+10 to +20)
	Kaub	1820	-4	-7 to +22 (+6 to +14)	0 to +35 (+12 to +20)
	Cologne	2498	-5	-7 to +23 (+6 to +14)	-2 to +36 (+13 to +23)
	Lobith	2683	-5	-6 to +23 (+6 to +16)	0 to +35 (+12 to +28)
	Rockenau (Neckar)	189,6	-7	-11 to +24 (-8 to +16)	-12 to +34 (+5 to +20)
	Raunheim (Main)	303,7	-7	-21 to +30 (+14 to +16)	-43 to +46 (-)
	Trier (Moselle)	442,3	-6	-8 to +28 (+7 to +13)	-7 to +38 (+18 to +27)

Table 8: (continued)

NM7Q Summer	Basel	648,4	-2	-35 to +5 (-7 to -5)	-62 to +7 (-)
	Maxau	750,8	-5	-36 to +2 (-12 to -5)	-57 to +2 (-)
	Worms	824,8	-5	-36 to +1 (-15 to -4)	-56 to -1 (-24 to -21)
	Kaub	956,3	-5	-35 to +1 (-19 to -3)	-54 to -5 (-28 to -18)
	Cologne	1105	-6	-34 to +1 (-22 to -3)	-53 to -6 (-32 to -17)
	Lobith	1173	-5	-33 to 0 (-22 to -2)	-53 to -6 (-32 to -17)
	Rockenau (Neckar)	47,21	-7	-24 to +16 (-20 to +8)	-38 to +7 (-23 to -2)
	Raunheim (Main)	81,35	-3	-33 to +22 (-21 to +4)	-46 to +15 (-23 to -6)
	Trier (Moselle)	58,07	-11	-51 to +9 (-28 to -7)	-68 to +9 (-32 to -26)
NM7Q Winter	Basel	544,0	0	-17 to +15 (-2 to +7)	-32 to +26 (-8 to +8)
	Maxau	687,2	-2	-12 to +11 (-7 to +5)	-38 to +22 (-14 to +7)
	Worms	785,4	-3	-15 to +10 (-10 to +4)	-41 to +20 (-18 to +5)
	Kaub	952,4	-2	-17 to +10 (-15 to +2)	-42 to +21 (-21 to +1)
	Cologne	1177	-4	-20 to +9 (-18 to +3)	-46 to +21 (-23 to -1)
	Lobith	1264	-4	-20 to +9 (-19 to +3)	-45 to +20 (-27 to -1)
	Rockenau (Neckar)	62,67	-4	-28 to +23 (-24 to +6)	-40 to +30 (-28 to +20)
	Raunheim (Main)	109,4	-4	-33 to +17 (-19 to +8)	-41 to +23 (-25 to -3)
	Trier (Moselle)	111,8	-11	-43 to +14 (-21 to +1)	-54 to +23 (-29 to -9)

Table 9: Indicators of 'frequent', 'medium', and 'extreme' flood (high flows) change (definition based on the scenarios of the flood hazard maps) vs. 1981-2010 (%, HQ10, HQ100, HQ1000)

*Notes on the column 'Projected changes': See table 5 and section 2 for an explanation of the colour code and further information on the values shown. The procedure for determining the parameters differs from the previous tables. See section 'Indicators for flood extremes' in section 2.2. *very uncertain*

Indicator	Gauge	Projected change (%)	
		Near future 2031-2060	Distant future 2071-2100
HQ10 'frequent'	Basel	-8 to +11	-8 to +20
	Maxau	-1 to +20	-1 to +30
	Worms	+2 to +26	+2 to +36
	Kaub	-1 to +24	-1 to +40
	Cologne	-7 to +27	-7 to +38
	Lobith	+8 to +21	+12 to +37
	Rockenau (Neckar)	0 to +44	0 to +44
	Raunheim (Main)	-18 to +48	-18 to +48
	Trier (Moselle)	0 to +31	0 to +36
HQ100 'medium'*	Basel	-12 to +21	-18 to +21
	Maxau	-5 to +42	-5 to +43
	Worms	-3 to +45	-3 to +47
	Kaub	-8 to +56	-8 to +56
	Cologne	-26 to +61	-26 to +61
	Lobith	+5 to +18	+7 to +42
	Rockenau (Neckar)	-17 to +67	-17 to +67
	Raunheim (Main)	-24 to +94	-24 to +94
	Trier (Moselle)	-20 to +49	-20 to +52
HQ1000 'extreme'*	Basel	-25 to +32	-28 to +32
	Maxau	-12 to +59	-12 to +59
	Worms	-13 to +81	-13 to +81
	Kaub	-18 to +89	-18 to +89
	Cologne	-39 to +97	-39 to +97
	Lobith	+3 to +20	+5 to +51
	Rockenau (Neckar)	-31 to +155	-31 to +155
	Raunheim (Main)	-27 to +151	-27 to +151
	Trier (Moselle)	-38 to +94	-38 to +94

4 Additional impacts of climate change

River flow changes in the Rhine catchment are relevant for various water management strategies. While the sections above summarise the current status of knowledge in this respect, there are additional specific and regional aspects that are relevant to understand the dynamics of the hydrological system of the Rhine river. This section provides **extra insight on how the system in the Rhine basin will develop in the future due to climate change**, including shrinking glaciers and snow packs, effects of lake dynamics, heavy precipitation events, and effects of sea level rise.

4.1 Influence of glaciers and snow

Snow and glacier melt historically and currently makes a vital contribution to discharge in the Rhine (especially in the upper reaches) and has an influence on the main Rhine river down to the Netherlands. A reduction of winter snow storage and glacier volume due to rising air temperatures changes the snow and glacier fed (glacial or nival) flow regimes in the Alpine area and thus influences the combined flow regimes in the middle and lower reaches of the Rhine, too (cf. section 3.2).

The amount of melt water is particularly important to support river flow during long-lasting dry spells in the summer months. Understanding the developments of glacier and snow dynamics under climate change is, therefore, of vital importance with respect to **low flow situations** in the main course of the Rhine. Research by Switzerland (FOEN, 2021) and the International Commission for the Hydrology of the Rhine basin (CHR, 2016 and 2022) casts light on this aspect.

Snow melt: The proportion of precipitation which falls as snow is controlled by the air temperature and has already decreased considerably in Switzerland due to warming (FOEN, 2021). The most important aspect is the elevation of the zero-degree isotherm which distinguishes between rainfall and snow fall. This 'line' shifts by around 150 meters in elevation per degree Celsius of temperature change (CH2018). This means that in a warming climate less precipitation will be stored in the snowpack, and the snow will store the water later in the year and melt earlier in the year. To date, mainly lower and medium elevations are affected. The Hydro-CH2018 scenarios indicate a decrease in the average annual water quantity stored in the snowpack by the end of the century: 42% with climate change mitigation (RCP2.6) and 78% without climate change mitigation (RCP8.5). At the same time, the maximum snow volume will shift from March to February. While temperature rises, the expected increase in winter precipitation will only have a positive impact on the snowpack at very high elevations. It will not compensate for the general decrease in snow volumes.

Glacier melt: The Swiss glaciers have already lost 60% of their volume since 1850 (glamos.ch)[15]. By the end of the 21st century, remnants of the great glaciers will only remain at very high elevations. In the Alps, with climate change mitigation (RCP2.6), some 37% of the 2017 glacier volume will remain, but only around 5% without climate change mitigation (RCP8.5). Only considering the alpine Rhine catchment and the RCP8.5 scenario, all glaciers will disappear by the end of the century. Since glaciers often take decades to adapt to a new climate, further glacier retreat cannot be prevented anymore, even in the case of immediate and resolute climate protection (Zekollari et al. 2019).

With the retreat of the glaciers, summer discharge from glaciers will be strongly reduced. This will be recognizable further downstream. At the same time, the permafrost in the glaciated area is thawing, increasing the potential for natural hazards (FOEN, 2021).

Downstream effects: The effects of snow and glacier storage change are conceptually (roughly) reflected in the hydrological models underlying this report. For example, the models are capable of simulating the effects of increasing direct winter runoff instead of snow storage in the catchment due to rising temperatures. Also, basic glacier modules are implemented in some models (e.g. LARSIM-ME). These effects in part explain the seasonal changes shown e.g. in figure 4.

In the framework of a CHR study, special attention was paid to '<u>The snow and glacier melt components of streamflow of the river Rhine and its tributaries considering the influence of climate change</u>' (ASG; CHR, 2016 and 2022). Here, the snow and ice melt water were computationally 'traced' from the origin down to the German-Dutch border. The analysis was

[15] Swiss Alps: Glacier volume around 130 km^3 (in 1850), 77 km^3 (in 2001), 49 km^3 (in 2022) (GLAMOS, 2022)

done for the past (Phase 1 of ASG 1; CHR, 2016) and the future using observed climate data and a selection of climate projections (phase 2 of ASG, see label 'ASG II' in section 2 and the technical appendix A; CHR, 2022). For different gauging stations, estimates of the absolute and relative proportion of snow and ice melt water are given on a daily basis.

In the long-term mean, the snow melt fraction amounts to 39% of the total annual discharge at Basel (upper reach of the Rhine), declining to 34% at Lobith (lower reach of the Rhine). As mentioned above (section 3.2), snow is an important determinant of the flow regime at all gauging stations on the main Rhine. The average annual fraction of glacier melt is only about 2% at Basel and 1% at Lobith. In extreme dry situations, however, the fraction amount to 25% and 17% at Basel and Lobith, respectively. Thus, glaciers are important water sources during droughts and low flow situations. Moreover, the results show that the low flow support from glaciers in the Rhine at Basel has passed its peak already (known as 'glacier peak water'). This means that climate warming has already caused a strong melting in the past, leading to a shrinking of the glacier volume and resulting currently in a reduced melt water input to the rivers. This decrease in melt water input will continue in the future.

4.2 Water levels of the greatest upstream lakes in the Rhine basin

The lakes are important subsystems for regional ecology and economy. The great lakes in the Rhine catchment are included in the hydrological models regarding their influence on water retention and evaporation. Because this report mostly focuses on flowing water and river gauges, some of those lakes are given special attention here.

The lake levels are known to be variable on different time scales due to natural water availability and human water management.

Lake Constance: Related to the predominantly alpine catchment, the water level of Lake Constance is characterised by a pronounced seasonal course with average maximum values in the summer months and minimum values in the winter months. It shows a snow fed regime (cf. 3.2) resulting from precipitation being stored as snow and thus not generating runoff in winter, and snowmelt and rain in spring/summer.

More than 100 years of lake level observations at gauge Constance shows an overall increase in winter lake level and a decrease in summer lake level (KLIWA, 2016). Climate change could be the driving factor. A lower amount of snow stored in winter, an earlier melting in spring, and higher evaporation rates lead to an overall lowering of the lake level in summer. In wintertime, precipitation falling as rain instead of snow leads to an increase of the lake level. The current management of the dams and storage systems in the Alps, determined by the energy market, enhances the effects of climate change. Water is stored in summer and released in the winter months during the natural low water period of Lake Constance. As a result, the previously pronounced seasonal water level differences in Lake Constance between the winter and summer months have meanwhile become smaller on a seasonal average. The impact of reservoir management on the low water level of Lake Constance is, however, generally considered to be very low compared to the discharge behaviour of the Alpine Rhine.

Climate change will continue to influence the development of the lake level and its seasonal dynamics. For the future, a further climate change-related decrease in the summer months and an increase in the winter months can be assumed. This would reduce the amplitude of the seasonal annual change in Lake Constance water levels. Besides the change in the water regime, other important lake parameters such as water temperature, lake mixing as well as flora and fauna are also subject to change due to climate change (see e.g. IGKB, 2015).

Regulated lakes in Switzerland:[16] Climate change will greatly affect the inflows into the lakes and reservoirs. On the unregulated lakes, this will have a direct impact on water levels and will result in lower levels in summer and autumn in particular. In the regulated lakes, the effects can be partly alleviated, but the weir regulations were not created with this objective (FOEN, 2021). Studies are therefore currently being carried out by the Federal Office for the Environment (FOEN) on what impact the inflow changes will have on the lake levels in the regulated lakes.

First results are available for the regulated Lake Zurich (Wechsler and Zappa, results in preparation). Due to lake regulation, Lake Zurich follows a yearly regime with lower winter lake levels and higher summer lake levels. The future high and low lake levels will increase slightly in the winter months and decrease slightly in the summer months. Under the RCP8.5 emissions

[16] This example can also be extended to the other reservoirs and regulated lakes in the basin.

scenario, the lowest discharges from Lake Zurich could shift from winter to summer. It is conceivable that the demand for abstraction of water from the lakes will increase, particularly in summer, and this may conflict with reduced water availability.

4.3 Compound effects of hydrological change and sea level rise in the Rhine Delta and the IJsselmeer areas

This report focuses on the effects of climate change on the inland hydrological cycle. The main area under investigation thus ends at the gauge of Lobith just beyond the German-Dutch border. However, the **Delta region including the IJsselmeer area** holds additional challenges for regional water management under climate change. Here, the compound effects of changing inland hydrology in the upstream catchment, local hydrological processes (precipitation, evaporation) and sea level rise come into play.

Sea level rise scenarios: As a consequence of climate change, the sea level will continue rising in the next hundreds of years. Between 1901 and 2018, the global average sea level rise was about 20 cm with an average sea level rise of 1.7 mm/year. In recent years (2006-2018), an acceleration in the global sea level rise is observed with an increase to 3.7 mm per year (KNMI Klimaatsignaal ’21, 2021 & KNMI’23 Gebruikersrapport, 2023). At the Dutch coast the sea level rise was 1.8 ± 0.1 mm per year until approximately 1990. In the last 30 years the rate has increased to an average annual rise of 2.9 ± 0.4 mm (Zeespiegelmonitor, 2022). Depending on the worldwide greenhouse gas emissions, the rate in which sea level rise will continue might differ. In table 10, the sea level scenarios for the Dutch coast are shown. Germany applies the SSP5-8.5 high-emission scenario, which assumes an increase of +29 cm (2050, 83rd percentile) or +100 cm (2100, 83rd percentile) (e.g. GDWS, 2023).

Take into account, however, that the sea level rise can reach up to around 2.5 m in 2100 if uncertain processes occur, such as instability of the Antarctic Ice Sheet (not shown in table 10).

Table 10: Indicative numbers for sea level rise at the Dutch Coast under several emission scenarios[17] for 2050 (2046-2055) and for 2100 (2096-2105), in comparison to 1995-2014, with an uncertainty bandwidth of 90%. The numbers include subsidence of soil due to tectonic and other processes (KNMI’23 Gebruikersrapport & KNMI’23 database).

Year	**2050 (2046-2055)**		**2100 (2096-2105)**	
Emission scenario	SSP1-2.6	SSP5-8.5	SSP1-2.6	SSP5-8.5
Sea level rise in cm	+24 (16-34) cm	+27 (19-38) cm	+44 (26-73) cm	+82 (59-124) cm
Rising rate in mm/year	+3 (1-6) mm/year	+5 (4-8) mm/year	-1 (-4-4) mm/year	+11 (6-23) mm/year

Compound effects on drainage: As mentioned in section 3.3, winter discharges of the Rhine are projected to increase, leading to greater water surpluses from the catchment in the Delta and IJsselmeer area. At the same time, the sea level rises, certainly leading to drainage restrictions. For example, if the sea level rises more than 0.65 m, the water level of the Wadden Sea will become higher than the water level of the IJsselmeer even under low tide. Under these conditions, the drainage of the IJsselmeer to the Wadden Sea will become impossible under free fall (Deltares, 2018). As a consequence, the water has to be either stored in the IJsselmeer (leading to a higher level) or pumped out (Deltares, 2022).

Compound effects on flood risk management: Flood risk management in the Rhine-Meuse Delta is directly affected by the rise in sea level and the discharge volume and distribution in the Delta (Rhine, Meuse, Waal, IJssel, and Nederrijn). Human intervention such as the Europoort storm surge barrier reduce the effect of sea level rise on the water level in the river system. Due to sea level rise, the number of closures of the Europoort barrier will increase. During a temporary closure of the barrier the area landwards of the barrier stores river water. Sea level rise will thus lead to an increased frequency of river water storage due to increasing closures of the barrier (KP ZSS, 2023).

In addition to the direct effects of rising water levels, morphological processes of the riverbed play a role (KP ZSS, 2023). Sea level rise will lead to a 'sand accretion wave' that migrates from

[17] The figures are based on ‘SSP scenarios’, which are based on the 6th IPCC report. SSP5-8.5 is a high emission scenario, SSP1-2.6 is a reduced emission scenario. Compared to the ‘RCP scenarios’ on which the rest of this report is based, the reference values for sea level rise are higher in the new scenarios.

downstream to upstream in the Delta (Ylla Arbós et al., 2023). The river will move towards a new morphological equilibrium as a result of both the change in sea level and discharge frequencies. Assuming a sea level rise of 1 m, the main channel riverbed could eventually rise by 1 m as well as long as sufficient river sediments are available (KP ZSS, 2023), although the time scale of this change is in the hundreds of years.

Compound effects on fresh water supply and salinity: The sea water level, the precipitation and evaporation, and the river discharge determine the fresh-salt water equilibrium in the Rhine-Meuse estuary. Because of sea level rise and low summer discharge, the salt water intrudes through the river system and will reach farther land inwards, leading to high salt concentration at water extraction points for agricultural use and drinking water. Groundwater and open water systems will also be affected (Deltares, 2018).

The Dutch fresh water strategy is aimed at maintaining certain strategic fresh water zones including certain buffer zones. The IJsselmeer area is an important fresh water buffer which is becoming increasingly vulnerable in regard to water quantity and quality due to climate change (KP ZSS B, 2023). The expected lower river discharge in summer, increased evaporation and sea level rise will cause an increase of salt load in the lake - also because more salt is flowing into the IJsselmeer from regional waters and via the sea locks due to rising sea levels. Moreover, when salt intrudes into the Ijsselmeer area it is difficult to remove it from the lake.

In the Lek and Haringvliet-Hollands Diep branches of the Rhine-Meuse estuary, the salt intrusion is balanced by adding additional discharge surplus from other river branches (e.g. Waal). If both a sea level rise beyond 1 m and extreme low summer discharges occur, these additional surplus discharges may no longer be available or may not be sufficient to combat salinity. As a consequence, it will become unbeneficial to maintain some of these fresh water buffers. In addition, due to sea level rise the Haringvliet-Hollands Diep system will in particular become more vulnerable for salt intrusion due to wind set-up. Events of wind-induced salt intrusion may therefore pose long-lasting (weeks at least) limitations on water extraction points.

4.4 Heavy rainfall and flash flood events

The climate and hydrological models underlying this report produce data in a daily time step and in grid cells or catchments covering several square kilometres. While these models are able to simulate many meteorological and hydrological phenomena on these spatial and temporal scales, they cannot fully cover phenomena that exist only at sub-daily or sub-grid scales. Convective heavy rainfall events - characterised by a large precipitation amount in short time over a small area potentially resulting in flash floods and associated with soil erosion - belong to the latter group of phenomena.

So far, mostly theoretical considerations led to the conclusion that these events, e.g. summer rains, will increase in intensity and number with climate warming (Trenberth 1999; Pfahl et al. 2017). Only recently, a new generation of climate models, so called convection-permitting climate models, allows projecting of the probable future development of convective rainfall events. Due to their high spatial and temporal resolution, the models are able to resolve individual showers and thunderstorms (Poncet et al., 2023).

Up to now, large convection-permitting ensembles are still missing. A first ensemble with 5 members has recently been compiled and exemplarily analysed by the German KLIWA cooperation. Driven by the high emission scenario RCP8.5, the models show that in summer heavy rainfall events indeed increase in intensity as well as in frequency. While the signal of change is clear, the spread is wide - e.g. the intensity of a one-hour event with a ten-year return period will increase by 10 to 30% depending on the projection. In addition, a larger proportion of summer precipitation will probably fall as heavy rainfall in the future (KLIWA 2023, 2024).

4.5 Interference and impacts of non-climatic aspects

It is well known that assessment of future climate impacts covers only part of what will be the real 'future'. This is not only because of the unknown greenhouse gas emission or concentration pathway humankind decides to take (i.e. the level of mitigation). This is also because on top of climate, many drivers of hydrological change will alter in the future too. For example, **demographical** change will alter the number and age of people living in different parts of the Rhine catchment. **Economical** together with **technological** change will alter the amount of and way water is supplied to people, agriculture, and industry. Management paradigms accounting for sustainability focus on water that is needed for ecological functioning of the system 'Rhine' including **ecosystem services**.

These **socio-economic aspects** seem to be 'non-climatic' drivers at a first glance. A deeper view shows, however, that they interfere with climate change as well: climate change-induced migration contributes to demographical change; the amount of water needed for drinking, irrigation, cooling, and ecosystems can be expected to increase with rising temperatures. Furthermore, climate mitigation will to some extent need more and/or result in a new redistribution of water between uses, sectors and regions.

These interferences could positively or negatively add to the hydrological changes summarized in the report. They are, however, hardly quantifiable yet, especially for future time horizons.

5 Discussion and conclusions

In accordance with the mandate of the working group HCLIM, this report compiles current knowledge and data on future discharge changes in the Rhine catchment, as well as some aspects of past changes and meteorological changes. All riparian countries were involved, five research teams contributed data. All data sets are based on a high emission scenario and global climate data consistent with the 5th IPCC assessment report, thus updating the scenarios of the earlier ICPR expert group EG KLIMA that were consistent with the 4th IPCC report. However, the data sets differ in various methodical aspects such as regional climate and hydrological models.

On the one hand, the projection data base underlying this report can be regarded as one of the largest available for the area studied. It could potentially give a more complete picture of different climate futures of the Rhine than earlier studies. But on the other hand, the interpretability of the data is limited due to methodical differences in generating the individual data pools and several yet unresolved research questions. Evaluating the causes of the differences and answering the research questions was beyond the mandate and the resources of the working group HCLIM.

The integration approach chosen here shows the dominant discharge changes that have to be expected for the Rhine - assuming a high emission scenario for precaution. Due to the integrated perspective, the spread of the results is larger than those published by the five contributing research teams.

This chapter summarizes the main results with respect to projected discharge changes (section 5.1), compares them to those of the earlier report (section 5.2), and draws conclusions on the use of the results in the ICPR process and in the research network (section 5.3).

5.1 Main results on future discharge and hydrological system changes up to 2100

In summary, the evaluation of long-term changes in the past (observations) and the future (projections of RCP8.5) support the picture of a change towards **more rain-fed flow regimes** to the disadvantage of snow- and glacier-fed flow regimes in the Rhine catchment. This leads to decreasing summer flows, increasing winter flows, almost unchanged annual flows, and - in many river sections and tributaries - an intensification of low and high flow extremes. Although not shown with a specific indicator here, existing data also suggests drought persistence and thus more persistent low flow periods due to the reduction of snow-fed flows and the dependence on rain-fed regimes, amongst other reasons.

While the general picture seems overall coherent and fits theoretical considerations of the Rhine catchment in a warming climate, the uncertainty spans are large. Some projections even show contradictory change signals. This is the result of the complexity and dynamics of the hydrological system of the Rhine, and the different modelling and data treatment procedures applied. The sequence of extreme low flow years of the last decade shows that real developments of river flows can (at least for some time) differ from the general picture drawn from long term observed and projected data. Similarly, in recent years winter discharge reductions could be observed, which contradicts the long term observations of the 20th century and the projections of the 21st century.

In addition to the climate change impacts that can be assessed by the application of regional climate model data in hydrological models, this report highlights some specific features of the hydrological system of the Rhine River. **Glaciers** have until now been important water sources during long lasting dry weather situations. Research projects focusing on snow- and ice-related river flow components show that the low flow support from glaciers in the Rhine at Basel has passed its peak already (known as 'glacier peak water'), decreasing to almost zero by the end of the century under a high emission scenario (RCP8.5). The **large lakes** in the upper reaches of the Rhine catchment generally follow the aforementioned seasonal effects of climate change (higher levels in winter, lower levels in summer and fall) due to the changes of inflow. In the delta region, the compounded effects of hydrological change and **sea level rise** have to be taken into account. Both aspects will affect drainage opportunities, flood risk management, as well as fresh water supply and salinity. Also here, current management practices and targets may come to their limits within the context of climate change.

5.2 Comparison with the ICPR report from 2011

When preparing the previous study (ICPR, 2011), the then ICPR expert group KLIMA (EG KLIMA) was able to draw on extensive preliminary work by the International Commission for the Hydrology of the Rhine Basin (CHR). As part of the Rheinblick project (CHR, 2010), the CHR partners had carried out essential preparation work by acquiring, combining and analysing projections of meteorological variables (temperature, precipitation) and hydrological variables (discharge or flow). The projections were based on the climate model data underlying the 4th IPCC assessment report (CMIP3, scenario SRES A1B), the EU project ENSEMBLES and national research activities.

Integrated results like those of the Rheinblick project were not available for the present scenario study. Instead, steps of acquisition and integration of data from different sources had to be taken by HCLIM. This was only possible by providing data from various HCLIM partners and involving a climate service that is established at one of the participating partner institutions. However, due to limited resources and the lack of a mandate, it was not possible for EG HCLIM to carry out an in-depth scientific analysis and complete technical integration of the data provided. Instead, analyses were carried out based on the raw projection data (time series) using a standardised procedure (scenario, indicators, time periods).

The reference period was shifted by 20 years (1981-2010 vs. 1961-1990 previously) because of the advance in time with respect to the previous study and because climate model data for the current study was not available for the reference period of report no. 188 (ICPR, 2011). The 'near future' had to be shifted by 10 years (2031-2060 vs. 2021-2050 previously) because the 'near future' period of the earlier scenario study had already begun at the time of writing (2023). Furthermore, some additional indicators and one additional gauging station were added to the evaluation scheme, and results are no longer rounded to the next 5% as in the earlier report.

Due to these preconditions and methodical differences, the **comparability of the ICPR studies of 2011 and 2023 is limited**. Nevertheless, the general presentation of the results in the form of a colour-coded set of tables is similar for both studies. Appendix B displays and compares the scenario results of the 2011 and 2023 studies.

The scenarios generally show **similar directions of projected change** for both studies. They point to more low and high flow extremes associated with - and in part explainable by - a seasonal redistribution of river discharge from summer to winter. However, there are a few exceptions. First of all, the **span of results is higher** for most indicators and locations. This is in part due to the multitude and heterogeneity of the climate models, data treatment schemes (regionalisation, bias correction methods, delta change, etc.), and different hydrological models applied.

In summary, considering the updated scenarios which are now in line with the 5th IPCC Assessment Report, the continuously improved capabilities of climate and hydrological models, and the new span of change signals, **HCLIM recommends re-evaluating the ICPR adaptation strategy and its contributing reports** (e.g. water temperature) based on the new information.

5.3 Suggestions for further use of data and results

This report has compiled and produced information that can be publicly accessed and may be used by different actors in the field of climate impact assessment and adaptation.

Strategical level actors may use the aggregated information offered in this report to decide if their strategies have to be revised. Although the general directions of change do not differ too much from earlier findings, new data sets were processed in this report and some additional references have been made (e.g. on the droughts of the 2010s, rapid glacier melt or the interference of reservoir operation). This may be reason enough to reassess earlier decisions.

Scientific actors or delegates in the ICPR groups e.g. on flood and low water (WG H, EG LW), ecology (WG B) and water quality (WG S) as well as water temperatures (EG STEMP) will find valuable summarised information in this report. If needed, further indications for the determination of their own 'driving' scenarios (high and low flow, respectively), can be found in the graphic appendix (published online: CHR-website). Here the results of the contributing hydrological research teams from Switzerland, France, Germany, the Netherlands, and the CHR are visible in the form of individual 'climate change factors' on an ensemble and projection level. Individual model runs may be selected for individual gauges to calculate indicators that were not included in this report. Likewise, **scientific actors outside the ICPR** can assess the data in detail, down to individual time series at individual gauging stations.

There is also the possibility of further developing the extensive data pool in order to **further consolidate climate change factors**. For example, the German länder on the Rhine might want to determine specific flood change factors within the range shown here on the basis of further information and expert knowledge. For example, historical time series of gauging stations and hydraulic information can be used as further information.

The graphs and data can be accessed via the **web page of the International Commission on the Hydrology of the Rhine basin** (CHR) (see here). The selection of gauges is limited to the indicators and stations mentioned in this report. **More data for many more gauging stations** can be accessed on request to the **ICPR secretariat** via sekretariat@iksr.de. If necessary, the Secretariat will forward the enquiry to the relevant **members of the EG HCLIM** and/or refer to the **research groups and national climate services** mentioned in the foreword or in the report.

6 Outlook

As climate change continues and the knowledge about its possible consequences grows, it can be expected that this current update of the ICPR discharge scenarios will not be the last one. Already now, new scenarios and global climate model outputs have been published with the latest 6th IPCC assessment (section 6.1). Furthermore, the expert group HCLIM has formulated a series of research questions to be addressed by the research network in the upcoming years (section 6.2). The results of these and more activities will be evaluated and reflected in the next ICPR update (section 6.3).

6.1 New trends emerging from AR6

The ICPR report no. 188 (ICPR, 2011), produced by the expert group 'KLIMA' (EG KLIMA), was essentially based on the **4th IPCC Assessment Report** (IPCC, 2007), which was the latest available report at the time of preparation (2010). In particular its core statements and scenarios (mainly intermediate scenario SRES A1B), and the climate model data generated on this basis (CMIP3, EU-ENSEMBLES) were used. Hydrological model results were compiled by the research team Rheinblick (CHR, 2010), following a standardised procedure.

In this current report of the expert group HCLIM, the underlying data sources for national and federal adaptation strategies in the riparian states at the time of preparation (2023) were used. These include the so-called RCP scenarios (Representative Concentration Pathways, mainly high emission scenario RCP8.5) as published in the **5th IPCC Assessment Report** (IPCC, 2014), new climate simulations (CMIP5, EURO-CORDEX), and a variety of hydrological models (as used in the national studies, cf. table 1 and appendix A).

At the time of writing, a new set of scenarios (Shared Socioeconomic Pathways, SSP) and global climate models (CMIP6) was published with the **6th IPCC assessment report** (IPCC, 2021), with a synthesis published in 2023 (IPCC, 2023). However, regional climate change information (i.e. downscaling of the CMIP6 model results) for the Rhine catchment and hydrological impact assessments were not available from all riparian states. Also, a clear decision on the scenario that would best be applied for adaptation purposes had not been made yet.

Figure 5 compares global temperature changes given by the aforementioned IPCC reports assuming high and low emission scenarios. Especially the high emission scenarios tend to result in successively higher global temperature changes. This may be regarded as a first indication that the next generation of change scenarios for the Rhine will come up with larger changes as well.

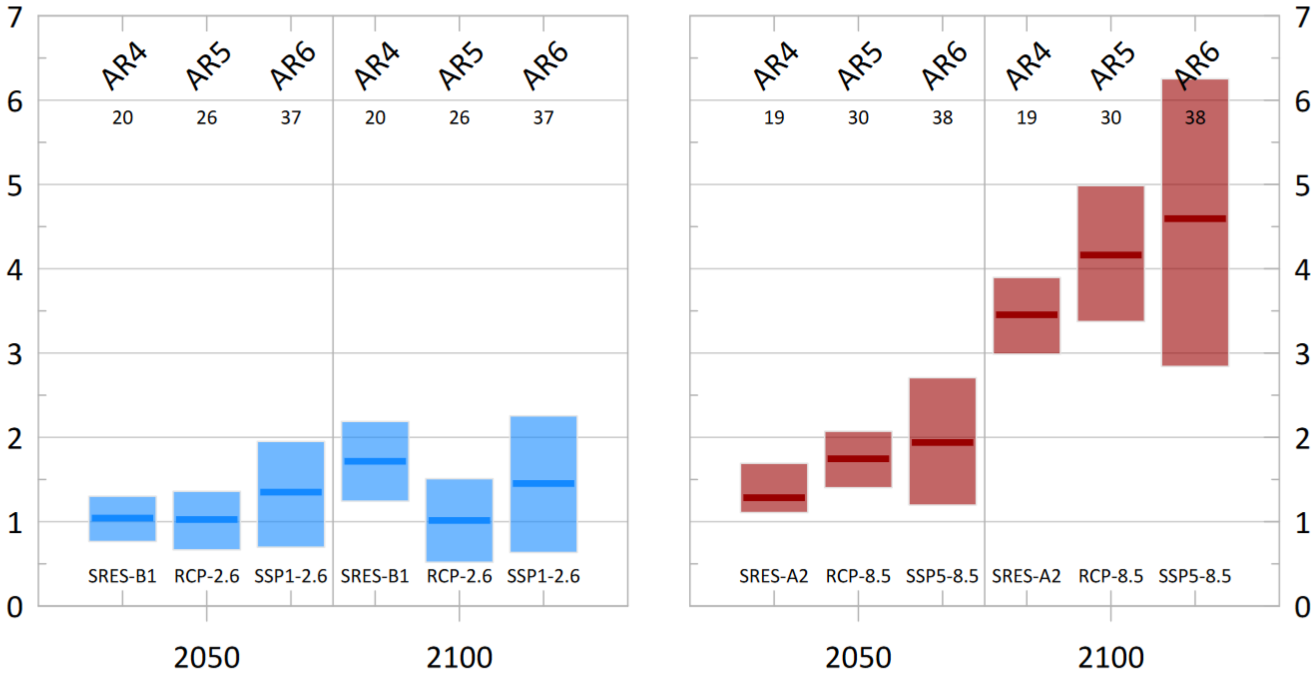

Figure 5: Tentative comparison of global surface temperature change as given by global climate models underlying the 4th, 5th, and 6th IPCC report assuming low emission or mitigation scenarios (left: SRES-B1, RCP2.5, SSP1-2.6) and high emission scenarios (right: SRES-A2, RCP8.5, SSP5-8.5). All changes are averaged for 20 years relative to the period 1986-2005. The size of the respective ensembles is given as numbers in the graphs. Data from Knutti & Sedláček (2012), and Tebaldi et al. (2021); compilation and visualisation by BfG.

In the AR5 report, the climate scenarios consist of emission scenarios (RCPs) based on the concentration of greenhouse gas emissions. The new IPCC AR6 report (IPCC, 2021) uses SSPs instead. The SSPs look at different social and economic developments, which are complimentary to the emission scenarios. For example, SSP5-8.5 consists of social-economic narrative 5 (fossil-fuelled development) and emission scenario RCP8.5. A global comparison based on the new high emission scenario (SSP5-8.5) points towards higher global temperature changes with larger uncertainty than in the respective scenario of the 5th IPCC report underlying this report (KNMI’23, 2023).

The Netherlands are already using the information from the new AR6 report for national and regional impact assessments: the so-called **KNMI’23 scenarios**. In all KNMI’23 scenarios, the temperature is rising (KNMI’23 Gebruikersrapport, 2023). Like the temperature, winter precipitation will continue to increase for all scenarios. In comparison to the winter precipitation in 1991-2020, the winter precipitation will increase between 4 and 24% for the Ld (low emission, dry variant) and Hn (high emission, wet variant) scenarios respectively. This is caused by an increase of western winds, which deliver moist air from the North Atlantic Ocean. In contrast to the increase in summer precipitation in the Netherlands over the last ten years, the four climate scenarios show a decrease in summer precipitation. The highest decrease is up to 29% in the Hd (high emission, dry variant) scenario in 2100. Summer precipitation is expected to decrease because of dry, continental winds from the east. These winds will become more common, due to changes in seawater temperature west of Ireland and strong warming in southern Europe (KNMI’23 Gebruikersrapport, 2023).

Additionally, the frequency of extreme events - extreme showers and droughts - will increase. This means that an extremely dry summer in the present will be an average summer in 2100. As the KNMI’23 discharge projections are still in development, it is unclear what the effect on the future discharge will be.

The new AR6 IPCC scenarios will also be applied by other research teams for their hydrological projections amongst others in the Rhine catchment (e.g. BfG). As these teams wait for an ensemble of regional climate models (building on the global models) to be published presumably in 2025, a new compilation of discharge projections from the riparian countries is still several years ahead.

6.2 Research needs

Unlike in 2011, the commissioned ICPR expert group HCLIM could not draw on completed work of the research network (as it was the case for Rheinblick 2050). The step of integrating different research results for the Rhine basin had to be taken by HCLIM. This was done by (a) gathering the individual data sets from the contributing research teams or their contact persons in the EG HCLIM and (b) consolidation and evaluation by the BfG within the framework of the DAS basic service 'Climate and Water'. Within the scope of its mandate and the available time budget, the expert group was only able to provide technical integration. An in-depth scientific analysis of the differences identified was not possible.

During this procedure, and during the writing process, several research questions arose:

1. Is there a way towards **more uniform approaches to regional or national climate impact assessments**? While it is clear that each national climate impact assessment also needs to answer specific regional questions, the heterogeneity of approaches in the international catchment of the river Rhine seems currently very high. Conceivable levels of integration could include combining the expertise available in all partner countries with the aim of improving the various hydrological models or even developing one joint model. Furthermore, adopting a common simulation protocol or using an integrated evaluation scheme of model outputs would be desirable.
2. How can **differences between simulation ensembles for individual gauges** be explained or reduced? While the results integrated in this report show many similarities and a general matching picture for larger sub-catchments of the Rhine, it turned out that the results of contributing research teams differed remarkably for individual gauges in the tributaries even if the same forcing data were used. These differences show that hydrological processes are captured differently by the individual hydrological models. Thus, they offer the opportunity for mutual learning and model improvements, allowing the next ICPR scenarios to cover more regional details.
3. How can **flash flood-like events** be better covered in climate impact assessments? Short-living and local heavy precipitation events have shown to be very relevant for water management. Current climate models are, however, not able to fully cover this type of events because they produce only daily - rather than hourly or sub-hourly - data on grid cells of several square kilometres, and usually do not fully reproduce atmospheric convection processes. New convection-allowing models should be used in future hydrological climate impact assessments.
4. Are there better methods to assess changes in **extreme values**? Changes in high and low extremes are associated with high risks and are thus particularly relevant for decision makers. Despite initial approaches on national level, up to now it is very challenging if not impossible to assess changes of events occurring once in 100 or even 1000 years from both observations and projections because the length of those series is relatively short (100-200 years maximum, often shorter). The current results have to be regarded as very uncertain. Better methods and a higher level of agreement about which assessments are possible and permissible are needed. Possibly, an inventory of methods for identifying changes in extreme values or extreme value test statistics and possibly the development of standardised extreme value statistics (to determine extreme values over the entire Rhine catchment area) should be carried out. Currently, the Netherlands are already using a precipitation generator and hydrological and hydraulic models to generate discharges for extreme return periods - a method in which artificially long future series are generated on the basis of observations.
5. How can we tackle challenges of **compound effects of climate change**? Climate drives changes in the international catchment of the Rhine in several ways. In this report, much attention has been paid to the impacts of climate change on inland hydrology. Other effects of climate change such as the effects of sea level rise on the Rhine delta or combined effects of climate change with future water uses and water management in the catchment have only briefly been touched. More insight is needed regarding those compound effects.
6. How can effects of socio-economic change be reflected in the next version of scenarios? As mentioned in section 4.5, the future socio-economic change will interfere with direct hydrological effects of climate change, causing both positive or negative feedbacks (aggravating or reducing the direct climate change effects). However, as quantitative information is still missing, these feedbacks cannot be accounted for in this report. More

data and research in the field of **socio-hydrology** (impact of socio-economic activities on hydrology) is needed.

The ICPR has no resources and no mandate to undertake its own research in this field. The commission and its expert groups act as observers and guides for research programmes covering or touching the Rhine catchment related to the above mentioned and related questions.

Therefore, the EG HCLIM passes the questions on to the research network as research impulses, hoping to see answers to some of these issues in the next years.

6.3 Next update of the ICPR report

The next update of this scenario report is scheduled by the program Rhine 2040 in connection with or ahead of the ICPR climate change adaptation strategy updates scheduled every 10 years (next update 2035). This would mean that an update of the discharge scenarios should be undertaken in approximatively 2032.

Obviously, the ICPR must take into account new technical and scientific developments in this field, which may in the future allow for more regular or even more rapid updates and regionalisation of discharge scenarios after the publication of IPCC assessment reports.

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APPENDIX

Appendix A: Technical and methodological background

The national institutes and services that supplied data for this study (cf. section 2.1 of the report), have independently chosen different approaches, methods and models. Table 1 in section 2.2 of the report shows some similarities and many differences between the respective studies.

The following subsections give some background to the decisions lined out in section 2.2 of the report (Data integration and analysis scheme). They summarise the main similarities and differences between the different data packages and discuss potential implications on the results of this report. More detailed information can be found in the references and project reports of the underlying climate impact projects and teams mentioned in section 2.1 of the report.

1. Coverage and scenarios

1.1 Spatial coverage

The studies contributed to EG HCLIM cover various gauging stations of the Rhine catchment. However, not all studies cover the complete international Rhine catchment i. e. the non-tidal part of the Rhine up to and including the Lobith gauging station at the DE/NL border. Some studies are confined to specific parts of the catchment.

As a consequence, the data base differs between Rhine stretches and gauges evaluated in this study (see table 1).

1.2 Temporal coverage

Except for two contributing research teams, all data packages delivered for this report cover climate changes through the 21st century up to 31st December 2100 based on daily values. They differ however in the starting year (see table 1). This is due to different spin up strategies of the hydro modelling teams at the simulation start. All contributing research teams except two provided continuous simulation from the first to the last year. Two contributing research teams provided data for selected time slices only (see project documentation).

Overall, the differences in the starting years interfere with the selection of the reference period (see table 1). The time slice-based studies show a few differences to the other studies (see Table 1 and text below).

1.3 Underlying IPCC report

At the time of writing, all contributing research teams still referred to the 5th IPCC assessment report (IPCC, 2013) thus updating their respective previous activities that referred to the 4th assessment report (IPCC, 2007). One contributing research team (NL) has already started working on the information underlying the 6th IPCC report (IPCC, 2021, IPCC, 2023), but results were not available at the time of writing this report.

Thus, with respect to the underlying IPCC report version, all studies used to update the discharge scenarios are comparable.

1.4 Selected scenario

The 5th IPCC report offered various Representative Concentration Pathways (RCPs) suggesting stronger (RCP8.5) through weaker (RCP2.6) modifications of the climate system by human activity. While some contributing research teams investigated more than one scenario, all contributors investigated the high emission pathway RCP8.5 for reasons of precaution. This scenario is thus adopted for this study.

Thus, with respect to the climate scenario, all studies are comparable.

2. Model chains

The following sections describe the similarities and dissimilarities of the modelling approach of the studies that are integrated in this report: the model and processing chain consists of climate models, data selection and processing schemes and hydrological models.

The choices were made by the individual contributing research teams in advance of the EG HCLIM activity. Adjusting the choices was not possible in EG HCLIM.

2.1 Climate models

All contributing research teams except for one rely on outputs of coordinated regional climate modelling activities (CORDEX). Two contributing research teams included climate model runs from an additional source (ReKliEs). One contributing research team chose another approach relying on outputs of selected global climate models (CMIP), another contributor chose two alternative approaches. Differences exist between the groups relying on the CORDEX output because different model runs and sub-ensembles were selected (cf. section 2.3 of appendix A). For the hydro-meteorological analysis (section 3.1 of the report) the DAS-ensemble was used including three additional runs that were not intended to be used for hydrological analyses of DAS.

This heterogeneity limits the compatibility between the results of the different research teams to some extent.

Table 11 gives an overview of the different choices made.

Table 11: Overview of the GCM-RCM runs used in the studies underlying this report. * indicates alternative climate data processing schemes (cf. section 2.2 of appendix A).

RCP	GCM	RUN	RCM	ASG2	H-CH2018	KLIWA	DAS/XPN	KMNI14	MOSARH21	Number
RCP85	CanESM	1	CCLM4	x						1
RCP85	CanESM	1	RCA4		x					1
RCP85	CanESM	1	REMO2015				x			1
RCP85	CNRM	?	*AdvDC*						x*	1
RCP85	CNRM	?	ALADIN						x	1
RCP85	ECEARTH	12	CCLM4	x		x	x			3
RCP85	ECEARTH	12	CCLM5		x					1
RCP85	ECEARTH	3	HIRHAM5		x					1
RCP85	ECEARTH	1	RACMO		x	x	x	x*		4
RCP85	ECEARTH	12	RACMO			x	x	x*		3
RCP85	ECEARTH	12	RCA4	x	x	x	x			4
RCP85	ECEARTH	12	REMO2015				x			1
RCP85	GFDL	?	*AdvDC*						x*	1
RCP85	HADGEM2	1	CCLM4		x					1
RCP85	HADGEM2	1	CCLM5		x					1
RCP85	HADGEM2	1	RACMO		x		x			2
RCP85	HADGEM2	1	RCA4		x		x			2
RCP85	HADGEM2	1	REMO2015				x			1
RCP85	HADGEM2	1	WRF			x				1
RCP85	IPSL	1	*AdvDC*						x*	1
RCP85	IPSL	1	RCA4	x			x			2
RCP85	IPSL	1	WRF						x	1
RCP85	MIROC	1	CCLM4	x		x	x			3
RCP85	MIROC	1	CCLM5		x					1
RCP85	MIROC	1	REMO2015				x			1
RCP85	MIROC	1	RCA4		x					1
RCP85	MPIESM	1	CCLM4	x		x	x			3
RCP85	MPIESM	1	CCLM5		x					1
RCP85	MPIESM	1	RCA4	x	x	x	x			4
RCP85	MPIESM	1	REMO2009				x			1
RCP85	MPIESM	2	REMO2009				x			1
RCP85	MPIESM	1	WRF			x				1
RCP85	MRI	?	*AdvDC*						x*	1
RCP85	NORESM	1	RCA4		x					1
			Number	7	14	9	16	3		

Specific explanations on KNMI'14 scenarios:

The runoff projections selected in this study (label: KNMI'14) use the hydrological model HBV and are based on the high emission scenario RCP8.5, among others. The Dutch dataset differs from the other datasets in terms of data preparation and approach.

In the KNMI'14 climate scenarios, regional climate variability is driven by the global mean temperature, which is derived from the temperature behaviour of the global CMIP5 model ensemble for the period 1951-2100. In addition, regional climate changes are used as a further driver to cover a scenario range. The resulting model projections are divided into four different scenarios. The scenarios have links to the scenarios with higher emissions from the IPCC 5th Assessment Report (without being identical), namely RCP4.5, RCP6.0 and RCP8.5 (Deltares and KNMI, 2017): 'minor' changes (G_L and W_L) and "strong" changes (G_H and W_H) in winter precipitation - G and W stand for minor (G for Dutch "gematigd", i.e. moderate) and strong (W for Dutch "warm", i.e. warm) global temperature changes, respectively - with the W scenarios being focused upon RCP8.5. Furthermore, a W_{Hdry} was generated to capture particularly dry conditions. These scenarios are fed into the hydrological model (HBV) to generate runoff and runoff statistics that are used both in flood risk management (for assessment and design tools) and in drinking water management.

2.2 Climate data processing schemes

The way climate data is processed for hydrological modelling includes several steps: for example, spatial aggregation or disaggregation of the original climate model data (depending on the spatial resolution of the hydrological model). Among others, there are several ways to handle climate model biases (deviations of observed and simulated climate). In general, two different approaches have been used by the contributing research teams.

The approach labelled 'bias correction' uses observations[18] to correct the climate model outputs by factors determined by comparison of simulated and observed meteorological fields[19]. This approach maintains for example the temporal structure of the climate models; i. e. continuous timeseries of daily values. The approach labelled 'delta change' shifts observations by change signals determined by comparing the simulated future and the past climate system states[20]. This approach generally maintains more properties of the observed meteorological fields and allows time slice assessments instead of continuous assessments. Both approaches have advantages and drawbacks. Differences in climate data processing schemes limits compatibility of the results between the different research teams but a 'best approach' cannot be selected and therefore both approaches have been integrated in this analysis.

2.3 Ensembles (number of members)

The uncertainty inherent to the climate system and the climate models is usually captured by using an ensemble of climate simulations (projections) instead of a single simulation (projection). However, the number of ensemble members varies in a wide range between the data packages contributed by the research teams for this study. The reasons include computational resources, criteria of quality checks and model selection.

As not only the number of ensemble members but also the selected models and model runs (cf. section 2.1 of appendix A) were different between the delivered data packages, the selection of ensemble members is given. Changing this was not possible within the mandate of EG HCLIM.

The ensemble size and thus the sample size has a clear impact on the comparability of the results between the different research teams and the statistics (extreme values) that can be applied to the data.

2.4 Hydrological models

Table 1 in section 2.2 shows the different hydrological models used to calculate the regional water balances and the river discharge that are the core data used in this study. Hydrological models differ in the representation and discretisation of hydrological processes such as evaporation, groundwater recharge, snow storage, water management routing etc. in catchments or grid cells and in the data used for model setup (soil, landcover, topography etc.). Even models labelled identically in the table show differences, e. g. LARSIM with spatial resolutions of 1 km and 5 km.

It is beyond the scope of this study to assess and explain the differences between the hydrological models used in detail, but this could be part of future research (see section 5.4). In principle, the application of different hydrological models contributes to a holistic uncertainty assessment and allows mutual learning and model improvement. In other words, model uncertainties are somehow reduced by showing a bigger range of possible evolutions.

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[18] different observation products in different contributing studies
[19] e. g. monthly correction factors for different quantiles of air temperature or precipitation
[20] e. g. by comparing the simulated future and the past climate system states as presented by multi-annual time slices (usually 30 years) of air temperature or precipitation

2.5 Time periods

Changes signals are obtained by comparing river flow statistics of future time periods with a reference period. In the original studies of the research groups, different reference periods were selected (Table 1). In EG HCLIM, the common reference period **1981-2010** was chosen. Setting the reference period to 1961-1990 as in the earlier report (ICPR, 2011) was not possible due to lack of model output (see section 1.2 of appendix A). The period 1991-2020 was not selected as reference because starting with the year 2006, the CO_2 concentrations underlying the climate and hydrological simulations are based on the scenarios of the 5th IPCC assessment report (thus: assumed/projected values, not observed).

As more than 10 years have passed between the end of the selected 'reference period' (2010) and 'today', EG HCLIM decided to calculate the 'present' - defined as the period **1991-2020** - change signals based on observations to evaluate the recent changes.

With respect to future periods, there was an approximate match of the 'distant future' ('far future', 'end of the century') between the original studies of the contributing research teams, defined as the period **2071-2100** (2069-2098) (Table 1). For the definition of the 'near future ('mid of the century') the original studies differed. For EG HCLIM, the period **2031-2060** was selected.

Appendix B: Comparison of old and new discharge scenarios

Please find detailed explanation on this comparison between the old ICPR report no. 188 (ICPR, 2011) and the current report in section 5.2.

Table 12: Comparison of previous (ICPR report no. 188; ICPR, 2011) and current report on discharge scenarios. Annual indicators of mean, low and high flow change (%, MQ, MNQ, MHQ) vs. 1961-1990 (report 188) vs. 1981-2010 (current report).

For explanation of the colour code and further information on the illustrated values, see report 188 and section 3 of this report.

Indicator	Gauge	Projected change (%) (ICPR report no. 188)		Projected change (%) (Current report) Values without brackets: 'integrated picture': minimum to maximum changes of all projections/ensembles Values in brackets '()': 'common part': intersection of the different ensembles of the contributions	
		Near Future 2021-2050	Distant Future 2071-2100	Near Future 2031-2060	Distant Future 2071-2100
MQ	Basel	n.d.	n.d.	-15 to +11 (-6 to +5)	-26 to +10 (-8 to -2)
	Maxau	n.d.	n.d.	-14 to +12 (-7 to +4)	-23 to +12 (-8 to -1)
	Worms	n.d.	n.d.	-12 to +13 (-7 to +4)	-19 to +14 (-7 to +2)
	Kaub	n.d.	n.d.	-13 to +13 (-5 to +6)	-16 to +17 (-4 to +4)
	Cologne	n.d.	n.d.	-12 to +11 (-4 to +7)	-13 to +19 (-3 to +8)
	Lobith	n.d.	n.d.	-11 to +11 (-4 to +10)	-12 to +19 (-3 to +13)
	Rockenau (Neckar)	n.d.	n.d.	-13 to +24 (-11 to +16)	-13 to +28 (-2 to +15)
	Raunheim (Main)	n.d.	n.d.	-22 to +23 (+5 to +15)	-44 to +33 (+11 to +15)
	Trier (Moselle)	n.d.	n.d.	-12 to +19 (0 to +10)	-12 to +27 (+7 to +23)
MNQ	Basel	n.d.	n.d.	-32 to +8 (-)	-57 to +9 (-)
	Maxau	n.d.	n.d.	-26 to +7 (-8 to 0)	-48 to +6 (-15 to -6)
	Worms	n.d.	n.d.	-27 to +7 (-11 to 0)	-48 to +3 (-19 to -6)
	Kaub	n.d.	n.d.	-27 to +6 (-15 to -1)	-46 to +1 (-23 to -5)
	Cologne	n.d.	n.d.	-29 to +4 (-18 to -2)	-47 to -1 (-27 to -6)
	Lobith	n.d.	n.d.	-29 to +4 (-19 to -3)	-48 to -1 (-27 to -6)
	Rockenau (Neckar)	n.d.	n.d.	-28 to +18 (-21 to +7)	-35 to +15 (-22 to +4)
	Raunheim (Main)	n.d.	n.d.	-33 to +16 (-19 to +8)	-42 to +21 (-25 to -3)
	Trier (Moselle)	n.d.	n.d.	-51 to +8 (-26 to -4)	-66 to +16 (-30 to -21)

MHQ	Basel	-5 to +10	-25 to +15	-14 to +17 (0 to +10)	-17 to +24 (+5 to +8)
	Maxau	-5 to +15	-20 to +15	-7 to +30 (+2 to +14)	-3 to +28 (+9 to +14)
	Worms	-10 to +20	-15 to +15	-3 to +43 (+3 to +16)	-3 to +31 (+12 to +17)
	Kaub	-5 to +25	-10 to +20	-3 to +44 (+4 to +19)	-8 to +37 (+15 to +21)
	Cologne	0 to +20	-5 to +20	-4 to +39 (+5 to +21)	-12 to +38 (+17 to +22)
	Lobith	0 to +20	-5 to +20	-7 to +36 (+5 to +21)	-12 to +37 (+16 to +30)
	Rockenau (Neckar)	n.d.	n.d.	-9 to + 69 (-3 to +46)	-16 to + 46 (+5 to +35)
	Raunheim (Main)	0 to +35	0 to +35	-20 to +42 (+8 to +28)	-27 to +60 (+24 to +33)
	Trier (Moselle)	-10 to +15	-10 to +20	-1 to +35 (+6 to +21)	-12 to +49 (+23 to +31)

Table 13: Comparison of previous (ICPR report no. 188; ICPR, 2011) and current report on discharge scenarios. Seasonal indicators of mean, low and high flow change (%, MQ, NM7Q) vs. 1961-1990 (report 188) vs. 1981-2010 (current report); hydrological seasons.

For explanation of the colour code and further information on the illustrated values, see report 188 and section 3 of this report.

Indicator	Gauge	Projected change (%) *(ICPR report no. 188)*		Projected change (%) *(Current report)* Values without brackets: 'integrated picture': minimum to maximum changes of all projections/ensembles Values in brackets '()': 'common part': intersection of the different ensembles of the contributions	
		Near Future 2021-2050	Distant Future 2071-2100	Near Future 2031-2060	Distant Future 2071-2100
MQ Summer	Basel	-10 to +5	-25 to -10	-25 to +4 (-16 to -2)	-48 to -4 (-21 to -15)
	Maxau	-10 to +5	-25 to -10	-24 to +5 (-16 to -1)	-47 to -3 (-21 to -14)
	Worms	-10 to +5	-25 to -10	-23 to +6 (-16 to 0)	-46 to -1 (-21 to -12)
	Kaub	-10 to +10	-25 to -10	-21 to +7 (-16 to +1)	-43 to +2 (-20 to -10)
	Cologne	-10 to +10	-25 to -10	-21 to +6 (-17 to 0)	-42 to +3 (-21 to -8)
	Lobith	-10 to +10	-25 to -10	-20 to +6 (-17 to +4)	-42 to +4 (-21 to -6)
	Rockenau (Neckar)	n.d.	n.d.	-16 to +24 (-16 to +19)	-37 to +22 (-20 to +6)
	Raunheim (Main)	0 to +25	-20 to +10	-30 to +27 (-10 to +8)	-56 to +27 (-13 to +3)
	Trier (Moselle)	-5 to +10	-25 to -5	-26 to +15 (-21 to +6)	-41 to +19 (-25 to +10)
MQ Winter	Basel	0 to +20	+5 to +25	-10 to +22 (+6 to +14)	0 to +32 (+10 to +20)
	Maxau	0 to +20	+5 to +25	-2 to +21 (+5 to +14)	+4 to +31 (+9 to + 19)
	Worms	0 to +20	+5 to +25	-4 to +21 (+4 to +14)	+3 to +32 (+10 to +20)
	Kaub	0 to +20	+5 to +25	-7 to +22 (+6 to +14)	0 to +35 (+12 to +20)
	Cologne	0 to +15	+5 to +25	-7 to +23 (+6 to +14)	-2 to +36 (+13 to +23)
	Lobith	0 to +15	+5 to +25	-6 to +23 (+6 to +16)	0 to +35 (+12 to +28)
	Rockenau Neckar)	n.d.	n.d.	-11 to +24 (-8 to +16)	-12 to +34 (+5 to +20)
	Raunheim (Main)	0 to +25	+15 to +40	-21 to +30 (+14 to +16)	-43 to +46 (-)
	Trier (Moselle)	0 to +20	+10 to +30	-8 to +28 (+7 to +13)	-7 to +38 (+18 to +27)

NM7Q Summer	Basel	-10 to +10	-20 to -10	-35 to +5 (-7 to -5)	-62 to +7 (-)
	Maxau	-10 to +10	-20 to -10	-36 to +2 (-12 to -5)	-57 to +2 (-)
	Worms	-10 to +10	-25 to -10	-36 to +1 (-15 to -4)	-56 to -1 (-24 to -21)
	Kaub	-10 to +10	-25 to -10	-35 to +1 (-19 to -3)	-54 to -5 (-28 to -18)
	Cologne	-10 to +10	-30 to -10	-34 to +1 (-22 to -3)	-53 to -6 (-32 to -17)
	Lobith	-10 to +10	-30 to -10	-33 to 0 (-22 to -2)	-53 to -6 (-32 to -17)
	Rockenau (Neckar)	n.d.	n.d.	-24 to +16 (-20 to +8)	-38 to +7 (-23 to -2)
	Raunheim (Main)	0 to +20	-20 to 0	-33 to +22 (-21 to +4)	-46 to +15 (-23 to -6)
	Trier (Moselle)	-20 to +20	-50 to -20	-51 to +9 (-28 to -7)	-68 to +9 (-32 to -26)
NM7Q Winter	Basel	+5 to +15	0 to +15	-17 to +15 (-2 to +7)	-32 to +26 (-8 to +8)
	Maxau	0 to +10	-5 to +15	-12 to +11 (-7 to +5)	-38 to +22 (-14 to +7)
	Worms	+5 to +15	-5 to +15	-15 to +10 (-10 to +4)	-41 to +20 (-18 to +5)
	Kaub	0 to +15	-5 to +15	-17 to +10 (-15 to +2)	-42 to +21 (-21 to +1)
	Cologne	0 to +15	0 to +20	-20 to +9 (-18 to +3)	-46 to +21 (-23 to -1)
	Lobith	0 to +15	-5 to +15	-20 to +9 (-19 to +3)	-45 to +20 (-27 to -1)
	Rockenau (Neckar)	n.d.	n.d.	-28 to +23 (-24 to +6)	-40 to +30 (-28 to +20)
	Raunheim (Main)	+5 to +15	0 to +20	-33 to +17 (-19 to +8)	-41 to +23 (-25 to -3)
	Trier (Moselle)	-15 to +15	0 to +20	-43 to +14 (-21 to +1)	-54 to +23 (-29 to -9)

Table 14: Comparison of previous (ICPR report no. 188; ICPR, 2011) and current report on discharge scenarios. Indicators of 'frequent', 'medium', and 'extreme' flood change (%, HQ10, HQ100, HQ1000) vs. 1961-1990 (report 188) vs. 1981-2010 (current report); see text for particular uncertainties associated with these values.

*For explanation of the colour code and further information on the illustrated values, see report 188 and section 3 of this report. *very uncertain*

Indicator	Gauge	Projected change (%) *(ICPR report no. 188)*		Projected change (%) *(Current report)*	
		Near Future 2021-2050	Distant Future 2071-2100	Near Future 2031-2060	Distant Future 2071-2100
HQ10 'frequent'	Basel	-10 to +10	-20 to +20	-8 to +11	-8 to +20
	Maxau	-15 to +20	-15 to +25	-1 to +20	-1 to +30
	Worms	-15 to +15	-10 to +35	+20 to +26	+2 to +36
	Kaub	-15 to +15	-5 to +40	-1 to +24	-1 to +40
	Cologne	-5 to +15	0 to +40	-7 to +27	-7 to +38
	Lobith	-5 to +15	0 to +35	+8 to +21	+12 to +37
	Rockenau (Neckar)	n.d.	n.d.	0 to +44	0 to +44
	Raunheim (Main)	0 to +30	5 to +40	-18 to +48	-18 to +48
	Trier (Moselle)	-5 to +15	0 to +25	0 to +31	0 to +36
HQ100 'medium' *	Basel	-20 to +10	-30 to +25	-12 to +21	-18 to +21
	Maxau	-10 to +15	-25 to +30	-5 to +42	-5 to +43
	Worms	-5 to +20	-25 to +35	-3 to +45	-3 to +47
	Kaub	-5 to +20	-10 to +25	-8 to +56	-8 to +56
	Cologne	0 to +20	0 to +25	-26 to +61	-26 to +61
	Lobith	0 to +20	0 to +25	+5 to +18	+7 to +42
	Rockenau (Neckar)	n.d.	n.d.	-17 to +67	-17 to +67
	Raunheim (Main)	0 to +20	0 to +35	-24 to +94	-24 to +94
	Trier (Moselle)	-5 to +30	-5 to +25	-20 to +49	-20 to +52
HQ1000 'extreme' *	Basel	-20 to +35	-10 to +50	-25 to +32	-28 to +32
	Maxau	-20 to +35	-20 to +65	-12 to +59	-12 to +59
	Worms	-15 to +30	-20 to +45	-13 to +81	-13 to +81
	Kaub	-5 to +25	-10 to +30	-18 to +89	-18 to +89
	Cologne	-5 to +25	0 to +30	-39 to +97	-39 to +97
	Lobith	-5 to +20	-5 to +30	+3 to +20	+5 to +51
	Rockenau (Neckar)	n.d.	n.d.	-31 to +155	-31 to +155
	Raunheim (Main)	-5 to +40	0 to +45	-27 to +151	-27 to +151
	Trier (Moselle)	-35 to +20	-20 to +45	-38 to +94	-38 to +94