Study of Scenarios for the Discharge Regime of the Rhine

state: April 2011

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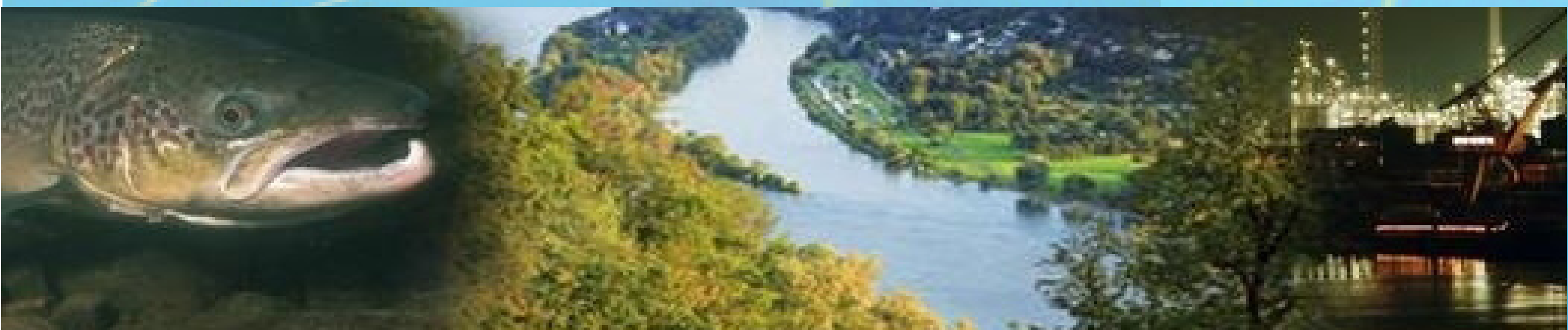

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Abbreviations

Abbreviation	Explanation
WG H, WG B, WG S	Working Group (H = Floods, B = Ecology, S = Water Protection/Emissions)
BAFU	Federal Environment Agency
BMVBS	Federal Ministry of Transport, Building and Urban Development, Germany
BfG	Federal Institute of Hydrology, Germany
DWD	National Meteorological Service, Germany
EG KLIMA	ICPR Expert Group "KLIMA"
HYRAS	BfG-DWD project „Hydrometeorological reference data for Central Europe (grid)"
IKSR	International Commission for the Protection of the Rhine
IKSMS	International Commissions for the Protection of the Moselle and the Saar
IPCC	Intergovernmental Panel on Climate Change
KHR	International Commission for the Hydrology of the Rhine Basin
KNMI	Royal Dutch Meteorological Institute
LANUV-NRW	Federal Agency for Nature, Environment and Consumer Protection, Northrhine-Westphalia
NRW	Northrhine-Westphalia
MHQ	Arithmetic average of the highest daily discharge values of homogenous periods of time (e.g. hydrological half-year periods) of the period under consideration (e.g. period 2021-2050)
MQ	Arithmetic average of the all daily discharge values of homogenous periods of time (e.g. hydrological half-year periods, months) of the period under consideration (e.g. period 2021-2050)
NM7Q	Lowest Arithmetic average of the discharge values of 7 days during homogenous periods of time (e.g. hydrological half-year periods) of the period under consideration (e.g. period 2021-2050)
HQ_T	Flood discharge (here: highest daily value) determined for the period of successive years T.
OcCC	Advisory Board on Climate Change, Switzerland
ONERC	National Observatory on the Effects of Global Warming, France
SumhN	Sum of area precipitation (surface average) across homogenous periods of time (e.g. meteorological seasons) of the period under consideration (e.g. period 2021-2050)
UBA	Federal Environment Agency, Germany
WMO	World Meteorological Organization

Projects:

(if mentioned in the text; alphabetical order of acronyms or of title)

Title	**Acronym**	**Internet Address**
Developing adaptive capacity to extreme events in the Rhine basin	ACER	http://www.climateresearchnetherlands.nl
Klimaänderung und Hydrologie in der Schweiz	CCHydro	http://www.bafu.admin.ch/wasser/01444/01991/10443/index.html?lang=de
Coupled Model Intercomparison Project	CMIP	http://cmip-pcmdi.llnl.gov/
A coordinated regional climate downscaling experiment	CORDEX	http://wcrp.ipsl.jussieu.fr/RCD_CORDEX.html
Deutsche Anpassungsstrategie	DAS	http://www.bmu.de/klimaschutz/downloads/doc/42783.php
Deltaprogramm	(ohne)	http://www.deltacommissaris.nl/english/
ENSEMBLES – Climate change and its impacts	ENSEMBLES	http://ensembles-eu.metoffice.com
Extremwertuntersuchung Starkregen in Nordrhein-Westfalen	ExUS	http://www.klimawandel.nrw.de
Flood, low water, Moselle and Saar	FLOW MS	http://www.flow-ms.eu
Interdisziplinäre Forschung zu Klimawandel, Folgen und Anpassung in Hessen	INKLIM-A, INKLIM2012	http://klimawandel.hlug.de/forschungsprojekte/inklim-a-und-weitere-projekte.html
Kennis voor Klimaat	(ohne)	http://www.climateresearchnetherlands.nl
Auswirkungen des Klimawandels auf das Abflussverhalten in Gewässern und Einzugsgebieten Nordrhein-Westfalens	KLAVE	http://www.klimawandel.nrw.de
Klima-Anpassungsstrategie der Schweiz	(ohne)	http://www.bafu.admin.ch/klima/00493/06573/index.html?lang=de
Anpassungsstrategien an den Klimawandel für Österreichs Wasserwirtschaft - Kurzfassung	(ohne)	http://publikationen.lebensministerium.at/publication/publication/view/3414/28637
Kooperationsvorhaben "Klimaveränderung und Konsequenzen für die Wasserwirtschaft" (Bundesländer Bayern, Baden-Württemberg, Rheinland-Pfalz sowie Deutscher Wetterdienst)	KLIWA	http://www.kliwa.de
Auswirkungen des Klimawandels auf Wasserstraßen und Schifffahrt	KLIWAS	http://www.kliwas.de

Title	Acronym	Internet Address
– Entwicklung von Anpassungsoptionen		
Nationales Forschungsprogramm "Nachhaltige Wassernutzung"	NFP 61	http://www.nfp61.ch
Prediction of regional scenarios and uncertainties for defining European climate change risks and effects	PRUDENCE	http://prudence.dmi.dk/
Impact of regional climate change on discharge in the Rhine River basin	RheinBlick2050	http://www.chr-khr.org/de/node/266
Statistical and regional dynamical downscaling of extremes for European regions	STARDEX	http://www.cru.uea.ac.uk/projects/stardex/
World Climate Research Programme	WCRP	http://www.wmo.int/pages/prog/wcrp/wcrp-index.html

1. Assignment

Changes of climate parameters impact hydrological processes and thus the regional hydrological regime, discharge regimes and the temperature regime of water bodies. Therefore, on October 18, 2007 the Conference of Rhine Ministers commissioned the ICPR to draft a Study of Scenarios for the Discharge Regime of the Rhine (Communiqué of the Conference of Rhine Ministers, 2007 – www.iksr.org).

The effects of climate change concern major sectors of water resources management as flood protection, water supply, water protection, ecological aspects, hydro-morphological water body development and different uses of water bodies (hydro power, navigation, cooling water, drinking water supply, agricultural uses). Specific adjustment strategies will possibly have to be developed with respect to future developments. These can however only be promising if based on vast and practical knowledge on changes in the above mentioned sectors of water management.

Within its assignment the ICPR has thus adopted a three-staged procedure:

(a) Summary analysis and representation of climate changes so far and possible future climate changes, of changes in water regime and water temperature within the period of time relevant for planning until 2050 (global analysis of climate scenarios up to 2100).

(b) Recognize possible dangers and risks (WG H, WG B and WG S);

(c) Development of forward looking, sustainable precautionary water management concepts/adjustment strategies.

In 2008, the ICPR created an Expert Group "Climate" (EG KLIMA) as sub-group of the WG Floods (WG H) to deal with the tasks listed under (a). Knowledge acquired will be rapidly exchanged with the Working Groups "Floods" (WG H), "Ecology" (WG B) and "Substances" (WG S) in order to prepare the development of forward looking, sustainable water management adjustment strategies.

This report summarizes the findings of the EG KLIMA concerning the tasks mentioned under (a).

2. Characteristic Features of the Discharge Regime

The discharge regime describes the overall behaviour of river runoff with respect to the average multi-annual course and the characteristic development of extreme flood and low flow situations (Belz et al., 2007). In the Rhine catchment, different discharge regimes are overlapping (fig. 1).

The southern part near the Alps (Basel gauging station) is characterized by the interplay of snow cover constitution and in winter and snow melt comparatively high precipitation in summer ("snow regime" or nival regime). As a consequence, low water periods mainly occur in winter and flood events mainly occur in summer.

Waters draining the Central Upland region (Neckar, Main, Nahe, Lahn, Moselle, etc; Trier gauging station) are characterised by a "pluvial regime" with prevailing winter floods and low water flow in summer.

Since these two regimes overlap, the downstream discharge distribution over the year ("combined regime", Cologne gauging station) is increasingly uniform.

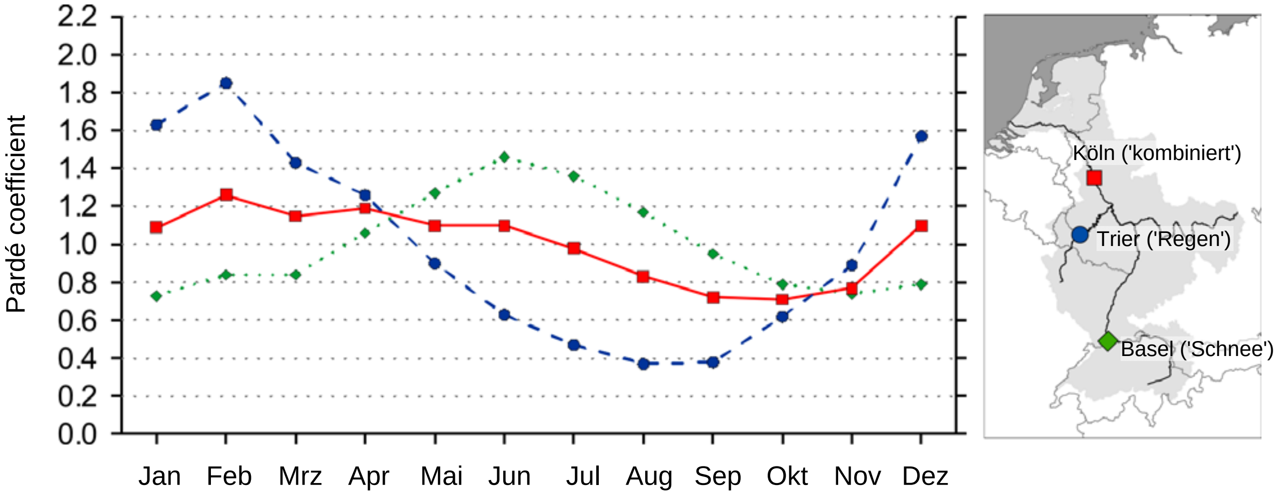

Figure 1: Typical discharge regime in the Rhine catchment according to Pardé[1]; reference period 1961-1990

Changes of the climatic framework conditions impact the discharge regime. During the 20th century, a tendency towards more rainfall with increasing discharges in winter has been stated (Belz et al., 2007). Considering the seasonal distribution of discharges, this leads to more homogenous runoff in the south, while the seasonal distribution becomes more marked in the north. These tendencies continue during the 21st century and, due to reduced runoff in summer, they might even be intensified (see chapters 4.1 and 4.2).

3. Survey over Literature and Data focussing on the Rhine Catchment

3.1 Preliminary remarks

In the "robust findings" of its 4th Assessment Report (IPCC 2007a, p. 72), the Intergovernmental Panel on Climate Change of the United Nations summarizes that, considering the air and ocean water temperature, melting of snow and ice and the rise of the global average sea level, warming of the climate system is "unequivocal" and has, during the past 50 years, mainly been caused by increasing anthropogenic emissions of greenhouse gases.[2] During the past 30 years, and on a global level, this is "likely" to have had a discernible influence on observed changes in many physical and biological systems.

Investigations concerning eventual future consequences for the climate require the use of models flawed by uncertainties (see figure 2 in chapter 3.3). Although the findings of the EG KLIMA on the consequences of climate change for the Rhine reflect the most recent state of knowledge, they must also be interpreted against this background. In practice, the result is a spectrum of information instead of one, generally valid statement. Due to a greater number of sources of uncertainties, this particularly applies to statements concerning the future and to the consequences of climate change which, in general, must be assessed by means of complex model chains.

[1] Pardé coefficient = ratio of multi-annual monthly discharge and multi-annual annual discharge.
[2] "Climate change of anthropogenic origin" (in the following: climate change)

During the past 10 years, numerous scientific publications and project findings considerably improved the state of knowledge and data on possible consequences of climate change in the Rhine catchment.

This information contributes to testing the reliability of individual statements. In addition, the model findings indicate a spectrum and recordings to be used as a spectrum and not as individual recordings.

3.2 Literature

3.2.1 Key publications – global and European scale

During the past five years and with the publication of

(a) The fourth IPCC Assessment Report (IPCC, 2007) mainly based on Phase 3 of the Coupled Model Intercomparison Project (CMIP, 2009) of the World Climate Research Program (WCRP) and of the

(b) Report on findings of the EU projects PRUDENCE (EU-FP5; PRUDENCE Partner 2007), STARDEX (EU-FP5; STARDEX Partner 2005) and ENSEMBLES (EU-FP6; ENSEMBLES Partner, 2009)

on global and regional climate change in Europe, the quality and variety of data and methods available have been considerably improved. On this basis, several on-going projects and working groups are developing possible future pathways of developments for the framework conditions for water management actions.

3.2.2 Knowledge on the Rhine

Substantial findings exist on climate change and its effect on water bodies in the Rhine catchment. However, often these findings only concern sub-catchments or they are based on different methods and data. This heterogeneity makes it difficult to derive concrete indications for the Rhine gauges which can be applied in hydrological practice.

As explained below, the EG KLIMA has, on the one hand, compiled the state of knowledge until 2009. On the other hand, it has created a dialogue between scientific institutions and water management administrations which have established a new state of knowledge by 2010 or will do so by 2011. Finally, progress expected and already emerging for 2013 and later is indicated.

<u>State 2009:</u>

In order to compile the knowledge on the issue by the beginning of 2009, the EG KLIMA had commissioned a bibliographic study (ICPR, 2009). It includes research findings of different institutions in the Rhine bordering countries and federal states resulting from research during 1997 to 2009 and published in 110 technical contributions. Among others the findings of the OcCC (Switzerland), the ONERC (France), the KLIWA cooperation project (federal states Bavaria, Bade-Württemberg, Rhineland Palatinate and DWD), of the project INKLIM2012 (federal state Hesse), of the federal state Northrhine-Westphalia (KLAVE; ExUS), of the BfG (Germany), the UBA (Germany), of the KNMI (Netherlands), of the Delta Commission (Netherlands) and of different projects and reports published by the CHR and the ICPR are included.

Completeness of the list of literature assessed (see ICPR, 2009: 44 following) is not being claimed. The data basis, methods and study areas used are very heterogeneous. Major findings are compiled in the tables of Appendix A and Appendix B.

State 2010:

Following the bibliographic study (ICPR, 2009) several further papers have been presented, consolidating the state of knowledge on the consequences of climate change for the Rhine. Important papers have resulted from the „KLIWA project“ (KLIWA, 2009a and b), the Dutch project „ACER“ (Hurkmans, 2009; Te Linde et al., 2010a and b) the NRW projects KLAVE (Richter et al., 2009) and ExUS (LANUV-NRW, 2010), the CHR project "RheinBlick 2050" (Görgen et al., 2010) and the BMVBS project „KLIWAS“ (Nilson et al., 2010; Krahe et al., 2009) and are here mentioned as examples.

KLIWA (2009a) gave rise to findings on the water temperatures of Lake Constance under observed climatic peripheral conditions during 1960-2007 and on the complex reaction of the lake to changed conditions (air temperature, wind field).

KLIWA (2009b) is an analysis of low water flow in Rhine tributaries in Bade-Wurttemberg, Bavaria and Rhineland-Palatinate. The studies give new quantitative and regionally differentiated evidence of the general statements made in the bibliographic study concerning a future increase of low water flow during winter months and a reduction during summer months compared to the reference period (here: 1971-2000) and in future (here 2021-2050).

Within the ACER project, runoff was among others simulated for the entire Rhine and until 2100. In contrast to the findings of the bibliographic study, during the first half of the 21st century (here: 2002-2050) the average runoff (monthly MQ) for all gauging stations for all months indicate a rise by + 5 % to +20% as compared to the reference period (here: 1952-1998). For floods (HQ_{50}) changes for Lobith may achieve +7.5% to +21%, which is consistent with earlier results (Hurkmans, 2009)[3]. In the low water area[4] and compared to the reference period, the intensity of short recurrence times seems to be less, but some more extreme low flow situations are also being simulated.

The KLAVE projects simulated the runoff at different gauging stations in Northrhine-Westphalia until 2100. Compared to 1971-2000, the average low flow, medium and flood runoff during 2021-2050 will not change or change insignificantly (most changes < 10 %)[5]. Within the project "Investigation into extreme recordings of intense rainfall in Northrhine-Westphalia (ExUS)" it has, among others, been investigated into, whether a change of intense rainfall patterns may be derived from the monitoring data of precipitation monitoring stations in Northrhine-Westphalia. Among other findings, the results show that, in particular during the winter half years, the number of days with intense precipitation has increased over the past 59 years (1950-2008). There is no perceptible increase in the measured intensity of storms.

Studies mentioned so far and used for the literature evaluation are based on model chains (see chapter 3.3), each using a global and a regional climate model[6]. The EU project ENSEMBLES which ended in the fall of 2009 made available several further chains of global and regional climate models representing the European state of climate modelling.

The CHR „RheinBlick2050“ project as well as its contributing projects represent the first runoff projections on this basis for representative gauging stations along the Rhine which were evaluated according to a cross border procedure the project partners had agreed upon. In this connection, the RheinBlick2050 project played a coordinating role integrating the findings of different hydrological institutions in the Rhine catchment, among others the findings of the BMVBS project KLIWAS which considerably contributed to RheinBlick2050. The findings of RheinBlick 2050 are presented in chapter 4.2.

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[3] Extreme flood ($HQ_{100;}$ fig. 4.12 in Hurkmans, 2009)) was only extrapolated by a general distribution of extreme values. Synthetic time series recommended for analysing extremely rare events have not been used by Hurkmans (2009) (see Görgen et al., 2010).

[4] Sum of periods remaining below the FDC_Q75 of the reference period 1952-1998.

[5] Assessment of MNQ, MQ and MHQ for meteorological seasons.

[6] In most cases data of the German GCMs ECHAMS (run 1) regionalised with the help of WETTREG2006 or REMO_UBA were used.

With a view a scientifically based presentation of the impact of climate change on Austrian water management the Austrian Federal Ministry of Agriculture, Forestry, Environment and Water Management commissioned a study entitled "Strategies for the Adjustment of Austria's Water Management to Climate Change" which was accomplished in December 2010. The main statements on climate change until 2050 were summarized in 10 theses (Federal Ministry of Agriculture, Forestry, Environment and Water Management, 2010).

State 2011:

Research into the consequences of climate change for the Rhine catchment is continuing.

An improved basis for investigations into changes of water temperature is expected for the Rhine downstream of Basel. The German Commission for Rhine Pollution Prevention has set up an ad-hoc working group in charge of creating a homogenous data basis for water temperature modelling (personal communication Dr. Keller, BfG[7]). The Rijkswaterstaat has commissioned Deltares to establish a water temperature model for the Rhine which is capable of representing the effects of temperature discharges and climate change. Deltares will closely cooperate with the BfG.

Within the KLIWA cooperation project, new findings have equally been announced for early 2011. The new studies based on new climate projections not only concern the Rhine tributaries of the southern German Länder but also gauging stations on the main stream (Upper Rhine).

In Hesse, several projects on climate change and adjustment options are going on, summarized under the acronym INKLIM-A. Within these projects, regional climate projections are further developed and used. Extreme values of the 20th and 21st century are investigated into.

Under the overall control of the CIPMS and with the participation of Rhineland-Palatinate, the Saarland, Luxemburg and France the INTERREG-IV-A project FLOW MS is being carried through on the Moselle. Among others, the aim is to assess eventual consequences of climate change for floods and low water flow in the Moselle and Saar catchment and to develop adjustment strategies.

The German Land Northrhine-Westphalia is financing a bundle of 40 projects on climate change. Here, too, several new findings concerning regional climate modelling, the analysis of effects on hydrological regime and hydrological extreme values and adjustment options are expected.

Work on the KLIWAS will equally continue. Based on experience so far, models and procedures will be improved, databases and analyses will be complemented in order to analyse hydrological, hydraulic and morphological aspects of climate change along the Rhine and other rivers.

In the Netherlands, the research programme "Kennis voor Klimaat" (knowledge on climate) including different projects concentrating on the Rhine is going on. It is a joint project of research institutions and universities concentrating on the effects of climate change and adjustment strategies on the Dutch society.

The Delta programme is a national, Dutch programme f national authorities, provinces, municipalities and water boards cooperating with social organisations. The target is to protect the Netherlands against floods and to dispose of sufficient drinking water for the generations to come.

[7] The group received its mandate on 27 April 2010. The Land offices of Baden-Württemberg, Rhineland-Palatinate, Hesse and Northrhine-Westphalia as well as the BfG participate in the working group.

Outlook 2012 +

None of the above mentioned studies may claim completeness. Therefore, the studies and this final report include an outlook on further need for research and development. Thus, a continued revision and improvement of the present state of knowledge may be expected for the years to come.

At the time being, the next, fifth Assessment Report of the Intergovernmental Panel on Climate Change is being prepared and will be published in 2013/2014. Calculations based on a new generation of global climate models and regionalisation procedures are carried out within the projects CMIP5 and CORDEX. The derived simulations, e.g. of the hydrological regime in the Rhine catchment will be revised accordingly. Among others, this is planned within KLIWAS.

Updated climate scenarios will presumably be presented by KNMI in 2013.

Progress is also expected in the fields of observational data, the understanding of the hydrological system and hydrological modelling. The plausibilisation of runoff data and the impact of the snow and glacier runoff on the discharge of the Rhine are further issues of new CHR projects[8].

A new cross border meteorological data product, "HYRAS", is being created in cooperation between the BfG and the DWD and will be made available as new reference database. A new uniform database will make studies from different regions of the Rhine catchment more comparable than what is the case today.

In Switzerland, it is expected that the final report of the bundle of projects CCHydro (under the control of the BAFU) will be available in 2012. In this connection, climate scenarios existing in Switzerland will be updated and consequences for the hydrological regime, low water periods, floods and the glacial regime will be assessed (Volken, 2010). Furthermore, a pilot study on 'Water Temperatures' will be drafted.

On 1 January 2010 the national research programme "Sustainable Water Use" (NFP 61) was started in Switzerland. It will last through 2013 and develops scientific bases and methods for a sustainable use of water resources which are increasingly under pressure. The „NFP 61" investigates into the effects of climate and social changes on this resource and identifies risks and future conflicts in connection with its use (e.g. Leibundgut, 2010). It develops strategies for sustainable, integrated water resource management. As early as 2009, the Swiss government had commissioned the administration to draft a National Climate Adjustment Strategy by the end of 2011. Since the end of 2010, a draft of the sectored partial strategies, among others for water management and natural risks are available, the coordinated global strategies will be available one year later. In addition, a parliamentary initiative requires a "National Water Strategy" beyond climate change by 2012. In this connection, the legal basis will be checked in order to grant for implementation.

3.3 Assessment of the present state of knowledge

Literature and knowledge for deriving information relevant for decision-making from the variety of data on climate change and its consequences are heterogeneous. This is true of the period covered by the monitoring data (1901-2010) and, to a greater extent, for the period covered by the projection (2001-2100). The studies differ with respect to the areas under investigation, the periods under investigation, the data basis and the methods. Furthermore, objectives and thus analysis and interpretation also differ.

[8] CHR project „HYMOG" (Bases for Hydrological Modelling in the Rhine Basin) and „Runoff Shares from Melting Snow and Glaciers in the Rhine and its Tributaries against the Background of Climate Change"

In spite of this heterogeneous character of the studies, uniform tendencies and trends do sometimes stand out (s. appendix A). Due to the variety of methods it is however not possible to make detailed quantitative comparisons or to regionally differentiate between changes.

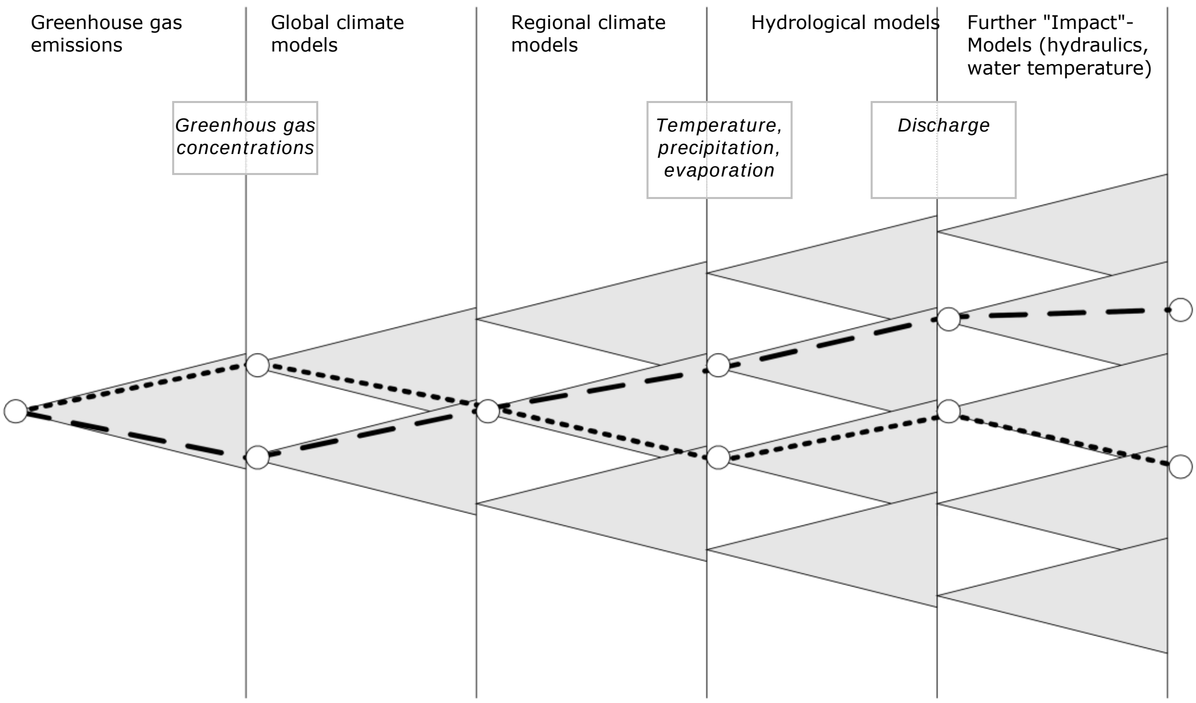

Figure 2: Scheme of a model chain serving to analyse the consequences of climate change with "cascade of uncertainty" resulting from the passing on of uncertainties from one link of the chain to the next (according to Viner, 2002). The broken and the dotted lines show that, due to the cascade of uncertainties, the choice of certain “pathways” leads to different results.

The common element of all studies focussing on statements on eventual future development is a so-called model chain. Taking greenhouse gas emissions (or concentrations) as a starting point, global and regional climate models are used to project the main input data for river basin models of the Rhine (or of sub-catchments) simulating runoff on this basis (fig. 2); if required, further "impact" models are linked to the chain.

Thus, as a matter of principle, methods used by the different projects for analysing the consequences of climate change are comparable. As a matter of principle, all projects are based on up-to-date data and current methods. These however present specific variations and deficits and thus occasionally differ from one another. The decision in favour of certain data and procedures thus affects the results.

This fact must be taken into account when assessing the state of knowledge and will, in the following, be explained with the help of the model chain.

<u>Emission scenarios</u>

A major uncertainty when analysing future climate development concerns the emission scenarios of climate-active gases. The future development of world economy, the world’s population and thus of emissions is not known. Scenarios used in this context are hypotheses concerning possible pathways of development which, today, seem plausible. In particular, the choice of an emission scenario affects the model result for the period beyond 2050. In the end, its probability of occurrence cannot be defined. Therefore, for the second half of the 21st century, as many emission scenarios as possible must be taken into account.

Climate monitoring and climate modelling

Considerable uncertainties remain with respect to climate monitoring and climate modelling. Gaps in the monitoring networks and measurement errors affect observation data as well as the models based on them. As far as models are concerned, uncertainties exist, which are, on the one hand, caused by our lacking understand of the system, necessary simplifications and model errors but which, on the other hand, are also brought about by chaotic climate behaviour (see Krahe et al., 2009). Uncertainties residing in the system can never be eliminated but, with the increasing number of climate simulations, it is possible to improve their assessment.

Uncertainties residing in the model among others determine the extent of the so-called „Bias" of climate models, that is, the more or less systematic deviation from simulated and observed climate data of the same period. Research is going on in this field and will continue. Today, these uncertainties still cause the differences existing between the different climate simulations. The choice of the climate model will influence the characteristic feature of the result (humid/dry, warm/cool variants).

The way uncertainties in connection with the findings of regional climate models are dealt with is a major factor distinguishing between the existing approaches to derive climate scenarios for the Rhine catchment. Three different approaches were presented within the EG KLIMA:

1. The Dutch delegation contributed with experience when developing the so-called "KNMI06 scenarios" (KNMI, 2006).

   The KNMI06 climate scenarios reduce the entire corridor of climate scenarios / climate projections which would result from the assumption of a large number of imaginable combinations of emission scenarios and global climate models to four scenarios. Uncertainties concerning two atmospheric values are covered: Different temperature developments (+ 1° resp. + 2°) and different modifications of the atmospheric circulation (considerable resp. low).

   As a matter of principle, this approach is pragmatic and positive, as a large number of global climate models is assessed (about 20) and the choice is made transparent. In general, the scope of KNMI scenarios must regularly be compared with the results of the most recent climate projections. Recent scientific development has not outdated the general scenarios for future climate change in the Netherlands presented by the KNMI in 2006. According to present findings, the four KNMI scenarios of 2006 taken as a whole describe the most probable changes in the Netherlands with the appropriate uncertainties. This is the result of an assessment of investigations of the past years, particularly taking into account the importance for climate change in our environment (Klein Tankand Lenderink, 2009).

2. The German Länder in the Rhine catchment are focussing on the „hydrological plausibility" of individual runs of climate models used as decisive criterion for their choice and future processing when modelling the hydrological regime. Model runs are considered to be plausible, which (a) reproduce today's climate with respect to structures in space and time and (b) satisfactorily reproduce the order of magnitude of the climate parameters.

   Among the model runs investigated into so far, the statistical regionalisation procedure WETTREG2003 and WETTREG 2006 and the high-resolution dynamic regionalisation procedure CCLM4.2 have fulfilled the criteria (a) and (b). The evaluation of CCLM4.8 is not yet available.

The procedure presented is transparent and comprises an intensive validation of regional climate models. In the end, the objective is to find the "best" model according to defined criteria. In this connection it must be pointed out that, so far, only regionalisation based on a global climate model conveying its individual characteristic on the results has been used (ECHAM, version 4 and 5).

3. The network partners of the RheinBlick2050 and KLIWAS projects have developed investigation elements integrating different approaches when generating regional climate and runoff scenarios. The core of the approach is a consequent multi-model approach, that is, an assessment of all available emission scenarios, of global and regional climate models. Within the assessment, different implausible simulations and those not giving comprehensive coverage of the Rhine are discarded. The remaining climate simulations are corrected taking into account their bias (meaning, they are approximated to observation data) and thus serve as a basis for runoff modelling[9].

   A positive feature of this "multi-model" approach is that the present state of knowledge of regional research on the consequences of climate change is almost completely taken into account and made available for the hydrological assessment of the consequences of climate change. It must however be pointed out that partly considerable bias-corrections are necessary in order to make the findings of the climate models applicable to river basin modelling. Bias-corrections do however not improve the models. The analysis of all effects of this bias-correction is not yet available.

Hydrological Data and Models

Hydrological data and models present further uncertainties. The consequences of the different model approaches for the simulation results for the gauging stations along the Rhine and its major tributaries must still be investigated into.

Also, it is known that human activities[10] impact the runoff pattern. Over time, this impact has increased and due to the lack of knowledge about the socio-economic development its future development cannot be predicted. While the corresponding effects could at least partly be taken into account for the past, future simulations mostly continue today's "status quo" concerning the influence of human activities. Repercussions of eventual new adjustment measures have not yet been taken into account. The possible future runoff presented in this study thus only applies under the assumption of the "status quo" scenario.

The following chapter deals with the modelling of flood extremes.

Flood extremes (HQ_T-values, flood index)

Statements on the future development of flood extremes are less reliable than those on average discharge.

When deriving values for extreme floods (HQ_T-values) numerous hydro-dynamic aspects (dike overflow, dike breaches, retention effect of the foreshores, flood retention measures, etc.) must be taken into account. This applies both to the simulated past and to future projections.

These hydrodynamic aspects were not taken into account when analysing the statements on eventual future developments presented in chapter 3. Against this background, only signals for changes between the simulated present and the simulated future may be interpreted as indicators for eventual future developments. Within the applied "model landscape" these are consistent, although absolute values may differ from reality. In this

[9] According to the state in the summer of 2010, 37 climate simulations were assessed and 20 of them were found to be useful for the runoff simulation in the Rhine catchment.
[10] Hydraulic engineering, water management, agriculture, etc.

connection, in particular extreme flood runoff may be overestimated, as the mitigating effects of dike overflow are not taken into account.

The figure (chapter 3) takes into account the difference between model and reality by not representing flood parameters as HQ_T-values but as indexes for "frequent", "moderate" and "extreme" floods.

Water temperature

Water temperature modelling for the entire Rhine only began recently. The bibliographic study (ICPR, 2009) contains first data, according to which, during the 20th century, in some sections, Rhine water temperature has increased by about 1°C to 2.5°C (see appendix A). Data density and quantity are however insufficient for constructing models comprising the entire Rhine.

4. Synthesis of results

Integrated studies leading to a consistent statement on climate change and its consequences, covering the entire Rhine and comprising regional differentiations are rare.

For changes concerning the 20th century, the following numerical values are based on the CHR-study by Belz et al. (2007), as far as the 21st century is concerned, they are based on the CHR study by Görgen et al. (2010). They only refer to the Rhine catchment until the Lobith gauging station, as, in the Netherlands, the Rhine splits into several branches. The methods applied and the findings have been coordinated by several hydrological institutions and project groups in the Rhine bordering countries.

The approach for the investigation on the future is to comprise as much information as possible within the model chain, even though this partly requires considerable corrections. Thus, a large number of up-to-date climate projections are assessed and used reflecting today's state of knowledge which is certainly not satisfactory in all parts. The IPCC (2007), the EU Guidance Document 24 (European Communities, 2009) and DAS (German federal cabinet) all recommend this multi-model approach as "good practice".

The results of past studies for sub-catchments or individual gauging stations (ICPR, 2009) may serve as comparison.

4.1 Changes observed during the 20th century

4.1.1 Data basis and representation

The following synthesis is based on the data annexed to the report issued by Belz et al. (2007) as databank. The runoff data have been verified, but no correction was made with respect to impact of anthropogenic origin in the catchment (lake management, etc.).

The data of Table 2 represent multi-annual average values of 30-year-periods in the beginning and at the end of the 20th century and signals of change between these periods[11]. The reference to 30-year-periods corresponds to the WMO conventions.

[11] Signal of change = difference between the ending and the starting value (i. e. average of the period 1971-2000 compared to 1901-1930) in per cent of the starting value.

Changes in area precipitation (SumhN), of mean water discharge (MQ) and of the lowest 7-daily mean runoff (NM7Q) per half year and of the highest mean daily runoff (MHQ) per year were assessed. Table 2 does not represent changes of air temperature, but these are mentioned in the overall view (chapter 4.1.2). MQ and NM7Q refer to hydrological half years (November to April, Mai to October), MHQ refers to hydrological years (November to October). Area precipitation refers to meteorological summer and winter (June, July, August, resp. December, January, February).

The precipitation evaluation refers to sub-catchments upstream of the gauging stations listed in table 2 (see map in appendix C). Their choice permits a separate consideration of the effects of the Alpine region (area upstream the gauging stations Basel, resp. Maxau), of the Central Upland regions (Neckar, Main, Mosel) and of the entire Rhine (upstream of Lobith).

The gauging stations chosen for the discharge analysis are also mainly located along the main stream. The choice of the gauging stations Rockenau (Neckar), Würzburg (Main) and Trier (Moselle) covers main features of the Central Upland regions (maps in Appendix C).

The colour codes indicate the trends of the changes. Blue indicates a rise, orange a fall of the parameter under consideration (table 1).

Table 1: Colour codes of the signals for change during the 20th century (see table 2).

Colour Code	**Meaning**	**Explanation**
Orange	Decreasing tendency	Readings ≤ -5 %
Grey	No tendency	Readings between -4,9 % and +4,9 %
Blue	Increasing tendency	Readings ≥ +5 %
White	No statement possible	No readings

4.1.2 Overall view of results

Table 2: Multi-annual mean area precipitation (SumhN), mean discharge (MQ), low flow (NM7Q) and flood discharge (MHQ) in the beginning (1901-1930) and at the end of the 20th century (1971-2000) and changes between these periods in per cent. Location of the gauging stations and catchments see Appendix C. Colour code see table 1 (data basis: *Belz et al., 2007).*

Parameter	Gauge	1901-1930	1971-2000	Change [%]
SumhN [mm] Meteorological summer (JJA)	Catchment until Basel	378	397	+5,1
	Catchment until Maxau	406	396	-2,4
	Neckar catchment (Rockenau)	262	259	-1,2
	Main catchment (Würzburg)	227	227	+0,2
	Moselle catchment (Cochem)	231	216	-6,5
	Catchment until Lobith	287	278	-3,1
SumhN [mm] Meteorological winter (DJF)	Catchment until Basel	301	321	+6,8
	Catchment until Maxau	248	280	+13,1
	Neckar catchment (Rockenau)	176	211	+19,9
	Main catchment (Würzburg)	161	185	+16,2
	Moselle catchment (Cochem)	224	249	+11,2
	Catchment until Lobith	210	236	+12,7

Table 2 (continued)

Parameter	**Gauge**	**1901-1930**	**1971-2000**	**Change [%]**
MQ [m^3/s] Hydrological summer half year (May-Oct)	Basel	1312	1218	-7,2
	Maxau	1460	1349	-7,6
	Worms	1559	1466	-6,0
	Kaub	1678	1642	-2,1
	Cologne	1900	1887	-0,7
	Lobith	2009	1963	-2,3
	Würzburg (Main)	72.1	76.5	+6,2
	Trier (Moselle)	161	151	-6,1
MQ [m^3/s] Hydrological winter half year (Nov-Apr)	Basel	797	910	+14,1
	Maxau	1036	1170	+12,9
	Worms	1225	1386	+13,1
	Kaub	1531	1738	+13,5
	Cologne	2149	2401	+11,7
	Lobith	2406	2580	+7,2
	Würzburg (Main)	143	150	+4,8
	Trier (Moselle)	402	418	+4,0
NM7Q [m^3/s] hydrological summer half year (May-Oct)	Basel	688	648	-5,8
	Maxau	802	747	-6,9
	Worms	870	811	-6,7
	Kaub	965	929	-3,7
	Cologne	1112	1071	-3,7
	Lobith	1253	1151	-8,1
	Würzburg (Main)	40.4	43.3	+7,4
	Trier (Moselle)	72.1	57.8	-19,9
NM7Q [m^3/s] hydrological winter half year (Nov-Apr)	Basel	451	542	+20,4
	Maxau	576	688	+19,4
	Worms	676	775	+14,6
	Kaub	798	934	+17,1
	Cologne	991	1156	+16,6
	Lobith	1168	1252	+7,2
	Würzburg (Main)	55.0	59.2	+7,8
	Trier (Moselle)	121	113	-6,7
MHQ [m^3/s] hydrological year (Nov-Okt)	Basel	2492	2734	+9,7
	Maxau	2861	3168	+10,7
	Worms	3155	3568	+13,1
	Kaub	3916	4344	+10,9
	Cologne	5924	6538	+10,4
	Lobith	6454	6642	+2,9
	Würzburg (Main)	631	583	-7,6
	Trier (Moselle)	1683	2010	+19,4

Development during the 21st century

During the 20th century and depending on the region in the Rhine catchment, temperature changes varied between +0.5°C and + 1.2°C and were thus slightly above the global average of +0.6 to +0.9°C. The rise in temperature was more distinct during the winter than during the summer and more important in low altitude (< 500 m) than in higher altitude (KLIWA, 2005; ICPR, 2009).

Precipitation during winter time has increased in the entire Rhine catchment (+ 10 to + 20%). The increase was slightly less in the Alps. Summer precipitation has hardly changed (between -5 to + 5 %).

Thus, all discharge parameters MQ and NM7Q at the gauging stations along the main stream of the Rhine tend to increase (mostly + 10 to + 15 % for MQ; + 15 to + 20 % for NM7Q). During summers, MQ and NM7Q decrease by up to 8 %. Mainly, this is an effect of rising temperatures (more evaporation) combined with stagnating precipitation and coincident reduced snow volume in the Alps.

The flood discharge (MHQ) evaluated for entire hydrological years (Nov. - Oct.) indicates an increase by about + 10 %. A more close consideration of data shows that this is not due to an increase of extreme peak flows[12] but due to frequent moderate and great floods.

At the gauging stations Würzburg and Trier the development of parameters is different, sometimes opposite and can neither be aligned with the changes in the hydro-meteorological constraints nor with the discharge pattern at other gauging stations. This is also true of the inconsistent development of some parameters of the Rhine gauging stations Cologne and Lobith and requires further investigation.

4.2 Modelled changes observed during the 21st century

4.2.1 Data basis and representation

The following synthesis is based on the results of the CHR project RheinBlick2050 (Görgen et al., 2010). The data have been established on the basis of numerous model chains (fig. 3). They are based on all regional climate simulations available by end 2009 and drafted within different European and national research projects. The simulated fields for air temperature, precipitation and global radiation[13] were checked as to their plausibility, chosen, submitted to bias correction and then used as input data for the HBV hydrological model (Eberle et al., 2005). This model was then used to generate daily discharge time series for the different gauging stations in the Rhine catchment.

Table 4 represents changes of area precipitation (SumhN), mean discharge (MQ) and the lowest 7-daily mean runoff (NM7Q) per half year. There are no representations of changes of air temperature which are mentioned in the overall view (chapter 4.2.2).

The flood parameters (MHQ and highest daily mean value of different recurrence times) presented by Görgen et al. (2010) are based on a reduced number of climate projections processed with other methods (non linear bias correction and weather generator) due to requirements of extremes statistics. The starting point is 7 climate simulation runs, while predominantly 20 simulations were used for the other parameters[14].

The findings of the analysis of extreme flood recordings are thus indicated separately (Table 5). Also, during the simulation of extreme floods, the limits of hydrological models

[12] Here: Highest mean daily runoff

[13] In individual cases also duration of sunshine

[14] 17 projections are available for the analysis of the "remote" future (2071-2100). For area precipitation in the near and remote future one projection less is considered for each case.

mentioned in chapter 3.3 are to be taken into account. The recordings indicated are indicators for the risk of "frequent", "moderate" and "extreme" floods.
The methods applied are assessed to be applicable to the gauging stations downstream the Central Upland region (downstream of Kaub) characterized by winter floods, but not to sections of the Rhine characterized by summer floods (Basel to Worms). Therefore, no statements are made concerning the latter gauges (white signature in Table 5). In this connection, for 2011, new findings are expected to result from on-going research and projects; e.g. CCHydro, KLIWA, KLIWAS.

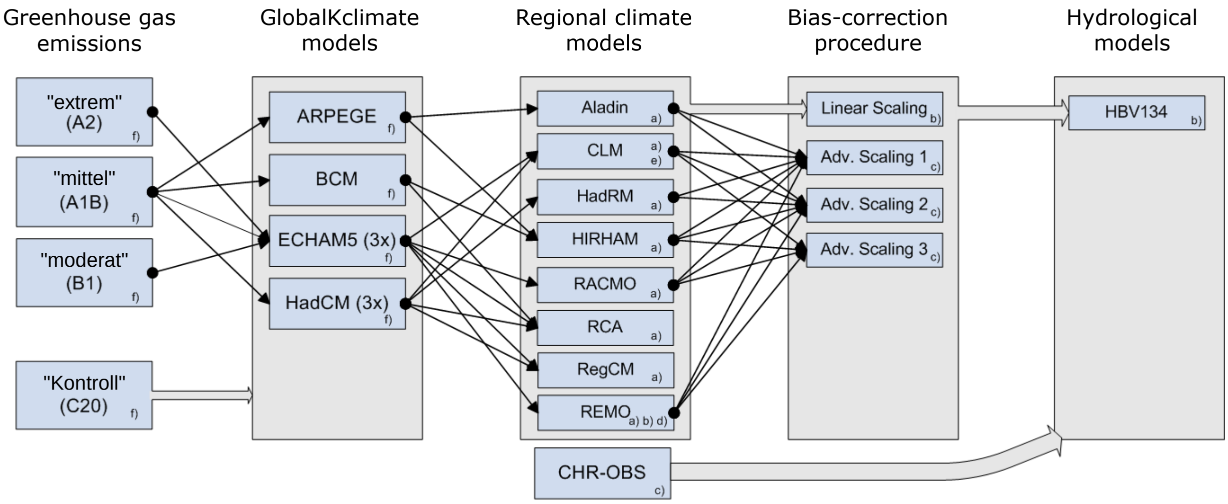

Figure 3: Survey over the coupling of models at the basis of the analysis (see scheme in Figure 2)
Grey boxes resume models treated in the same way during further processing. CHR-OBS correspond to hydro-meteorological observation data used for validating the hydrological model HBV134. The letters identify the data sources: (a) EU-ENSEMBLES, (b) BMVBS-KLIWAS, (c) KHR, (d) MPI-M-UBA, (e) BMBF-CLM, (f) CMIP3/IPCC_AR4. Source: Nilson et al. (2010, modified)**.**

The indications of Tables 4 and 5 represent signals of change[15] between 30 year periods of the simulated present (1961-1990, so-called control run), the middle (2021-2050, projection of the "near future") and the end (2071-2100, projection of the "remote future") of the 21st century. The uncertainties and variation of the different emission scenarios mentioned in paragraph 3.3 are of particular relevance for the period 2071-2100. It is not possible to make any statement on the probability of the occurrence of these emission scenarios. Evaluations only indicate the already known sensitivity of the regional climate and of Rhine runoff with respect to further increasing concentrations of atmospheric greenhouse gases.

[15] Signal of change = difference between the control value and the projected value (i. e. average of the period 1961-1990 compared to 2021-2050 resp. 2071-2100) in per cent of the control value.

Area precipitation refers to meteorological summer and winter (June, July, August, resp. December, January, February). The other indications refer to hydrological half years (May to October resp. November to April for MQ and NM7Q) or years (November to October for all flood parameters). Partly, area references of the precipitation analysis differ from what is represented in Chapter 4 (see map in Appendix C)[16]. As far as gauging stations are concerned, the Würzburg gauging station is replaced by the gauging station Raunheim further downstream. However, this gauge was not available for the historic analysis (Chapter 4.1).

The scopes of recordings do not represent the entire scope of the "model ensembles" evaluated. Instead, per gauge and parameter only the scope which was particularly often simulated by different model chains is represented (so-called scenario corridors, "inner" bandwidth, compression areas). The definition procedure for the area is explained by Görgen et al. (2010, p. 46 following). Outliers are not taken into consideration.

The procedure for flood evaluations (Table 5) will equally differ in this point. Due to distinctly less simulation runs (7 instead of 20) the complete range (maximum and minimum) is represented as corridor of scenarios.

The limits of the corridors of scenarios are rounded off to 5 per cent. Margins ≥50% are indicated by the colour code "no statement". This is also true of the flood parameters of the gauging stations Basel, Maxau and Worms (see legend Table 3).

A colour code (see Table 3) serves an additional interpretation of readings with respect to similar trends of future developments standing out. Again, the procedure for flood evaluations differs.

Table 3 Colour codes of the signals of change of the 21st century (see Table 4 and Table 5). Due to a different data basis and different methods the codes for flood evaluations (Table 5) differ from the other parameters (Table 4).

Colour Code	**Meaning**	**Explanation**
Orange	Decreasing trend	In Table 4: A great majority (~ 80 %) of projections indicates a decreasing trend. In Table 5: *The mean value of projections indicates a trend < -5%.*
Grey	No unambiguous trend	In Table 4: Approx. the same number of trends shows an increase resp. decrease In Table 5: The average reading of projections indicates trends between -5% and +5%.
Blue	Increasing trend	In Table 4: A great majority (~ 80 %) of projections indicates an increasing trend. In Table 5: *The mean value of projections indicates a trend > +5%.*
White	No statement possible	Spread of values ≥ 50% or methodical deficits

[16] The „Middle Rhine" area does not coincide with usual definitions (see map in Appendix C)

4.2.2 Overall view of results

Table 4: Changes of area precipitation (SumhN), mean discharge (MQ) and low flow (NM7Q) between 30 year periods of the simulated present (1961-1990) and the middle (2021-2050) resp. end (2071-2100) of the 21st century in per cent.

The recordings of the last period (in italics) represent the general sensitivity of precipitation and discharge in the Rhine catchment compared to a continued rise of greenhouse gas concentrations. The considerable uncertainties of emission scenarios are to be taken into account when interpreting the findings (chapter 2.3). The table represents corridors of scenarios of a group of 20 discharge projections (17 projections for the "remote future"). Location of the gauging stations, catchments and sub-catchments see Appendix C. Colour code see table 3 (data basis: Görgen et al., 2010)

Parameter	**Gauge**	**Corridors of scenarios**	
		Change in % Near future	***Change in % Remote future***
SumhN Meteorological summer (JJA)	Catchment until Basel	-10% to +5%	*-30% to -10%*
	Sub-catchment southern Upper Rhine	-10% to +5%	*-30% to -15%*
	Sub-catchment Middle Rhine /northern Upper Rhine	-10% to +10%	*-30% to -10%*
	Sub-catchment Lower Rhine	-10% to +10%	*-30% to -10%*
	Neckar catchment	-10% to +10%	*-30% to -10%*
	Main catchment	-10% to +10%	*-30% to -5%*
	Moselle catchment	-15% to +5%	*-30% to -15%*
	Catchment until Lobith	-10% to +5%	*-25% to -10%*
SumhN Meteorological winter (DJF)	Catchment until Basel	0% to +10%	*0% to +20%*
	Sub-catchment southern Upper Rhine	0% to +15%	*+5% to +25%*
	Sub-catchment Middle Rhine /northern Upper Rhine	0% to +10%	*+10% to +20%*
	Sub-catchment Lower Rhine	0% to +15%	*+5% to +20%*
	Neckar catchment	0% to +10%	*+5% to +20%*
	Main catchment	0% to +15%	*+10% to +20%*
	Moselle catchment	0% to +10%	*+5% to +20%*
	Catchment until Lobith	0% to +15%	*+5% to +20%*

Table 4 (continued)

Parameter	**Gauge**	**Corridors of scenarios**	
		Change in % Near future	***Change in % Remote future***
MQ Hydrological summer half year (May-Oct)	Basel	-10% to +5%	*-25% to -10%*
	Maxau	-10% to +5%	*-25% to -10%*
	Worms	-10% to +5%	*-25% to -10%*
	Kaub	-10% to +10%	*-25% to -10%*
	Cologne	-10% to +10%	*-25% to -10%*
	Lobith	-10% to +10%	*-25% to -10%*
	Raunheim (Main)	0% to +25%	*-20% to +10%*
	Trier (Moselle)	-5% to +10%	*-25% to -5%*
MQ Hydrological winter half year (Nov-Apr)	Basel	0% to +20%	*+5% to +25%*
	Maxau	0% to +20%	*+5% to +25%*
	Worms	0% to +20%	*+5% to +25%*
	Kaub	0% to +20%	*+5% to +25%*
	Cologne	0% to +15%	*+5% to +25%*
	Lobith	0% to +15%	*+5% to +25%*
	Raunheim (Main)	0% to +25%	*+15% to +40%*
	Trier (Moselle)	0% to +20%	*+10% to +30%*
NM7Q Hydrological summer half year (May-Oct)	Basel	-10% to +10%	*-20% to -10%*
	Maxau	-10% to +10%	*-20% to -10%*
	Worms	-10% to +10%	*-25% to -10%*
	Kaub	-10% to +10%	*-25% to -10%*
	Cologne	-10% to +10%	*-30% to -10%*
	Lobith	-10% to +10%	*-30% to -10%*
	Raunheim (Main)	0% to +20%	*-20% to 0%*
	Trier (Moselle)	-20% to +20%	*-50% to -20%*
NM7Q Hydrological winter half year (Nov-Apr)	Basel	+5% to +15%	*0% to +15%*
	Maxau	0% to +10%	*-5% to +15%*
	Worms	+5% to +15%	*-5% to +15%*
	Kaub	0% to +15%	*-5% to +15%*
	Cologne	0% to +15%	*0% to +20%*
	Lobith	0% to +15%	*-5% to +15%*
	Raunheim (Main)	+5% to +15%	*0% to +20%*
	Trier (Moselle)	-15% to +15%	*0% to +20%*

Table 5: Changes of the mean runoff (MHQ) and of discharge during "frequent", "mean" and "extreme" floods (in the order of magnitude of recurrence times 10, 100 and 1000 years) between 30 years periods of the simulated present (1961-1990) and the middle (2021-2050), resp. end (2071-2100) of the 21st century in per cent.
The recordings of the last period (in italics) represent the general sensitivity of discharge in the Rhine catchment compared to a continued rise of greenhouse gas concentrations. The considerable uncertainties of emission scenarios (here: scenario A1B) are to be taken into account when interpreting the findings (chapter 2.3). The table represents the spreads of the ensembles of 7 discharges (6 projections for the "remote future"). Colour codes see table 3. (Data basis: Görgen et al., 2010)

Index	**Gauge**	**Corridors of scenarios**	
		Near future	***Remote future***
MHQ hydrological year (Nov-Oct)	Basel	-5% to +10%	*-25% to +15%*
	Maxau	-5% to +15%	*-20% to +15%*
	Worms	-10% to +20%	*-15% to +15%*
	Kaub	-5% to +25%	*-10% to +20%*
	Cologne	0% to +20%	*-5% to +20%*
	Lobith	0% to +20%	*-5% to +20%*
	Raunheim (Main)	0% to +35%	*0% to +35%*
	Trier (Moselle)	-10% to +15%	*-10% to +20%*
Discharge during "frequent" floods	Basel	-10% to +10%	*-20% to +20%*
	Maxau	-15% to +20%	*-15% to +25%*
	Worms	-15% to +15%	*-10% to +35%*
	Kaub	-15% to +15%	*-5% to +40%*
	Cologne	-5% to +15%	*0% to +40%*
	Lobith	-5% to +15%	*0% to +35%*
	Raunheim (Main)	0% to +30%	*5% to +40%*
	Trier (Moselle)	-5% to +15%	*0% to +25%*
Discharge during "mean" floods	Basel	-20% to +10%	*-30% to +25%*
	Maxau	-10% to +15%	*-25% to +30%*
	Worms	-5% to +20%	*-25% to +35%*
	Kaub	-5% to +20%	*-10% to +25%*
	Cologne	0% to +20%	*0% to +25%*
	Lobith	0% to +20%	*0% to +25%*
	Raunheim (Main)	0% to +20%	*0% to +35%*
	Trier (Moselle)	-5% to +30%	*-5% to +25%*
Discharge during "frequent" floods	Basel	-20% to +35%	*-10% to +50%*
	Maxau	-20% to +35%	*-20% to +65%*
	Worms	-15% to +30%	*-20% to +45%*
	Kaub	-5% to +25%	*-10% to +30%*
	Cologne	-5% to +25%	*0% to +30%*
	Lobith	-5% to +20%	*-5% to +30%*
	Raunheim (Main)	-5% to +40%	*0% to +45%*
	Trier (Moselle)	-35% to +20%	*-20% to +45%*

Development until 2050

According to these projections, the development until 2050 is characterized by a continuous rise in temperature which, for the period 2021 to 2050 compared to the present (1961-1990) will amount to an average of +1 to +2°C for the entire Rhine catchment. In the south (Alps) it will tend to be greater than in the north.

As far as precipitation is concerned, no considerable changes are to be noted in summer. For the winter, moderate increases are projected which, for the entire Rhine, will vary between 0 % and + 15%. Thus, the trends of changing precipitation established for the 20th century remain.

These developments are accompanied by mostly moderate changes of the discharge pattern. Compared to the present, the mean and lower discharges (MQ and NM7Q) in summer remain almost unchanged. Increased precipitation in winter which, due to rising temperatures increasingly occurs as rainfall, will lead to a rise of the mean discharges and low flow in winter by about 10 % of the median of spreads (0 % to + 20 % and 0 % to + 15 % for MQ, resp. NM7Q). For flood discharges, downstream of the Kaub gauging station, mostly recordings of -5% to + 15%, resp. 0% to + 20% and -5% to +25% are to be registered for "frequent", "mean" and "extreme" floods. Due to deficits in methods, no statements are made for Basel, Maxau, Worms (see chapter 3.3).

Partly, the evaluations result in slightly differing findings for the tributaries under consideration. Along the Moselle, a trend towards less precipitation in summer is recorded, for the Main many projections show an increase of average runoff and low flow.

Sensitivity analysis up to 2100

Under the assumption of continued increasing atmospheric greenhouse concentrations until the end of the 21st century, changes compared to the present (1961-1990) will be obvious.

A rise in temperature of + 2°C to + 4°C (until 2100) is projected. The regionally differing tendencies – stronger rise in temperature in the south than in the north – will remain unchanged compared to the "near" future. Also, the rise in temperature is stronger in summer than in winter. Unlike the changes in precipitation stated until 2050, precipitation in the Rhine catchment will considerably fall during the summer months, mostly by -10 % and – 30 %. On this basis, falling mean runoff and low flow in summer is simulated in comparable orders of magnitude.

The increase in precipitation during the winter months projected until 2100 for the entire Rhine mostly ranges between + 5% to + 20 %. It lies above the values pointed out for the near future (0 % to 15 %). The increase of the mean runoff and of low flow in winter largely corresponds to that of area precipitation.

As far as flood parameters are concerned, many projections indicate rising levels for the gauging stations downstream of Kaub (up to + 30 %). However, some projections also indicate opposite developments, so that, partly, considerable ranges of variation result for the entire ensembles (Trier: -20% to +45%). For the reasons mentioned in chapter 3.3 no statements are made for Basel, Maxau and Worms.

5. Conclusions

This report compiles up-to-date results on the possible consequences of climate change along the Rhine. Cross-institution research and projects (KLIWA; KLIWAS; CHR projects "Discharge Regime" and "RheinBlick2050") have processed a vast amount of data with methods agreed upon across the borders for different hydrological regimes of the Rhine catchment and thus grant an integrated view of today's state of knowledge. No precise and "true" statements concerning the future may be made. Instead, the bandwidth of findings is considerable.

This particularly applies to simulated discharge extremes. Methodical deficits have been revealed with respect to floods with considerable recurrence time. This is in particular true of the Upper Rhine. At this stage, some aspects of hydrodynamics, e.g. the retention effects of dike overflow and dike breaches, the retention effect of the foreshores, and flood retention measures are not taken into account.

In several cases, the bandwidth of changes this report presents for the middle of the 21st century (2021-2050) includes values published so far (see Appendix B; ICPR, 2009; KLIWA, 2006). The bandwidth presented makes uncertainties of simulation with today's models transparent. It must however be taken into account that, in spite of the considerable complexity and number of models used, the "real" future might not be covered by this bandwidth. The present models do not take into account all elements of the climate system or of the hydrological regime. E.g. the global climate models do not include any coupled carbon cycle. This will change with the next IPCC Assessment Report (by 2013/2014).

The presented findings of the average "ensemble" (median, central estimation) are mostly more moderate than the values published so far. However, this must not be understood as an "All clear signal". More recent calculations partly result in changes in double digit per cent reaches and, if they prove to be true, they would require the "Rhine" system to show a high "adaptive capacity" in addition to that of the 20th century. Furthermore, as shown in the sensitivity analyses presented and assuming that greenhouse gas concentrations continue to rise through to the end of the 21st century, considerable changes would occur.

This report does deliberately not present any average ensemble which, as far as the median is concerned, only represents the centre of a bandwidth of simulations which must all be considered to be equally probable[17]. There are no objective reasons for its choice. Reducing the discussions on adjustment to a single „climate value" could lead to a distortion of the actual state of knowledge about possible consequences for the climate.

Decision finding for an adjustment strategy must take into account the uncertainties of projections for the future. Part of the responsibility of policy makers is to decide whether an adjustment measure is based on the upper or lower edge or on the central estimation of the ensembles.

[17] As a matter of principle, scenario-based analyses cannot name any objective probabilities. In this connection, "probabilities" are always due to subjectively chosen hypotheses and models.

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Appendix A

Changes during the 20th century (state 2009)

Table 6: Summary of changes of (hydro-)meteorological parameters in the 20th century based on heterogeneous data[18] (as quoted in ICPR, 2009). *Winter and summer are to be understood as meteorological seasons (DJF, JJA). Source: ICPR (2009)*

Parameter	**Outcome**
Precipitation, winter	Overall increase, + 16% to + 37%
Precipitation, summer	Mainly decreasing, in particular in the south
Annual precipitation	Depending on seasonal changes increase (+ 8% to + 10% or no changes)
Air temperature, winter	Strong rise, +1 to + 1.6°C
Air temperature, summer	Rise, 0.6 to 1.1 °C
Mean annual temperature	Rise, 0.5°C to 1.2 °C
Glacier and snow	Decrease (snow depth, duration of snow cover, number of days with snowfall, glacier volume, etc.)
General weather situations	Increase of humid situations in the non-alpine region. Increase of western cyclonic situations in winter (in favour of flood generation)

Table 7: Summary of changes of hydrological parameters in the 20th century based on heterogeneous data (as quoted in ICPR, 2009). *Winter and summer are to be understood as meteorological seasons (Nov-Apr, May-Dec). Source: ICPR (2009)*

Parameter	**Outcome**
Annual course	Re-distribution of runoff from summer towards winter. Thus increase of interannual variability in the pluvial regime (Central Uplands, north) and decrease during the glacial-nival regime (Alps, south).
Annual discharge	No changes in the south, increase in the north
Floods	Widespread increase of average floods in winter
Floods (rare)	No distinct or no trends
Low flow	Increase, significant (nival regime) or tendency (pluvial regime)
Water temperature	Rise

[18] If nothing else is mentioned, the changes of mean values are concerned. Within this summary it is not possible to differentiate between significant trends and insignificant tendencies. Nor is it possible to make quantitative statements for all parameters. Details are included in the ICPR compilation (2009) and the literature it quotes.

Appendix B

Changes by the mid 21st century (state 2009)

Table 8: Summary of changes of (hydro-)meteorological parameters until the mid 21st century based on heterogeneous data (as quoted in ICPR, 2009). *Winter and summer are to be understood as meteorological seasons (DJF, JJA). See footnote 17. Source: ICPR (2009)*

Parameter	**Outcome**
Precipitation, winter	Increase, + 4% to +35% depending on region and model chain
Precipitation, summer	Decrease, -4% to -20% depending on region and model chain
Annual precipitation	n.s.
Air temperature, winter	Rise, +1.1 to +2.4℃
Air temperature, summer	Rise, +1.4 to +2.8℃
Mean annual temperature	n.s.
Glacier and snow	n.s.
General weather situations	n.s.

Table 9: Summary of changes of hydrological parameters during the first half of 21st century, based on heterogeneous data (as quoted in ICPR, 2009). *Winter and summer are to be understood as meteorological seasons (Nov-Apr, May-Dec). Source: ICPR (2009)*

Parameter	**Outcome**
Annual course	Increase in winter, +14% to +40% No changes or decrease in summer, 0 to -42% Depending on region and model chain
Annual discharge	n.s.
Floods	Widespread increase of average floods in winter
Floods (rare)	Increase, +15% to +25%
Low flow	Decreasing inflow to Lake Constance and in the area of the High Rhine, apart from that also increasing inflow
Water temperature	n.s.

Appendix C

Figure 4: Survey map of the evaluation areas and gauging stations mentioned in the report. *The chosen delimitations of the regions "Sub-catchment Lower Rhine", "Sub-catchment Middle Rhine/northern Upper Rhine" and "Sub-catchment southern Upper Rhine" differ from the usual definitions (e.g. WFD areas of operation).*