
Federal Ministry of Transport and Digital Infrastructure (Hg.)

Concluding report of the BMVI - technical conclusions from the results of the KLIWAS research programme

KLIWAS Schriftenreihe

Vorgeschlagene Zitierweise/Suggested citation:
Federal Ministry of Transport and Digital Infrastructure (Hg.) (2015): Concluding report of the BMVI - technical conclusions from the results of the KLIWAS research programme. Berlin: Federal Ministry of Transport and Digital Infrastructure (KLIWAS Schriftenreihe, 57/2015). https://doi.org/10.5675/Kliwas_57/2015_Synthese_ENG.

Federal Ministry
of Transport and
Digital Infrastructure

KLIWAS
Climate · Water · Navigation

KLIWAS

Impacts of Climate Change on Waterways and Navigation in Germany

Concluding report of the BMVI

Technical conclusions from the results of the KLIWAS research programme

KLIWAS

Impacts of Climate Change on Waterways
and Navigation in Germany

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Technical conclusions from the results of
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Preface

Climate change is an important and highly topical issue and will remain so in future. Both globally and in Germany, the year 2014 was the warmest since comprehensive weather records began. Extreme weather events such as the flooding of the Elbe and Danube in June 2013, severe storm and precipitation events, and the resulting damages and disruptions mean that we must carefully observe climate trends and adapt our infrastructure and its operating processes in such a manner that our mobility and provision remain safeguarded as reliably as possible.

However, it is also important that we focus more on global warming trends and their consequences, which might not be characterised by dramatically tangible events, but which are nevertheless constant. In this context, it is imperative that we not only increase our efforts to reduce greenhouse gas emissions, but also take suitable measures to adapt to unavoidable impacts and to fill the knowledge gaps that exist. The EU strategy on Adaptation to Climate Change, which was passed in April 2013, calls for this, as do the German Strategy for Adaptation to Climate Change (DAS, 2008) and the related Action Plan of the Federal Government (APA, 2011), which the government will continue until the end of 2015. The departmental research institutes of the BMVI, which have national competencies and responsibilities with regard to climate, weather and water, have a special role here.

In the light of the fact that impacts of climate change on maritime, coastal and inland waters, which can influence navigation and waterways, are already apparent, the BMVI took the timely decision in 2008 to commission its research institutes, the German Meteorological Service (DWD), the Federal Institute of Hydrology (BfG), the Federal Maritime and Hydrographic Agency (BSH) and the Federal Waterways Engineering and Research Institute (BAW), to conduct the KLIWAS research programme "Impacts of Climate Change on Waterways and Navigation in Germany" (2009–2013). In cooperation with numerous renowned scientific institutions both nationally and internationally, and an engaged Scientific Advisory Board, KLIWAS has embarked on an exciting path that has been met with great interest and recognition. The involvement of the German Federal Waterways and Shipping Administration and other interest groups connected with the waterways ensured the necessary practical orientation. Since 2009 valuable scientific findings and methods have been discovered, which flow successively into the operative action on the waterways and guarantee qualified advice on policy. For this I wish to express my gratitude to all concerned.

I am delighted to be able to present you a summarising final report by KLIWAS, which illustrates clearly the scientific and application-oriented contribution made by KLIWAS to the BMVI business unit and beyond. KLIWAS thus also demonstrates how the transfer of complex interdisciplinary research in a network of departmental research institutes and experts can succeed in its practical implementation. The KLIWAS model must now be developed further so as to address urgent problems and the remaining unanswered questions.

State Secretary Michael Odenwald
Federal Ministry of Transport
and Digital Infrastructure

As shown clearly by the 5th Report by the IPCC, climate change demands political action. In order to restrict global warming to a maximum of 2 °C above pre-industrial levels, the report recommends strengthening the precautionary measures against climate change. At the same time it stresses the necessity to expedite adaptation to the consequences of climate change. At an international level – and also in Germany – the reduction of greenhouse gas emissions and measures for adapting to climate change are seen as complementary strategies for minimising the causes and managing the consequences of climate change.

Adaptation to climate change is a topic that is also gaining significance nationally. By presenting the German Strategy for Adaptation to Climate Change (DAS, 2008) and the Adaptation Action Plan (APA, 2011), as well as announcing the progress report and the continued action plan, the federal government has already shown clearly that it considers political measures to be necessary in the area of adaptation to the impacts of climate change. Adaptation is a prevention policy and thus corresponds with the fundamental principle of German environmental policy.

The results of climate change will affect all areas of life, including our environment and our economy – differentiated in each case in terms of space, time and intensity. In contrast to climate protection, which has clear objectives to minimise emissions, adaptation targets cannot be prescribed across all areas of activity. Instead, we must ensure that the existing political objectives can be achieved in the various areas of activity, also in the face of climate change. This requires defining the requirements for action in each field on the basis of scientific research.

KLIWAS, which was initiated in March 2009, is a comprehensive research programme of the BMVI that analyses the current and future situation of navigable waters and which aims to safeguard the future of inland and coastal waters as a mode of transport, also under the conditions of climate change. The research project has provided, among other things, improved climate projections as well as functional and model chains, which can be used for the further development of the DAS. In addition, of course, the ecological questions addressed by the project are also of particular interest to the BMUB. For example, the KLIWAS research findings were integrated into studies by the International Commissions for the Protection of the Rhine (ICPR) and for the Protection of the Danube (ICPDR) on the subject of the impacts of climate change and adaptation thereto.

However, the special feature of the research programme is its holistic and interdisciplinary approach. KLIWAS has taken a pioneering role here in the field of adaptation research and can act as a role model for agents of other areas of activity. Furthermore, KLIWAS is also an example of the performance capability of the departmental research institutes and of the potential that exists in the coordinated cooperation of these highly competent establishments, which must continue to be activated and utilised.

Dr. Helge Wendenburg
Head of the Directorate for
Water Management and Resource
Protection

Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety

KLIWAS has enabled a cross-disciplinary and scientifically effective cooperation between four departmental research institutes of the BMVI, relating to all areas of the climate change process. The synergy thus created between those involved in the KLIWAS programme – in all, more than one hundred co-operative agreements – is worth highlighting, as it has created a fundamentally new contribution to the stochastically-based assessment of climatic consequences. The Scientific Advisory Board firmly believes that such a research programme creates the necessary basis for decision-making on the planning and realisation of infrastructural projects, especially in terms of the preservation and further development of all interdependencies in the natural biospheres, living spaces and economic areas of our country.

Our work was concerned with actively promoting the efficient interaction between all participating projects with regard to the entire structure and over the whole period of the programme. It also required looking beyond the specific structural and specialist boundaries of the institutions. The discussions with the researchers on the procedures and scientific approaches were always fruitful for all parties. The recommendations of the Scientific Advisory Board were well received and contributed to the continually positive progress of the research programme.

Particularly close attention was paid to the methodical, procedural and scientific bases that were employed in each case, in order to be able to judge the findings that were reached and to modify, where necessary, the approach followed. It was very important to us not only to address the technical and scientific requirements, but also to include the natural conditions and environmental concerns. The numerous modelling instruments used and the results they produced were converted into a multi-model approach by the project participants using a structural matrix, and the data used in the model chain was recorded uniformly. They also illustrate the interdisciplinary network.

KLIWAS enjoys a unique position in Europe due to its high degree of networking and its thorough penetration of the object of research. The programme is an excellent example of how the political sphere can be provided with substantial scientific advice by means of the interaction of departmental research and the basic research conducted by universities, major research facilities and private scientific service providers, most of which was financed by the BMBF and the DFG.

We recommend that the departmental research institutes continue to work together on designing an integrated scenario. By these means, the BMVI will receive the best possible foundation for its decisions on the ecological and economic adaptation of transport infrastructure in Germany.

Franz Nestmann

Professor Dr.-Ing. Franz Nestmann
Karlsruhe Institute of Technology
(KIT), Institute for Water and River
Basin Management

Chairman of the Scientific Advisory
Board

Extreme weather events, rising sea levels and flooding have a noticeable impact on the water systems in Germany and thus on navigation and waterways. Climate change is presenting new challenges to us in the Federal Waterways and Shipping Administration. We are meeting these challenges with the results of the KLIWAS research programme, in order to be able to maintain a reliable and "climate-proof" transport infrastructure in the future.

KLIWAS is a success for the waterways and navigation in Germany! Essential scientific foundations were created in order to specifically counteract climate change and its consequences.

The Waterways and Shipping Administration supported KLIWAS actively from the outset. We now have the necessary "tools" to be able to plan the operation, maintenance and expansion of the federal waterways in a timely and forward-looking manner.

Accordingly, in the Federal Waterways and Shipping Agency we have established the department for "Environment, Civil Engineering, Waterborne Tourism", in which the subject of climate change is firmly anchored. With the help of the new findings by KLIWAS we can now develop early adaptation strategies.

With the participation of numerous scientific institutions, and with its publications and status conferences, KLIWAS compiles facts and figures and thus makes a decisive contribution to transparency.

This places us in a position to harmonise the new requirements demanded of waterways and navigation by the economy and ecology. That is necessary; after all, a functioning network of waterways, right into the metropolises, is indispensable for the German economy.

In all, more than 500 million tons of cargo are transported annually on the federal waterways, both inland and maritime. The economic benefits are therefore obvious: Germany's waterways relieve the pressure on overused motorways and the strained railway network, and help to manage the increase in transport volume in an environmentally friendly manner.

However the 7,300 kilometres of inland waterways and 23,000 km² of marine waterways in Germany are not only transport routes, but also a basis of life for people and nature.

With the findings gleaned by KLIWAS we will be able to take responsible and promising measures for our waterways, which will actively counteract negative impacts of climate change for navigation.

The scientists and all those involved in the KLIWAS research programme have done a good job.

Thanks to KLIWAS we are well prepared for the future!

Dr. Hans-Heinrich Witte
President of the Federal Waterways
and Shipping Agency

Introduction

Background

In September 2008 the then Federal Ministry of Transport, Building and Urban Development (BMVBS) commissioned its four departmental research institutes, the Federal Institute of Hydrology (BfG), the German Meteorological Service (DWD), the Federal Waterways Engineering and Research Institute (BAW) and the Federal Maritime and Hydrographic Agency (BSH) to conduct the research programme entitled "KLIWAS – Impacts of Climate Change on Waterways and Navigation in Germany" from 2009 to 2013. KLIWAS thus became the first and most important component of the German Strategy for Adaptation to Climate Change (DAS), which took effect in 2008, and for the German Action Plan for Adaptation (APA, 2011).

The catalyst for these research activities was the need to obtain robust scientific evidence of the impacts of climate change on the river systems in Germany and thereby on waterborne transport, in order to be able to take timely precautionary measures that will safeguard the reliability of this mode of transport. After the flooding on the Elbe in 2002 and the extreme low water phases in the summer of 2003, the question that arose in the public sphere, the media and those industries on the Rhine that depend on navigation was whether the reliability of the waterways as a means of transport in Germany will continue to exist in the future.

The following questions were among those that contributed to the formulation of the KLIWAS remit:

- How will the navigability of inland waterways be affected by changes in discharge regimes?

- What impact will these changes have on cargo capacity and transport costs?

- What impact will climate-induced physical changes have on maritime shipping, coasts and marine use?

- Will the functionality of the entrances to German ports be compromised as a result of more frequent storms and storm surges?

- Other questions concern the dynamics of sediment in marine and inland waters. Will pollutants be dispersed differently? Will it be necessary to adapt dredging strategies and maintenance concepts? Will it be necessary to modify river engineering concepts in the estuaries?

- To what extent are ecological assets, vegetation and fauna in and along waterways affected? How can these effects be reversed?

- What will the erosion on banks, revetments, underwater slopes and in the forelands be like in the future?

- Are there likely to be greater pressures on quays, locks or flood barrages

- Will there be any changes to the pressures induced by sea state on navigational aids, seagoing vessels, offshore structures, coastal structures, coastal protection structures, harbour facilities or in-river structures?

- Which adaptation measures can be considered?

The resources available were concentrated on the river basins of the Rhine, Elbe, Danube and coastal waters (North Sea), with different thematic focus areas.

Concept and structure of KLIWAS

With their national mandates and their statutory remit on climate, weather and water, the BMVI departmental research institutes have leading competences of cross-departmental significance. In the light of the strongly growing need to be in a position to evaluate the developments and impacts of climate change in a scientifically demonstrable manner with regard to shipping and waterways as a mode of transport, the BMVI decided in 2006 to integrate its research institutes, which would then develop a joint proposal to address this complex task. The different competences and disciplines of the research institutes allowed a comprehensive observation of an improved quality, using advanced methods. The KLIWAS research programme was launched by a survey entitled "Navigation and Waterways in Germany – Meeting the Challenges of Climate Change" (2007) and an initial pilot project for the Rhine (2007–2008) under the lead management of the Federal Institute of Hydrology. From the outset, the approach was directed towards the specific questions affecting navigational waterways as a mode of transport. This utilised the special prerequisites of the BMVI business unit, which combines departmental research with direct, operationally active administration, in order to adequately address the problem and enhance synergies. The findings achieved by these means enabled the KLIWAS research programme to refine its methodological approach, and it was set in motion in 2009.

An essential precondition for the success of KLIWAS was that the departmental research institutes involved were combined into one network. The existing competencies were reinforced by additional scientific personnel who were engaged for the duration of the programme. This meant that the knowledge gained could be developed directly in the constant, practice-related processing cycle of the research institutes with the Federal Waterways and Shipping Administration. For this reason, the coordination of the network programme was placed in the hands of the BfG, one of the specialist advisory authorities of the WSV. This ensured, on one hand, an immediate basic understanding of the practical needs and internal processes, which is not the case to the same

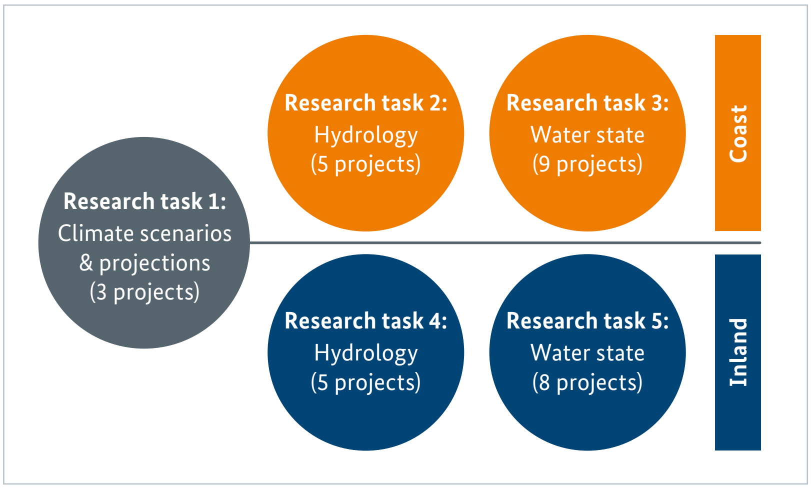

Fig.: Content structure of the programme

extent with external project sponsors, even after a long period of time. On the other hand, it enabled the internal connections between the specialist authorities within the business unit to be organised and intensified in a more targeted manner.

The research programme was divided into a total of 5 thematic research tasks, to which a total of 30 individual projects were assigned (see: Fig.: Content structure of the programme). Control of the 5 research tasks, and of the individual projects, was assumed by the research institutes of the BMVI, depending on thematic focus. A coordination unit was established in the BfG for the overall coordination of the research programme. In addition, a leading authority representative was named from each research institute, so as to provide support and guidance where necessary.

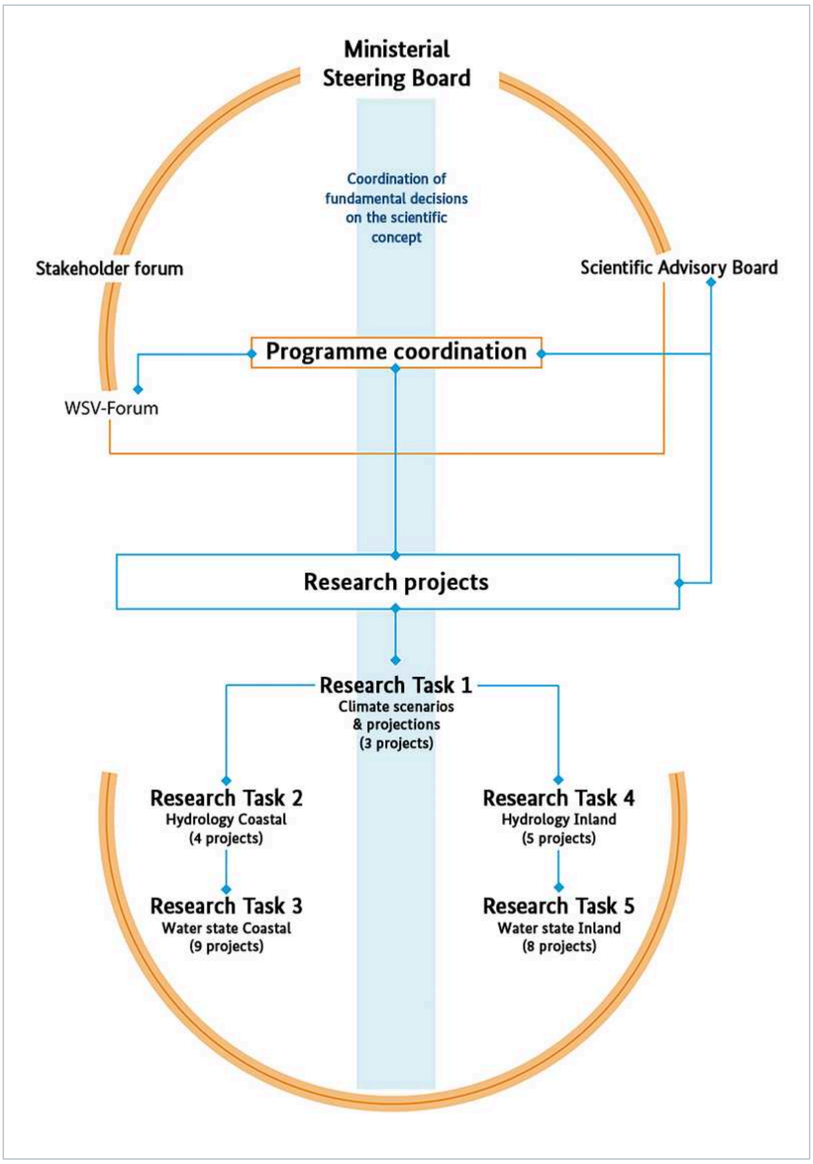

Fig.: Graph of the overall organisational structure

In order to adequately address the scientific challenge, the necessary expertise of the national and international research communities was also integrated. This was done in two ways. First, a European Scientific Advisory Board was established, composed of ten recognised academics covering the varying thematic fields, who monitored progress critically and constructively (see chapter "Recommendations of the Scientific Advisory Board"). Second, and independently of this, contracts were awarded to scientific institutes in a total of 100 co-operative agreements, in order to support the 30 projects in a targeted manner (see: Fig.: Cooperative agreements).

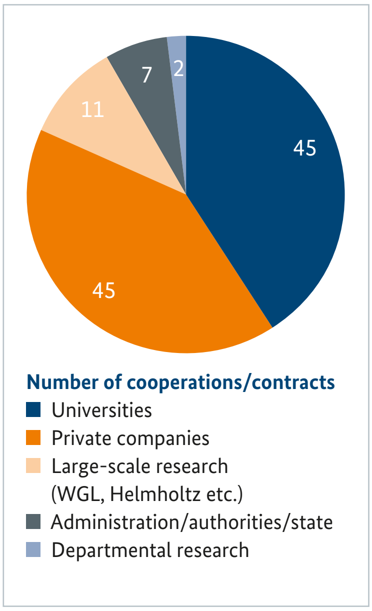

Fig.: Cooperative agreements

A ministerial steering board was established in the BMVI, under the leadership of the Waterways and Shipping Directorate-General, which included the specialists responsible for the research institutes as well as further specialists from other departments, who coordinated the topics (e.g. research officer of the BMVI). In addition, the Federal Ministry of the Environment, Building and Nuclear Safety (BMUB) was also represented in the ministerial steering board, as it funded one of the 30 projects and also, as the leading department, contributed to the drafting of the German Strategy for Adaptation to Climate Change (DAS), ensuring the progress of the programme with synergies for the DAS. The ministerial steering board met a total of 14 times, was informed regularly by the KLIWAS coordination unit, and intervened where necessary.

Two structures were established to allow the ordered participation of operative users (the Federal Waterways and Shipping Administration, commercial shipping, associations, and other interest groups connected with the waterways).

Firstly, a forum was created comprising employees of the WSV from the different regions, divided into a group of officials with executive responsibility and a group of administrators. While the officials were essentially involved in the landmark decisions taken by the aforementioned panels, the administrators maintained contact, where required, with the persons working on the KLIWAS projects. They also supported the scientists in larger regional working conferences and directed attention towards the practical needs.

Secondly, during the KLIWAS period the BMVI ministerial steering board invited important users and interest groups connected with the waterways to two all-day conferences (so-called stakeholder workshops) in the BMVI on 08.09.2010 and 18.06.2013, with representatives of the WSV and the research network, to discuss intermediary results and to gain impulses for progress.

In order to guarantee an effective and successful progress of the programme with the many participating committees, an internal communication concept was formed at the beginning, which created a basic common understanding of the objectives, the cooperation and the external presentation of the programme. This was completed on the understanding that the BMVI, as client, would accept the results with an open mind.

A plenary session was conducted each year, five times in all, for the purpose of internal communication and coordination by the research network, the Scientific Advisory Board and the BMVI, at which the intermediary results were discussed and then presented in writing to the BMVI and the WSV. On this basis, the BMVI conducted a total of three very well-attended KLIWAS status conferences at the BMVI, with all of the involved parties (18/19.03.2009; 25/26.10.2011; 12/13.11.2013) and presented the progress to the specialist public and politicians. BMVI publications were issued for the KLIWAS status conferences and stakeholder workshops. Furthermore, an exhibition stand and information brochures on KLIWAS were created and used for publicity purposes. The KLIWAS scientists were encouraged to present their findings at numerous national and international events. By these means, important international, European and national initiatives, strategies and programmes (e.g. KLIMZUG, KLIMA-MORO) for the adaptation to climate change were enhanced methodically and by the results attained, and an awareness was created for the fact that there is not just "one" correct climate projection, but rather a scientifically secure range to help decision-makers.

It should also be mentioned that the public appearance and presentation of members of the various different research establishments occurred under one KLIWAS layout, which reinforced awareness of the internal network and made a positive external impression.

We can establish that all those involved not only achieved great progress in terms of the subject matter, but they also gained organisational experience. The calculated overall budget for temporary scientists at the BMVI research institutes and costs for material and awarding contracts was almost 18 million Euros. Quite apart from the demanding nature of the subject under research, a scientific programme of this size and dynamic also presents organisational challenges, which were mastered admirably.

KLIWAS utilised all of the possibilities for interaction between all levels of a federal administration in one area of business (ministry, upper, intermediate and lower authorities). In an exemplary and successful manner, applied departmental research on complex topics in a network of experts with a direct practical application was realised and implemented. This experience with KLIWAS must be utilised and developed even further in a targeted manner.

"Due to the network, KLIWAS enabled an increase in knowledge that would not have been possible for individual working groups. Now that we know the range of future changes, we as federal scientific institutes are now able to act together in one direction with appropriate tools and prudence in crucial aspects of life. Thus a good foundation has been created with which to confront future matters in an economically sound and sustainable manner."

Dipl.-Ing. Michael Behrendt
Director and Professor of the Federal Institute of Hydrology

"KLIWAS has made a valuable contribution to implementing the German Adaptation Strategy and has demonstrated the added value of a coordinated, inter-agency approach. Moreover, KLIWAS has also provided an important foundation for other areas of action."

Professor Dr. Gerhard Adrian
Head of the German Meteorological Service

"Our research results show that the expected climate-related changes can be counteracted effectively by means of adaptation measures in waterways engineering. This safeguards economic shipping on inland and coastal waterways in the long term. With our methodical and procedural instruments we can achieve high-quality results and are therefore very well equipped to meet future developments and challenges."

Professor Dr.-Ing. Christoph Heinzelmann
Head of the Federal Waterways Engineering and Research Institute

"The KLIWAS research has made an important contribution in terms of evaluating future climate-related risks and potential for shipping, harbours and the economic use of the North Sea. This must now be expanded further and put into operation for adaptation measures."

Monika Breuch-Moritz
President of the German Federal Maritime and Hydrographic Agency

"The KLIWAS findings provide policy makers with a much improved scientific basis on which to make decisions relating to the large navigable waterways. In terms of our future investment decisions, the completion of necessary tasks and the securing of public services in relation to our waterways, the results will form an important foundation for understanding the impacts of climate change in an appropriate and timely manner. It is important that we continue to increase this level of specialist knowledge and expand it purposefully."

Reinhard Klingen
Director-General Waterways and Shipping at the BMVI

Concept of this final report

This document provides an overview of the development and structure of the KLIWAS research programme and its essential results. In the following chapters, the BMVI expresses and positions itself as the client, the WSV as user, and the Scientific Advisory Board as an active supporter. In the process, reference is made to the synthesis report presented by the KLIWAS research network, which summarises the individual published reports on all 30 KLIWAS projects and is included as an appendix, as well as to the project reports themselves. The document concludes with a brief résumé and a perspective by the BMVI, which details how the adaptation to climate change should be seen as a challenge and developed further as a new permanent task based on the foundations of KLIWAS.

Technical conclusions of the BMVI

Introduction

The resources available for KLIWAS were used by the BMVI and the responsible KLIWAS officials to concentrate on the inland areas of the Rhine, Elbe and Danube, and in coastal areas primarily on the North Sea region.

In the following chapters the BMVI refers to the results of the KLIWAS research community, which the BMVI received as the client, and which are contained in the appendix as a synthesis report. First the most important statements from the point of view of the BMVI are highlighted, before conclusions are provided.

Rhine

KLIWAS Results Rhine

Climate and hydrology

Near future (2021–2050)

In the Rhine river basin, no clear trends are discernible for precipitation in the near future (2021–2050).

Air temperatures may rise by up to 2.5 °C.

No clear change is shown with regard to the mean discharges (MQ) in the hydrological summer, while an increase is shown for the hydrological winter.

With regard to the annual hydrological balance, until the middle of the century the low water discharges (NM7Q) show an increasing tendency wherever influences from the snow regime currently prevail. Outside the area of influence of the snow regime (e.g. at the gauges of the low mountain-range rivers Neckar and Moselle), there is a neutral picture. In the upper discharge area (HM5Q), practically all of the projections in the sphere of the low mountain range show increasing tendencies of up to +20% as a result of increasing winter precipitation, while no clear changes can be discerned at the gauges in the vicinity of the Alps (cf. Basel and Maxau, in the distant future also Worms).

With regard to the number of days of lower deviation at low water levels, more detailed analyses of projections on changes to shipping-relevant parameters show a regionally differentiated picture from a shipping viewpoint in the near future, with either an indifferent or a positive signal (i.e. a lower frequency of low water conditions).

At high water levels (where critical thresholds are exceeded) a preponderant increase in exceedance days is shown for the near future.

Simulations of the costs structure of inland shipping on the Rhine, which build on the range of projections, show changes in transport costs of −5% to +5% in the near future, depending on the scenario.

Distant future (2071–2100)

In the distant future (2071–2100), a decreasing summer precipitation trend and an increasing winter precipitation trend are discernible for the Rhine river basin.

Air temperatures will continue to rise.

The mean discharges and baseflows may decrease in the summer months, with temporary impacts on navigation and logistics along some stretches. In winter the trends towards increasing mean discharges will continue.

The trends in the upper discharge levels correspond with the tendency towards a higher number of days of exceedance, as described for the near future.

Simulations of the cost structure for inland shipping on the Rhine, based upon these results, show additional transport costs of up to 10% in the distant future, depending on the scenario.

Near and distant future

In both the near and distant future, low water events will be more relevant to inland navigation on the Rhine than flood events, because of their relatively long duration.

Sediment balance and river bed trends

Projections of the sediment balance and river bed trends in the Rhine show that, at least in the near future, the choice of maintenance strategy will have a far greater influence on the bed elevation development and on the sediment balance than changes resulting from a climate-related change to the discharge characteristics of the river catchment area.

Conclusions for the Rhine

The projected climate and discharge changes will not jeopardise the exceptional importance of the Rhine for transport, either in the near or in the distant future. By observance and further development of the findings from the KLIWAS results, the necessary transport services can also be provided reliably into the future. This ensures planning security for investments in shipping, industry and trade on the Rhine with regard to the reliability of the waterways in the coming decades.

It is clear from these KLIWAS results that there is sufficient time to become attuned in an informed and appropriate manner to possible longer-term changed discharge conditions on the Rhine. For this purpose, the recording and assessment of the discharge conditions must be continued, and the projections must be updated whenever new climatological data is received. This is especially true with regard to a possible increase in low water situations in summer in the distant future, and the corresponding planning for the further optimisation of shipping conditions on the Rhine. Additional methodological steps are necessary to evaluate particularly rare, respectively extreme flooding events under changed climatic framework conditions.

The methodology developed by KLIWAS – to date, for the Rhine only – of the impact on transport costs and fleet structure, and it results, are helpful for the future planning of the shipping-related industry and should be further developed and transferred to other waterways.

Together with the relevant countries and neighbouring states, rigid measures for the examination, securing and removal of polluted sediments in the riverbeds (especially along the Upper Rhine, so-called secondary sources) will continue to be pursued, in order to enable a more economical maintenance and avoid jeopardising the attainment of environmental quality goals (EU-WFD und ICPR) for the downstream free-flowing river area.

Elbe

KLIWAS Results Elbe

Climate and hydrology

Near future (2021–2050)

In the river basin of the Elbe, no clear trends are discernible for changes to precipitation in the near future (2021–2050).

Air temperatures may rise by up to +2 °C in summer and +3 °C in winter.

The projections for mean discharges (MQ) tend towards slightly drier conditions in summer in the near future (2021–2050) compared to the reference period, with values between −15 % and +5 %, while the values for the hydrological winter, at −10 % to +10 % are indifferent, as in the annual average.

In terms of low water discharges (NM7Q) relating to one water balance year, an indifferent picture is produced for the Elbe catchment area in the near future, with maximum limits to the range of climate signal of −10 % to +20 %, depending on the gauge. More detailed analyses of projections of changes to shipping-relevant parameters in the low water levels (failure to reach critical thresholds) accordingly show an indifferent signal for the near future.

Distant future (2071–2100)

For the distant future (2071–2100) there are clearer trends for precipitation in the river basin of the Elbe. The projections of precipitation show a decrease in summer and an increase in winter for this period.

Air temperatures will continue to rise.

The projections of the mean discharge (MQ) of the whole year, and even more so in summer, show a predominantly decreasing tendency for the Elbe region in the distant future (2071–2100) compared to the reference period, with values from −30 % to +10 %. For the winter there continues to be no clear direction of the ensemble in the distant future, however the range of possible conditions will increase to values between −30 % and +15 %.

These limits for low water discharges will lay between −35 % and +10 % in the distant future. More detailed analyses of projections of changes to shipping-relevant parameters in the low water levels (failure to reach critical thresholds) accordingly show, for the distant future under a considerably enlarged range of results, a clear increase in some cases of the number of days on which critical thresholds are not reached.

Near and distant future

Projections of high water discharges in the Elbe area (upper discharge levels, HM5Q) show an indifferent picture for both future periods. It can be seen that even the choice of reference period can considerably influence the change signals identified for the Elbe region, due to multi-decade variability. Added to this are the impacts of changed water management in the catchment area. Additional methodological steps are necessary to determine the change of impacts in terms of flooding.

As with the Rhine, it is also true of the Elbe that low water situations are more relevant to inland navigation than high water events, due to their relatively long duration.

Sediment balance and riverbed development

The projections of sediment loads show a significant correlation with the discharge projections, however no clear trend is discernible for the distant future.

Conclusions for the Elbe

When evaluating the results it should be considered that the water balance in the Elbe catchment area is already strained under current climate conditions, i.e. in many regions potential evaporation exceeds precipitation. The water management sector has reacted to this increasingly since the 1960s with the construction of dams and water diversion systems. The Elbe region thus has the highest density of dams of all European rivers. The influences of dam control and water management in open-cast lignite mining on the runoff rates in the Elbe river basin complicate the analyses of climate-related changes. KLIWAS has created important foundations for the analysis and modelling of the hydrological regime in the Elbe river basin, and has developed new findings. It should be noted that the influences of water management are greater than the signals of climate change.

It is clear from these KLIWAS findings that particular attention must be paid to the increased climatic influences in the distant future.

For the near future, these findings anticipate that no investment decisions must be made based directly on climate change in order to preserve the Elbe as a navigation route. Nevertheless, in particular the development of summer discharge conditions and high water discharges must be followed with close attention, also in the near future. Additional methodological steps are necessary to evaluate particularly rare, respectively extreme flooding events under changed climatic framework conditions. The recording and assessment of the discharge conditions must be continued, and the projections must be updated whenever new climatological data is received.

The BMVI will continue the process begun in the framework of the overall concept for the Elbe, together with officials from the federal government, the states and the municipalities, as well as with the major interest groups, in order to develop a joint and comprehensive system awareness of the Elbe based on the findings of KLIWAS and, building on this, to coordinate and define scenarios and measures that will guarantee the sustainable development of the Elbe and its uses (including shipping).

Danube

KLIWAS Results Danube

Climate and hydrology

Near future (2021–2050)

No clear trends are discernible for precipitation in the Danube area in the near future (2021–2050). Air temperatures may rise by up to +2.5 °C.

In terms of mean discharges, predominantly inconsistent changes are projected for the hydrological winter in the near future (2021–2050), with the exception of the Inn and the Danube downstream from the mouth of the Inn, where increasing discharges are projected. In summer a general tendency towards decreasing discharges can be discerned.

For low water discharges, the projections at the gauges of the Danube show predominantly a tendency towards a decrease in discharges.

Distant future (2071–2100)

In the distant future (2071–2100) precipitation in the Danube region could decrease in summer, while the projections show no clear trends for the winter.

Air temperatures will continue to rise.

The projections of the hydrological parameters in the Danube area for the distant future (2071–2100) show similar tendencies to those described for the near future.

Conclusions for the Danube

These KLIWAS findings lead us to expect that the usability of the Danube for inland navigation in the next decades until around the middle of the century will not be changed in principle by climate change.

In addition, possible climate-related changes to discharge conditions may be buffered by reservoirs in the reservoir-controlled sections of the Danube. However, there are signs of decreasing discharges in the hydrological summer, so that low water situations could increase.

This climate-related development will form a focus for continued observation and examination, in order to be able to react in a timely manner with adaptation options.

The recording and assessment of the discharge conditions must be continued, and the projections must be updated whenever new climatological data is received. In particular the development of summer discharge conditions and low water discharges above the mouth of the Inn should be observed, also in the near future.

KLIWAS results on the supra-regional inland area and conclusions

The progressive increases in global air temperature documented in the current IPCC report (AR5, WG1), which are inconsistent at regional level, are also detectable in the KLIWAS results for the inland waterways and their water temperatures. In the future there will be fewer ice-related downtime days for shipping on the canals and the reservoir-controlled waterway sections. The BMVI will pay attention to whether this outlook will be counteracted by atmospheric influences on weather patterns in Europe, triggered by the observed decline in oceanic ice, which may lead to colder winters.

With regard to the expected progressive warming of water temperatures in inland waterways and the associated ecological impacts and restrictions on thermal discharges, it should be considered that the decommissioning of nuclear power plants (energy transition) and the associated reduction in the discharges of heated cooling water may represent a heat relief in the waterways. The impacts of the expected global warming on water temperatures could be compensated in part in this manner. The BMVI will follow this development with close attention with regard to its operational and maintenance responsibilities in the inland waterways, using existing monitoring programmes.

Environmentally hazardous substances (metals, biocides) can be discharged into the waterways from hydraulic engineering materials and building products. With regard to the studies parameters of ionic strength, pH value and temperature, no need for action on the part of the WSV due to climate change was identified. The inflows of environmentally hazardous substances into the waterways, also from the catchment areas, may increase in connection with climate change, e.g. due to increased UV protection or the increased use of biocides to combat the faster population growth of parasites.

Extreme flooding and precipitation after longer dry periods could lead to a massive influx of faecal-borne microorganisms into the waterways, and thus to a health-threatening rise in germ counts. The BMVI will follow the recommendations of the KLIWAS and test whether special information must be compiled or occupational safety regulations must be adapted for operational WSV personnel with regard to hygienic protection measures.

The composition of plant species in the floodplains is influenced by climate change. A “simple” shifting of all habitats (e.g. to deeper layers in case of sinking water levels) is not expected, instead the distribution pattern will change on a small scale. The faunistic settlement structure of the waterways will also change along with climate change, including due to changed water temperatures and food webs. The Waterways and Shipping Administration will take account of these aspects in its maintenance plans and in the operation of its systems on the inland waterways, adapting its ecological evaluation methods where necessary.

Coastal and marine waters

KLIWAS Results coastal and marine waters

The resources available to KLIWAS for the coastal area were concentrated primarily on the North Sea region.

While there is meteorological measurement data of a high temporal and spatial resolution on the mainland, there is a lack of comparable values at sea. That also applies to the North Sea. Compared to the mainland, there are very few continuously registering permanent measurement stations at sea. One must often rely on ship observations, mainly by trading ships that travel along fixed shipping routes.

To improve the validation basis for climate projections, new climatologies were developed with KLIWAS for the North Sea (atmosphere and ocean), based exclusively on quality-assured observation data. Furthermore, climatologies of the oceanic fronts in the North Sea were developed on the basis of satellite observations.

It is a special achievement by KLIWAS to have systematically prepared the available climate data for the North Sea and made these functional for reanalyses. The front climatology developed with KLIWAS, which enables the validation of the oceanic dynamics in climate projections, was adopted as a core service into the European COPERNICUS programme.

KLIWAS has led to growing awareness that a coupling of ocean and atmosphere must be performed in climate models for the necessary advisory quality (e.g. for the projection of shipping-relevant atmospheric and oceanic parameters such as water and air temperature, wind direction, strength, surge and sea state). The KLIWAS results of coupled model runs seem to be much more realistic than projections on an uncoupled basis. KLIWAS has advanced the quality of regional climate projections for the North Sea.

In the coastal area, no sufficiently detailed climate projections could be made available for the subsequent model chains during the course of KLIWAS, in contrast to the inland area. Therefore, sensitivity studies were conducted in some KLIWAS coastal projects within a range of possible climate-related changes, in order to be able to make statements on the impacts of hydraulic engineering plants and adaptation options.

Detailed KLIWAS analyses of the water levels of the North Sea have shown that the average rise of the mean tidal waters over the last 100 years at the gauges at the mouths of the Ems, Weser and Elbe estuaries is 1.1 to 1.9mm per year, without the influence of land subsidence. Under the additional consideration of land subsidence, this value is 1.6 to 2.9mm per year. No acceleration of the rise in mean tidal waters over the last 100 years at the gauges at the mouths of the Ems, Weser and Elbe estuaries can be demonstrated.

Since the 1950s, high and low water have developed at the coasts and in the inner German Bight in a different manner to the trend of the average sea level. Extreme high water levels show a stronger positive trend than the mean sea level, while extreme low water levels, in contrast, show a negative trend. The causes are not likely to be climate-related.

By the end of the century, the rise in the sea level of the North Sea, caused by warming of the global ocean and changed wind conditions alone, will be ca. 0.25m. This does not include contributions of the possible effects from the melting of mountain glaciers and ice sheets, the impact of which is insufficiently known to date. The current IPCC Report (AR5) states a possible global rise of between 28 and 100 cm, depending on the scenario used.

With increasing sea levels, higher peak water levels could occur under future storm surges. However, under the assumption of Scenario A1B, the frequency of storm surges is likely to remain at around the current level in the near and distant future.

With a newly developed model configuration a possible increase in sea state was calculated for the eastern North Sea by 2100, and a possible decrease in the western North Sea. In the German Bight, an increase in significant wave height of up to 10 percent seems possible. KLIWAS studies on sea state show that current formulae for measuring the effect of sea state on sea structures possibly underestimate measurement-relevant wave height.

In the coupled projections, sea level and air temperatures increase clearly to the end of the century: average annual water temperature by up to 2.5 °C, air temperature by up to 2.8 °C, whereby in the cold half of the year the warming could exceed 3 °C.

The salt content of the North Sea decreases slightly due to high precipitation and an increased inflow of Baltic Sea water into the North Sea via the Kattegat. Clear changes to the ecosystem of the North Sea might occur as a consequence of changing climatic conditions.

In the North Sea estuaries, a rise in average tidal waters is accompanied by an increase in flow current dominance, upstream sediment transport increases and the brackish water zone shifts upstream. This results in a likely decrease in pollutants due to the inflow of less-polluted marine material. In connection with projections on freshwater discharge and the associated changes to the influx of suspended solids from the interior regions into the North Sea estuaries, decreasing, but also increasing pollutant-content is shown in the sediments, depending on the scenario. Under very unfavourable assumptions in one scenario, pollutant guideline values for dredged materials may be more often exceeded in the tidal Elbe. The other model runs do not lead us to expect any pollution-related restrictions with regard to dredging in the North Sea estuaries.

For most of the model chains observed for the near future, and all of those for the distant future, it is expected that the lack of oxygen in the Elbe estuary will expand over time.

In the near and particularly in the distant future, a potential increase in the risk of wound infections is expected in the coastal area, e.g. due to vibrio while working on the waterways, and in tourist use.

Foreshore vegetation in the North Sea estuaries is subject to its drivers which change by climate conditions. The KLIWAS results show a natural tolerance of the shoreline vegetation towards the projected impacts of climate change. A key driver is the sediment accumulation on the marshes under increasing high water levels. If the sediment rate is high enough, no significant impairments will occur. Single drivers, such as the climate-related increase in tidal current velocity or the increase in wave height may lead to an impairment of two important functions of the tidal reed as shore protection and as a habitat.

Conclusions for coastal and marine waters

These KLIWAS findings lead us to expect that marine shipping will remain a reliable mode of transport under consideration of the currently possible statements on the rise in sea levels and changes in the North Sea and its estuaries.

To date, the analysis of previously applied model configurations for the A1B emissions scenario (balanced use of all sources of energy) shows no distinctive challenges or restrictions to navigation or to the waterways infrastructure in the coastal area. More research is required to attain clarity about the necessity of preventative changes to the assessment specifications for infrastructure and operations. The knowledge gained so far must be secured further by the continued use of coupled ocean-atmosphere models with regard to the future effects of climate change on marine waterways and navigation.

The concept of sensitivity studies, used by KLIWAS complementary to the projections of the model chain, has proven its worth and has provided the opportunity to examine in detail the impacts on hydraulic engineering structures and adaptation options under the assumption of scenarios. Despite large existing uncertainties in the climate projections at the coast, it is possible to develop statements on the impacts and adaptation options, for and with the Waterways and Shipping Administration.

KLIWAS has greatly improved the state of knowledge regarding the sediment and suspended matter balances, the distribution of pollutants, the factors influencing shore vegetation, water quality, especially the oxygen balance, and water hygiene in the coastal waters and river mouth areas. The influence of changed freshwater discharges, water temperatures and the rise in sea level on these parameters can now be better described. Some of the results are already being used for ongoing river engineering and the maintenance management of tidal waters, while at the same time demonstrating adaptation options for conditions that may be changed in future. Findings on a maintenance strategy that is adapted to various headwater conditions were developed, in particular for sediment management in the tidal Elbe.

The KLIWAS results also benefit other areas of activity (e.g. the operation of coastal protection structures and offshore wind turbines as well as findings about possible changes to the marine ecosystem).

Conclusions of the WSV

Navigation on coastal and inland waters forms part of a reliable, economical and environmentally-friendly logistic chain and safeguards Germany's competitiveness as an industrial location. A core task of the Federal Waterways and Shipping Administration (WSV) is therefore to guarantee the ease and security of navigation on the federal waterways, also with regard to climate change and its impacts. It is a task that must be fulfilled reliably and sustainably with the requisite foresight.

The guiding principle for the activities of the Federal Waterways and Shipping Administration, "Enabling mobility and protecting the environment" fittingly expresses this objective.

The WSV has actively supported the KLIWAS research programme from the very outset. From the conception of the research topics to the execution (e.g. data and knowledge provision, support with field work) and the discussion and assessment of the results achieved, there was continuous cooperation between KLIWAS and the WSV at all levels. This interaction between research and an infrastructure administration on such a large scale is unique in the research and administration landscape. It was facilitated by the primary practical orientation of the departmental research institutes (BfG, BAW, BSH, and DWD) of the BMVI, and the corresponding organisational cooperation between the BMVI, its higher authorities and the WSV in a common administrative structure. Via the KLIWAS network, the WSV could immediately exploit the latest findings from the research community. With the advances in knowledge gained through KLIWAS, realistic future scenarios have become clear, showing which impacts climate change can have. Thus KLIWAS has made an important contribution to the objectification of public discourse about the effects of climate change on waterways and shipping.

With its ensemble approach, KLIWAS based its climate projections not just on one model, but on many models and projections. By these means, KLIWAS demonstrated the range of possible changes and identified the uncertainties contained in the projections. The essential feature was the development of additional regional climate models, which were coupled with the global models, in order to be in a position now to make statements on regional or territory-based questions of the WSV. Thus KLIWAS has provided new findings on the basis of robust and reliable scientific methods, which now allow future-oriented questions, as well as planning and decision-making on adaptation measures, to be conducted with the necessary security.

The task of the WSV now is to carefully analyse the results presented and, in full awareness of the existing uncertainties, to make decisions on the consequences of action, e.g. with regard to spatial planning, land management, technical assessments, expansion and maintenance concepts, etc.

In summary, we can establish that the impacts of climate change on waterways and navigation in Germany are manageable. By the middle of the century we can expect that the present discharge conditions into the waterways, with their current variability, will not change fundamentally.

Periods of low water levels and flooding will continue to occur, the extent of which will be similar to the situations we have seen in the last few decades. However, as an increase in such extreme situations is projected in the long term, and it cannot be determined with certainty when such a noticeable change will occur, the WSV with its hydrological staff will have to continue to closely observe the development of discharge conditions. Only by these means can changes be detected in a timely manner, and adaptation measures introduced. Already now, with the updating of river engineering concepts, we are not only looking to the past, but also to the future, using KLIWAS projections.

As large-scale changes to river engineering concepts can take decades before they are realised, due to increasingly complicated approval procedures and limited budgets, it is appropriate to include "no regret" measures in the ongoing plans, which provide benefits even without climate change. These could be measures to improve the channel depths during low water conditions, measures to stabilise riverbeds, improved water management concepts or even more flexible sediment management concepts. A follow-up project for a water management model has already begun, one to relieve bottlenecks in the water management of the Kiel Canal and the inland waters connected to it. In the scientific processing of this follow-up project there will be a continuous and necessary specialist dialogue between the departmental research institutes, the WSV, the state authorities and the water and soil associations, so as to record all relevant input and control variables. This serves to ensure the quality of the results, as well as transparency.

The need for further follow-up projects is to be examined. Measures to ensure a more balanced discharge regime, in other words the buffering of high discharges and low water discharges in the river basins would be welcome, but the responsibility for this in most cases lies with the federal states.

Relief for the maintenance efforts of the WSV is likely with regard to the ice conditions, which will become shorter and rarer due to the temperature increases caused by climate change. Here the necessary resources must be deployed in such a manner that adequate ability remains to act in severe cases, despite rarer incidences.

As well as looking to the future, KLIWAS has contributed to a better systemic understanding of the federal waterways, with its diverse project topics. This refers to aspects of water balance, sediment management, water quality, shore maintenance, water hygiene and hydraulic engineering materials, which flow into the maintenance and development concepts of the WSV. Some methods, models and new findings have already enriched the WSV's "toolbox" during the course of research.

In the course of the reformation of the Waterways and Shipping Administration, the WSV has taken on the task of adapting to climate change and also climate protection, and has created the organisational prerequisites to work on these tasks. That includes examining the existing administrative rules and regulations for any updating requirements. The objective is to integrate "climate proof" into the working processes.

The WSV brings its knowledge and skills to the German Strategy for Adaptation to Climate Change (DAS). For example, it supervises the indicator "Navigability of the Waterways" and has introduced proposals for action to the Federal Government's Adaptation Action Plan (APA).

Summary

The KLIWAS research programme has fulfilled the scientific demands of the task and has provided important practical and needs-related foundations for waterways and shipping in Germany.

KLIWAS demonstrates that immediate effects of climate change on waterways and navigation will not have any significant impacts, but at the same time the KLIWAS also underlines the need to be vigilant towards change. The WSV relies on the "toolbox" that was developed by the higher authorities of the BMVI being continuously cultivated and developed, also with a view to worldwide research activities. Therefore, the WSV supports the efforts of the BMVI to network its departmental research institutes even further, in order to adopt new findings on climate change in relation to all modes of transport, and to process these in a application-oriented manner for the administrative practice. This also requires a strengthening of the climate services of the federal authorities, whose meteorological and hydrological services are indispensable for the management of the waterways, both inland and in coastal areas.

With this environmentally friendly and economical logistic chains will also be possible in the long term, in order to secure Germany's competitiveness as an industrial and business location.

Thanks to the BMVI for the research programme!
Thanks to KLIWAS for the results!

Recommendations of the Scientific Advisory Board

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KLIWAS services in the internal and external cooperation for policy consultation

The departmental research institutes commissioned by the BMVI – the BfG, DWD, BSH and BAW – and their scientific network have addressed a topic of great political relevance. Using expedient technical and scientific methods, they managed to combine positively different disciplines in order to answer practical questions. During the introductory phase, the fundamentally clear orientation found its way into concrete project work with the coordination of the working programme, the interfaces and the chronology of the interdependent products. The cooperation within and between the research tasks developed constantly during the course of the work, and there was a continuous increase in quality from year to year. Ultimately, a very high level of sectoral processing has allowed a very good picture to emerge.

Due to the multi-layered model outputs, the progress of the effective processes in the model chain and the necessary contexts for the data transfers could not, at first, be easily detected at all points. The challenge for scientists was to specify which data and information they required from other projects at which point in time, and which projection periods would have to be analysed uniformly. Intensive discussions were particularly necessary between the project partners providing the regionalised climate data and those developing the integrated models, so as to manage the task successfully. One very positive aspect amongst others was the systematic preparation of raster-based hydro-meteorological reference data ("HYRAS"). These data can be used for other research projects and applications, well beyond the purpose addressed here.

The approach of the research programme, to view the waterways integrally as a system, should be highlighted positively. In all, the selection of methods is transparent and also well documented, with the help of project reports and the portals of the authorities. An innovative feature of KLIWAS was that it generated a range of projections at the level of the model chain, and indeed created an awareness in the scientific adaptation discourse in the first place. The approach helped to improve the acceptance of scientific results on the topic of climate change by the administration and political decision makers.

The research programme also led to great development in an understanding of the international context, with the help of its close cooperation between projects and their partners. This could be seen clearly in the substantial discussion with other research programmes such as KLIWA, KLIMZUG, REKLIP, CORDEX, with the CLM community, KLIMA-MORO, AdSVIS and in the cooperation in joint working groups involving the federal government and individual states.

It is gratifying that the work in the 30 projects has led to numerous recognised publications. The deliberations on the topic of bias corrections in climate projections should also be mentioned in this context. It required weighing up scientific interest and feasibility, in order to then demonstrate the limitations and possibilities of these methods in the transfer process, and to objectify the discussion.

Recommendations for further action by the BMVI

As a Scientific Advisory Board we wish to encourage the KLIWAS network and the BMVI to continue their necessary research on the waterways system in the context of climate change. This also includes the future further organisational development of the departmental research on climatic consequences.

The regional scale relevant for adaptation measures is currently being determined by means of the interpolation of roughly resolved model output data from global climate models, or with the help of regional climate models. One research topic that could be discussed might be the development of direct dynamic modelling with global models, but with a higher resolution (7.5 to 10 km).

When transferring the data from the global climate models to the smallest fields of the regional scale, with the help of the regional models ("downscaling"), the question arose as to what extent these feed back to the global models. Further studies must be carried out on whether and to what extent other trends in the projections emerge due to the selection of the models. If model results have a greater bias than the climate signal, they would appear to be unsuitable for estimating relative changes. Furthermore, there is the problem of a consistent bias correction with many variables. The demand on ensemble approaches continues to be to carry out consistent procedures and to decide whether data should be entered into model chains with or without a bias correction. Existing expertise from outside the departmental research can be availed of to intensify these considerations.

The treatment of the interfaces between the disciplinary models and the transfer of model data between the parts of the model chains testify to the innovative strength of the programme. Comprehensive advances were also made in the spatial implementation of these interfaces. Nevertheless, the integration of further existing interfaces at the level of individual processes is recommended, e.g. in the processes of lateral exchange between the river and adjacent floodplain system.

In terms of a possible expansion of storage capacities of the transshipping economy connected to the Rhine as an option for action, impacts of climate change on transport chains would appear to be fewer than previously assumed. However, in the adaptation discussion, respectively the decisions of the

BMVI, the question of whether additional hydraulic engineering measures will be necessary must be addressed. This question should only be answered in connection with the ecological effects of the hydraulic engineering adaptation measures. In order to assess the consequences for the environment, the monetarisation of the effects should be integrated. Also, with regard to future federal transport route planning, the work on economic aspects, begun in KLIWAS, must be continued, in order to be able to serve obvious interfaces. It should be noted in this context that while economic studies have been conducted on the impacts of climate change on inland shipping, especially on the Rhine, as yet this has not been done for maritime shipping. This should be remedied.

The approaches for modelling the sediment transport into the estuaries are varied. In line with the multi-model approach, they are each justified. However, the reasons for observing similar processes with different methods could be presented in a more transparent manner.

With regard to the sensitivity analyses and modelled projections carried out in parallel in KLIWAS, we suggest that assumed starting values for sensitivity analyses should also lie within the ranges of projected ensemble results in the future. Otherwise a need for argumentation might arise on the part of the BMVI as to why results from current projections are not being considered in adaptation decisions.

In KLIWAS it was possible to successfully build a bridge between the dominating modelling of the parameters of the waterways system and the statements, based on measurements, on topics such as hygiene and pollutants. For the future it is also recommended to underline water quality observations with the help of up-to-date simulation calculations, either by extending capacities in the department or by involving external competencies. In view of the likely increase in dredged material volumes, especially in the estuaries, the use of detailed models for sediment-bound pollutant transport is a future issue, irrespective of the influences of climate change.

The equally innovative approach of coupling atmospheric and ocean models can provide impulses for the work of the International Commission for the North Sea and Baltic Sea. Indeed, all of the KLIWAS results could be used more intensively in such programmes.

The ecological knowledge intensified in the context of KLIWAS can now be used in the first instance by the BMVI and WSV, but also by other institutions for the adaptation discussion. It should be intensified further in continued studies. Individual aspects, e.g. fish as a relevant indicator group in the ecological area for the water maintenance in inland waterways, should be added to the study spectrum in subsequent investigations. In all there are promising links to the management tasks resulting from the EU-WFD, which could be further supported by these means. This is also a future perspective for the use of existing KLIWAS results and the future development of the instruments.

When selecting and supplementing topics for future research, the ongoing discussions of the international research community on the suitability of the parameters chosen for the EU-WFD should be considered.

Documentation and publication

The work in the KLIWAS projects was well documented by means of internal intermediate reports, such that the Scientific Advisory Board, the WSV and the BMVI were constantly informed of the progress, including publication activities. For the future it is recommended to create a publication concept at the programme level from the very outset. This would mean that important publications, naming the specialist target readership and the most suitable platform, could be included in the target planning as strategic goals and milestones from the beginning. It should include a balanced mixture of scientific publications with peer-review processes and practice-oriented specialist journals. Worthwhile and desirable topics for now completing publications can be found in the area of the reproduction of statistical errors in the model chain. Aspects related to transport science could also be assessed in more detail. In this context it is also desirable that the authorities will make the results data fully accessible to all via its data portals.

Communication and coordination

In general, the communication and coordination work in KLIWAS was good, both at the level of the research tasks and projects, and also in the overall programme. The success can be seen in the “KLIWAS traces” in the German Strategy for Adaptation to Climate Change (DAS), which has been substantially supplemented, and also in the close cooperation with the WSV as the user of the research results. In future, communication work should be a fixed part of every departmental research programme, and should be furnished with the necessary resources from the very beginning.

KLIWAS has shown that specialist support and leadership of the temporary staff by experienced employees is necessary, otherwise induction periods are too lengthy and there is a risk of missing the point. From an organisational perspective, more consideration must be made of this additional load on the permanent workforce. In addition, it must be ensured that the knowledge obtained by the temporary personnel is secured and that perspectives are developed for those on limited contracts. Any new ongoing task, such as the provision of climate projections as a basis for decisions to safeguard and develop the transport infrastructure, cannot be achieved in the long term by using temporary staff.

Cooperation

With regard to cooperation in the research network, the ongoing results of the basic research should be considered continuously and also integrated into future work. The achievements of the research partners involved could be emphasised somewhat more. In return, the departmental research institutes should communicate their problem-oriented approach more clearly, in order to be perceived better. The internal linking of the BMVI departmental research institutes with the very good experiences from KLIWAS should be developed further, and a systematic search for cooperation partners for an effective collaboration should be carried out. One recommendation that is directed more at the research organising and financing ministries is to pay more attention to the tasks and interfaces between the institutions of the research community and to allocate the responsibilities more clearly in order to avoid discussions about competencies.

The success of KLIWAS in terms of policy consultation emerged as a result of the networking of the departmental research institutes and the cooperation with their scientific partners. The support of a Scientific Advisory Board is not simply a matter of course for research institutes, and it enabled important impulses. The decision to appoint an advisory committee was therefore welcomed, and the members were very committed and enjoyed an enriching experience. In retrospect we, as scientific advisors, and independent of the persons involved here, also recommend such support and quality assurance as an organisational measure for further BMVI research programmes. In our view, the collaborative work produces added value for all involved.

The instruments used and tested in the KLIWAS research programme present great opportunities to further develop climate scenarios and to integrate these with other scenarios, such as demographic and economic development. Also, with regard to safeguarding a robust transport infrastructure, the BMVI now has good possibilities to develop well-founded scenarios across all modes of transport, which should be used rigidly.

Résumé and outlook of the BMVI

The federal waterways in Germany will continue to be available as high-performance transport routes in the future, even under climate change conditions, and waterborne transport will be able to provide the necessary services as a reliable means of transport.

The meteorological, hydrological and oceanographic framework conditions for navigation (including discharge conditions of the rivers, rise in sea levels, sea state conditions, and storm surges) will remain almost at the levels of current conditions in the next few decades, until around the middle of the century.

The adaptation of waterways and navigation to changed discharge conditions has always been an instrument of public service and will be continued with the new findings. Climate change is therefore only one, but a new one, decision-making factor amongst others that play a role in planning and decision-making processes for the waterways as a mode of transport.

These results will not yet trigger any direct investment decisions based solely on climate change. The climate-related changes projected by KLIWAS for the near future (until 2050) are of a size that can be managed in principle with the existing planning tools. However they must continue to be observed with close attention.

With its limited resources, KLIWAS could not include all German river basins and coastal areas in its study. Furthermore, concrete studies on economic aspects were conducted exemplarily in a first step for the Rhine only. The aim is to close the most pressing knowledge gaps (spatial and technical) further in a targeted manner. Scientifically robust results about possible climate consequences (looking to the future based on prognoses and projections) have to be established as a fixed element in planning for and making decisions on investment and maintenance measures on the federal waterways. The new findings from KLIWAS will be fed in successively to the planning processes for the federal waterways, in order to detect and process in a timely manner the need for ecologically and economically suitable adaptation measures, and to indicate future research needs.

The BMVI will continue the dialogue that was begun and established in KLIWAS with interest groups connected with the waterways and shipping.

In the course of the ongoing reform of the WSV, the organisational framework conditions were created to establish this new permanent task for the waterways as a mode of transport. This was done in the knowledge that the planning and implementation of larger adaptation measures can take decades, and it is assumed that further climate-related impacts can be expected from the middle of the century, necessitating the preparation of further adaptation measures. The floods of the recent past have made clear that the development of extreme weather events, which were not studied by KLIWAS, must be given special attention in the future in order to be able to recognise and introduce possible preventative measures to minimise damages and the interruption of commercial operations. The intensity of the changes caused by climate change must be categorised within the available frameworks of existing dynamic changes and loads, and the necessity and scope of activities must be prioritised accordingly.

When developing adaptation options and deciding upon the implementation of adaptation measures, a transparent communication of the underlying uncertainties is absolutely essential.

Cooperative approaches and staged concepts that allow a flexible reaction to new states of knowledge must be developed. The BMVI favours so-called “no regret” measures, which can contribute to safeguarding and advancing transport reliability, even without the occurrence of climate change.

In the process, both economic and environmental objectives must be considered appropriately. The cooperation between the fields of water management, environmental and nature protection, and waterways and navigation must be advanced even further. Joint adaptation measures should be identified and implemented, which will provide a benefit to all areas of responsibility on a waterway.

In the context of the legal competencies and responsibilities in each case, the BMVI will support measures of the federal states aimed to ensure a more balanced discharge regime, buffering of high discharges and low water discharges in the river basins. This serves to reduce the dangers of flooding and also reduces the discharge-related restrictions on navigation (win-win solutions).

The knowledge and the scientific tools created by KLIWAS must be preserved, cultivated and further developed, in order to meet the challenges of climate change. The existing knowledge deficits must be removed. New findings on global emissions scenarios and climate projections must be transferred successively to the regional conditions in Germany, the impacts on conditions on the waterways must be identified and communicated to the decision-makers in the BMVI and the WSV.

With their national mandates and their international networks, the DWD, BfG and BSH provide elementary data to the federal government on climate, weather and water for all areas of activity. With KLIWAS, these institutions have developed new methodological knowledge within a network, and reached findings that represent an indispensable foundation for public utilities in the context of the implementation of the German Strategy for Adaptation to Climate Change (DAS), well beyond the transport sector. This foundation is visible in the elaborations of the DAS progress report.

In the course of passing the 2015 DAS progress report and the Adaptation Action Plan II, the BMVI recommends the federal government to expand in a targeted manner and with an increased budget the operational services in the areas of climate, weather and water, which are already laid out in the departmental research institutes DWD, BfG, BSH and BAW, into a prognosis and projection service for climate, extreme weather and waterways developments and states ("climate services").

In order to ensure that the quality achieved with KLIWAS, a quality that is also required in the future, is guaranteed in policy consultation on climate change and associated future topics (e.g. energy transition and the environment), the BMVI will continue to strengthen the networking of its departmental research institutes and business fields, and develop expedient strategies. For the manifest and applied research needs that are required to safeguard the reliability of mobility in Germany, well beyond the topic of adaptation to climate change, the BMVI is preparing further alliances and networks of its departmental research institutes to form a BMVI expert network. By these means, the complex questions relating to future topics can be addressed in new, application-oriented formats, and the necessary consultation quality can be generated for policy- and decision-makers.

To underpin this, the BMVI will also advocate for the research funding by the federal government to be applied increasingly to operative processes. Against this background it makes sense that in future other departments (e.g. BMVI, BMUB, BMEL, BMVg, etc.) also receive a right of proposal for new focuses in research funding by the BMBF.

Abbreviations

AdSVIS: Adaptation der Straßenverkehrsinfrastruktur an den Klimawandel. (Adaptation of road traffic infrastructure to climate change. Research programme of the BASt.)
BASt: Bundesanstalt für Straßenwesen (Federal Highway Research Institute)
BAW: Bundesanstalt für Wasserbau (Federal Waterways Engineering and Research Institute)
BBSR: Bundesinstitut für Bau-, Stadt- und Raumforschung (Federal Institute for Research on Building, Urban Affairs and Spatial Development)
BfG: Bundesanstalt für Gewässerkunde (Federal Institute of Hydrology)
BMBF: Bundesministerium für Bildung und Forschung (Federal Ministry of Education and Research)
BMEL: Bundesministerium für Ernährung und Landwirtschaft (Federal Ministry of Food and Agriculture)
BMVg: Bundesministerium der Verteidigung (Federal Ministry of Defence)
BMVI: Bundesministerium für Verkehr und digitale Infrastruktur (Federal Ministry of Transport and Digital Infrastructure)
BSH: Bundesamt für Seeschifffahrt und Hydrographie (Federal Maritime and Hydrographic Agency)

CLM-community:	Climate Limited-area Modelling-Community
CORDEX:	Coordinated Regional Climate Downscaling Experiment
DFG:	Deutsche Forschungsgemeinschaft (German Research Foundation)
DWD:	Deutscher Wetterdienst (German Meteorological Service)
EU-WFD:	Europäische Wasserrahmenrichtlinie (European Water Framework Directive)
ICPR:	Internationale Kommission zum Schutz des Rheins (International Commission for the Protection of the Rhine)
IPCC:	Intergovernmental Panel on Climate Change
IPCDR:	Internationale Kommission zum Schutz der Donau (International Commission for the Protection of the Danube River)
KLIMA-MORO:	Raumentwicklungsstrategien zum Klimawandel. (Spatial development strategies for climate change. Research programme of the BBSR.)
KLIMZUG:	Klimawandel in Regionen zukunftsfähig gestalten. (Future-oriented climate change management in regions. Research programme of the BMBF.)
KLIWA:	Klimaveränderung und Konsequenzen für die Wasserwirtschaft. (Climate change and consequences for water management. Cooperation between the federal states of Baden-Württemberg, Bavaria, Rhineland-Palatinate with the involvement of the German Meteorological Service.)
KLIWAS:	Auswirkungen des Klimawandels auf Wasserstraßen und Schifffahrt in Deutschland. (Impacts of Climate Change on Waterways and Navigation in Germany. Research programme of the BMVI.)
REKLIP:	Regio-Klima-Projekt, see also www.reklip.org
WSV:	Wasser- und Schifffahrtsverwaltung (Waterways and Shipping Administration)

Glossary

HM5Q:	The highest arithmetic mean of 5 consecutive daily values of the discharge in a high water period
MQ:	Average annual discharge
NM7Q:	The lowest arithmetic mean of 7 consecutive daily values of the discharge in a low water period

Appendix:
KLIWAS Synthesis Report for Decision-Makers

KLIWAS
Climate · Water · Navigation

Impacts of Climate Change on Waterways and Navigation

Development of Adaptation Options

Synthesis report for decision-makers

Federal Institute of Hydrology
German Meteorological Service
Federal Maritime and Hydrographic Agency
Federal Waterways Engineering and Research Institute
(eds.)

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1. Networked departmental research as a contribution to decision-making

The starting point for all considerations for the KLIWAS departmental research programme was the following question, posed by the BMVI:

> "What impact does global warming in Central Europe have on the navigability of the federal waterways?"

Our understanding of navigability encompasses not only the physical properties of the water, but also the water quality and the water ecology. These are observed beyond the narrower river geometry, especially in the context of the adjacent forelands, in other words in the entire biosphere of the river and the waterway. Accordingly, one objective of KLIWAS is to record the future development of the "Waterways System".

Two sources of knowledge are used to describe the development of rivers and coastal waters. One is the study of the past, which allows us to rely on measured values. Secondly, we must look to the future, supported by projections from numeric models. These model results, or projections, reach up to 100 years into the future. Recordings of hydro-meteorological and hydrological data, for example, go back around 200 years into the past. Using so-called proxy data we can review the extreme flood events on the Rhine, for example, as far back as the Middle Ages.

Both sources of knowledge must always be observed from the current standpoint. Thus a distinction must always be made between the present-day future and the future present. That also applies to the past. Here, too, there is always a present-day idea of the past, which can indeed change. For instance, the most extreme known flooding of the Rhine at Cologne, at 13.30 m, was proven only a few years ago by work carried out at the University of Bonn.

From the present-day perspective we can establish that the 20th century was a very good-natured one in terms of hydrology. And we can assume that the 21st century will be much more dynamic, not only in terms of hydrology. In other words, it will be warmer and drier, and at the same time also colder and wetter. The Elbe flooding in June 2013 is an example of the extreme events that are possible. We will also have to deal with similar such singular events in the future, also in other river basin areas.

The perception of research into the consequences of climate can be divided roughly into a scientific construction and a media/social construction. Departmental research is not an end in itself, but rather serves to create, use and convey knowledge. The media offers one opportunity to disseminate knowledge widely. Science and the media pursue different objectives, and therefore use a different language. Climate scientists communicate using standardised terms such as climate projection, scenario, model chain or model result.

The media must compete for short-term attention. That might explain the motivation for a type of reporting that uses the words climate catastrophe or climate collapse in order to meet the public's supposed desire for sensation. Scientific findings can – almost – never be regarded as final conclusions. Rather, the constant verification of existing findings is part of the essence of science. Yet terms such as "climate catastrophe" suggest something absolute and final, and can therefore give rise amongst the public to doubts about the credibility of scientists.

The contributions made by departmental research are focussed on science. While it must also provide a service to the media and society, it must nevertheless avoid emotionalism in its reporting. In line with this philosophy, the form of work carried out by the KLIWAS departmental research programme requires presenting the latest state of knowledge in each case, and the interweaving of this knowledge with the individual findings of the participating research institutes, the BfG, DWD, BSH und BAW.

Presenting and evaluating this knowledge in pairs of opposites, such as right/wrong, is a simplification that does not do justice to the questions that are relevant in practice. During many years of discussion on the consequences of climate for the water balance in Central Europe, the approach of arranging the individual results in the overall multifaceted context of scientific findings has proven its worth. Presenting the knowledge has thus become a matter of scientific organisation, as this combined knowledge can no longer be conveyed by one single individual or institution. Therefore answering the upcoming complex questions in departmental research requires a network of personal and institutional knowledge. Only by these means can specific efficiencies such as “scenario capability” be achieved, which are needed for the scientific policy advice provided by the BMVI and other departments. High social demands on the preparation and execution of infrastructure projects do not leave any room here for particulate views.

In addition to fundamental research and applied research, the term “problem-oriented” research has also established itself in the discourse amongst scientific policy advisors.

In this respect, KLIWAS could not “solve” any problems, but was instead concerned with taking a position with regard to the recognised problems and to change it where possible. Thus we demonstrate development opportunities for those people who must make political decisions. As departmental research, this “decision-related science” has two further features: first, self-restraint when making statements, in other words, known unknowns, and second, refraining from wanting to be in the right.

2. Why KLIWAS?

For some years, climate change has been an object of research in many different projects. During this research work it was established that deviating findings were attained, depending on the (climate) model used. It therefore made sense to compile and compare the results of as many different climate models as possible. This approach was documented, for example, in various reports by the IPCC (2001 and 2007). Each of these reports was well received and accepted.

These reports and the effects of the long-lasting low water in the Rhine in the summer of 2003 prompted shipping associations and industrial firms to commission an assessment of the future usability of the Rhine as a waterway. Therefore in 2007 the Federal Ministry of Transport, Building and Urban Development (BMVBS) tasked the Federal Institute of Hydrology, in cooperation with the German Meteorological Service (DWD) with carrying out a study to evaluate and assess the hydrological conditions of the Rhine, a waterway of great economic importance for Europe, in the coming decades. The following questions were at the forefront:

- Which results already exist from international and national climate research?
- To what extent can climate change alter the hydrological conditions of the Rhine?
- How will shipping and the freight industry be affected by changed hydrological conditions?
- Which adaptation measures can be taken to minimise these economic impacts?
- Can the findings also be applied to other waterways?

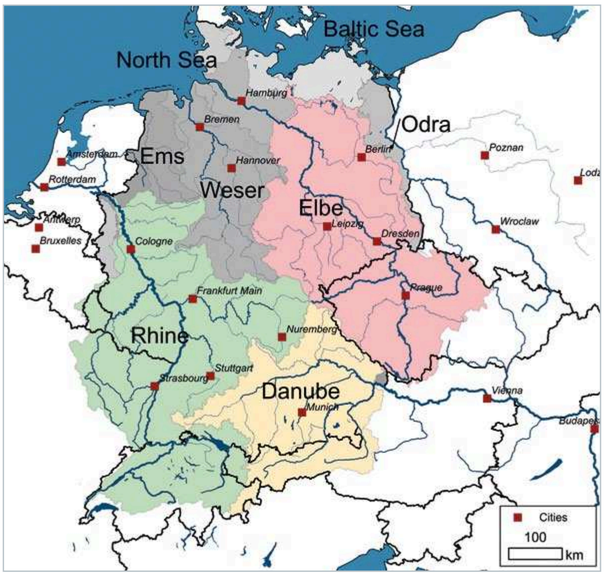

Figure 1: Map of the area studied in KLIWAS

The results of the commissioned study were published by the BMVBS in 2007 under the title "Navigation and Waterways in Germany – Meeting the Challenges of Climate Change". Building on these findings, the BMVBS tasked the Federal Institute of Hydrology (BfG), the German Meteorological Service (DWD), the Federal Waterways Engineering and Research Institute (BAW) and the Federal Maritime and Hydrographic Agency (BSH) to conduct the research programme "KLIWAS – Impacts of Climate Change on Waterways and Navigation in Germany. Development of Adaptation Options", to run from 2009 to 2013. As well as the Rhine, the Elbe, the Danube upstream from the Achleiten gauge on the German-Austrian border and the coastal waters with the estuary areas of the Elbe, Weser and Ems were studied, as well as the North Sea. Thus the area surveyed in KLIWAS encompasses the hydrological catchment areas, including parts outside Germany (see Figure 1: Map of the area studied in KLIWAS).

The aforementioned questions were supplemented by others:

- How will climate change affect the coasts and marine use (especially shipping)?
- Will the entrances to German harbours be restricted by a more frequent occurrence of storms and storm surges?
- Will contaminants be distributed differently in waters and sediments?
- Will it be necessary to change dredging and maintenance strategies?
- Will it be necessary to modify river engineering concepts in the estuaries?
- To what extent are ecological assets, as well as vegetation and fauna in and along the waterways affected? How can these effects be reversed?
- What will the erosion on banks, revetments, underwater slopes and in the forelands be like in the future?
- Are there likely to be greater pressures on quays, locks or flood barriers?
- Will there be any changes to the pressures induced by sea state on navigational aids, seagoing vessels, offshore structures, coastal structures, coastal protection structures, harbour facilities or in-river structures?
- What adaptation measures can be considered?

Finding answers to these questions should reveal existing uncertainties in the projection results of research projects and present options for minimising these imponderabilities as far as possible, in order to justify political decisions on future adaptation measures with well-founded scientific results. This complex topic was addressed in the following stages: (a) description of the current state, (b) research into the causes, (c) development of measures to prevent negative occurrences, related to different scenario corridors. The final stage, (d) the decision to implement preventative strategies, is a political one, and thus beyond the remit of science.

KLIWAS has united more than 100 highly qualified scientists from the field of departmental research, and their partners. These “knowledge creators” have invested much energy and analytical skill. Numerous existing research results were included in their analyses. They have pursued the objective of attaining the best possible results in accordance with the latest knowledge and the most up-to-date methodology in a comprehensive manner, i.e. both in breadth (different scientific fields) and depth (different methods). From these results they derived adaptation possibilities, which they now present to the political sphere, enabling it to make the necessary, informed decisions.

3. The integral research approach

3.1 Features of KLIWAS

Scientists from app. 20 disciplines in the Federal Institute of Hydrology (BfG), the Federal Waterways Engineering and Research Institute (BAW), the Federal Maritime and Hydrographic Agency (BSH) and the German Meteorological Service (DWD) cooperated in the KLIWAS research programme with app. 100 European scientific institutions. The objective was to assess the climate-related influences on waterways in the near future (2021 to 2050) and the distant future (2071 to 2100) according to the latest state of science and technology, and to develop and evaluate adaptation options, thus providing a rational basis as an important component for political decision-making. KLIWAS was characterised particularly by its integral approach across a wide variety of disciplines and regions.

From Earth system to waterways: Multidisciplinary cooperation

Creating a link between global climate events and comparatively local effects is a great challenge. To do so, the entire Earth system must be observed, which is determined by a complex interplay of positive and negative feedback and non-linear processes on different scales of time and space. It is not obvious when certain processes are prevalent, or under which circumstances, and thus relevant. KLIWAS was concerned with using the best possible descriptions of this complex interrelations and, building on this, quantifying the effect of changes on the influencing factors relevant to navigation, using its own approaches.

Foundation: Data and models

All studies are based on observations and, derived from this, models of the dynamics of the different sub-systems and the variables that describe their condition (e.g. precipitation, run-off, sediment transport, water quality, species composition). The global cause (emission scenario) is transferred to its impact on a regional scale, i.e. wherever people live and are potentially affected. The challenge in building a model with existing data lies in combining the process descriptions in such a way that the processes are, on the one hand, presented realistically, and on the other hand that errors due to a lack of knowledge about process details and their continuation in process chains are kept small.

Model chain: Linking the research focal points

Although the trend might be developing in the fields of science and research, there is still no such thing as one single, all-encompassing, integral, “best” Earth system model that unites all knowledge. The state of research is that the different specialist disciplines (and within each of these, several research groups) develop their own models for each of their sub-systems. It is customary practice when researching the impacts of climate change to link the models by using the result of the previous, generally large-scale model as an input variable for subsequent detailed models. Depending on the characteristics of the model results, it may be necessary to undertake and insert a correction when linking, to remove any systematic errors (or bias). That is not ideal, but unavoidable, as long as the systematic deviations of the models cannot otherwise be removed, especially by means of additional measurement data and – building on this – further model improvements. This so-called model chain with bias corrections was also used in KLIWAS, particularly in the inland area (see Figure 2: The KLIWAS model chain for inland waterways). For the North Sea region, regionally paired ocean-atmosphere modelling was used for the first time. No bias correction was used.

Starting point: Emissions scenarios and climate projections

At the beginning of the model chain there are assumptions relating to different global socioeconomic developments and, connected to these, different possible developments of anthropogenic emissions of greenhouse gases. These so-called emissions scenarios are then imprinted on global climate models (GCM) as external changes. The climate models calculate the reaction of the climate system on the scenarios and therefore do not produce predictions, instead they each project a possible picture of future climate development, the so-called climate scenario.

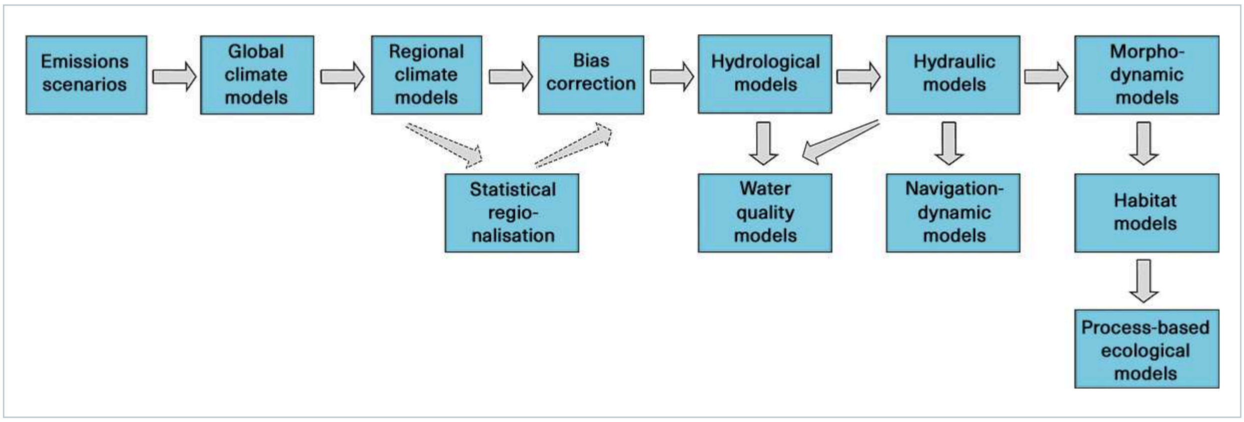

Figure 2: The KLIWAS model chain for inland waterways

Already at this level the individual climate model calculations contain uncertainties, as a result of the following sources:

- Assumption of the emissions scenarios
- Assumption of the initial conditions and constraints of the model runs
- Availability and quality of observation data
- Existing gaps in knowledge about processes and pairings in the climate system
- Process formulation and pairing within the model
- Parameterisation of the individual processes of the model
- Technical limitations of computing power and storage capacity

The scientific work in KLIWAS began with the preparation – suited to the research programme – of existing results from global and regional climate model runs, or with those that were completed by the start of the programme duration. KLIWAS was able to avail of the results of global climate models that were published in the IPCC Report of 2007, and especially the results of regional climate models created by the EU project ENSEMBLES, which ended in 2009. Further climate model calculations were also used, some of which were completed by KLIWAS itself or on its behalf by cooperation partners, by 2012. The global climate projections of this generation show for the long-term annual mean in Europe a tendency towards increasing precipitation in northern Europe and decreasing precipitation in southern Europe, respectively North Africa, and varying conditions within a certain range in Central Europe. However they do not provide any differentiated conclusions with regard to regional changes at the level of European river catchment areas. Therefore they were regionalised, i.e. scaled down to a suitable measure in a further modelling stage. Thus more processes and – due to a higher resolution – special regional features are taken into better account (e.g. the terrain and with it the windward and leeward effects of mountain ranges). These results then flow into the river basin and ocean models, which deliver statements, for example, on changes to discharges, water levels or tides, respectively sea states. Other scientists in turn access these results, for example to model morphological, chemical and ecological changes in and around the waters.

Multi-model approach: Ensemble of model results

The variety of the questions addressed along the model chain is the first building block of the integral approach. The second component is the so-called multi-model approach. That means that, as far as possible, the research in KLIWAS is based not only on one model and one scenario per modeling stage, but rather on many available models and scenarios in each case. This approach may at first be surprising, as it leads to a wider range of results than if only one model were used. Yet in many cases, no one single model can be given priority over another. In principle, of course, it is desirable to identify the best model or the best chain of models. In fact, however, this is not yet possible with the current state of data and the current process understanding of the complex connections in the Earth system. In KLIWAS, models that deviate greatly from observations are already excluded at the climate modelling level. The remainder, together with the previously mentioned correction process, form simulators of a possible future of equal value. On this basis, ranges of parameters of interest are determined by means of the subsequent models in the model chain. In a further step, a so-called scenario corridor is also defined using statistical methods, in which the majority of the project results are condensed.

Ensemble span: Dimension of uncertainty

It is obvious that uncertainties will be reproduced at every stage along the model chains. Every single model produces a "simplified picture of reality" and therefore does not take account of all influencing factors and links that occur in nature. The ensemble span (also called range or bandwidth) of results thus reflects the uncertainties of the modelling. This means in particular that it cannot be recommended to make far-reaching decisions on the basis of the results of one single model chain, for its study delivers statements about merely one possible future, but by no means about the future. This rigid approach sets standards that were not yet prevalent in the fields of science and technology, at least not at the beginning of the research programme. But the defined ranges should also not be overvalued in the sense that they represent only a limited number of climate scenarios and not all possible trends, and least of all the conceivable future scenarios (also those beyond climate development!). Whether the actual present that will occur in the future will lie within the scenario corridor of our current idea of the future depends on many factors. No clear predictions of the future are possible in any case. Yet the bundle of "possible futures" provides a starting point for the best-case and worst-case developments, thus giving decision-makers a basis on which to make decisions about adaptation measures under consideration of expense and damage potential, but also of social will and capability.

Adaptation options

For this reason, technical adaptation options to potentially changed conditions were also developed in the KLIWAS research programme, and their effect was assessed. These are based on scenarios, for example on different and equally potential changed discharges within an inland waterway. These options were also linked with the operational costs of navigation.

Our findings in brief:

- The KLIWAS research programme builds on the results of climate research. Comprehensive ranges of climate projections are linked to process models, creating projections for a large number of values, which are relevant for the management and the adaptation of the federal waterways. For the most part KLIWAS used the entire spectrum of climate model calculations that was available during its term.

- There is no such thing as the one, "true" prediction of future conditions. Depending on the model chain used, different developments are equally possible.

3.2 Reference data and climate projections for inland waters

In the context of KLIWAS, existing procedures for regionalising overland meteorological observation data were developed further in the DWD (Rauthe et al., 2013 and Frick et al, 2014). Regionalisation procedures were developed (e.g. linear multiple regression and semi-physical procedures) and bias correction methods (Imbery et al., 2013) were created to downscale statistically the climate projections of the parameters precipitation, temperature, relative moisture and global radiation to 5 × 5 km². In addition, software was developed for the climatological-statistical analysis of the HYRAS reference data and climate projections.

To analyse the observed climate time series in the observational period from 1951 to 2006 there are daily hydro-meteorological raster data (HYRAS) in the special resolution of 5 × 5 km² for the river catchment areas of the Rhine, Elbe and Danube which drain within Germany.

Table 1: Overview of the climate projections used for KLIWAS

DATA PROCESSING KLIWAS 1.02	INSTITUTE	FUNDED BY
ERA40_CLM2.4.6	ETHZ	EU-FP6 ENSEMBLES
ERA40_REMO5.7	MPI-M	EU-FP6 ENSEMBLES
ERA40_RM4.5	CNRM	EU-FP6 ENSEMBLES
A1B_BCM2_RCA3	SMHI	EU-FP6 ENSEMBLES
A1B_ECHAM5r1_CLM2.4.11	GKSS	BMBF
A1B_ECHAM5r3_RACMO2	KNMI	EU-FP6 ENSEMBLES
A1B_ECHAM5r3_REMO5.7	MPI-M	EU-FP6 ENSEMBLES
A1B_HadCM3Q0_CLM2.4.6	ETHZ	EU-FP6 ENSEMBLES
A1B_HadCM3Q0_HadRM3Q0	METO-HC	EU-FP6 ENSEMBLES
A1B_ECHAM5r3_HIRHAM5	DMI	EU-FP6 ENSEMBLES
A1B_ECHAM5r3_RegCM3	ICTP	EU-FP6 ENSEMBLES
A1B_HadCM3Q16_RCA3	C4I	EU-FP6 ENSEMBLES
A1B_ECHAM5r3_RCA3	SMHI	EU-FP6 ENSEMBLES
A1B_HadCM3Q3_RCA3	SMHI	EU-FP6 ENSEMBLES
A1B_ECHAM5r2_CLM2.4.11	GKSS	BMBF
A1B_ARPEGE_RM5.1	CNRM	EU-FP6 ENSEMBLES
A1B_ARPEGE_HIRHAM5	DMI	EU-FP6 ENSEMBLES
A1B_BCM2_HIRHAM5	DMI	EU-FP6 ENSEMBLES
A1B_HadCM3Q3_HadRM3Q3	METO-HC	EU-FP6 ENSEMBLES
A1B_HadCM3Q16_HadRM3Q16	METO-HC	EU-FP6 ENSEMBLES

The HYRAS data sets are available in the following versions:

- HYRAS Precipitation Version 2.0
- HYRAS Air Temperature Version 1.01
- HYRAS Relative Moisture Version 1.01

At the time of KLIWAS there were 17 post-processed climate projections for the SRES Scenario A1B, as well as three climate models (5 × 5 km² and bias-corrected) driven by reanalysis data (ERA-40) for the parameters precipitation, air temperature and global radiation for the period 1951 to 2100. For relative moisture there were regionalised (to 5 × 5 km²), non-bias corrected data sets. All climate projections available for Scenario A1B were used in KLIWAS, see Table 1: Overview of the climate projections used for KLIWAS.

For the analysis of the regionalised and corrected climate projection ensemble, the 15th and 85th percentile, amongst others, were formed. The 70 percent of the information in between can be seen as likely information from the ensemble. Then, from these 70 percent the ranges of possible changes in air temperature and precipitation were derived in Tables 5.1, 6.1, 7.1 of Chapters 5.1, 6.1 and 7.1.

In addition, the DWD conducted an analysis and created a visual representation of the original data sets in a spatial resolution of 25 × 25 km² (original resolution of the climate models) for Germany for the period 1961 to 2100. The analyses of 19 climate projections of Scenario A1B for the meteorological parameters and climate indices temperature, ice days, summer days, frost days, hot days, tropical nights and precipitation can be found in the DWD climate atlas under www.dwd.de/klimaatlas.

As well as the data processing, a concept for archiving and data provision was developed. This should safeguard a cross-departmental data management, the harmonisation of data sets, and the future provision of data.

The metadata sets on the 17 post-processed climate projections, the results of the objective weather conditions analysis of climate projections, and the HYRAS data, were entered into the Climate Data Centre (CDC) of the DWD. The climate projection data can be accessed directly via the web surface of the DWD, WebWerdis.

All of the data attained have been or will be published in the authorities' own portals. To ease research, a search function has been set up for all higher authorities involved in the KLIWAS research programme. This function can be found at www.kliwas.de under "Data, services, models".

The climate data for the analyses in the area of the North Sea are described in Chapter 4.1.

Our findings in brief:

- In KLIWAS, regionalised, river basin-related data sets of overland meteorological observation data were created.
- Regional climate projections were refined in their spatial resolution (5 × 5 km²) and bias-corrected for further effective modelling.
- 17 different climate projections of Scenario A1B were available for the further analysis of the impacts of climate change (analysis of ranges).
- Furthermore, the climate development for the KLIWAS area (see Figure 1) was analysed for the past and the near and distant future, based on the prepared data sets.

3.3 Methods for estimating the degree of impact

The results of research in KLIWAS are generally ranges of possible future developments within the parameters that are relevant to one field of action. This now raises the practical question as to what extent there is a “need for action”.

Here, the need for action should be understood in the sense of a prioritisation, in which it is identified which combination of field of action, river basin and time horizon requires particular attention from the institutions responsible, including the detailed inspection and assessment of possible effects caused by climate change. The question of whether such defined “need for action” must then actually lead to a “need for adaptation” for the waterways must be examined later, possibly in further analytical steps.

A simple analysis pattern was developed and applied to some parameters, in order to classify objectively the changes ascertained in terms of their significance for the different areas of action, both regionally and temporally. First the relevant scenario corridors were assessed with regard to the criteria “signal intensity” and “trustworthiness”, each of which is divided into three categories (o, +, ++). The combination of signal intensity, including the direction, and trustworthiness is used to form an indicator for a “need for action”.

The categorisation for both criteria depends on the position, the range and the marginal values of the scenario corridors (see Table 2: Explanation of the symbols in Table 3 and definition of the limit values):

A signal intensity greater than “o, neutral” is given when the scenario corridor shows a direction, quantified by a suitable measure for an asymmetry in the distribution of the members of the ensemble. To demarcate a classification in “+, signal” or “++, strong signal” a limit value is defined for the percentage amount of the least favourable marginal for each area of action in the defined scenario corridor.

Trustworthiness is connected to the range of the scenario corridor. The wider it is, the more blurred the projected future picture and the lower the basis of trust in the result. Three categories are also defined here (o not, + low, ++ highly trustworthy).

A need for action is given where there is a sufficiently clear change signal. This is established, for example, when at least the category “+” is present for both criteria, “signal intensity” and “trustworthiness”. In cases in which many parameters are relevant to a field of action, the analysis pattern can be easily expanded. The user of the pattern is free to define other criteria or to apply a different relevance to different combinations (e.g. “+”-“+” vs. “++”-“++”).

The system described is a model for the – in itself consistent – identification of a “need for action”, The (subjective) choice of the “parameters” of the method described, namely the category boundaries, determines the identification sensitivity, which can be adapted accordingly to the needs of those responsible by means of variation.

Table 2: Explanation of the symbols in Table 3 and definition of the limit values

Criterion	Symbol/class	Condition/significance
Signal intensity	++	Scenario corridor shows direction and change > 15 % (relevant marginal value)
	+	Scenario corridor shows direction and change ≤ 15 % (relevant marginal value)
	o	Scenario corridor shows no direction
Trustworthiness	++	Span of scenario corridors mostly ≤ 20 %
	+	Span of scenario corridors mostly > 20 % and ≤ 30 %
	o	Span of scenario corridors mostly > 30 % and/or methodical reservations

If the objective of action is to preserve or improve the current situation, such an identification pattern will be defined all the more sensitively as a result.

A tabular analysis with the following headers is suitable for application:

1. Area of action
2. Relevant hydrological parameter(s)
3. Associated parameter(s) for which the scenario corridor is known
4. Observed (partial) river catchment area
5. Periods "near future" and "distant future"
6. Each period divided into "signal intensity" and "trustworthiness"

Taking the example of Project 4.01[3] the parameters of the previously described method were defined as explained below, under the premise that the objectives of the administrative action do not change and the current situation should be maintained or improved.

Table 2 first shows the categories of the criteria used, "signal intensity" and "trustworthiness", dependent on the marginal values and the width of the scenario corridor. It is assumed that the scenario corridors show a direction if at least three-quarters of the range lies on one side of the neutral axis (these are the coloured cells of the tables in Chapters 5.2, 6.2 and 7.2).

To classify the "signal intensity", the limit between "+" and "++" was set at 15 percent, based on the experiences from discussions with interest groups.

"Trustworthiness" was classified for widths of more than 30 percent in "o", for widths below 20 percent in "++", and all those in between in "+".

This produced the prioritised need for action visible in Table 3 differentiated according to area of action/parameter. Only those combinations are listed that have at least one "+". A need for action is derived only from those combinations with at least "+" and under the assumptions made ("soon" or "from 2050"), otherwise none in the period studied. The illustration focuses on the compensation of negative climate consequences. No potential need for action that derives from positive developments, e.g. the higher low water discharges projected for the Rhine in the near future, are shown. Furthermore, the analysis is restricted to the selected river basins, areas of action, and periods that were addressed in Project 4.01. No claim to completeness or generalisability can be made. It is a pattern that, depending on the parameters set, makes a systematic, prioritising selection from all possible combinations of area of action, river basin and time horizon.

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[3] KLIWAS Project 4.01: Climate-related changes to the water balance and water levels, options for action for inland navigation and the transshipping economy.

Our findings in brief:

KLIWAS has produced climate signals for a large number of parameters, differentiated according to areas of action, river basins, and time periods, whose uncertainty is given due to the different ranges or scenario corridors. The question now is whether there is a need for action, and which cases deserve priority. The systematic models presented here allow us to classify this variety according to uniform criteria and thus to make a priority selection in a consistent manner of all possible combinations of areas of action, river basins and time periods. By varying the category limits and criteria, the selectivity of the methods can be varied. The prioritised need for action shown in Table 3 is produced by the contents of Chapters 5 to 7, in combination with the category limits and criteria defined in this chapter.

Table 3: Selected uses/functions in the area of water management with a grading of the need for action with regard to the impacts of climate change as presented in Project 4.01, differentiated according to area and period

No.	**Uses/functions depending on**	**Parameter (mean from 30 annual values)**	**Need for action**		**Assessment**	
			Area	**Period**	**Signal intensity**	**Confidence**
1	Water supply (e.g. water abstractions)	MQ, Hydrological year (Nov – Oct)	Rhine	none	o	+
			Elbe	from 2050	++	+
			Danube	from 2050	++	+
2	Summer discharge (e.g. water resource management)	MQ, Hydrological summer (May – Oct)	Rhine	from 2050	++	++
			Elbe	soon	+	++
			Danube	soon	+	++
3	Minimum water volume (e.g. fish migration, navigability)	NM7Q*, Water balance year (Apr – Mar)	Rhine	from 2050	+	++
			Elbe	from 2050	++	+
			Danube	soon	+	++
4	Mean annual high water discharge (sediment management, navigability)	HM5Q**, Hydrological year (Nov – Oct)	Rhine	soon	+	++
			Elbe	soon	++	+
			Danube	none	o	+

* for Danube parameter NMoMQ.
** for Danube parameter HMoMQ.

4. Coastal and marine waters

4.1 Climate, climate impacts and sea levels: North Sea and the Northeast Atlantic

Background and method

Global climate models are the foundation of every estimate of future climate-related changes to the environment. However, for regional applications, for example to determine possible changes in the North Sea, these models do not resolve enough spatially, such that they must be downscaled to an appropriate special scale, i.e. regionalised. These results are examined according to different parameters, including wind direction and velocity, water levels, air and water temperatures and salt content.

Numerical simulations of the incredibly complex natural conditions use simplifying assumptions when describing the exchange of energy and impulses between the individual components of the climate system. Different mathematical approaches and transfer rates are often used. As all of the model approaches could be correct, the resulting climate projections are also probable. For this reason, an ensemble of models is generally considered in order to take account of existing differences between the models used. The breadth of all results for a certain parameter is then called the range (see Chapter 3.1). Regional climate models (RCM) are embedded in global climate models; they get marginal values as a physical driver from global models (GCM). Thus, the results of the RCMs contain, in addition to their own uncertainties, also those of the driving GCMs. The consequence of this is that ranges can barely be reduced by regionalisation. An ensemble of regional models that is driven by one single global climate model, or by a family of models that are very similar to each other, usually produces similar results in the regionalised modelling.

Improved and new climatologies

Climate projections are not predictions of future conditions, for they build on assumptions of possible future trends, e.g. with regard to the development of greenhouse gas emissions. The plausibility of the model results can be assessed by comparing the climate model runs with observations or measurements for periods in the past. We have compared the modelling results of a reference period (1961 to 1990) with climate models with meteorological measurement data (station data, ship observations) from this period and with model-supported reanalyses. The deviation of the modelled data from the measured data is an indication of the quality of the models.

While there are meteorological measurement data of a high temporal and spatial resolution on the mainland, there is a lack of comparable values at sea. That also applies to the North Sea. Compared to the mainland, there are very few continuously registering permanent measurement stations at sea. One must often rely on ship observations. These are mostly made by trading ships that travel along fixed shipping routes. The spatial and temporal coverage of these observation data are therefore usually fragmentary. Some ship observations are based on estimates, for example in the case of sea state and cloud cover. Therefore, to ensure comprehensive climatologies of the North Sea, for instance, the observations of many ships are used.

The spatial grid of global meteorological reanalyses is much too coarse for the North Sea. In some cases, observation data and reanalyses deviate clearly from each other in coastal areas, as the influences of the land climate are “dragged” mathematically far out to sea. The use of global reanalyses for regional studies in seas is therefore problematic; improved climatologies and regional reanalyses are required for the atmosphere and the ocean.

To improve the validation basis, we developed new climatologies for the North Sea (atmosphere and ocean), jointly with the University of Hamburg (ICDC). Measurement data were processed with certain filtering and interpolation methods. These new climatologies offer a much improved basis for the forcing and the validation of regional climate projections.

To validate climate projections with regard to information about the occurrence and dynamics of oceanographic structures, a climatology of the oceanic fronts in the North Sea was developed on the basis of satellite observations. Fronts are meso-scale structures. They separate bodies of water with different physical, chemical, biological and dynamic characteristics. Fronts are also areas of increased biological productivity (Klein, 2012) and are therefore important for the ecology.

Our findings in brief:

- The newly developed climatologies for the North Sea with a spatial resolution of app. 0.25° × 0.50° for the ocean and 1° for the atmosphere, as well as a temporal resolution of one month, are based solely on quality-assured observation data.

- The new climatologies provide a much improved basis for the forcing and the validation of regional climate projections.

- Temporally and spatially variable partial climatologies can be generated.

- Specific statistical evaluations can be conducted for all KLIWAS-relevant parameters.

- A newly developed climatology for oceanic fronts in the North Sea is based on satellite observations. It enables the validation of the oceanic dynamics in climate projections.

- The climatology fronts newly developed in KLIWAS, and the methodology of its generation, has been adopted as a core service by the European COPERNICUS programme (formerly GMES).

Analysis of the EU ENSEMBLES projections for the North Sea area

In the context of KLIWAS, we analysed the uncoupled regional climate projections of the EU ENSEMBLES project (see also Hewitt & Griggs, 2004), which included the North Sea area, with regard to its statements relating to possible climate changes (atmosphere) and its fitness for the prognosis of meteorological parameters that are relevant to shipping. Uncoupled in this case means that interactions between the sea and the atmosphere are ignored in the regional climate models. The behaviour of the sea is prescribed in the form of a climatology and is static. This is a simplification and does not represent actual natural conditions (see below, chapter on “Regionalised coupling of ocean-atmosphere models”).

In order to quantify the deviations of the individual ENSEMBLES model results from the natural conditions, we compared the projections with the reanalysis ERA-40. Reanalyses are observation data extensively extrapolated with the help of weather models, and they are considered to be good approximations of natural conditions.

Depending on the model combination, the comparison of the uncoupled regional ENSEMBLES projections with the reanalysis ERA-40 shows greater or lesser, and at times even abnormal, deviations. However, reanalyses can also demonstrate weaknesses: so, for example, on the one hand their special resolution is too rough for regionalisation, such that the variability is curbed. On the other hand, mainland influences are extrapolated far into the open North Sea.

The analysis of the ENSEMBLES projections with regard to atmospheric parameters that are relevant to shipping, such as wind direction, wind strength and values derived from these (e.g. sea state, wind surges) over a period of 140 years (1960 to 2100) reveal significant positive and negative trends, as well as insignificant trends concerning the North Sea; however, these are very low. The time series are dominated by large variability across the decades.

Wind-dependent parameters such as sea state and storm surges show similar behavioural patterns to those of the wind.

With regard to the possible future impacts on shipping, we can summarise by stating that the analyses of ENSEMBLES and individual model combinations of the A1B scenario do not lead us to expect any substantial changes for the North Sea. The range of results is based on variability-related effects within the models and is strongly influenced by the non-systematic selection of the models and model runs used by the ENSEMBLES project.

Our findings in brief:

- In the EU ENSEMBLES project, the interactions between the sea and the atmosphere were ignored (uncoupled modelling). This created a necessity in KLIWAS to conduct coupled regional modelling (see below).

- The influence of the global climate models used in each case in ENSEMBLES strongly affects the regionalisation.

- In the validation of the ENSEMBLES model configuration used, the climate parameters deviate more or less from a reanalysis.

- Global atmospheric reanalyses are of limited value for validation of the North Sea, because a continental influence is extrapolated out into the sea area.

- Wind direction and wind strength are subject to great variability. Significant positive and negative trends for the period 1960 to 2100 are so low that no uniform statement can be made. This also applies in essence to wind-dependent phenomena such as sea state.

- Taking the assumption of Scenario A1B, storm surges will remain at the current level in terms of frequency and strength, both in the near and in the distant future.

- In terms of sea state, an increase was registered for the eastern North Sea and a decrease in the western North Sea. In the eastern German Bight (especially the Schleswig-Holstein coast), an increase of the significant wave height of up to +10 percent is possible by 2100. As no increases in wind strength can be established, this may be a result of changes in wind direction during strong winds.

- The analysis of the model ensemble and of individual model combinations of Scenario A1B does not suggest any restrictions to shipping.

Regionalised coupling of ocean-atmosphere models

Previous regionalisations carried out for the North Sea, for example in the EU ENSEMBLES project, were conducted with uncoupled models for atmosphere and ocean. That is unrealistic insofar as the ocean is not merely a recipient of climate signals from the atmosphere. Rather, the atmosphere influences the ocean, which then feeds back into the atmosphere. Until now, however, this feedback has been ignored in modelling. Therefore, to develop more realistic climate projections for the North Sea, we elaborated a small ensemble of regional coupled ocean-atmosphere climate models jointly with the MPI for Meteorology, the University of Hamburg, the Climate Service Center and the Swedish Meteorological and Hydrological Institute (SMHI).

The results derived from coupled models gave much better and more realistic results in the validation than the uncoupled models (Table 4 to Table 6). Despite this methodical progress, the inherent uncertainties of climate models remain. The results could be more robust, possibly by means of an expanded model ensemble.

If our results to date are confirmed in the future (Table 5, Table 6), there are clear signs of change, especially in the ecosystem of the North Sea. It is likely that fewer nutrients would be brought into the North Sea from the reduced and more stable top stratum of the northeast Atlantic, which could lead to a declining trophic state. Changed temperatures and salt content could influence the species spectrum. Weakened circulation would change the transport of sediment as well as of fish and other larvae.

Our findings in brief:

- The coupling of ocean and atmosphere models on regional scales such as the North Sea is useful, as that takes into account the interactions between the sea and the atmosphere.
- Regional couplings are technically possible to conduct.
- Regionally coupled ocean-atmosphere models produce much better results than uncoupled models. The ranges of climatological parameters are usually reduced considerably.
- In the coupled projections, sea and air temperatures increase considerably by the end of the century: water temperatures on an average by up to +2.5 °C, air temperatures by up to +2.8 °C, whereby in the cold half of the year the warming may exceed +3 °C.
- The salt content declines slightly due to increased precipitation and a stronger flow of Baltic Sea water into the North Sea.
- Changed conditions of sea currents and increased water temperatures could lead to severe changes in the ecosystem of the North Sea.

Table 4: Ranges of deviation in oceanic parameters in the North Sea in the period 1961 to 1990 for the near future (2021 to 2050) and the distant future (2070 to 2099), derived from the regionally coupled climate models of KLIWAS

		Range of change	
Parameters	**Seasons**	**Near future 2021 to 2050**	**Distant future 2070 to 2099**
Water temperature (surface)	Annual mean	+0.6 °C to +1.4 °C	+1.8 °C to +2.5 °C
	DJF	+0.6 °C to +1.4 °C	+1.9 °C to +2.7 °C
	MAM	+0.5 °C to +1.9 °C	+1.8 °C to +3.0 °C
	JJA	+0.6 °C to +1.2 °C	+1.6 °C to +2.3 °C
	SON	+0.8 °C to +1.2 °C	+1.7 °C to +2.3 °C
Salt content	Annual mean	−0.07 psu to +0.04 psu	−0.26 psu to −0.05 psu
	DJF	−0.05 psu to +0.04 psu	−0.24 psu to −0.04 psu
	MAM	−0.05 psu to +0.01 psu	−0.24 psu to −0.07 psu
	JJA	−0.08 psu to +0.05 psu	−0.27 psu to −0.04 psu
	SON	−0.09 psu to +0.06 psu	−0.27 psu to −0.04 psu
Sea level***	Annual mean	+0.07 m to +0.08 m	+0.25 m to +0.26 m
	DJF	+0.07 m to +0.09 m	+0.24 m to +0.25 m
	MAM	+0.07 m to +0.08 m	+0.27 m to +0.28 m
	JJA	+0.06 m to +0.08 m	+0.24 m to +0.26 m
	SON	+0.07 m to +0.08 m	+0.24 m to +0.26 m

*** For the sea level rise, only the contributions caused by global ocean warming (steric) and changed wind and current dynamics in the North Sea are listed in this table. However, in addition to parameters such as global steric expansion, the possible loss of ice from Greenland and Antarctica and, resulting from this, changes in the gravitational attraction of these land masses on the oceanic water masses, other effects not yet quantified must be kept in mind.

Table 5: Range of changes in the near future (2021 to 2050): Comparison between the uncoupled projections of the EU ENSEMBLES project and the regionally coupled projections of KLIWAS

		Range of change in the near future	
Parameters	**Seasons**	**EU ENSEMBLES**	**KLIWAS coupling**
Air temperature at height of 2 m	Annual mean	+0.7 °C to +1.9 °C	+0.9 °C to +1.6 °C
	DJF	+0.6 °C to +2.0 °C	+0.5 °C to +1.7 °C
	MAM	+0.8 °C to +1.8 °C	+0.7 °C to +2.0 °C
	JJA	+0.5 °C to +1.9 °C	+0.6 °C to +1.3 °C
	SON	+0.7 °C to +1.9 °C	+0.8 °C to +1.5 °C
Wind velocity	Annual mean	−0.06 m/s to +0.15 m/s	−0.15 m/s to −0.06 m/s
	DJF	−0.16 m/s to +0.36 m/s	−0.26 m/s to +0.09 m/s
	MAM	−0.16 m/s to +0.21 m/s	−0.38 m/s to −0.03 m/s
	JJA	−0.09 m/s to +0.17 m/s	−0.16 m/s to +0.09 m/s
	SON	−0.18 m/s to +0.32 m/s	−0.07 m/s to +0.05 m/s
Degree of cloud cover	Annual mean	−2.6 % to +0.3 %	−1.2 % to +0.8 %
	DJF	−2.4 % to +0.2 %	−1.1 % to +0.1 %
	MAM	−4.7 % to +0.7 %	−5.7 % to +0.7 %
	JJA	−5.6 % to +2.2 %	+1.0 % to +2.8 %
	SON	−2.1 % to +1.6 %	−0.5 % to +2.0 %
Precipitation	Annual mean	+0.8 % to +8.3 %	−4.9 % to +2.0 %
	DJF	+0.4 % to +14.9 %	−3.7 % to +1.4 %
	MAM	−6.7 % to +10.9 %	−15.5 % to−1.4 %
	JJA	−3.9 % to +7.4 %	+0.4 % to +5.5 %
	SON	+1.0 % to +15.5 %	−4.5 % to +5.6 %
Shortwave net radiation	Annual mean	−3.3 W/m^2 to +2.9 W/m^2	−2.0 W/m^2 to −0.9 W/m^2
	DJF	−1.1 W/m^2 to +2.5 W/m^2	−0.4 W/m^2 to +0.2 W/m^2
	MAM	−4.1 W/m^2 to +3.0 W/m^2	−2.1 W/m^2 to +4.7 W/m^2
	JJA	−7.2 W/m^2 to +7.4 W/m^2	−6.9 W/m^2 to −3.6 W/m^2
	SON	−2.7 W/m^2 to +1.6 W/m^2	−1.7 W/m^2 to −1.5 W/m^2
Longwave net radiation	Annual mean	−0.4 W/m^2 to +3.0 W/m^2	+1.4 W/m^2 to +2.0 W/m^2
	DJF	−0.3 W/m^2 to +2.9 W/m^2	+0.5 W/m^2 to +2.2 W/m^2
	MAM	−1.7 W/m^2 to +2.9 W/m^2	−0.9 W/m^2 to +1.8 W/m^2
	JJA	−1.8 W/m^2 to +3.6 W/m^2	+1.1 W/m^2 to +2.7 W/m^2
	SON	−0.9 W/m^2 to +3.5 W/m^2	+1.6 W/m^2 to +3.7 W/m^2

Table 6: Range of changes in the distant future (2070 to 2099): Comparison between the uncoupled projections of the EU ENSEMBLES project and the regionally coupled projectionsof KLIWAS

		Range of change in the distant future	
Parameters	**Seasons**	**EU ENSEMBLES**	**KLIWAS coupling**
Air temperature at height of 2m	Annual mean	+1.8 °C to +3.7 °C	+1.4 °C to +2.8 °C
	DJF	+1.9 °C to +3.7 °C	+2.1 °C to +3.1 °C
	MAM	+1.8 °C to +3.3 °C	+2.1 °C to +3.2 °C
	JJA	+1.6 °C to +3.5 °C	+1.8 °C to +2.4 °C
	SON	+1.7 °C to +4.0 °C	+1.9 °C to +2.7 °C
Wind velocity	Annual mean	−0.26 m/s to +0.25 m/s	−0.18 m/s to −0.06 m/s
	DJF	−0.52 m/s to +0.55 m/s	−0.10 m/s to +0.12 m/s
	MAM	−0.15 m/s to +0.34 m/s	−0.45m/s to −0.03 m/s
	JJA	−0.23 m/s to +0.25 m/s	−0.10 m/s to −0.02 m/s
	SON	−0.24 m/s to +0.26 m/s	−0.14 m/s to −0.05 m/s
Degree of cloud cover	Annual mean	−3.8% to +1.9%	+1.7% to +3.4%
	DJF	−2.6% to +2.1%	+1.0% to +1.4%
	MAM	−3.4% to +2.7%	−2.1% to +2.0%
	JJA	−10.0% to +3.6%	+3.9% to +7.0%
	SON	−3.5% to +1.5%	+1.5% to +3.9%
Precipitation	Annual mean	−1.3% to +15.5%	+5.0% to +10.2%
	DJF	+9.2% to +22.2%	+7.0% to +17.1%
	MAM	−4.2% to +24.7%	−4.0% to +9.7%
	JJA	−14.8% to +10.3%	+2.4% to +5.6%
	SON	−5.4% to +24.6%	+6.6% to +9.2%
Shortwave net radiation	Annual mean	−7.0 W/m^2 to +3.6 W/m^2	−7.4 W/m^2 to −5.7 W/m^2
	DJF	−2.9 W/m^2 to −0.3 W/m^2	−1.3 W/m^2 to −1.0 W/m^2
	MAM	−12.4 W/m^2 to +2.2 W/m^2	−6.9 W/m^2 to −1.6 W/m^2
	JJA	−13.4 W/m^2 to +10.7 W/m^2	−17.2 W/m^2 to −13.1 W/m^2
	SON	−4.2 W/m^2 to +2.0 W/m^2	−4.1 W/m^2 to −3.3 W/m^2
Longwave net radiation	Annual mean	+0.6 W/m^2 to +6.4 W/m^2	+4.7 W/m^2 to +7.2 W/m^2
	DJF	+1.5 W/m^2 to +6.3 W/m^2	+4.3 W/m^2 to +5.0 W/m^2
	MAM	−0.7 W/m^2 to +5.7 W/m^2	+2.3 W/m^2 to +4.9 W/m^2
	JJA	−2.1 W/m^2 to +8.1 W/m^2	+5.1 W/m^2 to +11.4 W/m^2
	SON	+1.2 W/m^2 to +7.0 W/m^2	+4.5 W/m^2 to +8.2 W/m^2

Studies on sea level rise

The mean sea level in the areas of the North Sea coast that are influenced by tides and anthropogenic activities is a parameter that is calculated from the water level curves of the coastal gauges. The water level at a particular place is composed primarily of the current astronomical tide and the surge caused by the wind (wind surge). Of these two, only the latter can vary according to climate.

A number of climate-related processes contribute to the global changes in sea level. The most important are the thermal (steric) expansion of oceanic water, the melting of mountain glaciers, and ice losses from the continental ice sheets of Greenland and the Antarctic, including the changes in the gravitational attraction caused by the latter. Regional modifications of the global sea level rise are caused by changes in wind systems and the reduced gravitational forces of the two big ice sheets. Tectonic rising or sinking of coastal sections cause an apparent, relative change to sea levels. As the loss of the ice sheets cannot be determined with any certainty, current findings are provisional.

In the long-term behaviour of the mean sea level (MSL) and the extreme water levels, significant fluctuations in tide levels were demonstrated in the German Bight for the recording period 1900 to 2008: until the 1950s, changes to the water levels were coupled primarily with the fluctuations of the MSL. In contrast, in the second half of the 20th century, a significantly diverging development dominated. In other words, since the end of the 1950s and since the beginning of the 1960s the trends of the MSL and of the extreme high and low water levels are divergent. While, independently of the current sea level rise, the extremely high percentiles show significantly larger positive trends than the MSL, the lower percentiles are characterised by significantly negative trends. Accordingly, changes in the extreme water levels are not necessarily coupled with changes to the MSL. This makes it more difficult to project into the future. The values shown in Table 3 for the future sea level contain only those percentages that are caused by the warming of the ocean water and by changes in wind and flow conditions.

Our findings in brief:

- Since the 1950s, at the coasts of the inner German Bight high and low water levels have developed differently to the trend of the mean sea level. Extreme high water levels show a stronger positive trend than the mean sea level, while extreme low water levels show a negative trend. The causes are probably not related to climate.
- Until the end of the century, the rise in mean sea level, caused by the warming of the global ocean and by changed wind conditions over the North Sea, may reach app. +0.25 m. The portions arising from the melting of mountain glaciers and continental ice sheets are not included in the consideration.
- Uncertainties continue to result from the lack of knowledge to date about the possible ice loss that may occur due to the changed dynamic of the continental ice sheets on Greenland and the Antarctic.

Studies of sea state on the North Sea

Our results from the studies on sea state come from uncoupled modelling. For an analysis of the present-day mean and extreme sea state, and the expected future changes, the period from 1961 to 2100 was divided into four 30-year periods: the period 1961 to 1990 as a reference period, the periods 2011 to 2040, 2041 to 2070 and 2071 to 2100 reproduce the corresponding future states in the climate runs. The mean and the 99th percentile (highest values) of the significant wave height (SWH) were investigated.

Our findings in brief:

For the mean significant wave height and its 99th percentile, a decreasing tendency (maximum up to −10 percent) in the annual mean is discernible for the western North Sea by the end of the century, while for the eastern North Sea, i.e. the German Bight, there is an increasing tendency (maximal up to +10 percent) in the annual mean. The extreme values could be some percentage points higher or lower in the different seasons.

Studies on storm surges in the German Bight

Storm surges in the North Sea can be generated through spatially very limited storm areas with a relatively short passage period of less than a day. The number of storm surges observed fluctuates strongly from year to year.

Our findings in brief:

In the climate model results until 2100, the temporal fluctuations of the annual number of storm surge-related events are much greater than the linear trend. No significant change in storm surge frequency is discernible.

4.2 Tidal characteristics and wave statistics (coast)

The analysis of climate change-related changes to oceanographic parameters presented in Chapter 4.1, which did not include tides, was supplemented in coastal areas and in the North Sea estuaries with a study of the climate change-related change to the tidal parameters (high tide level, low tide level, tidal range, flood period and ebb period) as well as the wave parameters in the immediate area of the coasts and the estuaries (wave heights, wave periods). Changes to tidal parameters and waves that have already occurred were determined on the basis of available water level and wave measurements. Future changes to these parameters were estimated exemplarily for one of the model chains shown in Chapter 4.1, expanded to include tides.

Historical changes to tidal parameters and wave statistics

Mean tide level:

Without the influence of the subsidence of the mainland, the increase of the mean tide level as determined over the past 100 years at the river mouth gauges of the estuaries Ems, Weser and Elbe is +1.1 to +1.9 mm per year. When corrected to take account of the influence of land subsidence, this value is +1.6 to +2.9 mm per year. No acceleration of the increase in mean tide level is discernible at the river mouth gauges of the estuaries Ems, Weser and Elbe for the last 100 years (Hein et al., 2011a).

High tide, low tide, tidal range, ebb period, flow period

The tidal parameters that are of particular importance in coastal engineering and coastal waterways construction demonstrate strong regional differences. On average, an increase in high tide of +0.28 cm is shown for the level of the German North Sea as described in Table 7, while the increase in low tide is on average +0.02 cm per year, thus an enlargement of the tidal range can be established. In terms of flow period, an increase of around +1 percent can be established at selected gauges on the German North Sea coast, although regionally, e.g. at the gauges of "Bremerhaven Alter Leuchtturm" and "Leuchtturm Alte Weser", there is a reduction of up to −1 percent. An increase in flow period is accompanied by a corresponding reduction in ebb period.

Phase shift of the tidal characteristics

The increase in mean tide levels is generally (i.e. only with a low morphological reaction) accompanied by an enlargement of the mean water depth. This leads to an increase of propagation speed of the tidal wave and therefore to a shortening of propagation time along the coast. It can be seen, for example, that in terms of high tide, in the secular mean, the propagation time from Borkum (Ems estuary) to the "Leuchtturm Alte Weser" (Weser estuary) had shortened by app. 3 minutes per 100 years, and in terms of low tide, by app. 23 minutes per 100 years.

Future changes to tidal characteristics and wave statistics

Mean tide level

Future changes to tidal characteristics are estimated exemplarily for one of the model chains shown in Chapter 4.1. In order to standardise the model chain with the tide level measurement values, the model chain must be supplemented by an estimate, not considered in Chapter 4.1, of the increase in sea level resulting from the melting of the ice sheet and also from astronomic tides. The resulting model chain, which includes tidal characteristics (ECHAM 5 / MPIOM, REMO, HAMSOM, HAMSOM Elbe), demonstrates the increase in mean regional sea level (mean tide level) as shown in Figure 3 for an IPCC-based scenario of the global increase in mean sea level (Mathies 2013).

In contrast to the historical change to the mean tide level (which can also be determined from gauge records, for example), when taking the global IPCC scenarios as a basis, an acceleration in changes to mean tide levels can be expected for the future. The causes of this are primarily the accelerated warming of oceanic waters (see Chapter 4.1), but also an increase in the melting of the ice sheets. Thus the acceleration of the increase in mean tide levels in the North Sea corresponds with the global changes to mean tide levels as predicted by the IPCC. However, there are no local reasons for an accelerated increase in mean tide levels in the North Sea.

Table 7: Linear increase in tidal characteristics at selected gauges

	Rate of increase		
Gauging station	**High tide [cm/a]**	**Low tide [cm/a]**	**Tidal range [cm/a]**
Borkum Südstrand (BORS)	+0.23	+0.12	+0.21
Borkum Fischerbalje (BORF)	+0.31	+0.14	+0.16
Emden Neue Seeschleuse (EMDN)	+0.34	−0.26	+0.59
Bremerhaven (BH)	+0.24	−0.27	+0.51
Leuchtturm Alte Weser (LHAW)	+0.27	+0.15	+0.15
Cuxhaven (CUX)	+0.27	+0.08	+0.18
Büsum (BU)	+0.29	+0.20	+0.09
Helgoland (HELG)	+0.26	+0.03	+0.22
Average value	**+0.28**	**+0.02**	**+0.26**

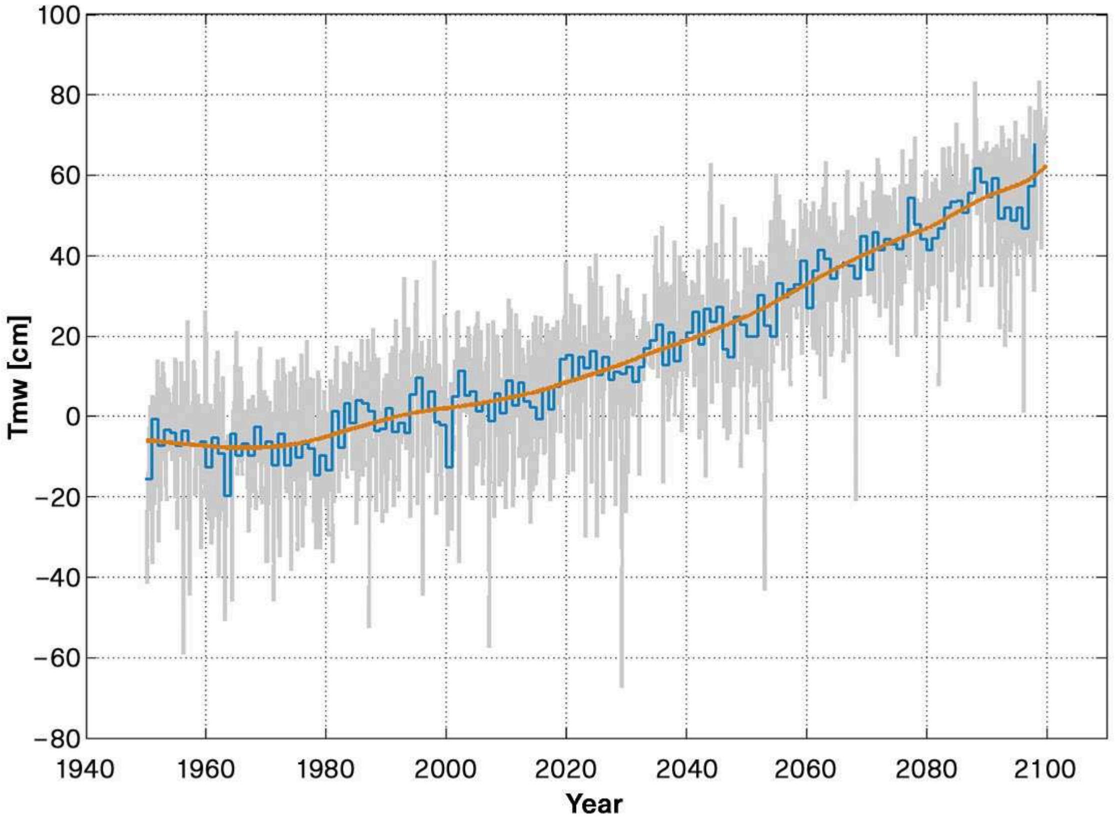

Figure 3: Estimate of the rise in sea level at the German North Sea coast from the model chain (ECHAM 5/MPIOM, REMO, HAMSOM, HAMSOM Elbe) taking the example of Cuxhaven gauging station

High tide, low tide, tidal range, ebb period, flow period

Our results for the tidal characteristics also show a differentiated picture for the future. At the Cuxhaven gauging station, in the event of an increase in mean tide levels as illustrated in Figure 3, an increase in high tide of +22 cm can be expected in the near future (2031 to 2050) and of +60 cm in the distant future (2081 to 2100)[3]. A smaller increase in low tide is also to be expected in the future. The Cuxhaven level shows an increase of +18 cm in the near future (2031 to 2050) and of +50 cm in the distant future (2081 to 2100).

With regard to ebb and flow duration, the model chain ECHAM 5/MPIOM, REMO, HAMSOM, HAMSOM Elbe would suggest an increase, respectively decrease of 1% in the near future and 1% to 2% in the distant future for Cuxhaven.

Sea state

To examine future wave conditions, the model chain including tidal characterisapp.tics (ECHAM 5/MPIOM, REMO, HAMSOM, HAMSOM Elbe) was linked to the SWAN wave model using statistical methods. While an increase in significant wave height can be established on the open North Sea coast, no trend is discernible in the Elbe.

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[3] The interval of only 19 years corresponds approximately to the period of the nodal tide (app. 18.67 years). If a 30-year time interval were used, the change signal would in part be “contaminated” by the natural periodicity of the nodal tide in a tidal observation.

Our findings in brief:

- At the river mouth gauges of the Ems, Weser and Elbe estuaries there was an increase in mean tide levels of between +11 and +17 cm in the last 100 years.
- High tide increased at these gauges by app. +28 cm ±2 cm per 100 years.
- At the same time, there was an inconsistent change of between +2 cm ±7 cm for low tide.
- Currently, no significant changes in the wave statistics for the North Sea estuaries are discernible.
- On the basis of the model chain (including tidal characteristics) and taking account of a typical IPCC scenario for global sea level increase, it can be seen that future changes to tidal characteristics will be greater than those observed in the last 100 years. In the distant future, a doubling of the rate of change cannot be ruled out.
- Where historical and future changes to tidal characteristics are concerned, the changes are subject to large temporal and spatial uncertainties and variables.

4.3 Geodetic contributions to KLIWAS

To attain a better assessment of the results of the rise in sea levels, the recordings by the gauges, and in particular the referencing of the gauge data, must be analysed. In the past, corrections were made to the heights of the gauge datum in some cases, which meant that the physical gauge datum, i.e. the staff gauges, was shifted. In order to derive long-term trends it is necessary to record corresponding changes based on the gauge records and to correct the water level time series accordingly.

As well as changes to the gauge datum due to the shifting of the staff gauges, vertical land movements must also be considered when analysing the increase in sea level. Such movements cause the land to sink or rise, and with it the gauges installed on it. The gauges therefore “dip” deeper or shallower into the water, leading to the recording of apparent changes to the water level. It is not possible to derive corresponding height changes on the basis of official ordnance surveys. For this reason the BfG installed GNSS (Global Navigation Satellite System) sensors, which enable the monitoring of such movements. Initial results (see Table 8) show more or less distinct changes, depending on the station (e.g. Borkum Fischerbalje: May 2009 to April 2011 change of −1.4 mm per year), though these cannot as yet be categorised as significant due to the short time series.

As well as the gauges, satellite altimetry provides a completely independent possibility to record sea level (see Figure 4). The sea surface is measured from satellites at a maximum interval of 10 days and described extensively. The intermittent and high time resolution level observations are supplemented very well by the extensive altimeter observations. It was established in the context of KLIWAS that both systems demonstrate a very high degree of agreement (a few cm), where direct gauge and altimeter observations are used instantaneously with each other (see for example Figure 5). The usual method for correcting tides and displacement effects on the basis of models is not expedient, as the correction models do not provide a sufficiently precise description of reality in the area of the German coasts.

Table 8: Heights and changes to heights at selected GNSS gauges

		Elliptical height 2008 to 2010		Amplitude	Linear Trend	Standard deviation
Station	**Epochs**	**Mean value [mm]**	**Standard deviation [mm]**	**Annual fluctuation [mm]**	**Without annual fluctuation [mm/year]**	**of the residues [mm]**
E2 (Hörnum)	170	62.728	2.8	n.n.	−0.1	3.1
HELG (Helgoland)	170	48.406	3.5	n.n.	0.2	3.7
TGKN (Knock)	128	53.419	2.8	2.1	−1.4	3.0
FLDW (Unterfeuer Dwarsgat)	140	58.990	2.9	2.7	−0.7	3.3
LHAW (LT Alte Weser)	128	68.262	3.3	3.5	−0.4	4.0
TGCU (Pegel Cuxhaven)	122	48.796	3.1	n.n.	0.7	3.3
TGBF (Borkum Fischerbalje)	102	48.765	2.5	n.n.	−1.4	2.7
TGBU (Büsum)	100	51.209	2.5	2.6	−1.0	2.4

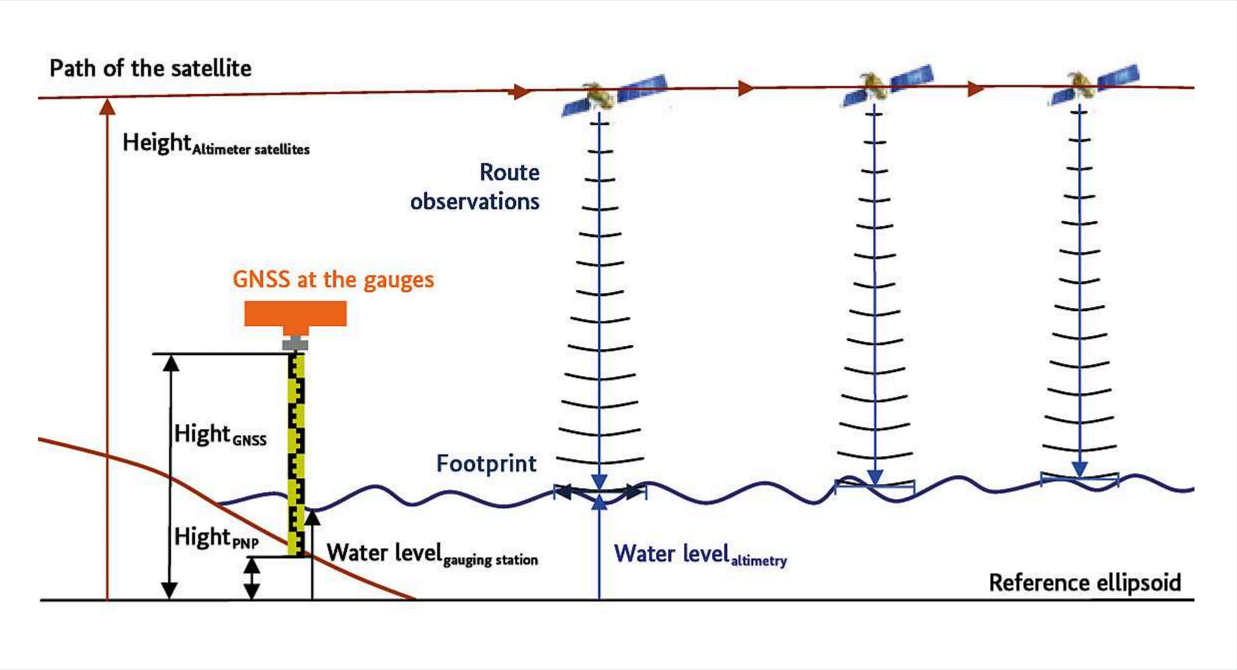

Figure 4: Measurement principle of the satellite altimetry

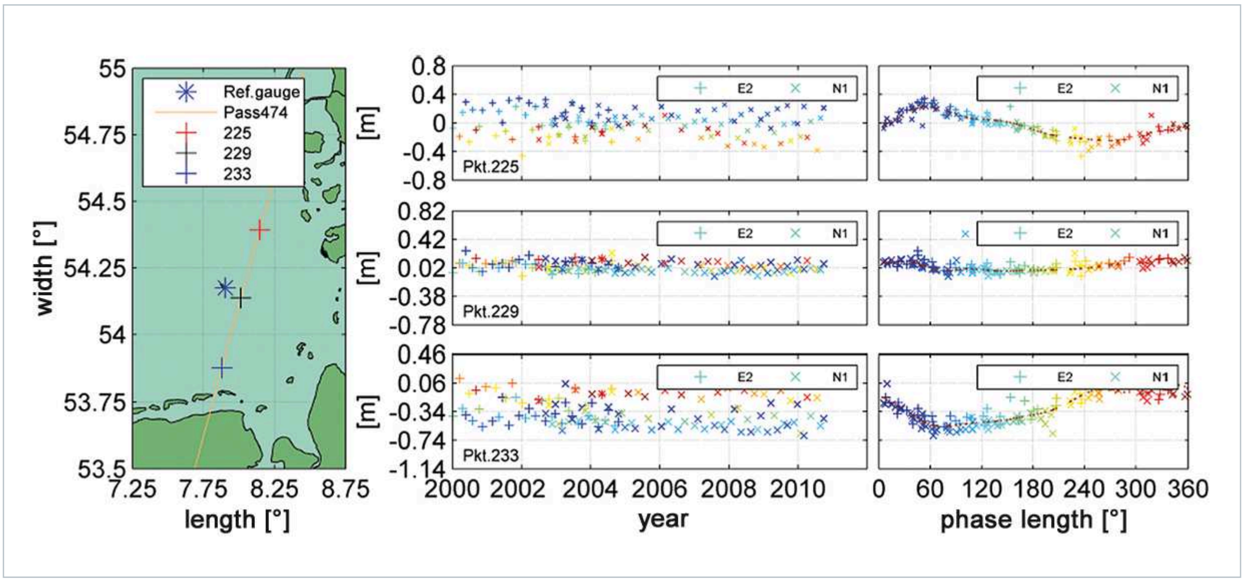

Figure 5: Differences between altimeter and gauge observations

Our findings in brief:

- When analysing increases to sea level, vertical land movements must be considered with regard to the referencing of gauge data to prevent the measurement of merely apparent water levels at the gauges.
- The gauge and altimetry observations of the North Sea area conducted in KLIWAS show a large degree of agreement and therefore complement each other very well.

4.4 Impacts on hydrodynamics in the North Sea estuaries and the Baltic Sea, and studies on adaptation options

The changed meteorological, oceanographic and hydrological conditions presented in Chapters 4.1 and 4.2 and in Chapter 5.1 also have an impact on the German coastal waters of the North Sea and Baltic Sea, including the estuaries, which are used widely as maritime navigation routes. As well as the previously discussed changes, changed currents, the displacement of the brackish water zone and changed sediment transportation are also discernible. This leads to impacts on, among other things, the area of nautical access conditions to the ports, coastal protection, safety of shore-side structure, the maintenance of waterways, and the securing of the hydraulic function of the waterways.

For this reason, the future management of the coastal zone relies on scientific findings. Setting the political agenda for the long-term development of shipping demands timely and technically secure foundations.

Concept of the study

To deal with the range of possible climate change, a corresponding range of possible adaptation measures must be developed. For this purpose, the parameters of sea level increase, freshwater discharge and wind velocity are varied in sensitivity studies, in order to determine the impacts. In a second step the effect of adaptation options is modelled with the same parameters.

In KLIWAS, these sensitivity studies were conducted with the help of three-dimensional hydrodynamic-numeric models of the North Sea estuaries of the Elbe, Jade-Weser and Ems, as well as of the Baltic Sea. We can derive the following statements based on these studies:

North Sea estuaries

A possible increase of mean sea level in the North Sea leads to a stronger increase in the mean high tide level than the mean low tide level in the estuaries (Elbe, Jade-Weser, Ems) (see Chapter 4.2). The tidal range increases. The shape of the tidal curve changes. The flood current velocities usually increase to a greater extent in most areas than the ebb current velocities, however there are exceptions in areas of the Lower Ems. Due to an amplified flow dominance, upstream sediment transport increases. The turbidity zones and the brackish water zones are pushed upstream (Holzwarth et al., 2011).

Long-lasting low freshwater discharges into the named rivers can have a much larger effect on the shifting of the brackish water zone upstream than an increase in sea level. In the case of very long-lasting low freshwater discharges, after a certain time the brackish water zone ceases to shift upstream. Changes to the brackish water zone caused by an increase in sea level are constant and permanent, while those caused by varying freshwater discharges result in short-term shifts of the brackish water zone.

Storm surges

For the targeted observation of the impacts of climate change on storm surges, simulations of historical storm surges were conducted in combination with different sea level rises, high freshwater discharges or an increase in wind velocities. The scenarios observed lead to an increase in peak water levels during storm surges, an earlier occurrence of the peak water level during storm surges, and longer-lasting high water levels. The height of the peak water level during storm surges is changed in the seaward reaches by events in the North Sea, i.e. the rise in sea level. In the middle to upper areas of the estuaries, both the rise in sea level and events in inland areas, i.e. the changed freshwater discharge, influence the peak water level during storm surges. Above the weir that is erected in the event of storm surges, freshwater discharge mainly determines the height of the peak water level during a storm surge (Rudolph et al., 2012). The influence of an increase in sea level on peak water levels during storm surges, as shown in Figure 6, is exemplary for the estuaries of the Ems, Weser and Elbe.

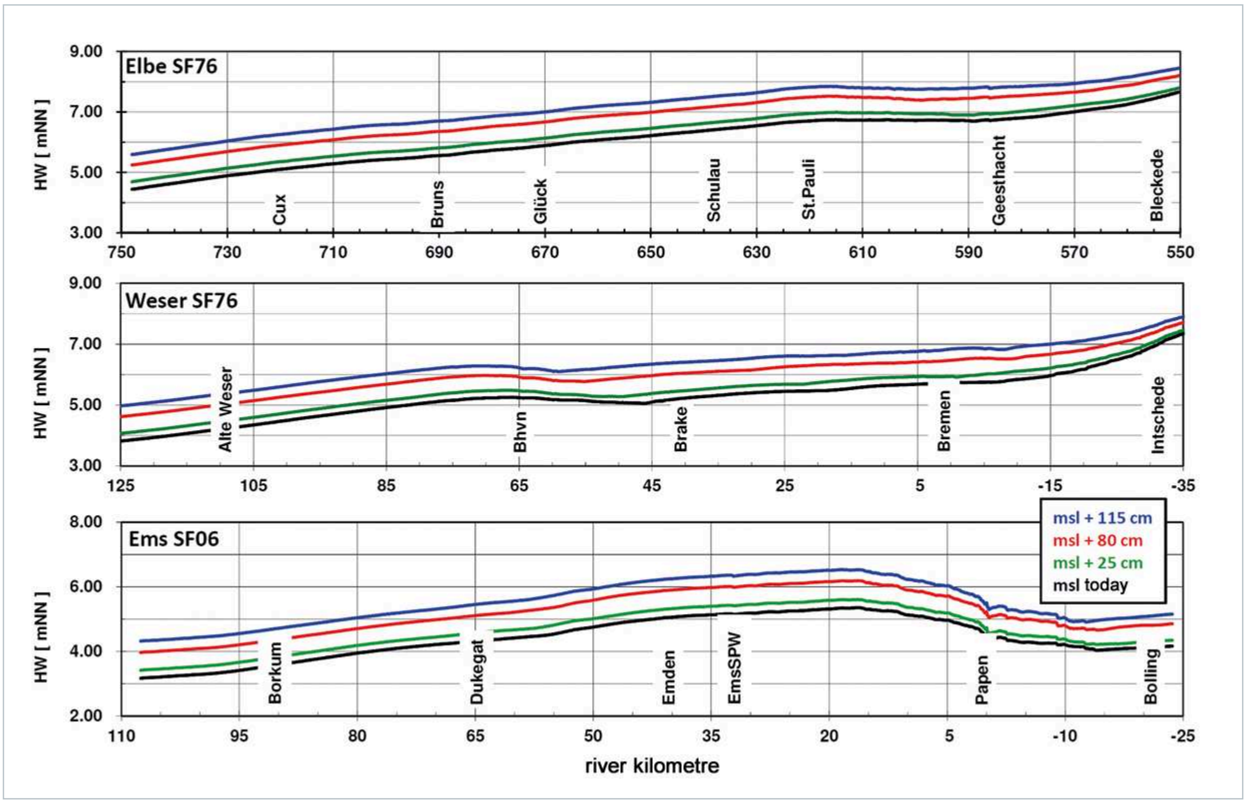

Figure 6: Peak water level during storm surges along the estuaries of the Elbe, Weser and Ems at current sea level (black) and with a sea level increase of +25 cm (green), +80 cm (red) or +115 cm (blue)

Our findings in brief:

- When influenced by a rise in sea level, high tide increases to a greater extent than low tide.
- The flow current dominance increases.
- The upstream sediment transport increases.
- The brackish water zone shifts upstream.
- In the short term, reduced freshwater discharges can contribute more strongly to the upstream shift of the brackish water zone than a rise in sea level. However, changes caused by increased sea levels are permanent.
- During future storm surges, higher peak water levels may occur.

Baltic Sea

In the Baltic Sea, no significant changes are expected to the dynamic of water levels (e.g. due to seiches or wind surges) for the currently presumed rise in sea level by 2100. There is merely an increase in mean sea level. Exceptions occur in inland territories, into which the variability of the Baltic Sea levels penetrate in an attenuated manner. It can be seen here that in these territories the attenuation declines due to the enlargement of the cross-section of the seaward reaches (see Figure 7). The result is an increase in the fluctuation range of the water level. The areas affected are the Schlei, the Bodden waters and the Szczecin Lagoon. Our detailed simulations of the Schlei show that the rise in sea level there leads to a greater exchange with water from the Baltic Sea.

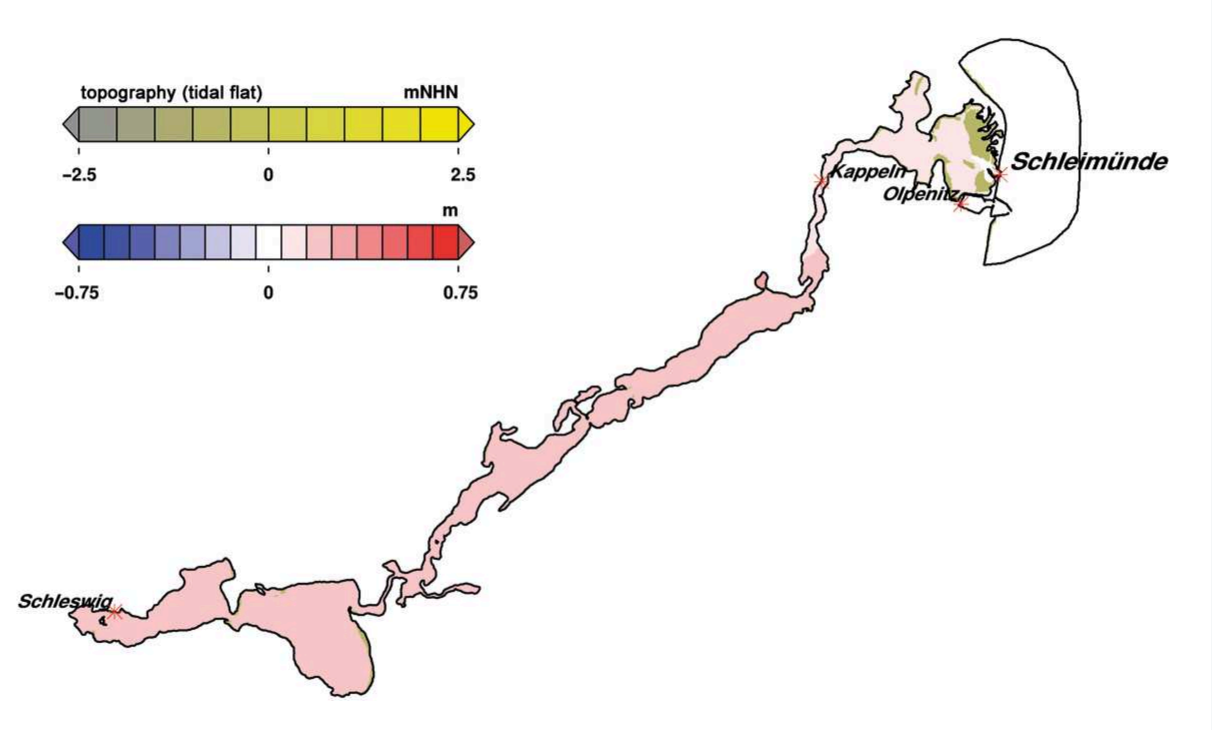

Figure 7: Change to the difference between the highest and lowest water levels in the territory of the Schlei due to a rise in sea level of +80 cm

Adaptation options

Our analyses of the consequences of climate change show that the challenges that already exist today on the federal waterways will probably increase due to climate change. In general, the objective of the study of adaptation options is to test and improve existing measures, and to develop new adaptation options. We examined the effectiveness of adaptation options with the help of hydrodynamic-numeric models of the estuaries of the Elbe, Jade-Weser and Ems.

For the sustainable minimisation of the seaward inflow of suspended solids into the Lower Ems, a low weir at the Ems flood barrier was examined in the context of the Ems action programme. We consider this measure to be suitable also for possible future climate conditions. Both in the case of a rising sea level and also long-lasting low freshwater discharge, the low weir demonstrates an effect that reduces the net transport of suspended solids and shifts the brackish water zone downstream.

Sensitivity studies on topographical changes in the seaward reaches of the Elbe from the KLIMZUG Nord research project show how important the tidal flats are for the tide dynamics of the entire Elbe estuary. A possible loss of tidelands must be prevented at all costs. The tidal flats support the low tide. A loss of the tidelands would increase the flow current dominance. The brackish water zone would shift even further upstream and the net upstream suspended solids transport would increase.

Storm surge barriers protect against storm surges. Particularly in the case of a rise in sea levels, barriers protect the hinterland effectively against increased peak water levels during storm surges. The peak water

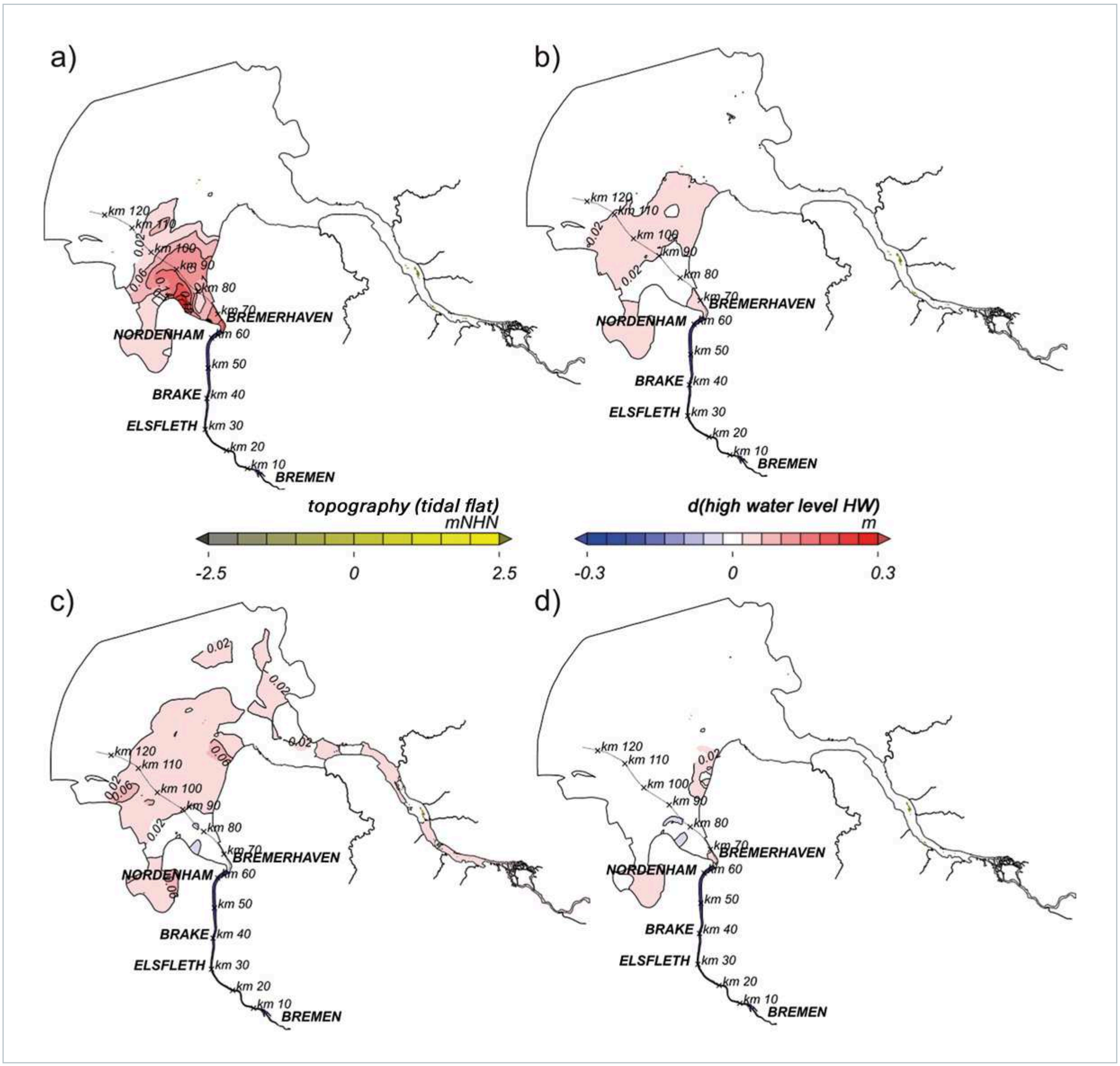

Figure 8: Change to the difference between the highest and lowest water levels: “with barrier” minus “without barrier” a) without rise in sea level, closing at NHN +3,50 m; b) without rise in sea level, closing at tipping point; c) with rise in sea level (+80 cm), closing at NHN +3,50 m; d) with rise in sea level (+80 cm), closing at tipping point

levels upstream of the barrier depend on the freshwater discharge, the time at which the barrier is closed, and the time it takes for the barrier to close. In contrast, in the unprotected areas on the seaward side of the barrier, the peak water level increases due to the rise in sea level. In addition, increased peak water levels may be caused by the barrier itself. The Ems barrier near Gandersum already protects the Ems against storm surges. Our simulations show that to a certain extent it will also provide sufficient protection under future climate conditions. In the seaward reaches of the Weser (south of Bremerhaven) we examined a storm surge barrier as an adaptation option (see Figure 8). Depending on the time of closing the barrier, it can trigger a flush and surge wave in the Weser, which spreads as far as into the Elbe estuary.

As a protection against storm surges, we also examined, as an alternative to barriers, narrowing measures in the seaward reaches of the Elbe, which are aimed at attenuating the peak water levels. The degree of attenuation depends on the degree of narrowing of the hydraulically effective cross-sectional area of flow and the location. In the inner seaward reaches, the degree of narrowing in the same intervention is greater than in the outer area. Due to the reduction of the cross-sectional area of flow, the current velocities in the area of the intervention increase considerably. While barriers can turn away storm surges completely, this intervention only partially reduces the impact of the increase in sea level on the peak water level during storm surges.

Our findings in brief:

- Any possible loss of tidelands must be prevented.
- Storm surge barriers protect the hinterland effectively. However, increased water levels can occur on the seaward side of the storm surge barriers.
- Narrowing interventions in the seaward reaches of estuaries can reduce the impact of sea level increases on peak water levels during storm surges.
- To minimise the seaward-side influx of suspended solids into the Lower Ems, a low weir at the Ems barrier is a suitable measure for possible future climate conditions.

4.5 North Sea estuaries: Sediment balance and contaminants

The North Sea estuaries are used for various socially-relevant purposes. One of these purposes is navigation; exports and imports of German industry are processed via the ports. In order to ensure the ease and security of navigation, app. 35 million m^3 of sediment are removed from the channels annually, most of which is re-deposited in the waters.

Source: Federal Waterways and Shipping Office (WSA) Bremerhaven

The question that arises for us is whether climate change could influence dredging measures in the North Sea estuaries in areas with sandy or fine-grained sediments with regard to the quantity of sediments and their quality (contaminants). In order to be able to answer this question, we further developed the necessary analytical tools to study the influence of climate change on the sediment balance, such as the software RhenoBedform tracking, and applied it to the tidal Elbe (Elbe estuary; see Figure 9). Supported by this tool, we analysed the dynamics of the sandy dunes on the bed of the river. This tool has been available for practical use to the Waterways and Shipping Offices in Hamburg and Cuxhaven since the beginning of 2013.

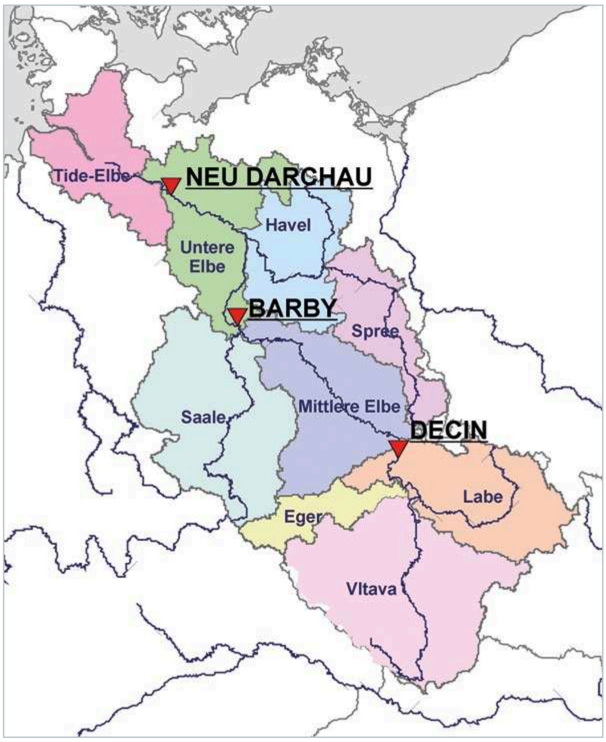

Figure 9: Catchment area of the Elbe with gauges

Previous studies have shown that only a low impact on the coarse sediment balance[3] and on bed load transport can be expected from a discharge driven by the changing climate. Therefore, the climate-related proportion of effort to maintain individual sandy shallows will also be negligibly small. Such individual shallows occur as a result of the growing of dunes (so-called transport body structures), which largely shape the morphology of the riverbed upstream from Brunsbüttel. Based on available data, only the influence of discharge on the migration direction and speed of dunes could be established, but not on their size development. We also do not assume that the contribution of the dunes to the attenuation of the tidal energy that enters the estuary with the incoming tide will change.

Furthermore, we have conducted analyses on the future development of dredging focal points with fine-grained dredged material. Using measurements, we have shown for the tidal Elbe how the discharge influences the transport direction and the ratio of the suspended solids loads at ebb and flow. A transport direction indicator (TDI) was developed to estimate the net suspended solids transport based on turbidity measurements semi-quantitatively. In addition, the TDI can be used to examine the influence of the discharge on the transport of suspended sediments. It was found that persistent periods of low discharge lead to an increase in the concentration of suspended solids upstream of Stade as the turbidity zone shifts upstream and the upstream transport of fine sediments increases. These increased concentrations of suspended sediments could deposit on the river bed, particularly in the existing focal points of dredging, e.g. in the section of the Elbe next to the city of Wedel and in the Port of Hamburg. Thus, we expect an increase of the future amounts of fine-grained dredged material. Under these conditions, the proportion of slightly contaminated marine sediments increases in the deposits to be dredged. This leads to a dilution of the contaminated sediments of fluvial origin transported downstream the estuary. A lowering of the contaminant concentrations is the consequence.

The evaluation of our projections for the discharge into the Elbe estuary revealed no clear changes for periods of persistent low discharge in the near future (2021 to 2050). For the distant future (2071 to 2100), this evaluation showed a tendency towards more frequently occurring and more extreme phases of a persistently low discharge (see Chapter 5.2). Therefore, additional amounts of fine-grained dredged material can be expected in the distant future as a result of climate change and the associated increase in upstream transport. Furthermore, the suspended matter contents that increase in such periods could further reinforce existing sedimentation processes in tributaries and shallow waters. Increased sedimentation can have a negative impact on the ecological functions of these areas and may lead there, for example, to a decline in the oxygen content, which is presently good compared to the oxygen content of the main current of the Elbe estuary. Any future rise in sea levels (see Chapter 4.1) will increase the effects of low discharge.

In the estuaries of the Weser and Ems, the same effect can be expected in principle with regard to the shifting of the turbidity zone, the flood-dominated upstream transport of fine sediments, and sedimentation. However, the estuary-specific boundary conditions demand more detailed studies in order to assess the concrete impacts on

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[3] The coarse sediment inventory of the Elbe is composed of sandy sediment and a small amount of fine-gravelly sediments, coarser sediment fractions are present in only very small quantities.

the dredged material and sediment management, and to take measures where necessary.

Sediments that have to be dredged must be examined for their quality. Under consideration of their level of contamination, most of them will be brought to aquatic deposit sites in the North Sea estuaries. When assessing sediment quality, also the requirements of the Water Framework Directive (EU-WFD) implemented by the Surface Water Ordinance of 2011 (OGewV), as well as the Marine Strategy Framework Directive (EU-MSRL) have to be taken into account. Statistical analyses of our long-term monitoring data from the North Sea estuaries of the Elbe, Weser and Ems show that concentrations of particle-bound contaminants, having their main sources in the inland reaches of the rivers (fluvial particulate matter), vary according to the discharge. Particle-bound contaminants comprise those that are bound to suspended solids and to fine-grained sediments. With increasing discharge and thus an increasing input of fluvial suspended solids, the particle-bound contaminant concentrations increase in the estuary and decrease again with decreasing discharge.

Input of fluvial suspended solids into estuaries that have been changed due to climate changes thus also lead to changed particle-bound contaminant concentrations. Based on the existing understanding of the transport of fine-grained sediments, a mixing model was used, with the components fluvial and marine sediments and their specific contaminant concentrations in order to estimate climate induced changes of contaminant concentrations in the estuaries. For selected stations, robust mean values of the mixing ratios between marine and fluvial sediments derived for selected contaminants were defined.

The results of projections of the suspended matter loads near Hitzacker (inland reach of the Elbe) (see Chapter 5.3) were assumed to represent inputs of suspended solids and accordingly of particle-bound contaminants into the estuary. Using the described approach, we carried out projections of the contaminant concentrations in the Elbe estuary in the near and distant future. To simplify the estimate of contaminant concentrations, the quantity of marine sediments in the estuary and the contaminant concentrations of the marine and the fluvial particulate matter were kept at constant levels.

In accordance with the wide range of projections for the suspended solids input, the range of projected changes of contamination is also large. A worst-case estimate of the changes of contaminant concentrations was based on the projection[4] with the greatest increase in the annual suspended matter load and compared with the natural variability of the contaminant concentrations. Only contaminant concentrations under medium discharge conditions and thus the most frequent discharge conditions were considered. In the distant future and with the strongest increase in suspended matter input, we expect an increase in contaminant concentrations of up to +49 percent at the Wedel station, located in the inner area of the estuary, and of up to +34 percent in Brunsbüttel, which is located nearer to the sea. The projected increase in contamination at Wedel exceeds the natural variability of contaminant concentrations in the reference period 2003 to 2012 considerably. In contrast, at Brunsbüttel, the reference state is exceeded only slightly. However, the changes to suspended matter loads projected for the near future with the same model run suggest only an increase in contaminant concentrations within the natural variability, both at Wedel and at Brunsbüttel. Two more of the selected projections show a slight increase in contaminant concentrations, both in the near and distant future, which are within the natural variability of the contamination in the reference period 2003 to 2012. The other two projections considered show decreases in the annual suspended matter loads and therefore of contaminant input into the estuary, which in turn leads to decreasing particle-bound contaminant concentrations.

Conclusion: The range of contamination in particulate matter of the Elbe estuary as a result of climate-related changed inputs of suspended solids lies, according to the projections we considered, at −10 to +26 percent for the near future and at −23 to +49 percent for the distant future.

Impacts on the contaminant concentrations in sediments due to changes in upstream transport driven by the assumed rise in sea levels were investigated by the BAW using a numerical simulation. The BAW's hydrodynamic-numerical model to simulate the transport of particulate matter in the tidal Elbe was expanded for the study of the transport of contaminated fine sediments. Initial model runs are able to reproduce the decreasing heavy metal concentrations along the course of the tidal Elbe towards

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[4] Projection: C20-A1B_EH5r3_RE-ENS_ls_wendling_Larsim.

the sea, which were known from long-term measurements by the FGG Elbe and the BfG. The concentration levels of selected heavy metals also correspond essentially with the measured values. The modelling thus confirms the increasing seaward mixing of higher-contaminated fluvial sediments with lesser- contaminated marine sediments, as derived from the measurement data (see above).

The model allows us to make statements about the future development of the transport processes occurring under selected changed boundary conditions. Thus, in the model, a rise in sea level of +80 cm is assumed, which leads to an increase in the upstream sediment transport and thus to an increase in the percentage of lesser- contaminated marine sediments. With very high discharge, a slight decrease in contaminant concentrations from the mouth of the Elbe up to around Elbe km 620 can be expected, due to the rise in sea level. In the case of low discharge, the model suggests an even smaller decrease in contaminant concentrations as a result of the rise in sea level, which is barely noticeable in the turbidity zone, as the less contaminated sediments already dominate transport there. Instead, a slight decline in cadmium concentrations in suspended matter between km 610 and km 620 was established. A comprehensive sensitivity study based on – among other things – the projected discharges for the Elbe (see Chapter 5.2) and suspended solid inputs into the Elbe estuary (see Chapter 5.3), is no longer possible in the context of KLIWAS.

No projections of climate-related changes to fluvial suspended solid inputs into the estuaries are available for the Weser or Ems. Therefore, for the purpose of a sensitivity analysis we assumed changes to the suspended sediment loads according to the largest increase and decrease of the loads in the Elbe. Even under these conditions, in the Weser and Ems estuaries there will be only slight changes that are within the variability observed for the reference contamination in the near future. In the distant future, the projections lead us to expect at most an increase in contaminant concentrations of between +9 and +15 percent in the Weser estuary and up to +22 percent in the Ems estuary.

The concentrations of some contaminants in sediments to be dredged from areas within and upstream of the turbidity zone of the tidal Elbe (from the dredging area Osteriff up to Hamburg) currently exceed the upper national assessment criteria of the existing regulations for the handling of dredged material in coastal waters seawards of the freshwater limit (Anonymous, 2009). The worst-case scenario of our sensitivity analysis shows for the distant future that in these areas in particular increased contaminant concentrations and thus increased exceedance of the national assessment criteria cannot be ruled out. In this case, it should be examined whether an adaptation of the dredged material management might be necessary. The results of the further model runs for suspended solids inputs, in contrast, do not lead us to expect any constraints of the placement strategy for dredged material. In the tidal Weser and the tidal Ems, no exceedance of the national assessment criteria is expected, even if the input of suspended solids from the inland reaches of these rivers increases. However, long-lasting high discharges lead to higher contaminant inputs into all estuaries, and furthermore to an increased input of contaminants into the North Sea.

Large quantities of contaminated sediments are deposited in many areas of low current velocities in the estuaries of the Weser and Elbe, which can potentially be mobilised by climate change. In most of these sedimentation areas studied, measurements in sediment cores with generally high contaminant concentrations at depths of > 1 m and with declining concentrations in the direction of the sediment surface indicate an existing tendency towards sedimentation. The rise in sea level and the tendency towards more frequent and extreme periods of a persistent low discharges also lead us to expect continued sedimentation in the lateral areas of the estuaries. Conversely, BAW studies also provide indications of a possible increase in the erosion of sediments from the contaminated lateral areas due to higher current velocities resulting from a rise in sea level. However, we do not expect that an increased erosion of the upper layers that usually show a similar contamination level as the suspended solids in the main current of the tidal Elbe, will lead to detectable impacts on the contaminant concentrations in particulate matter in the main current of the tidal Elbe or Weser.

Anthropogenic changes in the rivers investigated, such as remediation measures or hydraulic engineering measures could have a more rapid and possibly a stronger impact on contamination than climate change. Moreover, sediment management measures could considerably influence the transport and the distribution of particle-bound contaminant concentrations in the estuaries.

With regard to the sediment and suspended solids balance and contamination, there is no immediate need for action, as the consequences of climate change are small in the near future. A change in the placement strategy for fine-grained dredged materials with a selection of alternative deposit sites is a possible measure to adapt to the consequences of climate change. In order to detect early enough unfavourable developments in dredging quantities and contamination, system-wide monitoring should be established. Parts of such monitoring are already active. In the long term, the implementation of the measures defined in the management plans of the river basin communities represents an essential adaptation option that could counteract the negative impacts of climate change on the development of dredging quantities and, possibly, increases in contamination. For example, an improvement in the hydro-morphological structural diversity by means of the creation of new sedimentation areas would affect the suspended solids balance positively. Accordingly, the remediation of contaminated sites, as outlined in the management plan for the tidal Elbe, would lead to a considerable reduction in contaminant concentrations, and also the contaminant quantities in the estuary.

Our findings in brief:

- Changed discharges in the tidal Elbe influence the migration direction and velocity of dunes, but not their height. As a result, the dredging quantities from the maintenance of these individual sandy shallows remain constant.

- The tendency towards more frequent and extreme periods of persistent low discharge, and the rise in sea level, both of which are expected in the distant future, will cause increased deposits of sediments in the tidal Elbe, primarily of marine origin. Accordingly, the contaminant concentrations in sediments to be dredged will decline slightly during periods of persistent low discharge, whereby the decline will be reinforced by a simultaneous rise in sea level.

- In contrast, the increase in high discharges, which is expected according to several projections, especially in the distant future, could cause increasing inputs of fluvial suspended solids and contaminants into the estuaries of the Elbe, Weser and Ems and into the North Sea. Under these conditions, increased contaminant concentrations in dredged material may occur, especially in the Elbe, which could be attenuated by a simultaneous rise in sea level by a few percent.

- No resuspension of contaminated deposits, some of which are highly polluted (generally at a depth of > 1 m) from lateral areas of the Elbe and Weser estuaries is expected, even with a climate-related change in the hydrodynamics. Should upper layers with a lower level of contamination erode in part, the influence on the contaminant concentrations in the main current of the estuaries will be low.

- Measures to reduce contamination in the inland reaches of rivers display more rapid and, for example when reduced by 50 percent, stronger impacts in the estuaries than climate-related changes. Sediment management measures can also exert a more considerable influence on sediment balance and sediment quality than climate change.

4.6 Oxygen content and algae in North Sea estuaries

The maintenance of navigation channels in the North Sea estuaries of the Elbe, Weser and Ems, as well as various other uses of the estuaries must comply with the European Water Framework Directive (EU-WFD) and other legal requirements of nature protection. For this reason, we examined whether and to what extent the usage by navigation and the associated measures might impair the water quality of the estuaries. It can already be seen from the current state of the tidal Elbe that a low discharge in summer favours the development of algae in the Middle Elbe, meaning that more algae and their organic decomposition products are carried into the estuary. The microbial decomposition of the organic material then results in critical oxygen content in summer in the Elbe estuary.

The water quality of the Elbe estuary was calculated for the first time with the deterministic model QSim (Quality Simulation) over a long period from 1998 to 2010. To test the impact of altered discharge and altered air temperature resulting from climate change, sensitivity studies were carried out with a modified delta change approach. As a result "response surfaces" (a matrix) were generated for selected water quality parameters (e.g. water temperature, algae biomass and oxygen content), depending on the above mentioned climate influence factors. Direct reference was made to the air temperature and discharge projections of the KLIWAS model chain by integrating the change signals into the response surfaces. One of the advantages of the delta change approach is that it contains only the errors and uncertainties of the water quality model.

The projections of the KLIWAS model chains show an increase in air temperature for the Elbe in the near and distant future, while the discharge projections do not indicate any clear direction of change. As a direct impact of increased air temperatures, the water temperatures in the Elbe estuary will also rise. With the help of the delta change approach we were able to show that the influence of discharge on the oxygen content and the overall water quality of the tidal Elbe is more significant than an increase in air temperatures.

The projections for the distant future with the strongest decrease in discharge (up to −23.6 percent) (see Chapter 5.2) show the most negative impacts on the oxygen content. In contrast, strongly increasing air temperatures (up to +3.6 °C, see Chapter 5.1) and the associated increasing water temperatures, especially in summer, result in a decline in algae biomass (due to the exceeded optimum temperature for the algae) and thus lead to an attenuation of oxygen deficits in summer. However, in spring and autumn, the oxygen deficits in these projections intensify, as an increase in water temperature, towards the optimum temperature for algal growth causes higher input of algae from the Middle Elbe into the Elbe estuary.

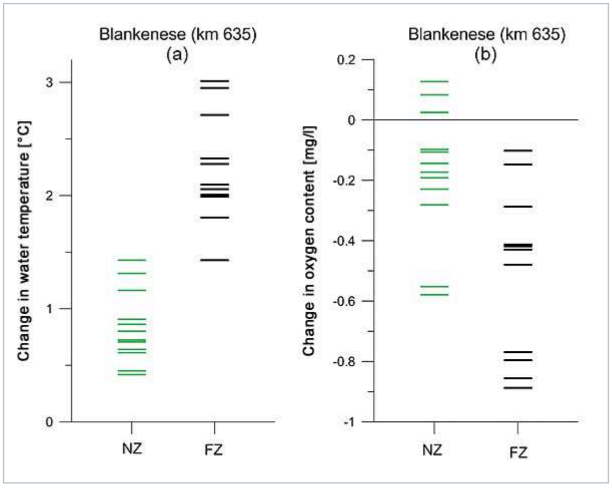

Figure 10: Change of the seasonal mean (01.04.–31.10) for a) water temperature and b) oxygen content in the Elbe estuary at the station Blankenese (km 635) for the near future (NZ) and distant future (FZ)

In the near future in the Elbe estuary, we determined an increase in the seasonal (April to October) mean water temperature by +0.4 to +1.4 °C (Figure 10a). Most of the projected changes in air temperature and discharge would result in a reduction of the oxygen content (Figure 10b). The seasonal mean for the reference period (1998 to 2010) is 6.6 mg/l. The range at the station Blankenese (km 635), which is situated in the area of Hamburg Port, is −0.6 mg/l to +0.1 mg/l for the near future. A larger range in oxygen contents occurs for the section of the Elbe estuary from Bunthaus to Grauerort, namely from −0.8 mg/l to +0.1 mg/l.

Across all model chains calculated, an increase in water temperatures and a reduction in oxygen content are discernible in the Elbe estuary in the distant future. The water temperature at the station Blankenese (km 635) rises on average by +1.4 to +3.0 °C for the period from April to October (Figure 10a), while the change range of the seasonal mean oxygen content is −0.1 mg/l to −0.9 mg/l (Figure 10b). With regard to the section of the Elbe from Bunthaus (km 609) to Grauerort (km 660), a range of oxygen reduction from −1.3 mg/l to −0.1 mg/l is expected.

It is expected that the oxygen deficit in the Elbe estuary will expand and intensify over time for most of the model chains investigated for the near and distant future. To attain a good ecological state, EU-WFD regulations demand an oxygen content of at least 6 mg/l. In the future, reduced discharges and higher air temperatures are likely to lead to an increase in days on which the oxygen content is less than 6 mg/l. The model chains that projected an increase in discharge partly lead to a slight reduction in the number of days on which the oxygen content is less than 6 mg/l (up to 48 days). However, reduced discharges may lead to almost twice as many days of low oxygen content (up to 95 days).

Our findings in brief:

- The oxygen content of the tidal Elbe is controlled by the discharge and thus by the algae transported from the Middle Elbe into the estuary and its organic decomposition products.

- Climate projections with a decreasing discharge that occurs less in the near future (2021 to 2050), but increasingly in the distant future (2071 to 2100), lead to declining oxygen content in the tidal Elbe.

- All climate projections demonstrate higher air temperature, accompanied by higher water temperatures. Water temperatures above 25 °C can considerably reduce algae growth, so that in projections of the distant future, especially in summer, less algae biomass and fewer of its organic decomposition products are transported into the tidal Elbe, thus relieving the oxygen balance. However, in spring and autumn, the load in these projections due to a higher input of algae biomass from the Middle Elbe increases.

- The changes to oxygen in the tidal Elbe caused by changes in discharge are stronger than the effects caused by changes to air temperature.

4.7 Microbiological-hygienic observation of coastal waters

Pathogenic microorganisms can, in some circumstances, endanger the health of people who work on, at, or in the water, who come into contact with fishery products, or who seek relaxation and recreation on the water. Model organisms for this study were bacteria of the genus Vibrio (*V. vulnificus, V. cholerae* non-O1/non-O139, *V. parahaemolyticus, V. alginolyticus*), which occur naturally in coastal waters. Investigations on pathogenicity factors showed that pathogenic strains do occur in German coastal waters, and there is a risk of infection. In rare cases, wound, ear or eye infections may occur or, in the case of oral intake, e.g. via seafood, possibly food poisoning/gastroenteritis.

Using monitoring programmes it was shown that potential human pathogenic vibrio are widespread in German coastal waters. In some cases their occurrence is spatially and temporally limited. The vibrio populations at the North Sea and Baltic Sea coasts differ very clearly, but they show a similar behaviour towards environmental factors. For example, the occurrence of *V. vulnificus,* a pathogen of wound infections, which can be severe, is concentrated on the brackish water areas of the North Sea estuaries and the Baltic Sea. In the Greifswald Bodden at the Baltic Sea, around 50 percent of samples (water and sediment) were tested positively for *V. vulnificus* in the reference period 2010/2011.

To detect and quantify the Vibrio spp. we selected, as in many other studies, a culture-based approach with molecular biological verification, although the overall population is underestimated due to the non-detection of viable but non-culturable (VBNC) cells. Accordingly, it cannot be ruled out that there may nevertheless be non-culturable vibrio in the samples analysed in the monitoring as “non-contaminated”. In addition, there are indications in the literature that the non-culturable stages continue to be infectious. Therefore the risk presented by vibrio in German coastal waters is possibly considerably underestimated.

The vibrio concentrations are one to three times as high in sediments as in water. They therefore act as a reservoir for potential human pathogenic vibrio. A suspended particle-associated drifting of potential human pathogenic vibrio, also into habitats previously considered to be atypical, cannot be ruled out. A particle transport model of the Federal Maritime and Hydrographic Agency showed that *V. vulnificus* can drift from the Ems estuary onto the bathing beaches of Borkum. This was confirmed by our field studies.

We estimated the impacts of climate-related influencing factors on the spatial distribution and abundance of vibrio based on monitoring results and laboratory examinations. Both correlation analyses and regression models showed that the water temperature is the decisive environmental parameter for the occurrence and abundance of different *Vibrio* species. The likelihood of their occurrence rises with increasing water temperatures. Water temperatures >20 °C encourage the occurrence of potential human pathogenic vibrio, especially the species *V. vulnificus*. At the coasts and the estuaries of the North Sea, the changes in water temperature of +0.4 to +1.5 °C, as projected as a consequence of climate change in the near future with KLIWAS model chains, may possibly lead to an increase in Vibrio abundancy by between +3 and around +57 percent. At a projected rise in water temperatures of +1.3 to +2.9 °C in the distant future, increases in Vibrio abundance of between +9 and +138 percent are possible. There will be species-specific differences in the increases. However the estimates do not include further abiotic and biotic interactions, which in turn may also be influenced by climate change.

Both on the North Sea and Baltic Sea coasts, the number of months per year in which the *V. vulnificus* in particular will find good growth conditions will increase as a result of the climate-related warming of the sea surface temperature (SST). On the North Sea coast, especially in the estuaries, there will be almost a doubling of months per year in the near and distant future, compared to the reference period (1979 to 1999), with an SST > 17 °C. The periods with an SST > 17 °C will also increase in the area of the Baltic Sea, especially in the inland waters of Mecklenburg-Western Pomerania from one month (reference period) to 2.5 months in the near future and 3 months in the distant future.

A possible shift of brackish water zones in the estuaries of the Ems and Jade/Weser due to climate change (with low discharge upstream, or with higher discharges seawards) may lead to a spatial displacement of the habitats of *V. vulnificus*. No differentiation between near and distant future is possible here. For the other vibrio species studied, no change in their spatial distribution is expected as a result of a possible shift of brackish water zones, as they can currently be detected in all areas of examination and across all salinity ranges.

In general, studies of the functional links between vibrio and biotic, abiotic or climate-sensitive environmental factors could contribute to a better understanding of the system.

There are many potential sources of infection for all persons who come into contact with water, sediments, biofilm and aerosols, such as employees of the Federal Waterways and Shipping Administration or of state authorities. In the near, and especially in the distant future, a potential increase in the risk of wound infections among those working on the waterways can be expected, especially in the Baltic Sea, but also in the area of the North Sea estuaries. Occupational safety measures, as well as awareness-raising and information about the risks can minimise the threat of infections. The potential increase in the risk of wound infections may also play a greater role than before in the areas of tourism and healthcare (e.g. rehabilitation clinics). By means of monitoring programmes and an expansion of the surveillance of bathing waters for vibrio, potentially harmful health situations may be detected at an early stage and preventative measures taken.

Our findings in brief:

- The occurrence of potentially pathogenic vibrio depends on the water temperature. Water temperatures of at least 20 °C favour the occurrence of *V. vulnificus* in particular, which has already emerged as a wound pathogen in Germany.

- The occurrence of *V. vulnificus* is concentrated on the brackish water areas of the Baltic Sea and the North Sea estuaries. In addition, *V. cholerae* non-O1, non-O139 is significant in the Baltic Sea as a potential wound pathogen. The habitats of these species, which live in brackish waters, may relocate as a consequence of the shifting of brackish water zones.

- Sediments represent a reservoir for potentially pathogenic vibrio. Further studies are required to determine to what extent the remobilisation of sediments may ultimately lead also to a drifting of vibrio.

- With regard to potential human pathogenic bacteria of the genus Vibrio, there are different conditions in the North Sea and Baltic Sea, each with their hazards and infectious potential, so that regional recommendations for action must be provided when dealing with water, sediments and dredged materials.

- The risk of wound infections can be minimised with occupational safety measures, awareness-raising and information.

4.8 Foreshore vegetation in North Sea estuaries

Estuarine foreshore vegetation provides numerous functions, both for humans and for the ecosystem. For example, it forms a natural erosion protection of the shore, it contributes to the self-cleaning of the rivers, it is used for agriculture, it provides material for thatches, it provides habitats for protected animal and plant species, and it contains numerous protected biotope types.

The estuarine vegetation of the Elbe and Weser, including habitats, certain plant features as well as characteristic growth and distribution strategies, was recorded using different study methods, ranging from laboratory experiments to open land field studies and experiments to remote sensing methods. In order to be able to estimate the climate-related impacts on the vegetation, we examined the influence of climate-relevant factors such as currents, waves or tidal parameters, ice, storm and storm surge-influenced flotsam deposits on the vegetation.

One key influential factor, amongst others, that affects shore vegetation is the elevation above the mean high water (MThw). A rise in sea level, which also causes the MThw in the rivers near the coast to rise, is a consequence of climate change. The increasing sea level and the resulting increase in the MThw will not lead to any changes in reed zoning, as long as the foreshore grows adequately, with sufficient sediment availability and sedimentation speed; otherwise, biotope and reed types will be replaced by flood-tolerant types. If the topography remains constant, higher water levels will lead to a loss of agricultural land, allowing new reed areas to form (Figure 11).

Furthermore, the increasing MThw also causes a higher flow current velocity, which increases the risk of shore erosion. In this context, a loss of reed areas in the vicinity of the shore may occur.

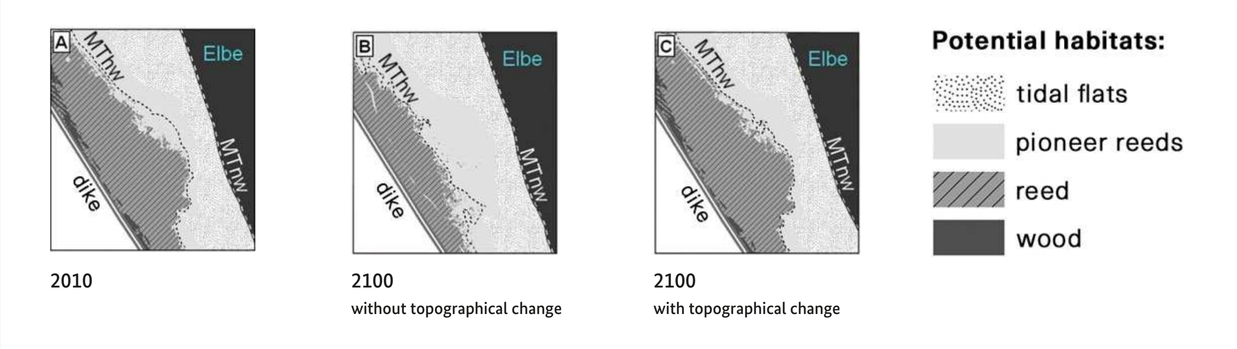

Figure 11: Habitat changes on the Elbe (Wischhafen) based on two scenarios. A: Reference data 2010, B and C: Modelled vegetation distribution 2100 without/with topographical change (=associated growth of the foreshore areas due to sedimentation) (Illustration from Fuchs et. al. 2013)

The future projected sea state indicates an increase in wave height, which can lead to more open soil locations on the shore. This will encourage pioneer vegetation. In freshwater foreshore areas, invasive neophytes can also benefit from this, and their spread may lead to a weakening of the natural protection of the shore against erosion.

Increasing air and water temperatures are projected for both the near and distant future, which will lead to a decline in ice events. Abrasion of the vegetation by ice will become rarer, and the disturbances will be reduced.

A sensitivity study conducted by the BAW leads us to expect increased storm surge peak water levels (Chapter 4.4). This will probably lead to increased deposits of flotsam on the dikes. As a result, the amount of flotsam deposited near the shore will decrease, meaning fewer disturbances. As no significant increase in storm surge frequency is expected, there is no change to the danger of shore erosion in terms of this influencing factor.

Our results show a natural tolerance on the part of shore vegetation towards the projected impacts of climate change. However, individual influencing factors, e.g. the climate-related increase in flow current velocity and the expected increase in wave height, can weaken the two important functions of the tidal pioneer reeds and the reed, i.e. as shore protection and as a habitat.

In order to counteract climate-related impairments, a substitute technical shore protection at suitable places should be considered, for example reed belts to protect against erosion. A loss of agricultural land would increase the nature conservation value. To maintain the foreland vegetation despite increasing mean high water, the potential habitats should be expanded, e.g. by creating spaces for estuarine natural shorelines and forelands. A monitoring system should be established in order to take suitable measures against undesirable changes in a timely manner.

Our findings in brief:

- Our results show a natural tolerance of foreland vegetation towards the modelled projected impacts of climate change. However, individual influencing factors, e.g. the climate-related increase in flow current velocities and the expected rise in wave height, could weaken important functions of foreland vegetation as shore protection and habitat.

- As long as the sediment availability in the estuary is sufficient, no change to reeds zonation is expected as a result of the rise in mean high water, as the foreshore can grow adequately. Otherwise, biotope and reed types will be replaced by flood-tolerant sedges – probably on a small scale only – and the foreland will be lost, which in some places may lead to a loss of agricultural land.

- Increased storm surges are likely to lead to more frequent deposits of flotsam near dikes. As no significant increase in storm surge frequency is expected, the risk of shore erosion will not change with regard to this influencing factor.

- The increase in temperatures expected for the near and distant future will lead to a decrease in ice-caused disturbances along the shore, due to the decrease in ice events.

- The increase in wave height modelled for the future could encourage pioneer vegetation due to the creation of more open soil locations. This can also lead to a spread of neophytes in freshwater forelands, particularly in limnic shore areas. The extent to which their spread will lead to a weakening of the natural protection of the shore against erosion must yet be examined.

- In order to counteract climate-related impairments, a substitution of technical shore protection against erosion by natural vegetation at suitable places should be considered (for example reed belts).

5. The Elbe

The Elbe as a waterway

Despite its near-natural appearance, the German Inner Elbe, app. 600 km long, is a federal waterway that has been developed along its entire course. Under normal discharge conditions from the border to the Czech Republic to just before Hamburg, the Elbe is maintained in its bed by means of flow control structures, in most cases groynes, whereby the freely flowing character of the river is mostly preserved.

As a system of waterways between the German-Czech border and Hamburg, the Elbe and its navigable watercourses connect the economic centres of the Czech Republic, Saxony, Saxony-Anhalt, Lower Saxony, Brandenburg and Berlin with the Port of Hamburg and with the western German inland waterways network. The Elbe is an international waterway and was identified by the EU in the recently revised TEN Guideline as a waterway with European significance.

For transport on the Elbe, shipping technology that has been adapted especially to the river is frequently used. Shallow-draught vessels ensure an economical and environmentally-friendly transport of goods and cargo, mostly independently of the fluctuations in water level that are natural in a free-flowing river.

The basic concept here is based on the use of pushed convoys. By these means, heavier loads and project cargo have been transported on the Elbe in recent years. This type of transport has many advantages. Because of the large clearance gauge of the Elbe, there are hardly any restrictions on the dimensions of the goods. The low load weights, for example of wind turbine parts, mean that transportation is also possible at low water levels.

The large clearance gauge, especially at the bridge clearances, allows three-layer container transport on the Elbe, in contrast to the canal routes. Thus containers could be transported in three layers on average on a multi-year average of 343 days per year between Hamburg and the Port of Magdeburg, and on 321 days per year between the Port of Magdeburg and Dresden. For example, ETS Elbe carries out a scheduled container transport three times a week from Riesa via Aken and Magdeburg.

By means of the targeted reservoir management of the Czech reservoirs as a wave release, ships' hulls for seagoing inland ships and tankers are transported from Czech shipyards to the North Sea.

Research had already been carried out on the Elbe prior to the start of the KLIWAS research programme with regard to future discharge. One example is the project GLOWA-Elbe. This is based on the then-customary method of modelling: only one model was selected within each model chain. Consequently, the results form a small part of the results range of the ensemble approach. This method requires fewer resources than the ensemble approach; however, it is not possible to estimate whether the calculated projections are situated more in the lower, middle or higher section (e.g. increase or decrease in discharges) of the range of results. For this reason we chose the ensemble approach, i.e. the use of as many models per modelling stage as possible (see Chapter 3.1) for the KLIWAS research programme.

5.1 Climate in the Elbe catchment area

In the following the meteorological parameters of relevance to KLIWAS, those of air temperature and precipitation, are observed for winter (December to February) and summer (June to August). In Table 9 the modelled changes for the near future (2021 to 2050) and the distant future (2071 to 2100) are shown, related in each case to the reference period (1961 to 1990). The methodology of the modelling along the KLIWAS model chain is described in Chapter 3.2.

For the catchment area of the Elbe an average increase in summer temperatures of +1 to +2 °C is expected in the near future (2021 to 2050) and +2.5 to +4 °C in the distant future (2071 to 2100). Similar values were produced for winter

This means that up to the middle of the century, no clear trends for precipitation are recognisable, neither for the meteorological winter (December to February) nor for the meteorological summer (June to August). For the distant future our projections show tendencies towards reductions in precipitation in summer and increases in precipitation in winter.

Our findings in brief:

- For the catchment area of the Elbe, an average increase in summer temperatures of +1 to +2 °C is expected in the near future (2021 to 2050) and +2.5 to +4 °C in the distant future (2071 to 2100). Similar values were found for winter.
- No clear trends are identifiable for precipitation in the near future (2021 to 2050), neither in winter nor in summer.
- In the distant future (2071 to 2100), a declining trend is discernible for summer precipitation, and an increasing trend for winter precipitation.

Table 9: Average changes to air temperatures and precipitation in the Elbe catchment area; Periods: 2021 to 2050 and 2071 to 2100, in each case compared with 1961 to 1990

Elbe		Near future 2021 to 2050	Distant future 2071 to 2100
Air temperature summer	**Elbe**	**+1 °C to +2 °C**	**+2.5 °C to +4 °C**
	Vltava	+1 °C to +2 °C	+3 °C to +5 °C
	Eger	+1 °C to +2 °C	+2.5 °C to +4.5 °C
	Labe	+1 °C to +2 °C	+2.5 °C to +5.0 °C
	Middle Elbe	+1 °C to +2 °C	+2.5 °C to +4.5 °C
	Saale	+1 °C to +2 °C	+2.5 °C to +4.5 °C
	Havel	+1 °C to +2 °C	+2.5 °C to +4.5 °C
	Lower Elbe	+1 °C to +2 °C	+2.5 °C to +4.5 °C
	Tidal Elbe	+1 °C to +2 °C	+2.5 °C to +4 °C
Air temperature winter	**Elbe**	**+0.5 °C to +2.5 °C**	**+2.5 °C to +5 °C**
	Vltava	+1 °C to +2.5 °C	+2.5 °C to +5 °C
	Eger	+1 °C to +2.5 °C	+2.5 °C to +5.5 °C
	Labe	+1 °C to +2.5 °C	+2.5 °C to +5.5 °C
	Middle Elbe	+1 °C to +3.0 °C	+2.5 °C to +5.5 °C
	Saale	+1 °C to +3.0 °C	+2.5 °C to +5.0 °C
	Havel	+1 °C to +2.5 °C	+2.5 °C to +5.0 °C
	Lower Elbe	+1 °C to +2.5 °C	+2.5 °C to +5.0 °C
	Tidal Elbe	+1 °C to +2.5 °C	+2.5 °C to +5.0 °C
Precipitation summer	**Elbe**	**−5 % to +10 %**	**−25 % to −5 %**
	Vltava	−10 % to +10 %	−20 % to 0 %
	Eger	−5 % to +10 %	−25 % to 0 %
	Labe	−10 % to +15 %	−20 % to 0 %
	Middle Elbe	−5 % to +10 %	−25 % to 0 %
	Saale	−5 % to +15 %	−25 % to −5 %
	Havel	−5 % to +5 %	−25 % to −5 %
	Lower Elbe	−10 % to +5 %	−25 % to 0 %
	Tidal Elbe	−10 % to +5 %	−25 % to −5 %
Precipitation winter	**Elbe**	**−5 % to +15 %**	**+5 % to +25 %**
	Vltava	−10 % to +15 %	+5 % to +30 %
	Eger	−5 % to +15 %	+5 % to +30 %
	Labe	−5 % to +20 %	+5 % to +30 %
	Middle Elbe	−10 % to +15 %	0 % to +20 %
	Saale	−5 % to +15 %	+5 % to +20 %
	Havel	−5 % to +15 %	0 % to +20 %
	Lower Elbe	0 % to +15 %	+5 % to +20 %
	Tidal Elbe	0 % to +15 %	+10 % to +25 %

🟦 Tendency to increase 🟧 Tendency to decrease ⬜ inconsistent change signal

5.2 Hydrology in the Elbe catchment area

With the ensemble approach (see Chapter 3.1), the KLIWAS research programme pursues the objective of gaining the best possible picture of the diversity of the currently imagined "futures" with the help of as many of the presently available models and model chains as possible, in order to be able to estimate how exactly the actual future situation can best be limited within the range.

Our analyses of the Elbe region were created with a hydrological model on a daily basis, which was driven by an ensemble of climate projections. This results in an ensemble of 20 discharge projections for the near future and 18 for the distant future.

All of the discharge parameters observed here were determined in each case from each individual discharge projection of these two ensembles. In the next stage, the climate change signal was calculated as a percentage deviation of its multi-year average of the periods 2021 to 2050 (near future) or 2071 to 2100 (distant future) compared with the reference period 1961 to 1990. For each discharge parameter this produced one ensemble of climate change signals for the near future and one for the distant future.

Table 10 shows the so-called scenario corridors of the results for average, low water and high water parameters at selected gauges in the Elbe catchment area. Rounded to 5 % steps, these mark the core area of each ensemble, in which the majority of the results are located particularly closely together.

In the near future the range of the climate signal of the average annual discharge (MQ), related to the entire hydrological year at all gauges surveyed, is within the limits of −10 to +15 percent, compared to the reference period. In all, the corresponding limits for the hydrological summer (May – October), at values between −15 and +5 percent, tend slightly towards drier conditions, while the values for the hydrological winter (November – April), at between −10 and +10 percent, are just as inconsistent as the annual average.

In the distant future, both the projections of the mean discharge (MQ) of the entire year and, even more so, those of the summer, show a mostly declining tendency in the area of between −30 and +10 percent, compared to the reference period. In the distant future there continues to be no distinct direction of the ensemble in winter, however the range of possible futures expands to values of between −30 and +15 percent.

For low water discharge (NM7Q relating to the water balance year) there is an indifferent picture for the near future in the Elbe catchment area, with maximum limits of the range of the climate change signal of between −10 and +20 percent, depending on the gauging station. The limits for the distant future are between −35 and +10 percent.

Compared to this, the corresponding results of the GLOWA-Elbe research project are situated clearly at the "dry" end of the span of mean discharge (MQ), as found out by KLIWAS.

Accordingly, more detailed analyses of the projections on changes to parameters that are relevant to shipping in the low water area (failure to reach critical thresholds) show an ambiguous picture for navigation in the near future. In the distant future the projections, with a much increased range of results, show in some cases a clear increase in the failure to each critical threshold.

Projections on flood discharges (upper discharge levels, HM5Q) produce an inconsistent picture for both future periods. Furthermore, a multi-decade variability of the climate signals is more apparent than is the case with the other parameters, i.e. depending on the selection of the reference period, the defined change signals fluctuate considerably.

Further methodological advances are necessary in order to be able to make reliable statements on changes to the probability of especially rare or extreme flooding events (HQ50 and greater) occurring under changed framework conditions.

In general, however, low water situations are more relevant to inland navigation than flooding events, due to their relatively long duration.

Table 10: Scenario corridors for average annual and semi-annual discharges (MQ) and the low water and high water discharges (NM7Q respectively HM5Q) at selected gauging points in the Elbe catchment area

			Percentage change compared to 1961 to 1990		
				Scenario corridors to	
		Observation (1961 to 1990)	Observation (1981 to 2010)	Near future (2021 to 2050)	Distant future (2071 to 2100)
Parameters	**Gauging station**	**[m^3/s]**	**[%]**	**[%]**	**[%]**
MQ Hydrological year (Nov.–Oct.)	Brandys			−10 to +15	−25 to +5
	Dresden	331	+2.4	−10 to +15	−25 to +10
	Aken	453	−2.2	−10 to +15	−20 to +10
	Barby	571	−2.7	−5 to +5	−20 to +5
	Neu Darchau	730	−3.4	−5 to +5	−20 to +5
	Prag (Moldau)			−10 to +15	−20 to +5
	Louny (Eger)			−10 to +15	−15 to +5
	Calbe-Grizehne (Saale)	125	−5.2	−10 to +10	−20 to +5
	Rathenow (Havel)	92	−13.7	−5 to +5	−25 to +10
MQ Hydrological winter (Nov.–Apr.)	Brandys			−5 to +10	−20 to +10
	Dresden	396	+7.0	−5 to +10	−20 to +15
	Aken	547	+1.8	−5 to +5	−20 to +15
	Barby	691	+1.3	−5 to +5	−20 to +10
	Neu Darchau	880	+1.2	−5 to +5	−25 to +10
	Prag (Moldau)			−15 to +10	−20 to +20
	Louny (Eger)			−10 to +5	−15 to +20
	Calbe-Grizehne (Saale)	152	−0.3	−10 to +10	−30 to +5
	Rathenow (Havel)	117	−10.8	−10 to +5	−25 to +10
MQ Hydrological summer (May–Oct.)	Brandys			−15 to +5	−30 to +5
	Dresden	271	−5.7	15 to +5	−30 to 0
	Aken	365	−9.5	−15 to +5	−30 to −5
	Barby	459	−10.0	−10 to +5	−30 to −5
	Neu Darchau	589	−11.1	−15 to +5	−20 to 0
	Prag (Moldau)			−20 to +5	−30 to −5
	Louny (Eger)			−10 to +10	−20 to −5
	Calbe-Grizehne (Saale)	98	−12.7	−10 to +5	−25 to −5
	Rathenow (Havel)	69	−19.4	−15 to +5	−20 to +10

Continuation of Table 10

			Percentage change compared to 1961 to 1990		
				Scenario corridors to	
		Observation (1961 to 1990)	Observation (1981 to 2010)	Near future (2021 to 2050)	Distant future (2071 to 2100)
Parameters	**Gauging station**	[m³/s]	[%]	[%]	[%]
NM7Q Water balance year (Apr.–Mar.)	Brandys			⬜ −15 to +20	🟧 −30 to 0
	Dresden	131	+0.8	⬜ −10 to +10	🟧 −25 to +5
	Aken	185	−2.8	⬜ −10 to +15	🟧 −20 to +5
	Barby	240	+0.3	⬜ −10 to +10	🟧 −25 to +5
	Neu Darchau	316	−6.0	⬜ −10 to +20	🟧 −25 to +5
	Prag (Moldau)			⬜ −10 to +15	🟧 −30 to +10
	Louny (Eger)			⬜ −10 to +10	🟧 −30 to 0
	Calbe-Grizehne (Saale)	57	−7.8	⬜ −10 to +5	🟧 −25 to 0
	Rathenow (Havel)	29	−36.6	🟦 −5 to +15	🟧 −35 to +10
HM5Q Hydrological year (Nov.–Oct.)	Brandys			⬜ −10 to +10	⬜ −25 to +20
	Dresden	1106	+19.5	🟧 −15 to +5	⬜ −15 to +10
	Aken	1464	+7.9	🟧 −15 to +5	🟧 −15 to +5
	Barby	1729	+8.5	🟧 −15 to +5	🟧 −15 to +5
	Neu Darchau	1783	+12.0	⬜ −10 to +5	🟧 −15 to +5
	Prag (Moldau)			🟧 −15 to +5	⬜ −15 to +10
	Louny (Eger)			⬜ −10 to +10	⬜ −15 to +10
	Calbe-Grizehne (Saale)	366	+4.5	⬜ −10 to +10	🟧 −20 to +5
	Rathenow (Havel)	162	−2.8	⬜ −5 to +10	⬜ −15 to +25

🟦 Tendency to increase 🟧 Tendency to decrease ⬜ inconsistent change signal

Furthermore it must be emphasised here that the area-based discharge of the Elbe region is almost three times less, for example, than that in the Rhine area. Accordingly, the water balance in the Elbe region is also managed much more intensively, and changed management measures at the scale of the projected changes are readily conceivable (e.g. low water elevations).

Our findings in brief:

- Mean annual discharges will barely change on the Elbe in the near future (2021 to 2050). A differentiated view of summer and winter shows that a tendency towards declining discharges can be discerned in summer, while inconsistent changes are projected for the winter.

- In the distant future (2071 to 2100) the difference between summer and winter will be greater. Both the projections of mean annual discharge and, even more so, of summer discharges, show a predominant tendency towards declining discharges. There continues to be no clear direction of the ensemble for winter in the distant future, but the range increases.

- With regard to the occurrence of low water situations, the ensemble does not show any distinct direction of development for the near future. Towards the end of the century, projections with more frequent or long-lasting low water periods predominate.

- According to the projections, small, i.e. frequent or annual occurrences of flooding will develop somewhat inconsistently, with a slightly declining tendency, depending on the gauging station.

5.3 Sediment budget and riverbed evolution

To study the sediment budget and riverbed evolution we used projections for which the multi-year average projected discharges remain the same, compared to the reference period 1961 to 1990, but which in some cases show clear changes in the high water area (parameter HM5Q). We used three-dimensional SSIM models to study climate-induced influences on small-scale morphological processes. The SSIIM-3D models intended for a scale integration (upscaling) are located without exception within the “erosion stretch” of the Elbe (km 120 to 290). With this method we pursued the objective of developing small-scale adaptation options for a future sediment management.

The area between Mühlberg and the mouth of the Saale is of particular interest. It is characterised by a bed erosion of app. 1 to 2 cm per year. In total, it proves to be a morphologically deficient system (WSV 2009). This section of the Elbe gets its sensitivity to climate influences and its ecological significance from the floodplain forests that are situated along the course of the river, and which are increasingly endangered due to a drop in water level caused by erosion in combination with an unfavourable change in the discharge characteristics.

Historical series on the concentration of suspended solids and sediment loads at selected measurement points along the Elbe show a clear influence of the algae population on the summer concentrations of suspended solids. Furthermore, a clear hysteresis in the passage of flood waves can be discerned, i.e. the sediment concentration is different in the case of increasing discharge than with a decreasing discharge. Furthermore, a declining trend is noticeable at Hitzacker (catchment area outlet) from 1965 to 2009, as well as a turning point around 1990: after 1990 the average annual sediment load is around 30 percent lower than before that year. We attribute this phenomenon on the one hand to the reduction in industrial and municipal wastewater inflows. On the other hand, changed land usage and management techniques in agricultural areas have caused reduced soil erosion and thus reduced sediment yield into the Elbe river network.

Moreover, during flooding events, net declines on suspended sediment loads along the Elbe have been observed, for example, at km 280 to 390, highlighting the importance of flood plains as sinks of fine sediments.

For the 1D modelling of the suspended solids transport with the SOBEK model, linear discharge-transport relationships for the inflows were derived from the historical measurement series. We used nine discharge projections for model runs on suspended loads and aggregated the simulated daily sediment loads to multi-year average values for the near and distant future. The simulated sediment loads follow the trend of the development of the average discharge (MQ). The changes to the sediment loads are more distinct, both upwardly and downwardly, than the change to the average discharge.

In parallel, soil loss due to flowing water in the catchment area of the Elbe was calculated based on a raster and using the PESERA soil erosion model, and was then converted into sediment yield using the method of dispersed sediment-delivery ratio. The model drive is based on climate statistics for the near and distant future, and on the reference period from five climate projections. Other area parameters such as relief, soil characteristics, land usage and land cover were kept constant in the sensitivity studies. The sediment inflow calculations, which build on the observed climate data (1961 to 1990) show good agreement with the multi-year averages (2003 to 2009) of the observed loads at the WSV sediment measurement points.

The model results of SOBEK and PESERA show very good agreement for each climate projection which was evaluated in both models with regard to the direction and extent of the changes. The range of the projected sediment loads is therefore generated by the climate projections and not by the selection of the model. The projected changes of average annual suspended loads of all model chains in the ensemble lie between −50 and +20 percent for the near future and between −60 and +60 percent for the distant future. To date there is no clear tendency towards an increase or decrease in sediment loads. Therefore, according to current estimates, no climate-specific adaptation options are recommended. As it is known from numerous studies that the fine sediments in the German Binnenelbe are highly contaminated in some cases (Heininger et al. 2003, Heise et al. 2005), the recommendations for action made in the sediment management concept of FGG Elbe (2013) would appear to be appropriate as "no regret" measures, also against the background of possible changes caused by climate change.

Our findings in brief:

- Current suspended sediment loads in the Elbe are shaped significantly by anthropogenic influences such as land usage in the catchment area.
- The projections produce a wide range of projected climate change signals for suspended sediment loads in the Elbe area, without any clear tendencies towards increases or decreases.
- The trend of the projections of annual suspended sediment loads follows the development of the average discharge (MQ). The change signals for annual sediment loads are generally more distinct than the change signals of the MQ. A significant change to the discharge regime of the Elbe would therefore lead us to expect significant changes in sediment loads and also in the inputs of suspended solids into the tidal Elbe.
- As there is no clear tendency towards an increase or decrease in sediment loads according to current estimates, no climate-specific adaptation options are recommended.
- In some cases, the fine sediments in the German Binnenelbe demonstrate a high level of contamination. The recommendations for action made in the sediment management concept of FGG Elbe (2013) would appear to be appropriate as "no regret" measures, also against the background of possible changes caused by climate change.

6. The Danube

With a length of almost 3,000 km, the Danube is the second-longest river in Europe; it flows through 10 countries. In Germany the Danube is navigable along a length of 200 km; the annual transport volume in Germany is app. 10 million t. The Danube flows from west to east. Cargo transport is possible between Amsterdam and the Black Sea via the Rhine, Main and Danube. Thus the Danube connects central Europe with southern Europe.

6.1 Climate in the Danube catchment area

In the KLIWAS research programme, studies were made on the Danube concerning regional climate change and the resulting changed quantitative hydrology. In the following the meteorological parameters of relevance to KLIWAS, those of air temperature and precipitation, are observed for winter (December to February) and summer (June to August). In Table 11 the modelled changes for the near future (2021 to 2050) and the distant future (2071 to 2100) are shown, related in each case to the reference period (1961 to 1990). The methodology of the modelling along the KLIWAS model chain is described in Chapter 3.2.

For the catchment area of the Danube an average increase in summer temperatures of +1 to +2 °C is expected in the near future, and +3 to +5 °C in the distant future. Similar values were produced for winter. In terms of precipitation, there is a clearer difference between the summer and winter seasons in the distant future. In the near future, average changes to precipitation of between −10 and +5 percent are expected in summer, and between −10 and +10 percent in winter. In the distant future, our results vary between −25 and −5 percent in summer and between −5 and +25 percent in winter.

That means that up to the middle of the century there are no clearly discernible precipitation trends, neither for the meteorological winter (December to February) nor for the meteorological summer (June to August). For the distant future, our projections show tendencies towards reductions in precipitation in summer and increases in precipitation in winter.

Our findings in brief:

- For the catchment area of the Danube, an average increase in summer temperatures of +1 to +2 °C is expected in the near future and +3 to +5 °C in the distant future. Similar values were found for winter.
- No clear trends are recognisable for precipitation in the near future (2021 to 2050), neither in winter nor in summer.
- In the distant future (2071 to 2100), a declining trend is discernible for summer precipitation, and an increasing trend for winter precipitation.

Table 11: Average changes to air temperatures and precipitation in the Danube catchment area; Periods: 2021 to 2050 and 2071 to 2100, in each case compared with 1961 to 1990

Danube		Near future 2021 to 2050	Distant future 2071 to 2100
Air temperature summer	**Danube**	**+1 °C to +2 °C**	**+3 °C to +5 °C**
	Upper Danube	+1 °C to +2 °C	+3.5 °C to +5 °C
	Inn	+1.5 °C to +2.5 °C	+3.5 °C to +5.5 °C
Air temperature winter	**Danube**	**+0.5 °C to +2.5 °C**	**+2 °C to +5 °C**
	Upper Danube	+1 °C to +2.5 °C	+2.5 °C to +5 °C
	Inn	+1 °C to +2.5 °C	+2.5 °C to +5 °C
Precipitation summer	**Danube**	**−10 % to +5 %**	**−25 % to −5 %**
	Upper Danube	−10 % to +5 %	−25 % to −5 %
	Inn	−5 % to +5 %	−25 % to −10 %
Precipitation winter	**Danube**	**−10 % to +10 %**	**−5 % to +25 %**
	Upper Danube	−15 % to +10 %	−5 % to +25 %
	Inn	−10 % to +10 %	−5 % to +20 %

🟦 Tendency to increase 🟧 Tendency to decrease ⬜ inconsistent change signal

6.2 Hydrology in the Danube catchment area

With the ensemble approach (see Chapter 3.1), the KLIWAS research programme pursues the objective of gaining the best possible picture of the diversity of the currently imagined “futures” with the help of as many of the presently available models and model chains as possible, in order to be able to estimate how exactly the possible future situations can best be limited within the range of projections.

The analyses for the Danube area were created with a hydrological model on a monthly basis, driven by an ensemble of climate projections. This results in an ensemble of 21 discharge projections for the near future and 18 for the distant future. The discharge regime of the Danube and its tributaries is influenced by an intensive reservoir and dam management, especially in the Alpine sections of the river basin area. The statements made here are based on the currently used reservoir management rules.

All of the discharge parameters observed here were determined in each case from each individual discharge projection of these two ensembles. In the next stage, the climate change signal was calculated as a percentage deviation of its multi-year average of the periods 2021 to 2050 (near future) or 2071 to 2100 (distant future) compared with the reference period 1961 to 1990. For each discharge parameter this produced one ensemble of climate change signals for the near future and one for the distant future.

Table 12 shows the so-called scenario corridors of the results for average, low water and high water parameters at selected gauges in the upper Danube catchment area. Rounded to 5 % steps, these mark the core area of each ensemble, in which the majority of the results are located particularly closely together.

Our projections for the average discharges of the Danube remain mostly inconsistent initially in the annual average. However, in the distant future the majority of projection results show decreases in discharge.

In hydrological winter (November to April of the following year) the results also show no clear changes to average discharge; this applies both to the near and distant future. Only at the Inn, which is dominated by the Alps, will there be an increase in average winter discharges due to precipitation, which in future will fall more frequently as rain than as snow.

For the hydrological summer (May to September within a year), the majority of our projections show decreases in discharge. These are more distinct in the distant future than in the near future.

For low water discharges (lowest average monthly discharges) our projections show a tendency towards decreasing discharge at the gauges of the Danube, This is less distinct on the Inn, as the increase in the proportion of rain in the precipitation events will have a predominantly balancing effect.

The results for the high water discharges (highest average monthly discharges) also differ according to the partial catchment areas. In the rain-dominated discharge regime of the Danube above the mouth of the Inn, the gauges indicate inconsistent tendencies for both future periods studied. In the snow-dominated Inn catchment area, the reduced meltwater influx in summer leads to a somewhat slight decrease in high discharges in the near future, and a clearer decrease in the distant future.

Our findings in brief:

- Average annual discharges will barely change on the Danube in the near future. A differentiated view of summer and winter shows projections of predominantly inconsistent changes in winter, with the exception of the Inn and the Danube downstream from the mouth of the Inn, where somewhat increasing discharges are projected. In summer a general tendency towards decreasing discharges can be discerned.
- According to the projections for average annual discharges, in the distant future the difference between summer and winter will increase, whereby the annual average predominantly decreases and fewer increases are projected. Higher discharges in winter are expected only for the Inn itself.
- Low water events can already be expected somewhat more frequently in the near future, with an increasing tendency towards the end of the century. This excludes the Inn and the gauges influenced by the Inn, where inconsistent conditions are expected.
- According to the projections, small, i.e. frequent or annual occurrences of flooding at gauges above the mouth of the Inn will tend to stagnate, and the frequency at the gauges influenced by the Inn will tend to decrease. These tendencies will intensify towards the end of the century.

Table 12: Scenario corridors for the average annual and semi-annual discharges (MQ) and the lowest and highest monthly discharges (NMoMQ respectively HMoMQ) at selected gauges in the Danube catchment area

			Percentage change compared to 1961 to 1990		
				Scenario corridors to	
		Observation (1961 to 1990)	Observation (1981 to 2010)	Near future (2021 to 2050)	Distant future (2071 to 2100)
Parameters	**Gauging stations**	[m³/s]	[%]	[%]	[%]
MQ **Hydrological year** **(Nov.–Oct.)**	Donauwörth	196	+3.5	−15 to 0	−30 to 0
	Pfelling	470	+0.6	−10 to +5	−30 to 0
	Hofkirchen	649	+1.2	−10 to +5	−30 to −5
	Achleiten	1,419	+1.8	−10 to +5	−25 to −5
	Passau-Ingling	729	+2.0	−10 to 0	−25 to −5
MQ **Hydrological winter** **(Nov.–Apr.)**	Donauwörth	206	+7.9	−5 to +5	−25 to +10
	Pfelling	492	+5.6	−5 to +5	−25 to +15
	Hofkirchen	656	+6.3	−5 to +5	−20 to +15
	Achleiten	1,206	+8.1	0 to +10	−10 to +20
	Passau-Ingling	505	+10.8	0 to +10	0 to +25
MQ **Hydrological summer** **(May–Oct.)**	Donauwörth	185	−1.0	−20 to 0	−40 to −20
	Pfelling	447	−4.5	−20 to −5	−35 to −15
	Hofkirchen	641	−4.1	−15 to −5	−35 to −10
	Achleiten	1,633	−2.9	−15 to −5	−35 to −20
	Passau-Ingling	956	−2.9	−15 to 0	−40 to −25
NM7Q **Water balance year** **(Apr.–Mar.)**	Donauwörth	105	+6.0	−15 to −5	−45 to −15
	Pfelling	273	+0.3	−15 to 0	−40 to −10
	Hofkirchen	397	+1.3	−10 to 0	−35 to 0
	Achleiten	816	+9.6	−5 to +5	−25 to 0
	Passau-Ingling	363	+10.9	0 to +15	−20 to +10
HM5Q **Hydrological year** **(Nov.–Oct.)**	Donauwörth	337	+4.1	−10 to +5	−25 to +10
	Pfelling	772	+2.2	−10 to +10	−20 to +10
	Hofkirchen	1,026	+3.9	−10 to +5	−25 to +10
	Achleiten	2,306	−1.5	−10 to 0	−25 to −5
	Passau-Ingling	1,364	−3.8	−15 to −5	−35 to −10

🟦 Tendency to increase 🟧 Tendency to decrease ⬜ inconsistent change signal

7. The Rhine

The Rhine waterway

The Rhine is the busiest inland waterway for transport in Europe. A large share of German imports and exports are processed via the ports at the mouth of the Rhine. For the transport-oriented industrial companies and centres at the Rhine, Ruhr, the western German canal area, Moselle and Saar, Main and Neckar, the Rhine represents the connection with the ARA ports, and is therefore the backbone of the German inland waterways network. With its network of canals and tributaries it still has load reserves. App. 170 million tons of cargo passes the German-Dutch border each year at the Lower Rhine, around 60 million at the Middle Rhine, and around 25 million at the Upper Rhine. Two million TEU containers, i.e. 90 percent of container transports conducted with inland ships, are processed in Germany via the Rhine. Prognoses assume a continually increasing transport volume.

Functionality, long-term calculable transport framework conditions and reliability are of key importance to businesses when choosing a location, and for assessing the usability of the waterway. As highly economical transport routes, waterways are comparatively environmentally friendly. The fact that this transport and also all other anthropogenic use takes place in a highly valuable and sensitive ecological environment must also be considered with the same degree of importance. The joint transport-related and water management maintenance of the Rhine secures – at least outside the industrial and urban areas – a shore structure that is as natural as possible.

Therefore an estimation of the consequences of climate change on its usability as a transport route and of the maintenance and adaptation strategies for the ecosystem waterway-shore-floodplain-land cannot be emphasised too strongly.

Source:
GDWS (Federal Waterways and Shipping Agency)

7.1 Climate in the Rhine catchment area

In the following the meteorological parameters of relevance to KLIWAS, those of air temperature and precipitation, are observed for winter (December to February) and summer (June to August). Table 13 the modelled changes for the near future (2021 to 2050) and the distant future (2071 to 2100) are shown, related in each case to the reference period (1961 to 1990). The methodology of the modelling along the KLIWAS model chain is described in Chapter 3.1.

As in the whole of Germany, for the Rhine catchment area an average increase in summer temperatures of +1 to +2.5 °C is expected by the middle of the century, and by up to +5 °C by the end of the century. In terms of precipitation, we cannot identify any clear trends neither for the meteorological winter (December to February) nor for the meteorological summer (June to August) until the middle of the century. For the distant future, our projections show drier summers and moister winters.

Table 13: Average changes to air temperatures and precipitation in the Rhine catchment area. Periods: 2021 to 2050 and 2071 to 2100, in each case compared with 1961 to 1990

Rhine		**Near future 2021 to 2050**	**Distant future 2071 to 2100**
Air temperature summer	**Rhine**	**+1 °C to +2 °C**	**+3 °C to +5 °C**
	High Rhine / Alpine Rhine	+1.5 °C to +2.5 °C	+4 °C to +5 °C
	Upper Rhine / Neckar	+1 °C to +2 °C	+3.5 °C to +5 °C
	Moselle	+1 °C to +2 °C	+3 °C to +5 °C
	Main	+1 °C to +2 °C	+3 °C to +4.5 °C
	Maas	+1 °C to +2 °C	+3 °C to +4.5 °C
	Middle, Lower Rhine	+1 °C to +2 °C	+3 °C to +4 °C
Air temperature winter	**Rhine**	**+0.5 °C to +2.5 °C**	**+2 °C to +5 °C**
	High Rhine / Alpine Rhine	+1 °C to +2.5 °C	+3 °C to +4.5 °C
	Upper Rhine / Neckar	+1 °C to +2.5 °C	+3 °C to +4.5 °C
	Moselle	+1 °C to +2.5 °C	+3 °C to +4.5 °C
	Main	+1 °C to +3 °C	+3 °C to +5 °C
	Maas	+1 °C to +2.5 °C	+2.5 °C to +4.5 °C
	Middle, Lower Rhine	+1 °C to +2.5 °C	+3 °C to +5 °C
Precipitation summer	**Rhine**	**−10% to +5%**	**−30% to −10%**
	High Rhine / Alpine Rhine	−10% to +5%	−35% to −15%
	Upper Rhine / Neckar	−15% to 0%	−30% to −10%
	Moselle	−15% to 0%	−35% to −15%
	Main	−10% to +5%	−30% to −10%
	Maas	−15% to +5%	−35% to −15%
	Middle, Lower Rhine	−10% to +5%	−30% to −10%
Precipitation winter	**Rhine**	**−5% to +10%**	**0% to +25%**
	High Rhine / Alpine Rhine	−15% to +10%	−5% to +20%
	Upper Rhine / Neckar	−10% to +15%	0% to +25%
	Moselle	0% to +15%	+5% to +25%
	Main	−5% to +15%	+5% to +25%
	Maas	0% to +15%	+5% to +25%
	Middle, Lower Rhine	0% to +15%	+5% to +20%

🟦 Tendency to increase 🟧 Tendency to decrease ⬜ inconsistent change signal

Our findings in brief:

- A rise in air temperatures of up to +2.5 °C is expected for the near future (2021 to 2050). In the distant future (2071 to 2100) we expect a further increase.
- No clear trends are recognisable for precipitation in the near future (2021 to 2050), neither in winter nor in summer.
- In the distant future (2071 to 2100), our projections show a decreasing trend for summer precipitation and an increasing trend for winter precipitation.

7.2 Hydrology in the Rhine catchment area

With the ensemble approach (see Chapter 3.1), the KLIWAS research programme pursues the objective of gaining the best possible picture of the diversity of the currently imagined "futures" with the help of as many of the presently available models and model chains as possible, in order to be able to estimate exactly how the actual future situation can best be limited within the span.

In the case of the Rhine area, the uncertainty of the hydrological modelling compared to climate modelling was tested exemplarily in the context of the CHR project RheinBlick2050 (CHR 2010), by also experimenting with an ensemble of hydrological models. It was shown that this increases the range. In all, however, it is dominated by the ensemble of different climate projections.

Our analyses of the Rhine region were created with a hydrological model on a daily basis, which was driven by an ensemble of climate projections. This results in an ensemble of 21 discharge projections for the near future and 17 for the distant future.

All of the discharge parameters observed here were determined in each case from each individual discharge projection of these two ensembles. In the next stage, the climate change signal was calculated as a percentage deviation of its multi-year average of the periods 2021 to 2050 (near future) or 2071 to 2100 (distant future) compared with the reference period 1961 to 1990. For each discharge parameter this produced one ensemble of climate change signals for the near future and one for the distant future.

Table 14 shows the so-called scenario corridors of the results for average, low water and high water parameters at selected gauges in the Rhine catchment area. Rounded to 5% steps, these mark the core area of each ensemble, in which the majority of the results are located particularly closely together.

The span of the climate change signals of the mean annual discharge (MQ) shows predominantly an increasing tendency (0 to +20 percent) at the gauges studied for the near future, compared with the reference period, while the development in the distant future is more indifferent

Table 14: Scenario corridors for average annual and semi-annual discharges (MQ)and the low water and high water discharges (NM7Q respectively HM5Q) at selected gauging points in the Rhine catchment area

			Percentage change compared to 1961 to 1990		
				Scenario corridors to	
		Observation (1961 to 1990)	Observation (1981 to 2010)	Near future (2021 to 2050)	Distant future (2071 to 2100)
Parameters	**Gauging station**	[m^3/s]	[%]	[%]	[%]
MQ **Hydrological year (Nov.–Oct.)**	Basel	1065	+1.4	−5 to +5	−10 to +10
	Maxau	1255	+2.1	0 to +5	−15 to +15
	Worms	1427	+2.2	0 to +10	−15 to +10
	Kaub	1710	+2.4	0 to +10	−10 to +15
	Cologne	2189	+1.2	0 to +15	−10 to +20
	Rees	2370	+0.8	0 to +10	−5 to +20
	Rockenau (Neckar)	137	+7.1	0 to +20	−5 to +30
	Würzburg (Main)	112	+14.1	0 to +15	0 to +30
	Trier (Moselle)	288	+3.5	−5 to +10	−5 to +10
MQ **Hydrological winter (Nov.–Apr.)**	Basel	884	+4.2	0 to +15	0 to +25
	Maxau	1130	+5.5	+5 to +15	+5 to +30
	Worms	1344	+5.7	+5 to +15	+5 to +30
	Kaub	1706	+6.0	+5 to +20	0 to +30
	Cologne	2380	+4.3	+5 to +20	+5 to +30
	Rees	2607	+4.0	+5 to +20	0 to +30
	Rockenau (Neckar)	170	+10.2	+5 to +25	0 to +40
	Würzburg (Main)	146	+15.3	+5 to +20	+5 to +40
	Trier (Moselle)	410	+7.1	0 to +15	+5 to +25
MQ **Hydrological summer (May–Oct.)**	Basel	1248	−1.4	−10 to +5	−30 to −10
	Maxau	1385	−1.6	−10 to +10	−30 to −10
	Worms	1511	−1.7	−10 to +10	−25 to −10
	Kaub	1712	−1.8	−10 to +10	−25 to −10
	Cologne	1996	−3.4	−10 to +10	−25 to −5
	Rees	2134	−4.2	−10 to +10	−25 to −5
	Rockenau (Neckar)	103	+1.4	−10 to +10	−30 to +5
	Würzburg (Main)	78	+12.0	−5 to +15	−15 to +25
	Trier (Moselle)	166	−7.0	−15 to +10	−35 to +10

Continuation of Table 14

			Percentage change compared to 1961 to 1990		
				Scenario corridors to	
		Observation (1961 to 1990)	Observation (1981 to 2010)	Near future (2021 to 2050)	Distant future (2071 to 2100)
Parameters	**Gauging station**	[m³/s]	[%]	[%]	[%]
NM7Q Water balance year (Apr.–Mar.)	Basel	519	+4.90	🟦 −5 to +10	⬜ −10 to +10
	Maxau	635	+6.6	🟦 0 to +10	🟧 −10 to +5
	Worms	705	+6.6	🟦 −5 to +10	🟧 −10 to 0
	Kaub	827	+7.2	🟦 −5 to +10	🟧 −15 to 0
	Cologne	1009	+4.8	🟦 −5 to +10	🟧 −15 to +5
	Rees	1119	+4.7	🟦 −5 to +10	🟧 −20 to +5
	Rockenau (Neckar)	44	+6.1	⬜ −15 to +15	🟧 −35 to −5
	Würzburg (Main)	40	+24.6	🟦 0 to +15	⬜ −10 to +10
	Trier (Moselle)	64	−5.3	🟧 −20 to +5	🟧 −50 to −20
HM5Q Hydrological year (Nov.–Oct.)	Basel	2176	+8.3	⬜ −5 to +10	⬜ −5 to +10
	Maxau	2669	+7.3	⬜ −5 to +10	⬜ −10 to +15
	Worms	3142	+7.0	🟦 0 to +10	🟦 −5 to +15
	Kaub	3937	+11.2	🟦 0 to +15	🟦 0 to +20
	Cologne	5768	+11.3	🟦 +5 to +15	🟦 +5 to +25
	Rees	6071	+12.9	🟦 0 to +20	🟦 +5 to +25
	Rockenau (Neckar)	643	+17.0	🟦 0 to +20	⬜ −10 to +20
	Würzburg (Main)	472	+20.0	🟦 +5 to +30	⬜ −10 to +20
	Trier (Moselle)	1481	+15.0	🟦 0 to +20	🟦 +5 to +20

🟦 Tendency to increase 🟧 Tendency to decrease ⬜ inconsistent change signal

(mostly within −15 to +20 percent). The corresponding limits of the span of mean discharges for the hydrological winter (November–April) show a relatively clear increasing tendency both for the near and distant future, while in the hydrological summer (May–October), in contrast, they remain indifferent in the near future and even tend towards drier conditions in the distant future.

The projected development of the low water discharge (NM7Q relating to the water balance year) shows an increasing tendency until the middle of the century wherever the influence of the snow regimes dominate today. Outside the area of influence of the Alpine snow regime, e.g. at the gauges of the examined low mountain range rivers the Neckar and Moselle, the scenario corridors are inconsistent. In the distant future, in contrast, there will predominantly be increases (–20 to +10 percent) everywhere, also in the area of influence of the snow regime.

Accordingly, more detailed analyses of the projections on changes to parameters that are relevant to navigation in the low water area (failure to reach critical thresholds) show an ambiguous, respectively positive picture for navigation in the near future. For the distant future our projections, with a much increased range of results, show many more frequent failures for each critical threshold.

Idiosyncrasies of the different discharge regimes are also apparent with regard to developments in the upper discharge area (parameter HM05Q). For example, with increasing distance from the Alps and thus an ever larger influence of the rising winter precipitation in the low-range mountains, practically all gauges show an increasing tendency in the scenario corridors in both future periods, until they come to rest from Kaub above zero (between around 0 and +25 percent). In contrast, at the gauges near the Alps (Basel and Maxau), increases and decreases are projected almost equally often with a roughly same range of scenario corridor. Elsewhere, equally inconsistent changes are also produced only in the distant future for the Neckar and Main.

More detailed analyses of projections on changes to navigation-relevant parameters in the high water area show many more frequent exceedances of critical thresholds, both in the near and distant future.

Despite an increase, the overall number of days and the duration of the phases above the high water threshold remain far behind the values for the days on which the low water threshold is not reached. Thus low water situations are and remain more relevant for inland navigation and loaders than high water events.

Further methodological advances are necessary in order to be able to make reliable statements on changes to the probability of especially rare or extreme flooding events (HQ50 and greater) occurring under changed framework conditions.

Our findings in brief:

- The majority of the projections for the Rhine show increasing mean annual discharges in the near future, whereby the increase, with inconsistent changes in summer, is primarily determined by increases in winter. According to the projections, in the distant future the difference between summer and winter will increase, whereby in the annual mean, slight decreases and increases were projected almost equally often, except for in the Lower Rhine.
- Low water situations will at first tend to increase slightly in the near future, before this trend reverses towards the end of the century.
- Small, i.e. frequent or annual occurrences of flooding will increase on average slightly in the near future and more strongly in the distant future. This means a more frequent exceedance of critical thresholds.

7.3 Assessment for inland navigation and the shipping industry on the Rhine

In KLIWAS, the possible future impact on the shipping industry was determined by means of simulations with a cost structure model for inland navigation, based on an optimistic and a pessimistic discharge scenario, in each case for the near and distant future. Under favourable discharge and unloading conditions, large ships have a considerable cost advantage over smaller ship types, as they can carry greater loads on one trip, thus reducing the proportional fixed costs per ton transported. On the other hand, their sensitivity to low water situations is also greater. In such cases, the smaller types of ships have cost advantages, as the proportional fixed costs of smaller load quantities are cheaper than for larger ship types that are not fully utilised.

Thus on the ascent of the Rotterdam-Upper Rhine (840 km) in the near future, for example, the costs for large ships and push-tow units sink by around 5 percent using an optimistic discharge scenario, while they increase by roughly the same amount under a pessimistic scenario. In the optimistic case, small ships do not make any profit, but in the pessimistic case they also suffer few losses. The differences then become more pronounced in the distant future. Large ships, for instance a GMS110 barge, could then expect cost increases of around 10 percent in the optimistic scenario, while small ships, such as a "Gustav Königs", would have to bear only around a third of that amount. This advantage remains in roughly the same ratio under a pessimistic scenario, but with additional costs of around 15 to 20 percent for the large ships.

If, analogously, we were to observe the effect of climate change on the entire transport costs of navigation on the Rhine, with otherwise identical conditions (e.g. fuel prices, fleet composition, staff costs, annual transport volumes), the additional costs in an unfavourable case (pessimistic scenario, distant future) would be around 10 percent (i.e. around 60 million €/year).

As shown exemplarily, these future scenarios can in principle be counteracted by means of adaptation measures, e.g. with innovative navigation technology, water engineering measures, optimised navigation and shipping operations, changed fleet structures or company logistics. Whether this is worthwhile and practical must be determined in more detailed analyses.

Our findings in brief:

- Even under a pessimistic scenario from the perspective of navigation, the transport costs for Rhine navigation would not rise by more than 10 percent in the distant future.

- It was shown exemplarily for Rhine navigation that innovative shipping technology, water engineering measures, optimised navigation and shipping operations, changed fleet structures and company logistics, for example, are in principle suitable as adaptation options.

7.4 Sediments, riverbed evolution and contaminants in the Rhine

For the navigability of the inland waterways, not only is discharge important, but the sediment balance and the development of the river bed are also decisive. Both the depositing tendencies of sediments and the large-scale and long-term erosion tendencies caused by low sediment inflow from upstream sections, demand active water management. The possible large-scale hydrological changes mentioned previously in Chapter 7.2 can have an influence on the channel depth and on the maintenance required to guarantee navigability (see Figure 12). For this reason, we determined and evaluated the impacts of potential climate change on the natural transport of sediment in the Federal waterways.

In order to achieve this goal, we extensively modified morphological models on the basis of our system understanding in the initial years of the project. Furthermore, we conducted a sensitivity analysis for the near future (2021 to 2050) and the distant future (2071 to 2100), based on available morphological data from 2004. The projection chosen from the KLIWAS ensemble for this observation (HBV134-EPW-C20_A1B_EH5r3_Remo_25_ls) is characterised by almost constant average water conditions for the near and distant future, as well as an average ten-percent increase in the highest arithmetic average of the discharge on seven consecutive days (HM7Q) for the distant future.

Our results show that the selection of the maintenance strategy, at least for the near future, has a much greater influence on the riverbed development and the sediment balance than changes resulting from a climate-related alteration of the discharge characteristics of the river catchment area. For the entire Rhine, the riverbed development for the aforementioned projection, with constant dredging and inflows at present levels, displays less pronounced differences between the three time segments calculated so far: the reference period, the near and the distant future. Large deviations are discernible only locally (see Figure 12 and Figure 13). The hydrological projection for the distant future shows a tendency towards increased erosion (see Figure 14 and Figure 15).

While severe morphological changes are possible locally in the near future, on average the sum of erosion and sedimentation remains the same. Only when the Rhine is separated into the Upper Rhine (km 336 to 580) and Lower Rhine (km 580 to 865) it is discernible for the distant future that the Lower Rhine might be affected more strongly by a climate change signal than the Upper Rhine. However, the identified change in riverbed level in the Lower Rhine deviates by 2100 by only a few cm from the state of 2004. The Middle Rhine, from Bingen to Boppard (km 530 to 580) is not shown in this observation, because the 1D model cannot sufficiently simulate this extremely complex river course morphologically, with its strong river bends and extensive bedrock areas.

Sediment redistributions, where the sediment is contaminated, lead to an uncontrolled downstream transport of contaminants. This process can contaminate shallow river sections, forelands or estuaries that are located far away from the contamination source by means of particle-bound contaminants. As the European Water Framework Directive (WFD) explicitly demands a “good chemical status” or “good chemical potential” in all waters, this aspect is important for all waterways and their maintenance.

In order to be able to model climate-related changes to contaminant content in sediments and suspended solids, the current state of the sediment balance must first be recorded. Our data show that the reservoirs along the German-French Upper Rhine considerably influence the sediment balance and thus the sediment loads. We built a three-dimensional sediment transport model for the reservoir in Iffezheim. This model calculates – as proven by the bearing data collected – the highest deposit rates at increased discharges. In low water phases, the deposited material is consolidated, and then the deposit height declines. There are uncertainties with regard to the erosion gradient of the sediments deposited in the reservoir at high discharges. Therefore, subsequent to the KLIWAS programme, field and laboratory measurements of the erosion stability were conducted. Furthermore, the soil

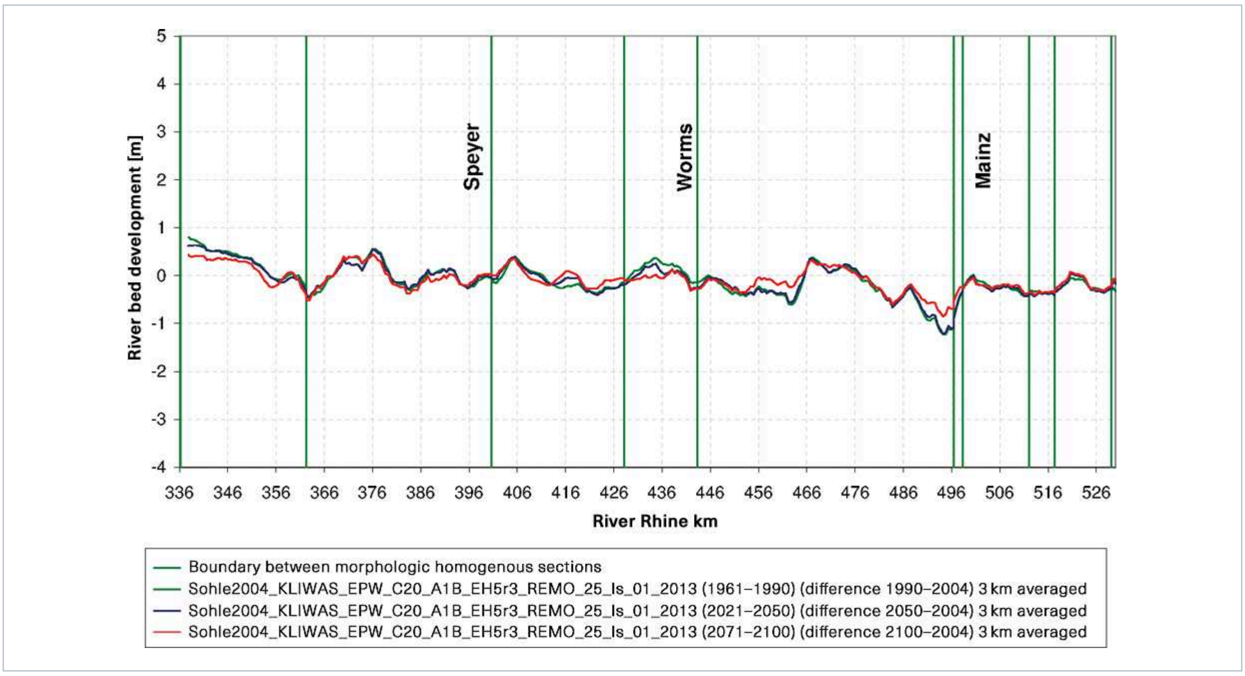

Figure 12: Relative river bed development in the Upper Rhine for the reference period, the near future and the distant future for the projection HBV134-EPW-C20_A1B_EH5r3_Remo_25_ls, in each case referring to 2004 (zero)

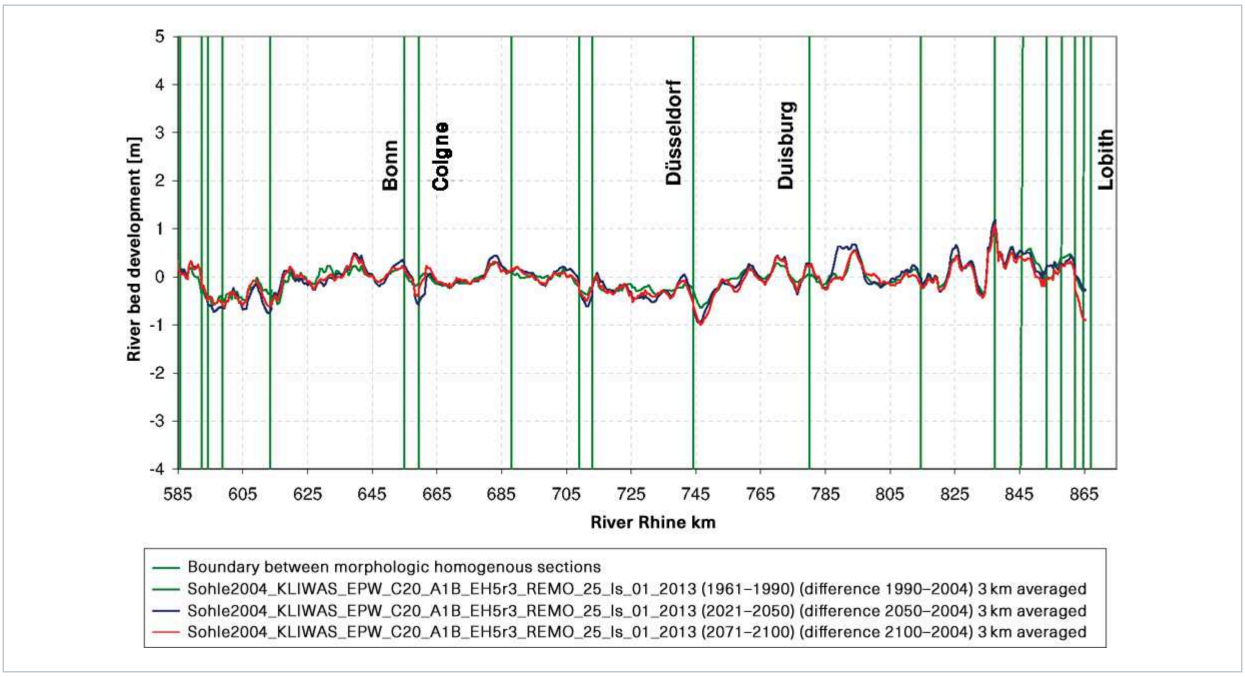

Figure 13: Relative river bed development in the Lower Rhine for the reference period, the near future and the distant future for the projection HBV134-EPW-C20_A1B_EH5r3_Remo_25_ls, in each case referring to 2004

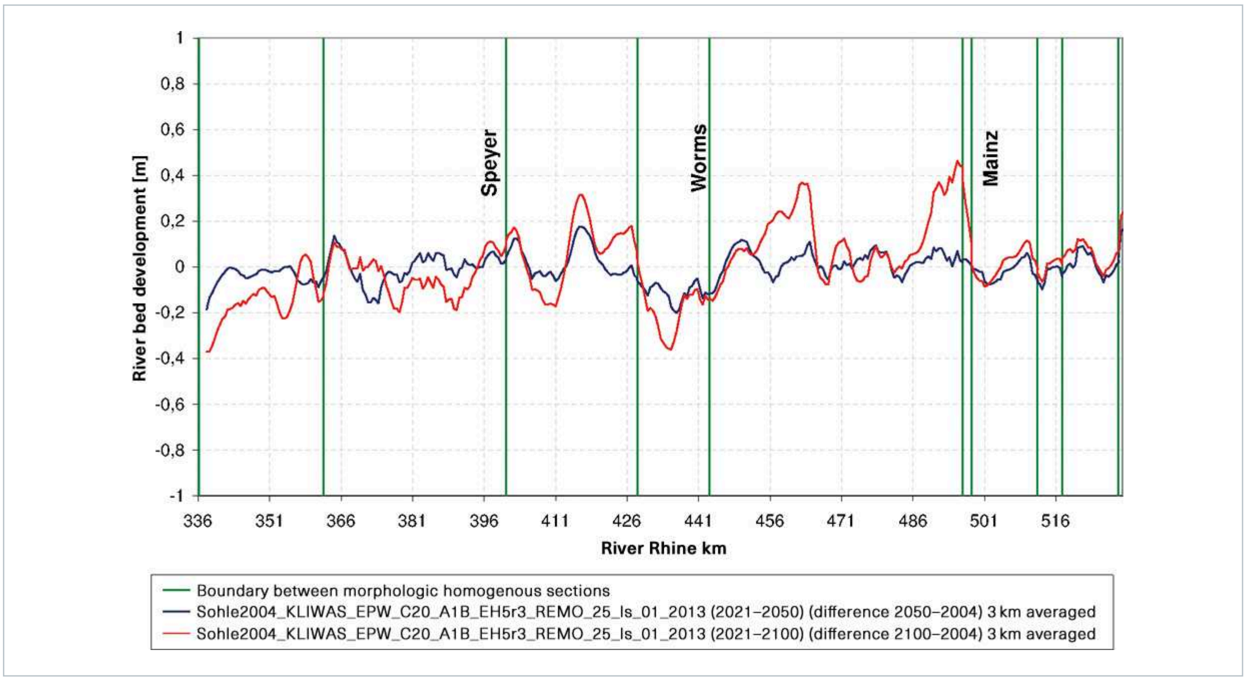

Figure 14: Relative river bed development in the Upper Rhine in the near and distant future for the projection HBV134-EPW-C20_A1B_EH5r3_Remo_25_ls, relating to the reference period 1961 to 1990 (zero)

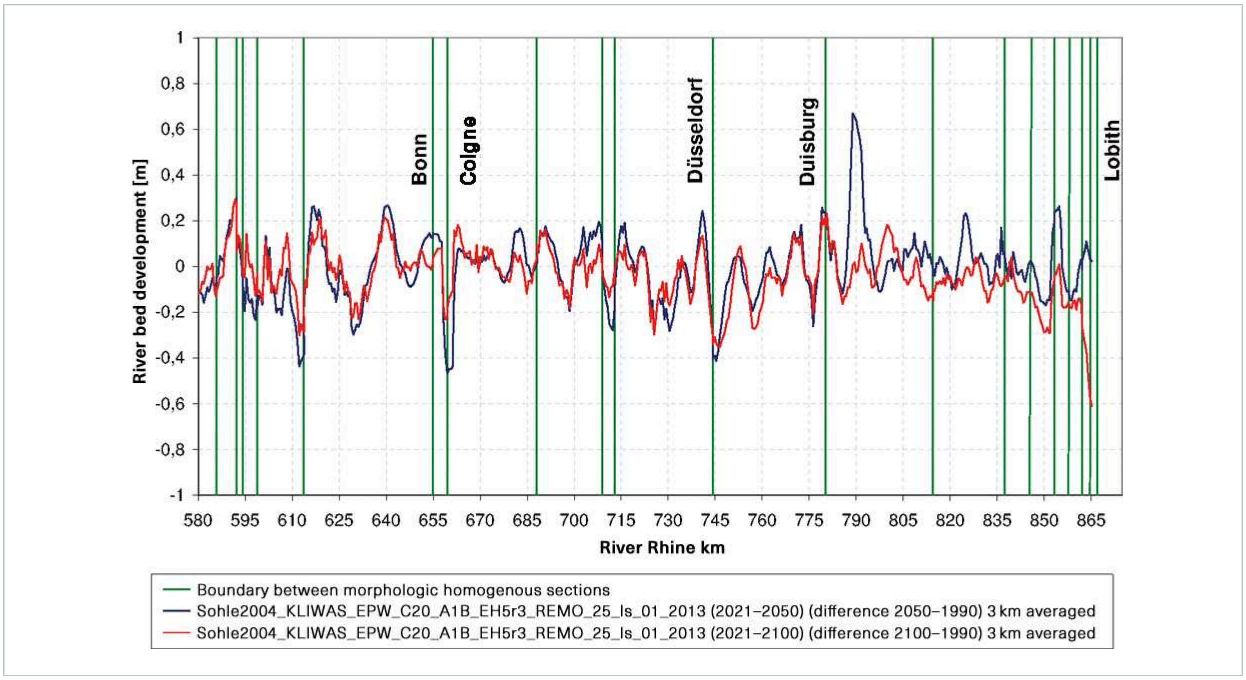

Figure 15: Relative river bed development in the Lower Rhine in the near and distant future for the projections HBV134-EPW-C20_A1B_EH5r3_Remo_25_ls, relating to the reference period 1961 to 1990 (zero)

erosion and the resulting sediment inflow were modelled for five climate projections, in the same manner as in the Elbe catchment area. While climate-related increasing fine sediment inflows from the Alpine region into the Rhine are relevant, no climate change signal concerning fine sediment inflow could be established in the simulation calculations from the soils of the catchment areas of the Main, Moselle or Neckar.

In order to record the impact of the fine sediment transport on the contaminants transport, we analysed multi-year data series on the particle-bound contaminants load. At the measurement point at Koblenz, the hexachlorobenzene (HCB) load declined clearly between 1985 and 1995 and has stagnated ever since. The loads for the congeners PCB-138 and PCB-153 (polychlorinated biphenyls) also stagnated in the period 1995 to 2007. Measures to investigate contaminated sediments in the river bed along the Upper Rhine (so-called secondary sources) are necessary, in order to take safety measures, or to remove these potential pollution sources, and thus avoid jeopardising attainment of the environmental quality objectives of the International Commission for the Protection of the Rhine (ICPR) for the downstream river section.

Our findings in brief:

- Already today, the reservoirs on the Upper Rhine clearly influence the sediment balance and the associated sediment loads.
- The choice of maintenance strategy has a larger influence on the riverbed development and the sediment balance than the possible variation in discharge characteristics related to climate change.
- Inflows of fine sediments from the Alpine region may increase due to climate change, while the projections do not show any clear trend for fine sediment inflows from the soils of the catchment areas of the Main, Moselle or Neckar.
- The loads of the contaminants HCB and PCB, which are transported with the fine sediments, have been stagnating since 1995. In order to reduce contamination further, contaminated sediments in the Upper Rhine must be examined and restored where necessary.

7.5 Water quality in the Rhine

To reach the objective set by the European Water Framework Directive of a “good ecological status” or “potential”, it is necessary to estimate the development of the water quality, in particular the water temperature, oxygen content, and algae growth in the future. For this purpose, we used and developed further the water quality model QSim, which was created by the Federal Institute of Hydrology. On the basis of a hydraulic model, QSim simulates physical, biological and biochemical processes in a river.

Numerous thermal discharges currently have an exaggerated influence on the temperature balance of the Rhine. The simulation runs show that the water temperatures of the Rhine between Karlsruhe and Bimmen will increase in the near future due to climate change by app. +1 °C (Figure 16). This corresponds roughly with the present rise in temperature caused by permitted thermal discharges. In the distant future the climate-related increases in water temperature will be more pronounced and will be around +2 °C (average annual value across nine measuring stations) in the free-flowing section of the Rhine between Karlsruhe and Bimmen. The water temperature will increase most clearly in the distant future in August (+2.6 to +3.4 °C; see Figure 16). Reduced thermal discharges could attenuate the effect of climate change for at least a while. However, no reduction in the high summer water temperatures would be possible, as even today heat discharge is downregulated during times of high water temperatures.

Despite the increase in water temperatures, only minimal effects of possible climate change on the oxygen concentration in the Rhine were modelled. These are reduced slightly primarily by the low physical solubility of oxygen at higher water temperatures. Changed discharges and water temperatures also have little effect on algae growth, the simulated changes are in the range of measurement and modelling uncertainties.

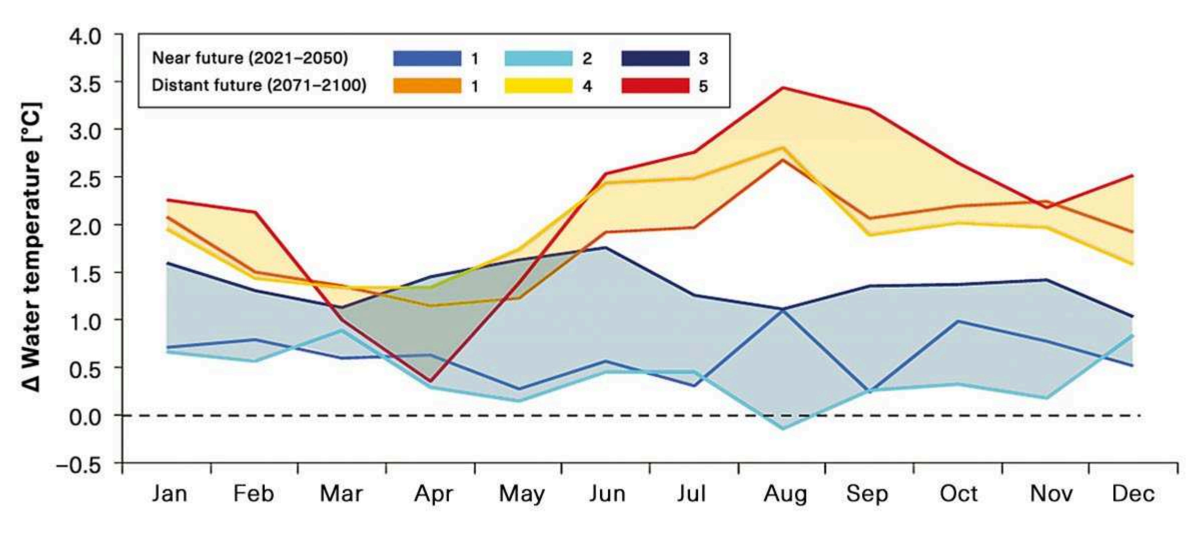

Figure 16: Projected changes to the water temperature (range of the monthly average) in the near (blue) and distant (red) future, compared with the reference period (1961 to 1990). Average values from nine measurement stations on the free-flowing stretch of the Rhine between Karlsruhe and Bimmen are shown.

Model chains:

1 = C20-A1B_ECHAM5r3_REMO-ENS (near and distant future)
2 = C20-A1B_BCM_RCA3 (near future)
3 = C20-A1B_HADCMQ0_HADRMQ0 (near future)
4 = C20-A1B_ECHAM5r3_RACMO (distant future)
5 = C20-A1B_ECHAM5r1_CLM24 (distant future)

The reason for these minimal climate effects is that water temperature is obviously not the most important factor in controlling algae growth in the Rhine, and that the projected discharge changes in spring, the main blooming period of the algae, are moderate (see Chapter 7.2). In contrast, the food web in the Rhine could be influenced considerably as an indirect consequence of climate change, due to the increase in water temperatures. This would be the case, for example, if certain species of molluscs that graze on algae, disappear or multiply as a result of high water temperatures. Such effects have not yet been examined, but are the object of planned studies. They could influence the water quality much more severely than a direct effect of climate change might.

Our findings in brief

- The water temperature of the Rhine is raised by thermal discharges and as a result of climate change. Climate change causes an increase in average monthly water temperatures of app. 0 to +1.5 °C in the near future and app. +0.5 to +3.5 °C in the distant future.
- The increases in temperature, which in the distant future are especially pronounced in summer, cannot really be balanced out by reducing thermal discharges.
- The modelled direct results of the rise in temperature for the oxygen balance and algae development are low. However, considerable indirect consequences are possible, due to the impact of higher water temperatures on the food web in the Rhine.

7.6 Hydraulic engineering adaptation options at the transition from the Upper to the Middle Rhine

The ensemble of possible development of low water discharge in the Rhine projected in KLIWAS shows on average a slight increase (−5 to +10 percent) in the near future (2021 to 2050). It is a different matter in the distant future, where decreases are expected (−20 to +10 percent), as can be seen in Chapter 7.2. In general there is the possibility that there will frequently be longer-lasting phases of both low water levels and the exceedance of HSW, compared to today. For navigation on the Rhine this means a decline in economic effectiveness and in the ease and safety of navigation (see Chapter 7.3). This can be countered in principle with innovative shipping technology, optimised navigation, a changed fleet structure or adapted logistics on the part of the companies affected, as well as hydraulic engineering measures.

The economic use of navigation on the waterways is based on the continuous availability of minimum channel depths, which are safeguarded by the provision of channels with a guaranteed breadth and water depth under defined reference water levels, such as the Equivalent Water Level (Gleichwertiger Wasserstand, GlW), i.e. the water level, when there are on annual average fewer than 20 ice-free days per year. The maintenance to guarantee this channel depth will be influenced by a future possible change in sediment transport to the different sections of the waterways. More frequent low water discharges mean that the current low water reference water levels will more frequently not be reached, respectively they will have to be defined at a lower level in the context of regular adjustments, which will have to lead also to adaptation measures in order to preserve the defined channel depths.

In principle, all types of measures that were taken in the past (independently of climate change) to improve the availability of the waterways are equally suited to compensate for the deteriorations resulting from climate change. Their application, however, depends on the technical aspects, but also on economic and political considerations in the battle between societal values.

The studies in KLIWAS show exemplarily other transport-related hydraulic engineering adaptation potential. Adaptation options to minimise the growing maintenance expense were developed using vessel-dynamic and hydraulic-morphodynamic studies.

The option of a general reduction in present-day channel widths at positions of depth constriction, or a recessed channel, was examined specifically from the perspective of navigation at the transition from the Upper Rhine to the Middle Rhine between Mainz and St. Goar, and tested by means of natural experiment. According to the test, almost all current traffic could continue unhindered, and only a few vessels had to shift encounters and passing to other sections of the route without waterdepth problems.

From a hydraulic-morphological perspective, the provision of currently existing channel depths in the event of potentially reduced reference water levels on a reduced channel width by exploiting extra depths also represents a suitable waterways engineering adaptation option. It must be examined more closely under consideration of safety aspects. By these means, the maximum projected increase in maintenance could be almost completely balanced out in some partial stretches of the pilot route.

In areas with alluvial deposit tendencies, an improvement to the channel conditions can be achieved with regulating measures that are aimed at increasing the forces affecting the bed, thus leading to a reduction in alluvial deposit rates. Regulating measures were identified in four areas between Mainz and St. Goar, which could reduce the maximum projected increase in river training measures.

Another option might be flexible regulating elements that take effect only with low water discharges, to increase the water level positions. Due to their temporary effect, such regulating elements would have a comparatively small impact both on the high water levels and on the morphology.

However, the adaptation options developed and assessed in the context of KLIWAS are for the most part section-specific. This affects measures to limit discharge in tributaries, which leads to an increase in water levels in the channel. Such hydraulic engineering measures always depend on local current conditions and the type of waterways bed (bedrock or gravel). In sections with a large amount of traffic, appropriate consideration must be made for transport concerns, in particular possible waiting times for sections with width constraints. Therefore the results outlined above cannot be transferred directly to other routes and/or river stretches, but the research methods developed in the context of the KLIWAS projects certainly can.

Our findings in brief:

All known river engineering measures and management concepts that already determine the navigability of the federal waterways today are in principle suitable for compensating possible future constraints, at least partially. They can be supplemented by measures with an innovative character, such as in the areas of navigation or shipping technology, or in the logistics chains.

8. Supra-regional topics

8.1 KLIWAS climatology for the inland

Precipitation

In the observed period (1951 to 2006) the average winter precipitation shows increases of +20 to +30 percent in the northwest of the KLIWAS evaluation area (German and bordering river catchment areas), in the south and east, in contrast, of only +5 to +25 percent. The tendencies for summer are weak, in the east of Germany decreases of up to −12 percent are found. Our ensemble analyses of the climate models suggest in the future decreases in precipitation in the summer months, whereas an increase in precipitation is likely in the winter months. The relative changes to average summer precipitation as projected by us demonstrate a range from a very low decrease to a decrease of up to −15 percent for the period 2021 to 2050 (near future) and up to −25 percent for the period 2071 to 2100 (distant future). A few of the climate models also show a slight increase in summer precipitation for isolated regions.

Air temperature

The average annual air temperature in the KLIWAS evaluation area rose by between +1.1 and +1.4 °C in the observation period 1951 to 2006. In the near future, an increase in the average annual air temperature of at least +0.5 °C can be expected for Germany. However, a temperature increase of more than +2 °C (northern Germany), respectively +2.5 °C (southern Germany) is unlikely. In the distant future we consider an increase in average air temperatures of at least +1.5 °C and at the maximum +3.5 °C in northern Germany and +4 °C in southern Germany to be likely, respectively.

Global radiation

The average values for global radiation will change very little by the middle of the century. For the end of the century we assume a decrease in global radiation in the winter months of between −5 and −20 percent and a slight increase in the summer months (up to +10 percent in northern Germany, maximally +15 percent in southern Germany).

Parameters

The reference and climate simulation data can also be used to calculate parameters such as “hot days” and “ice days” with the help of the daily maximum temperatures. Assuming an average diurnal cycle, we have estimated maximum values from the observation data.

Hot days

The parameter “hot days” represents a measured value for “extreme weather”, e.g. by counting the annual days with a maximum temperature of at least 30 °C: The number of hot days in the period 1951 to 2006 increased by 4 to 5 days. It is likely in both the near and distant future that the number of “hot days” will continue to rise. Until the middle of the century it is likely that the number of hot days will increase by between 5 and 10 in northern Germany and between 10 and 15 in southern Germany. For the end of the century a maximum increase of “hot days” by 10 to 15 days (northern Germany) and 30 to 35 days (southwest Germany) is likely. However, the projections of individual climate models also suggest a small probability that the number of “hot days” in Germany will remain unchanged for the entire time period observed.

Ice days

A further parameter is the number of annual ice days. These are days on which the maximum daily temperature is below 0 °C. The number of ice days decreased from 1951 to 2006 by 5 days. Both for the near and the distant future, all climate models of the ensemble we have used project a continued decrease in ice days. This affects first of all the Alpine region. Here, an average decrease of between 10 and 20 days is likely for the period 2021 to 2050, up to 30 days for the period 2071 to 2100, and in some very high altitudes also more than 60 days. In the remaining area of the study, a decrease of 5 to 20 days can be assumed for the near future and up to 15 to 30 days for the distant future

Statements regarding weather patterns in the distant future

Winter (December, January, February)

For all river areas of Germany our results show an increased occurrence of weather conditions that contribute to wetter conditions. This is caused by an increase in westerly weather patterns, which are usually accompanied by high precipitation. This, in turn, is caused by increased moisture transport by maritime-influenced westerly flows. At the same time, the drier easterly weather patterns (high pressure conditions) will decrease slightly. South-westerly weather patterns, which are associated with very high areal precipitation, will also occur more frequently.

At the same time, the south-westerly weather patterns will lead to generally very mild temperatures. Furthermore, we expect more frequent warm air advection from southern parts of Europe which will also cause milder winter temperatures.

Summer (June, July, August)

The weather patterns and thus the climatic parameters will also change in summer: We expect an increase in anticyclone westerly weather patterns (high pressure influence), frequently with little or no precipitation. At the same time, the cyclones (low pressure influence), which are associated with higher precipitation, will decrease in total. The frequency of heavy precipitation is likely to increase slightly.

Changes in weather patterns will contribute to warmer or hotter weather conditions. This is influenced on the one hand by warm or hot southerly flows. On the other hand cold snaps (e.g. due to areas of low pressure with cold, northerly flow) will be less strongly pronounced and will occur less frequently on average.

8.2 Ice formation

As well as low water events and flooding, ice formation can also lead to restrictions to navigation on the federal waterways. In the past, primarily the eastern German waterways, such as the Oder and Elbe, as well as the German canal system, were affected by this. But ice formation can also occur in the west during cold winters, especially on the impounded tributaries of the Rhine, leading to ice-related navigation blockages. However the Rhine itself last froze over in 1963. The main reason for this is the increased thermal discharge ever since by power plants, industry and sewage treatment plants.

The frequency and duration of the occurrence of ice in the winter season depends on the total sum of the amounts of negative average daily temperatures in winter. This so-called “winter cold sum” generally increases from the coasts (maritime climate) towards Europe’s interior (continental climate). According to available climate projections (see Chapter 8.1) a decrease in days with a maximum temperature below 0 °C is expected in Germany in both the near (2021 to 2050) and distant (2071 to 2100) future. The “winter cold sum” would also decrease accordingly. Figure 17 illustrates the range of changes according to the ensemble of climate projections used. Due to the level of cold sums, which is already low in the reference period, we expect great changes to the waterways located in the west, commencing in the near future. For the waterways situated further east we expect clear changes to the average “winter cold sums” (orange and red colours), both in the near future and once again in the distant future.

The parameter “winter cold sum” displays a good correlation with the navigation-relevant parameter “number of ice-related blockage days”, especially in the canal system, which is why statements can be derived on this basis for the future ice situation on German inland waterways. Accordingly, Figure 18 shows the range of the modelled

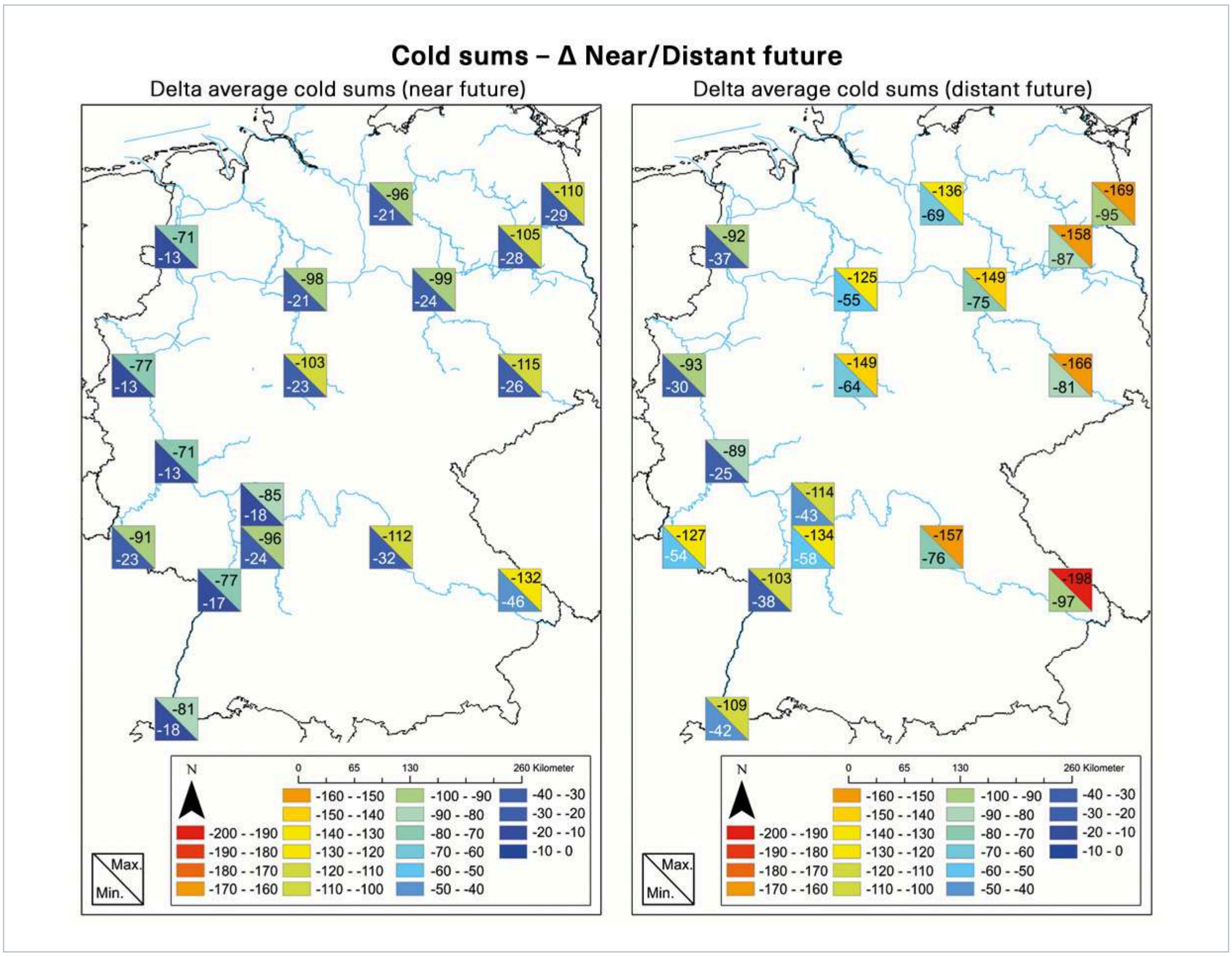

Figure 17: Change in cold sums (unit: degrees Kelvin × days [Kd]) between the selected reference period 1971 to 2000 and the near (left) and distant (right) future in Germany. Selected grid cells against the background of the water network of the federal waterways. "Min." and "max" represent the range from 14 (for 2021 to 2050), respectively 12 (for 2071 to 2100) KLIWAS model chains used

number of winters for four selected canal systems in each 30-year period, in which no ice-related blockages are expected.

Our results show clearly that:

- there will be a clear increase in winters without ice-related blockages in the near and distant future.
- the west-east gap, which is still clearly pronounced in the reference period and the near future, will almost disappear in the distant future.
- the model results for the eastern canal system show a greater range than in the west, especially in the near future.

The development shown for the canals can also be transferred qualitatively to the free-flowing and impounded federal waterways. However waters such as the Rhine, which are strongly influenced by thermal discharges, are already experiencing an ice situation that would otherwise be expected in the distant future.

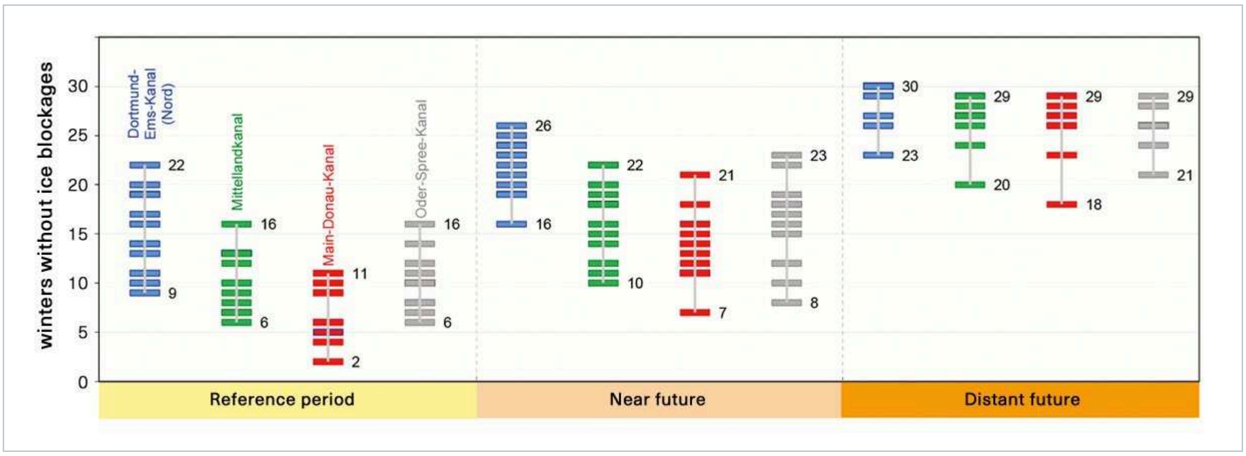

Figure 18: Comparison of winters without ice blockages for the periods 1971 to 2000, 2021 to 2050 and 2071 to 2100 on the DEK (Dortmund-Ems canal), MLK (Mittelland canal), OSK (Oder-Spree canal), and MDK (Main-Donau canal). The columns represent the range of results from 14 (for 1971 to 2000 and 2021 to 2050), respectively 12 (for 2071 to 2100) KLIWAS model chains used. The results of the individual model chains are shown, as well as the maximum and minimum of the span in each case

Therefore it is expected that climate change will lead to fewer ice events that hinder navigation, and in some case they may almost completely disappear. However, there may also be intermittent increases as a result of other influences, e.g. the decommissioning of power stations due to political decisions such as the new energy policy.

If ice occurrences increasingly form the exception rather than the rule in the future, and these represent an unusual event for navigation and waterways operators compared to today, it may be necessary to reassess the preventative measures to be taken.

To obtain more detailed analyses, e.g. of the changes in temporal dynamics, of the effects of changed conditions due to waste heat discharges, studies of special local features, or the occurrence of certain types of ice, the development and expansion of detailed coupled thermal-hydraulic ice models would be necessary, as well as corresponding measurement data.

Our findings in brief:

- The ensemble of climate projections lead us to expect an increase in winters without ice-related blockages, commencing in the near future, and more pronounced in the distant future.
- In the near future in particular, our projections show a greater span for those canal systems located in the east than in the west.
- The west-east gap, with more frequent ice events in the east (continental influence) than in the west (maritime influence), which is still very pronounced today and in the near future, will disappear for the most part in the distant future due to the general rise in temperature.

8.3 Animal ecology

Climate change is likely to change the settlement structure (fauna, taxa, abundance) in federal waterways. This will mean that the ecological communities that we know today, with their indicator organisms for ecological evaluations – e.g. in the context of the expansion and maintenance of the federal waterways – will no longer be suitable. Our objective is to adapt animal ecological assessments in a planning process, in order to provide an appropriate environmental feasibility test of measures, also in climate-related changed situations.

As a necessary foundation for deriving a new evaluation procedure, we conducted comparative studies of native and invasive Gammaridae (amphipod) species. Besides the species-specific temperature tolerance and preference, metabolic activity and the energetic condition of the animals were characterised in further laboratory investigations based on reserve substances. The invasive species *Dikerogammarus villosus* (killer shrimp), *Gammarus tigrinus, Echinogammarus berilloni* and the native species *G. fossarum, G. pulex* (common amphipod), *G. roeselii* were studied (see Figure 19).

The parameters used could provide indications of climate-related changes to living conditions, as well as the species-specific adaptation potential of the animals. Our laboratory studies took account of the range of the climate changes calculated in the KLIWAS research programme with regard to the temperature regime. The experimentally-determined species-specific temperature preferences were evaluated against the background of the projections of temperature regimes as defined in KLIWAS.

The successful invasive species *D. villosus* and *G. tigrinus* are characterised by strong preferences for high temperatures; in direct comparison the preferred temperature of the native species is lower (see Figure 20). Furthermore, in the studies the invasive species *D. villosus, G. tigrinus* and the species *G. roeselii* demonstrated significant acclimatisation effects, i.e. they could “adapt” their temperature preference to higher temperatures. This adaptation potential was missing in the native species *G. fossarum* and *G. pulex,* and in the invasive species *E. berilloni*.

Figure 19: *Dikerogammarus villosus* (killer shrimp, above) and *Gammarus pulex* (common amphipod, below).

The temperature tolerance (critical thermal maximum) was higher among the invasive than among the native species. However, it was above 30 °C in all species studied. In accordance with the temperature preference, *G. tigrinus,* followed by *D. villosus,* showed by far the greatest temperature tolerance. We could prove an adaptation potential in both species with regard to temperature tolerance. These effects were completely absent in the native *G. fossarum*. The native species *G. roeselii* and *G. fossarum* resembled each other with regard to the temperature dependency of metabolic activity.

Besides the examination of species-specific tolerance and preference, the study of the energy reserves that are present in the animals and in the overall population provide an important approach for estimating the development and endangerment potential of individual species (“physiological fitness”). Our studies show that the

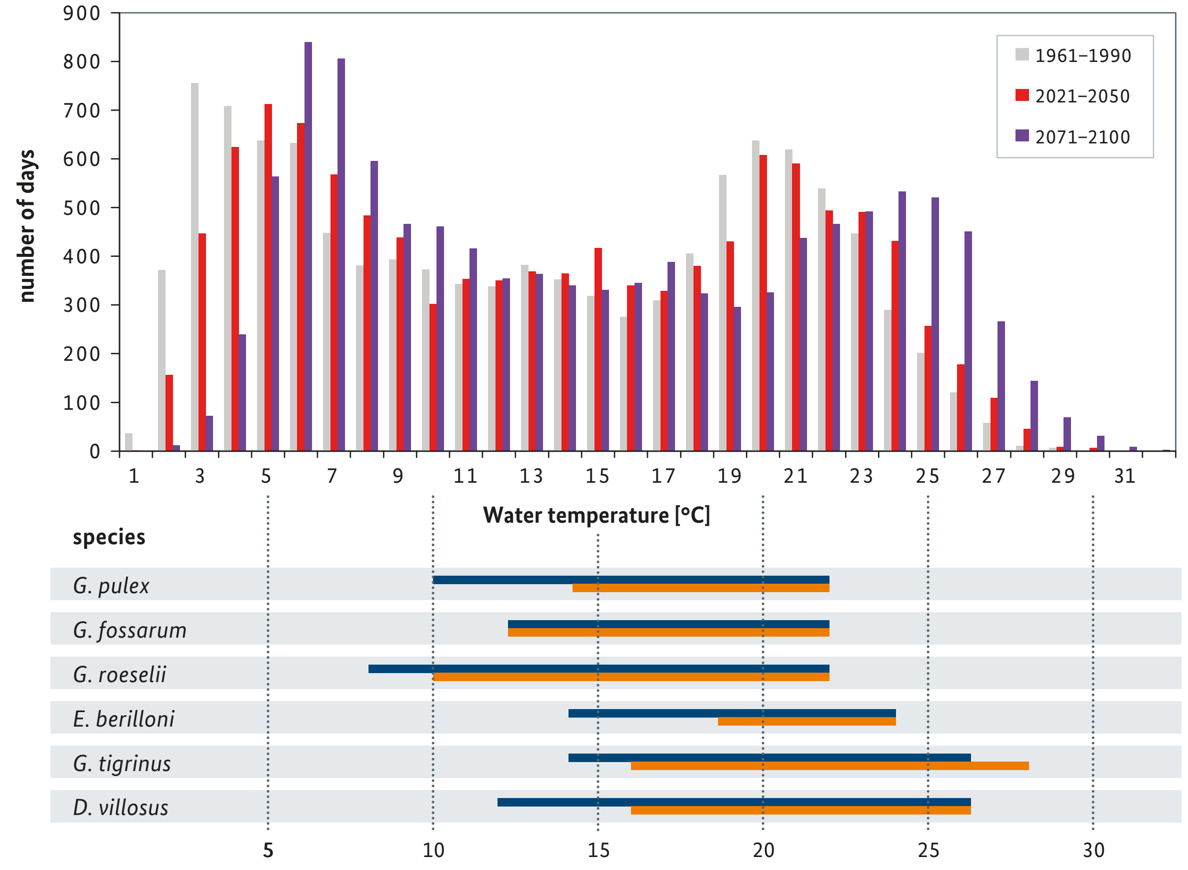

Figure 20: Comparison of the preferred temperature areas (as minimum and maximum temperature) of selected Gammaridae species with regard to average daily temperatures (as frequency distribution) in the near and distant future (Rhine km 590; temperature data: Project 5.02; A1B_ECHAM5-3_REMO5.7). Blue crossbar: acclimatisation at 15 °C, orange crossbar: acclimatisation at 20 °C

stored energy reserves in the native species *G. fossarum* and *G. pulex* vary considerably in the course of the year. This could result in energy deficits that could restrict the fitness of the organisms at least for a time, and might therefore lead to a lower potential to react or adapt to changed environmental conditions.

The results of our studies suggest that the projected increase in water temperature in the Rhine (cf. Chapter 7.5) could present a competitive advantage to the invasive Gammaridae species (except for *E. berilloni*), while the native species could be forced even further into cool habitat niches. The at times restricted reaction and adaptation potential of the native species studied, *G. fossarum* and *G. pulex,* could also play a role here.

Critical water temperatures (>30 °C) that lie within the area of the experimentally determined temperature tolerance and which could thus pose a general problem for the currently distributed Gammaridae species, are not reached in the near future in the available projections. However, these temperature tolerance limits could gain in significance in the distant future (Rhine km 590, 2071 to 2100) according to individual (extreme) KLIWAS model. In general, further changes to the faunistic settlement structure can be expected in the federal waterways in the future, in interaction with the known transport mechanisms for neozoa. It is also possible that more heat-tolerant species will immigrate.

Our findings in brief:

- Temperature tolerance and preference differs between different amphipod species.
- The successfully invasive species Dikerogammarus villosus and Gammarus tigrinus prefer and tolerate higher water temperatures than native species. This could create a competitive advantage for the invasive species over the native species, which could be forced into cooler habitat niches by the projected increase in water temperatures.

8.4 Construction materials in hydraulic engineering

Construction materials from different sources are used in construction and in maintenance of the federal waterways. Frequently, these materials contain various organic and inorganic contaminants. Until now there has been no systematic analysis on materials used for hydraulic engineering with regard to water chemistry and the release of contaminants. Therefore, the potential release of contaminants from construction materials in hydraulic engineering and a potential impact from climate change-related processes was examined by KLIWAS.

Our studies focused on the industrial by-product iron silicate armour stones (copper slag) which are commonly used in the North German waterways and biocides that may be released from construction material commonly used in terrestrial applications.

Due to the insufficient data basis, it was first crucial to develop a methodical and analytical basis. For this reason, we examined by means of laboratory experiments the extent to which climate-impacted parameters such as salt content (ionic strength), water temperature or the pH value may foster the release of contaminants from materials in hydraulic engineering. The developed methods aimed at addressing the long-term behaviour of materials in hydraulic engineering (e.g., use of passive samplers in leaching experiments). In addition, the conversion of biocides released from construction products was also examined, depending on the previously mentioned parameters.

The results show that the long-term release of metals and metalloids from construction materials in hydraulic engineering depend to a large extend on their binding forms. Results from standardised laboratory experiments, e.g. according to DIN or CEN, may be biased for some materials by methodical artefacts. Ultimately, for some of the studied metals and metalloids, it is now possible to link results from laboratory experiments to the application in the federal waterways.

The results of the laboratory experiments show that changes of ionic strength and temperature caused by climate change have an impact on the release of metals and metalloids from construction materials in hydraulic engineering. The release of selected metals and metalloids from the armour stones studied increased most noticeably due to a rising salt content. For Elbe km 609, a maximum change in conductivity of < 10 percent and a change in the average water temperature of max. +3 °C was derived for the near and distant future (Hein et al. 2014). With these moderate changes expected from climate change, no significant change to contaminant release or the chemical stability of the armour stones is expected. The results illustrate that the installation site with its specific field conditions, is of primary relevance for the stability and the release of substances from materials in hydraulic engineering. In future, these results should be taken into account when assessing impacts of the installation of armour stones on water chemistry.

Climate models project an increase of average annual temperatures and a change in radiation intensity. Therefore, it must also be expected in future that biocides and UV stabilisers will be used increasingly in building products, in order to prevent their degradation by microorganisms and UV radiation, as well as to prevent algae fouling. There have also been no comprehensive studies on the release of such substances from construction products under changing boundary conditions (such as paints, varnishes, acrylate polymers, epoxy resins. Therefore, we examined the possible influence of these products on the quality of flowing waters and the possible influence of climate-related changes on the influencing factors. The biocides Irgarol (Cybutryn) and Terbutryn were selected as model substances with a high relevance for federal waterways. Both biocides are of major environmental relevance, as they are priority contaminants of the Water Framework Directive (EG-WFD) with extremely low environmental quality standards (EQS) of 65 ng/L (Terbutryn) and even 2.5 ng/L (Irgarol). Irgarol is used as an algaecide in anti-fouling paints, for example for coating boats, to prevent the fouling by algae. Terbutryn and Irgarol are also used as protective agents in outdoor paints. The anti-fouling paints, which are applied to surfaces, develop their growth-inhibiting effect by dissolving the active components continuously from the paints. The biocides Irgarol and Terbutryn are therefore deliberately released. With our newly developed and sensitive analytical methods (Quantification limit: 1 ng/L) we studied the extent to which these biocides are already present in significant quantities in German rivers today. In addition to the building products that are being used in hydraulic engineering, other possible sources (e.g. sewage treatment plants) were investigated, as these biocides can also enter the rivers via the release from rain run-off from building facades, through sewers, and via sewage treatment plants.

It was also examined whether these results regarding release might also apply to other organic additives to building products. For this reason we analysed selected hydraulic engineering materials (e.g. polyacrylamide, polyurethane) for their potential to release currently unknown organic substances. The leaching experiments showed that, along with biocides, other complex mixtures are released from construction products based on polyacrylate, epoxy resins and polyurethane during hardening of these polymers. The individual substances in these mixtures have not yet been identified, so that a concluding assessment of the environmental hazard is still pending. However, initial results show that appreciable quantities of these substances are being discharged into the rivers.

Our studies proved clearly that building products emit detectable and relevant quantities of biocides, which may even contribute to the exceedance of the EQS. This therefore endangers the EU-WFD demand for a good chemical condition of rivers. Due to the climate-related increase in air temperature, an increased use of biocides and thus increased contamination with biocides (number, quantity) of rivers cannot be excluded. However, even for an increase in average monthly water temperatures of only +0.5 to +3.5 °C as expected in the next few decades, we assume that the climate-related increased release of biocides from building products will have no significant influence on the water quality, compared to other changes, such as the use of alternative construction materials and adapted uses in the rivers and in the catchments areas. With regard to the release of the two selected biocides, it is assumed that the contribution of construction material compared to the contributions from the urban areas is relatively small. This assumption is derived from the relatively high concentrations that were detected in the discharges from sewage treatment plants.

At present we do not consider it necessary for the WSV to act. However, one should always be aware of the fact that due to the low EQS (2.5 ng/L for Irgarol), even a release of small loads, for example from construction materials, might become relevant for the exceedance of that EQS. If alternative products with equal properties are available, we recommend the use of products that exhibit little or even no release of biocides. In any case, the biocide content of construction materials should be recorded across their entire life cycle when assessing the environmental compatibility of such products prior to their approval. In order to exclude negative impacts on the water quality and any damaging impacts on water organisms, we consider precise knowledge of the ingredients and the released substances and decomposition products to be indispensable.

Our findings in brief:

- The release of metals and metalloids from armour stones made from copper slag is enhanced by an increasing salt content and low pH values. Water temperature plays a less prominent role.

- For the use of armour stones made from copper slag, no adaptation of the maintenance concepts of the Federal Waterways and Shipping Administration (WSV) to the moderate climate-related changes of the influencing factors studied (ion strength, pH and temperature) seems to be necessary from the perspective of water chemistry. In principle the choice of materials and the installation site are of much greater importance for the release of metals and metalloids.

- Building products used primarily in the terrestrial area emit measurable quantities of biocides that enter rivers either directly or via sewage treatment plants. There, they can lead to an exceedance of the environmental quality standards of the EU-WFD (UQN). These emissions could increase further due to a possible increased use of biocides under growing climate-related warming.

- No direct need for action by the WSV is identified, as the biocides examined mostly come from building products of the terrestrial area that are discharged into rivers via sewage treatment plants. However, at present it is not clear whether these results are transferrable to other additives of construction materials.

8.5 Climate-relevant contaminants: Biocides, insecticides, UV filters

The climate-related increased average values of the annual temperature are likely to lead to a change/increase in the use of insecticides, herbicides and biocides. In order to be able to follow and quantify the change in biocide use in the future, new analytical methods were developed in KLIWAS for the determination of insecticides, herbicides, biocides, UV filters and pharmaceuticals in sediments and water samples down to the lower nanogram/L range. First, the contamination of the North Sea coast, inner Elbe, Elbe estuary, Saale, Black Elster, Havel, Rhine, Oder and numerous smaller inland waterways was monitored exemplarily.

Our studies showed that predominantly discharge changes alter the concentrations of organic contaminants in the waters. Low water levels in the inland waterways lead directly to increased concentrations of contaminants, because the discharge of sewage treatment plants into rivers remains largely constant, even in dry periods. As organic contaminants generally enter the waters via municipal sewage treatment plants, the introduction of a fourth purification step to remove organic substances would lead to a clear improvement in water quality.

No temperature influence on sorption and desorption in sediments for 87 selected insecticides, herbicides, biocides, pharmaceuticals, fire retardants and plasticisers studied could be proven. Therefore, it is rather unlikely that there will be a significant release of biocides adsorbed to sediments to the water phase, even with a climate-related increase in water temperatures of +0.5 to +3.5 °C on a monthly average.

Initial transformation products were identified from the temperature-dependent degradation studies and proven to be present in surface waters. The degradation rate of biocides increased in the temperature range between 4 and 20 °C. This applies to all substances examined that were microbiologically degradable. It can therefore be assumed that a climate-related rise in water temperature will lead to slightly higher degradation of most organic contaminants. With extreme water temperatures of 28 °C, however, a decline in the degradation of the contaminants was observed, presumably since the microbial community changed in the laboratory experiments. For anthropogenic substances that are not completely mineralised in the urban water cycle, the formation and removal of transformation products has to be implemented in substance licensing (e.g. pharmaceuticals, pesticides and biocides) and substance registration (e.g. REACH) as a fixed, obligatory test criterion. The influence of the temperature on the degradation rate and the formation of transformation products should also be taken into account.

A climate-related increase in water temperature will directly influence the contaminant concentrations of the sediments in the Rhine and other rivers only negligibly. However, a distinct climate warming would result in many various changes, both for agricultural practice (increased use of herbicides, insecticides and fungicides), but also for personal care products, such as cosmetic ingredients, detergents or disinfectants. The use of biocides (antibacterial) and UV filters (UV protection) may rise, to increase the microbial and chemical stability of the products. The use of sunscreen products, which contain UV filter substances, is also very likely to increase. Therefore, it can be assumed that the changes in the quantities consumed, but also the introduction of new, as yet completely unknown products, will influence the amount of substances discharged into the Rhine and other rivers much more than the moderate rise in concentrations resulting from the increased occurrence of low water periods, as projected for the distant future, and the associated relative rise of the percentage of treated wastewaterby 2 %.

Our findings in brief:

- Low water levels lead to an increase in the concentrations of polar organic contaminants in inland waterways, because the discharge from sewage treatment plants into rivers remains largely constant, even in dry periods.
- An increase in water temperature by +0.5 to +3.5 °C on a monthly average a) has no significant influence on the ratio of contaminant concentrations between the watery phase and sediment and b) can lead to an accelerated degradation of organic contaminants.

8.6 Algal toxins

An increase in the maximum water temperature and lower current velocities could lead to an increased occurrence of blue-green algae (cyanobacteria) which, under unfavourable circumstances, can produce highly active toxins (algal toxins). In order to detect the occurrence of blue-green algal toxins at an early stage, new, more sensitive analytical measurement methods were developed in KLIWAS, with which algal toxins could be quantified, even in very small concentrations (few nanograms/L). With the analytical LC-Tandem-MS methods now available, we have the technical possibilities to analyse the occurrence and behaviour of algal toxins, especially under changed climatic conditions.

The newly developed methods were applicable to both, to water samples and to eluates of sediments. By these means it was possible to prove initial findings of algal toxins in selected surface sediments (to a depth of 5 cm) of a harbour in the inner Elbe estuary and in the Baltic Sea.

Our findings in brief:

- The newly developed methods to quantify algal toxins were applicable to both water samples and eluates of sediments. By these means it was possible to get initial findings of algal toxins in selected surface sediments (to a depth of 5 cm) of a harbour in the inner Elbe estuary and in the Baltic Sea. As yet, no direct need for an action by the Federal Waterways and Shipping Administration (WSV) can be seen. However, for deriving the need for actions, the available data bases must be significantly enlarged.

8.7 Microbiological-hygienic aspects in inland waters

Intestinal pathogens that are transmitted during activities at and on the water can have an effect on human health even in low concentrations. As their determination is time consuming and expensive, we concentrated on the quantification of faecal indicators (hereafter faecal organisms). These are regarded as indicators for the occurrence of intestinal pathogens.

In the context of monitoring studies, we examined many climate-related changing parameters and their impact on the influx or survival duration of faecal organisms. Analyses at the Rhine, Moselle and Lahn clearly indicate, among other effects, that high discharges and precipitation favour the influx of faecal pathogens into waters. In contrast, under high sun radiation and increasing water temperatures, a decrease in the hygienic-microbial pollution was observed. We conclude that changed discharge and precipitation patterns, and an increase in year-round water temperatures, which are shown by our projections e.g. for the Rhine, influence the microbiological-hygienic water quality.

Furthermore we established that floods lead to a rise in faecal bacteria and viruses, which are hazardous to health, in the river sections we examined. Microbial pollution peaks can be expected before the actual flood peaks. To protect against infection it should be tested whether existing regulations for work at the water should be supplemented under this aspect, or whether special brochures should be issued.

During low discharge periods, the concentrations of faecal bacteria and viruses are for the most part relatively low. However for the Lahn we observed that heavy precipitation, especially after longer dry periods, could cause a massive increase in faecal organisms in the water. We attribute this on one hand to run-offs from agricultural surfaces, and on the other hand to the exceedance of the capacities of combined sewage overflows. This has a possibly hazardous potential, especially with regard to water sports, as the pollutions can also become noticeable in downstream areas that were not affected by the heavy precipitation.

Furthermore, our laboratory experiments show that faecal organisms survive longer in sediments than in the water phase. This would suggest that the resuspension of sediments – also by a remobilisation in the context of dredged material deposition – could play a role in the drifting of potential pathogens into the water.

While the statements made here for the Rhine, Moselle and Lahn describe a general pattern, nevertheless no robust statements can be made with the currently available data on the extent of the effects described. In addition, bacterial and viral pollution depend greatly on the type of water body and on the catchment area; results from individual measurement points are difficult to transfer to other river areas. Therefore the development of a spatially more differentiated model is necessary for an adequate estimation of hydrological hygienic conditions.

In general, the microbiological-hygienic water quality is influenced to a much greater degree by extreme precipitation and discharge events than by comparatively low changes to average values. However, as yet no projections have been made on the frequency and scope of future extreme events, so that it is currently not possible to estimate the extent to which climate change will cause more frequent or severe pollution peaks with faecal bacteria. In this context, however, future studies should pay special attention to weather situations in which longer dry periods in summer are followed by heavy rain events, as here potentially massive pollution peaks can be expected.

Our findings in brief:

- High discharges and precipitation enhance the influx of faecal organisms into water bodies. Their life span shortens with higher water temperatures and higher global radiation.
- Extreme high water leads to an increase in health-hazardous faecal bacteria and viruses. Therefore, hygiene recommendations should be issued for working at or on the water, to minimise the health risk.
- Precipitation after longer dry periods can lead to a massive influx of faecal microorganisms into water bodies. This deterioration of the water quality also affects areas downstream, and should be considered during water sports activities.
- Pollution with potential pathogens depends heavily on the type of water body and catchment area. Risk analyses must therefore be spatially differentiated.

8.8 Floodplain vegetation

Floodplain habitats such as forests, reeds, riparian forbs and floodplain grasslands fulfil numerous ecological and economic functions. Floodplain forests, for example, contribute to the preservation of water quality, aid sediment and water retention and sediment stabilisation, e.g. on river banks. Furthermore, floodplains are used as local recreation areas and they can aid flood protection as natural retention areas. Natural river floodplains are "hotspots" of biodiversity. In the KLIWAS research programme we examined the extent to which the habitats of floodplain plants could be changed or impaired by climate change. For this purpose we developed habitat models for a series of plant species that are typical for floodplains, and we studied floodplain habitats, especially along the Rhine. With the help of these habitat models, the future habitat potential for these plant species can be estimated, based on hydrological projection data (Figure 21).

According to the findings of the KLIWAS modelling, river water levels and their variability will change. This will influence the composition of the plant species in the floodplains, and small-scale distribution patterns will change. A "simple" shifting of all habitats (e.g. to deeper positions due to sinking water levels) is not expected; instead, individual species and species communities will react differently to changed environmental conditions. Whether a habitat will continue to be suitable for previous species depends on specific spatial factors, among others. Are cut-off meanders, flood channels, foreland depressions, for example, and similar structures present as typical habitats for floodplain species? Consequently, each river section must be observed on a small scale, in order to be able to estimate whether certain vegetation types will occur in the future.

Habitats in lower-lying locations in the floodplains (e.g. reeds, sedge reeds, flood meadows, and pioneer vegetation) already today show small areas of suitable habitat only. Should water levels continue to decrease, these habitats could suffer serious additional losses, as suitable areas in the floodplains would almost completely disappear due to a lack of geomorphological heterogeneity. Only the nowadays often narrow riverbank would then serve as a replacement habitat in such a case. One option for adaptation would be to systematically foster structural diversity on the foreland. This could be achieved by means of restoring and newly creating geomorphological structures (cut-off meanders, flood channels and foreland depressions).

Hydrology, altered by climate change, is not the only factor that will affect floodplain species. Humans also have a direct impact due to the land use of the floodplains, changing the habitat characteristics and thus the plant communities.

Biotic components (distribution, population dynamics, competition, etc.) are also important factors that are decisive for the actual occurrence of species. These biotic factors could also change as a result of changed environmental conditions and they are in any case decisive for the occurrence of species. However we have not included these biotic factors in our habitat models.

Our findings in brief:

- Changes to river water levels and their variability will lead to changes in the floodplain vegetation. These changes can be estimated using habitat models.
- A simple shifting of all habitats in line with changed water levels is not expected; instead, individual species and species communities will react differently to changed environmental conditions.
- The habitats of lower-lying locations in the floodplain are the most threatened. The new creation of low-lying geomorphological structures in the floodplain might counteract the loss of habitat in the event of declining discharges.

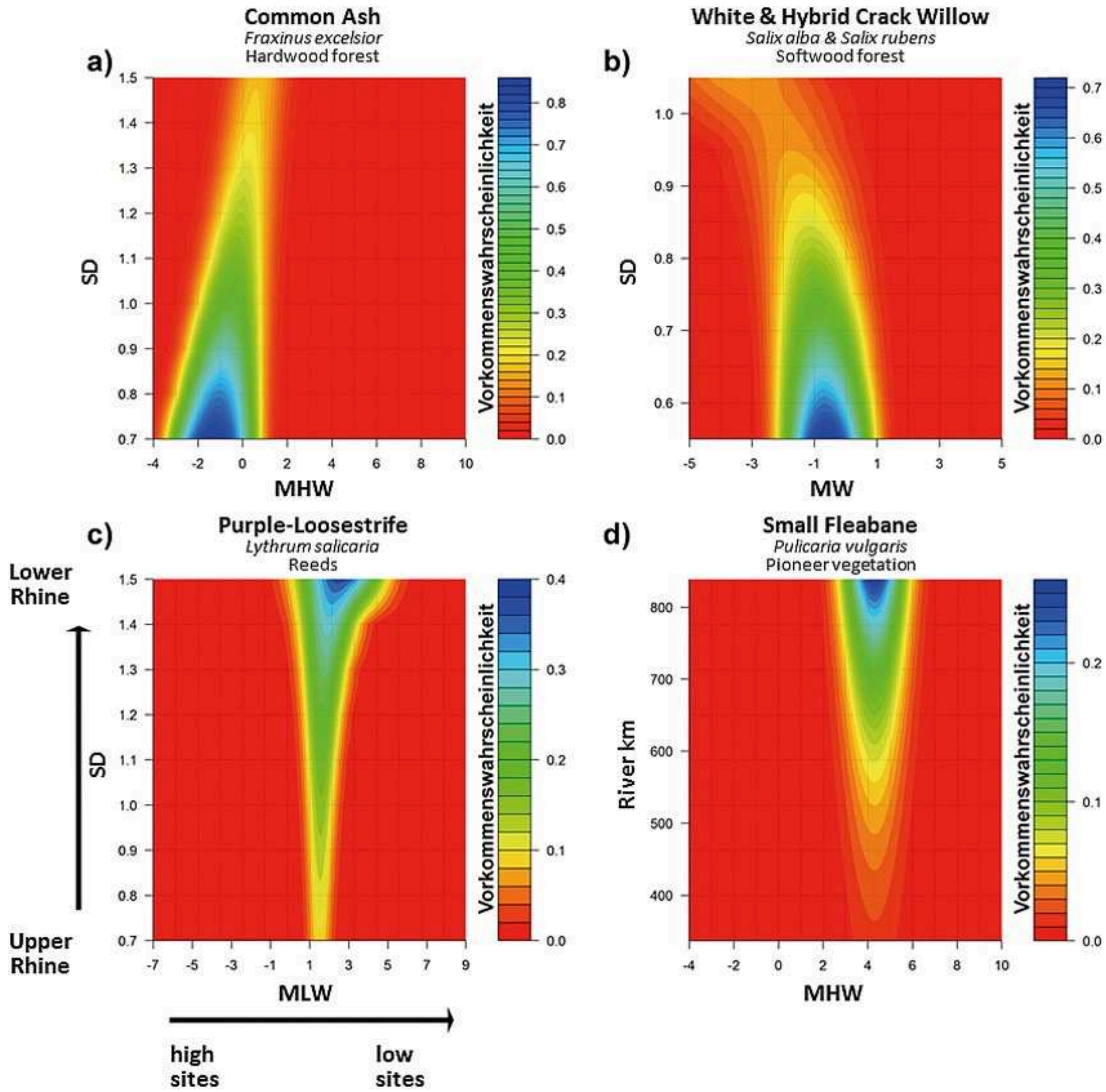

Figure 21: Modelled occurrence probability for four typical floodplain species or species groups (a–d) subject to the hydrological variable water level (X-axis) and water level fluctuation (Y-axis), respectively for the small Pulicaria vulgaris (d) subject to water level and river kilometre. Accordingly, the X-axis represents a gradient from high to low locations in the floodplain, the Y-axis shows the course of the Rhine from the Upper to the Lower Rhine.

8.9 Indicator concept

Indicators are tools to describe and evaluate system states, relationships and dynamics. They help those who have to take action not only to get an overview of the system state, but also to draw conclusions on how to achieve objectives.

KLIWAS research projects project the state of the inland waterways with the help of many different parameters. We record the parameters that arise from the research context and compile the operative parameters of the Waterways and Shipping Administration. We derive our indicators from these parameters. They describe the extent to which the "inland waterways" system is affected and the objectives for its management. We based the schedule for the indicator development on the work of the EEA (2003).

Our indicator concept serves as an aid to the BMVI and the Federal Waterways and Shipping Authority (GDWS) in making strategic decisions on measures for adapting to climate change.

We conclude that a combination of system-analytical approaches, such as DPSIR (Driver Pressure State Impact Response) and decision-theory approaches is necessary for the development of indicators. In formulating the indicators we focus on the requirements that arise from the decision-making processes.

We merged the complex interdependencies and dynamics in the KLIWAS model chain (integral approach) into an overall picture of the "inland waterways" system. There are points of reference for socioeconomic aspects.

We have based our factsheets on the "indicator factsheets" of the DAS (see Schönthaler et al., 2011). We outlined 35 main parameters of the research in factsheets. These include, for example, parameters on discharges, sediment inflows, the hygienic state of the waterways and water ecology. At the same time we defined 25 parameters that represent the operative business of the WSV, e.g. for the management of dredged materials and other maintenance measures.

The pyramid shape of the diagram (Figure 22) of indicators shows that there are more operative, river section-related parameters or indicators than those that are strategic, river basin-related and aggregated in the spatial and temporal statistical dimension.

Some of the parameters used commonly in the WSV and the BMVI differ from the parameters presented in model simulations with regard to terminology and temporal-spatial references. There are frequently differences in the spatial-temporal coverage. For example, the parameter "debris management" refers to sections of the Rhine, but it encompasses all maintenance measures and is modelled continuously over time. The parameters of the WSV distinguish between debris removal, addition and redistribution. They encompass different spatial scales and refer to individual maintenance events.

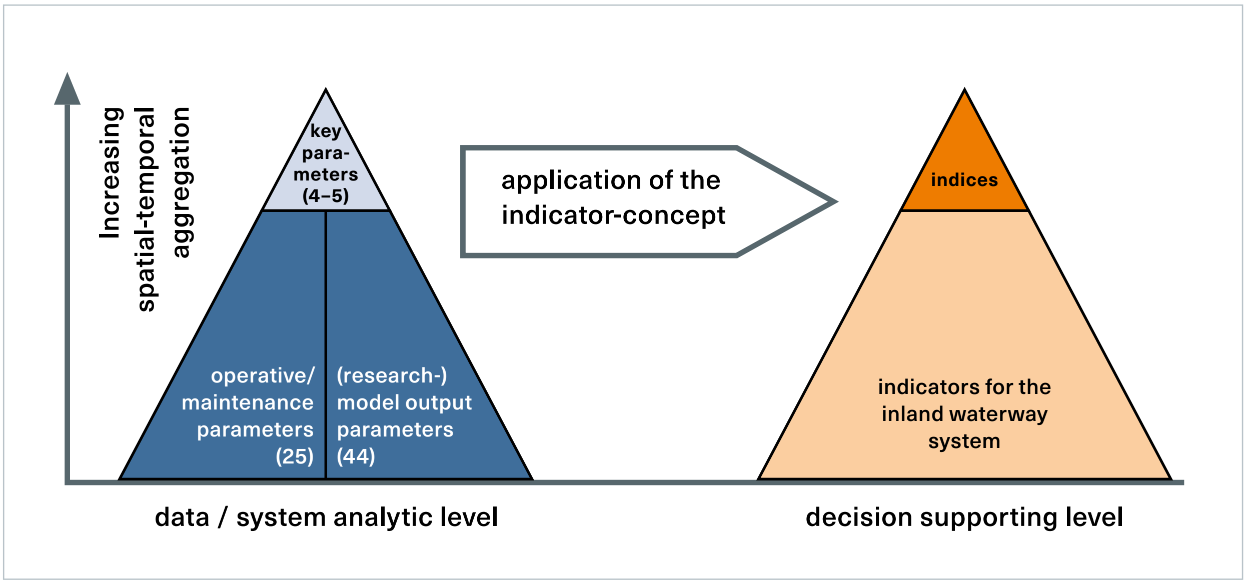

Figure 22: Diagram of the indicator concept

Finally, we spoke with the BMVI about the manner in which a large number of parameters can ultimately be utilised for decisions, or which "simple" parameters and indicators can be consulted for decision-making in practice, despite the complex connections.

We considered these findings when formulating the indicators. We selected identical units of measurement for each indicator for the reference data of the past and for future conditions (from projections), in order to be able to compare and assess changes. Operative and research parameters often aim at the same facts, but represent these differently. Where the field of research, for example, is concerned with sediment quantities, in practice this translates as dredged material quantities. Therefore, our work also resulted in recommendations to the modellers as to whether and how they can better orient the manner of presenting their parameters to meet the requirements of the decision makers.

9. Recommendations for further work / research requirements

The KLIWAS departmental research programme has fundamentally developed the scientific-operational tools and skills for dealing with impacts of climate change and in the process has revealed gaps in our knowledge that need to be closed. Following this path rigidly serves not only the objectives of the BMVI, but also the European and national strategy for adapting to climate change and the sustainable safeguarding of the infrastructure of the federal waterways. This results in the following recommendations:

9.1 Updating and intensifying the methods and procedures

Following KLIWAS it would be desirable to better safeguard the statements based on the projections places "at the end" of the model chains relating to the topics of ecology and water quality with further ensemble elements. Then we could answer questions that ultimately also affect the future handling of the federal waterways and their ecological potential.

Comprehensive reference data sets of historical conditions are necessary in order to prepare and evaluate climate projections and to apply effective models. This refers to all relevant data for the waterways, not only hydrological, but also material and ecological data. The routine continuation and methodical expansion of existing regional reference data is to be planned for this purpose. These reference data must relate to the scale of the overall catchment area and shall also be attained through the use of new analytical methods and remote sensing procedures (temporally and spatially high-resolution radar-supported precipitation climatology). This also includes the reprocessing of older data with the new methods. At the same time, the quality of future reference data depends on already existing monitoring concepts being continued.

The input variables for climate scenarios change continuously. This affects emission scenarios, for example, but also the dynamically changing use of land. Therefore new climate scenarios must always be updated in existing and future model tools.

One focus of future activity is the state of the art evaluation and preparation of climate projections. At present these are the results from CMIP5 (Coupled Model Intercomparison Project Phase 5 in preparation for the 5th IPCC Assessment Report) on the basis of the new emissions scenarios and EURO-CORDEX. The future development of climatic and weather extremes will also have to be observed. Furthermore we recommend to close the gap between short-term weather prognoses and the climate projections with seasonal prognoses and medium-term climate projections for up to 30 years.

The marine waterways part of KLIWAS has revealed a number of deficits, some of them severe, in the projections available to that point, which consequently would have led to incorrect input information for the development of adaptation options. The inadequacies range from imprecise atmospheric and oceanic drives for the climate models to insufficiently correct parameterising of physical values in models. In addition, they do not consider the constant interactions between the atmosphere and the sea. There is a lack of essential natural processes in the global climate models, such as the ejection of icebergs from the continental ice sheet, which has not yet been sufficiently describable in physical terms. This example demonstrates the large methodical uncertainties that are currently associated with statements on future sea level changes.

To improve the regional climate projections, the first coupled ocean-atmosphere models were developed in KLIWAS for the North Sea. With a view to the coastal region we recommend to continue this development in order to achieve more reliable climate projections. The monitoring should be intensified, and climatological data must be expanded with new observation data and a corresponding resulting comprehensive data production. In parallel, as for the inland area, the previously mentioned current projections from IPCC AR5 and the CORDEX project should be analysed and assessed. This is important not only for the seas, but also for the coastal region and its economic use. Against this background, the following topics and work should be given priority:

- Improvement to maritime climatologies for the North Sea and Baltic Sea. To validate the models and for the quality assurance of the model statements, the comparison with current measurement data is an indispensable precondition.
- Improvement to knowledge from new climatologies with regard to shipping-relevant parameters such as water level, storm surges, sea state and their extreme states.
- Development of prognoses on the development of the rise in sea level from current CMIP projections.

Just like the climatic, the hydrological medium and long term prognoses instruments must also be further developed and transferred to an operational consultation level. We recommend to implement this in the context of seamless prediction. For example, discharge and water level projection services are necessary for all federal waterways where there is a spatial proximity to roads and railways. As well as the hydrological and hydraulic models required for this purpose, the development of models for sea state/tidal parameters, ecological quality, water temperatures, floodplain vegetation and morphology are also needed. In the future, all of these models should be developed, expanded and operated with the new generations of climate models for the needs of the WSV and the German adaptation strategy.

The compilation of the available climate and hydrological projections in accordance with the multi-model approach is an indispensable basis. We recommend to compile and prepare updated river basin and coastal ensembles for policy consulting in Germany on a regular cycle, e.g. in the rhythm of the IPCC reports. These activities, begun in KLIWAS, would also cover the need for climate information on the part of the higher authorities of the BMVI and the areas of action of the DAS. They would make an essential contribution to the expansion of sector-specific climate services and could encompass the latest development activities, such as decadal climate predictions. In that respect, the continuation would also make an essential contribution to the GFCS (Global Framework of Climate Services) of the United Nations (Moser et. al. 2012).

9.2 Using the results to adapt the waterways to changing conditions

The range of climate projections for the large navigable inland waterways should be analysed and discussed with the operative level of the WSV, in order to recognise and evaluate the need for adaptation caused by climate change with regard to operation, maintenance and expansion. Against this background, detailed cost-benefit and socioeconomic questions must be addressed.

The quantification of climate consequences for the design and assessment of hydraulic engineering structures in the context of hydraulic and morphological issues is an urgent research topic in order to introduce preventative measures.

Foundations for a future management system with adaptation options in the coastal areas must be developed and intensified for the Ems, Jade-Weser and Elbe. For this purpose, the developed adaptation measures must be observed even more clearly in connection with the in-river construction strategies for each estuary. The current oceanographic projections should be linked more closely with the previously conducted sensitivity analyses.

For sediment management and flood protection, an intensive scientific treatment of morphological, hydrological and river engineering questions is necessary under the influence of the dynamics of the catchment area. Therefore, adaptation options in the area of the free-flowing waterways by means of changed flow regulation and maintenance concepts under the special consideration of nature conservation and flood protection must be developed for the different river sections, with each of their different section characteristics. As well as the hydro and morpho-dynamic effect of the structures, the maintenance and associated costs must also be estimated.

The research on adaptation options for inland shipping with new types of ships and drives, as well as an improved navigation with fully developed information systems should be continued. They can create an innovative boost to navigation.

Topics examined less intensively in KLIWAS include those relating to the Baltic Sea, Weser and Ems, as well as specialist topics such as the impacts of changed foreshore vegetation on the morphology of free-flowing inland waterways, the development of flow regulation concepts with flexible regulation structure, morphodynamics under the influence of ice, adaptation options for discharge and reservoir level control, turbidity influence from propeller scoring, course optimisation and the impacts on soil characteristics due to extreme weather events, to name just a few.

The costs and benefits of adaptation options must be evaluated. Together with the BMVI and the WSV, attainable adaptation capacities should be determined by selecting economically and ecologically suitable measures for each individual waterway. The management demands resulting from the measures, and especially environmental legislation, must be included. Wherever possible, no- or low-regret measures must be developed. These are measures that will produce favourable effects in any case, irrespective of the adaptation to climate change, or which are useful in the event of an unexpected unfavourable development, or which can be made useful by means of forward-looking planning without too much effort. Furthermore, we see a good opportunity to combine such studies with the methods of the federal transport planning process, respectively, these possibilities must be investigated.

The experience with KLIWAS made it clear that the transfer and processing of the complex research results at the operational level is a process that does not happen automatically, incidentally or subsequently, but rather it must be organised separately in projects. For this challenge, both the operative level, i.e. the WSV, and also any higher authorities that may be involved, must be furnished with sufficient resources. Finally, we recommend organising and funding fundamental work such as the implementation of monitoring networks and the regular updating and deriving of comprehensive data products as permanent operational services, also for the cross-border river areas of our federal waterways, independent of research projects.

9.3 Transfer of the findings to create a robust transport infrastructure

It should become a routine part of the investment planning of the BMVI to take into account possible climate changes on the basis of the current latest state of climate research.

We recommend creating scenarios to answer the adaptation questions in the near and distant future, which can be applied coherently and seamlessly to all business areas of the BMVI or to the modes of transport. Transport infrastructure measures always influence a number of other political areas. This effect in other political areas can lead to conflicts of objectives. A comprehensive assessment of the impacts on other business areas requires an advanced sensitivity analysis.

The BfG, DWD, BSH and BAW are offering to reinforce the development and application of their prognosis instruments. Our existing modelling and information systems must be better coordinated with each other, both conceptually and operationally (spatial and temporal harmonisation, automation of processes, standardisation of interfaces, etc.). For this purpose, the creation and application of our scientific tools should be enabled and the required work structures should be established in the business areas.

Along with climate change, new energy concepts, land use changes and demographic changes present a significant challenge to the waterways and navigation. They begin with the questions concerning the massive changes to the agricultural water and materials balance, unexpectedly severe ice formations on the waterways which were seen recently and which led to restrictions on inland navigation, and range, insofar as the water traffic required for the erection and maintenance of offshore wind parks is concerned. All of these aspects will place greater demands on the management of the waterways and on navigation. We consider it expedient to create references between water management, energy, the environment, agriculture, regional planning, industry and federal road planning processes. In addition, the ongoing activities in the German Strategy for Adaptation to Climate Change (DAS) indicates that there is a need for action in terms of examining the topic of vulnerability, respectively, the resilience of the waterways with the help of departmental research.

Previous studies have shown that process studies with marginal values of the projected ensembles or on the basis of sensitivity studies must be intensified. Projects on the characteristics of future hydrological extreme events and periods should be conducted for all relevant federal waterways. Of particular importance are the magnitudes, the progress of low water events/periods in combination with hot spells and their consequences for the qualitative and ecological parameters of the water bodies and navigation. Reservoir-controlled river sections are particularly sensitive. Special focus should be placed here under the aspect of possible effects on the ecological and chemical state. Such (sensitivity) studies on extreme events would also ensure a gain in knowledge with regard to low-regret measures for preventative flood protection.

In some urban conurbations, a dense network of waterways, excessive anthropogenic influence and high social demands on the function of water bodies clash (drinking water, leisure, cooling, etc.). For this reason, the process studies there should combine the topics of contaminants inputs and water quality with hydrological projections.

The vulnerability of the coasts and the coastal areas to climate change can be diverse. We consider it necessary to develop and analyse relevant indices for these areas and their uses. Changes in wind regime have a direct impact on currents and sea state and can present difficulties for shipping, fishing, offshore structures, navigational infrastructure and the stability of the coasts. Special attention should also be paid here to the identification and prognosis of extreme situations, such as severe storms and storm surges and their impacts. For the first time, so-called “freak waves” have been proven in the southern North Sea, for example “Three Sisters” and “Whopper”, with wave heights of up to 20 m in the area of the prescribed shipping routes of the southern North Sea and in the areas of the offshore wind turbines. Against this background, the work begun in KLIWAS to determine the adaptation needs for shipping, marine use and coasts, and the resulting adaptation options, should be intensified in future. This should be implemented in connection with the long-term safeguarding of climate monitoring in the maritime area.

In KLIWAS, knowledge was created that would not have been possible in any other programme. The continuation of the work of the departmental research institutes, as recommended here, once again offers an opportunity for diverse innovations, which would not occur in other areas, because there the specific questions relating to transport infrastructure are not being asked. With the knowledge thus generated, the BMVI has got an important prerequisite for the overall economic view in terms of a sustainable development of mobility and transport.

10. Abbreviations

BAW	Bundesanstalt für Wasserbau (Federal Waterways Engineering and Research Institute)
BfG	Bundesanstalt für Gewässerkunde (Federal Institute of Hydrology)
BMBF	Bundesministerium für Bildung und Forschung (Federal Ministry of Education and Research)
BMVI	Bundesministerium für Verkehr und digitale Infrastruktur (Federal Ministry of Transport and Digital Infrastructure)
BSH	Bundesamt für Seeschifffahrt und Hydrographie (Federal Maritime and Hydrographic Agency)
BSRN	Baseline Surface Radiation Network
BWaStr	Bundeswasserstraße (Federal waterways)
CEN	European Committee for Standardization
CHR	International Commission for the Hydrology of the Rhine Basin
CMIP5	Coupled Model Inter-comparison Project Phase 5
CNRM	Centre National de Recherches Météorologiques
DAS	Deutsche Anpassungsstrategie an den Klimawandel (German Strategy for Adaptation to Climate Change)
DIN	Deutsches Institut für Normung (German Industrial Standard)
DJF	Winter: December, January, February
DMI	Danish Meteorological Institute
DWD	Deutscher Wetterdienst (German Meteorological Service)
EEA	European Environmental Agency
ERA	Extended Reanalysis Envisaged
ETHZ	Swiss Federal Institute of Technology in Zurich
EU-MSRL	European Marine Strategy Framework Directive
EU-WFD	European Water Framework Directive
FGG Elbe	Flussgebietsgemeinschaft Elbe (Elbe river basin community)
GCM	Global Climate Models
GDWS	Federal Waterways and Shipping Agency
GKSS	GKSS-Forschungszentrum Geesthacht GmbH
GMES	Global Monitoring for Environment and Security
GZS	Globales Zentrum für Schiffswettermeldungen (Centre for Global Marine Meteorological Observations)
HAMSOM	Hamburg Shelf Ocean Model
HCB	Hexachlorobenzene
HM5Q	The highest arithmetic mean of 5 consecutive daily values of discharge in a high water period
HM7Q	The highest arithmetic mean of 7 consecutive daily values of discharge in a high water period
HmoMQ	Highest discharge of the year determined across one month
HQC	High Quality Control
HSW	Highest navigable water level
HYRAS	Hydrologically relevant raster data sets
ICDC	Integrated Climate Data Centre
ICTP	International Centre for Theoretical Physics
IKSR	Internationale Kommission zum Schutz des Rheins (International Commission for the Protection of the Rhine)
IPCC	Intergovernmental Panel on Climate Change
JJA	Summer: June, July, August
KLIMZUG	Klimawandel in den Regionen zukunftsfähig gestalten (Future-oriented climate change management in regions. Research programme of the BMBF.)

KNMI	Koninklijk Nederlands Meteorologisch Instituut (Royal Netherlands Meteorological Institute)
MPI	Max-Planck Institute
MPI-M	Max-Planck Institute for Meteorology, Hamburg
MPIOM	Max-Planck Institute Ocean Model
MQ	Mean water, arithmetic average of the discharge of one year
MSL	Mean Sea Level
MThw	Mean high tide
NM7Q	The lowest arithmetic mean of 7 consecutive daily values of discharge in a low water period
OGewV	Oberflächengewässerverordnung (Sea Surface Water Ordinance)
PCB	Polychlorinated biphenyl
PSU	Practical Salinity Units
RCM	Regional Climate Model)
REMO	Regional climate models of the MPI-M
SMHI	Swedish Meteorological and Hydrological Institute
SST	Sea Surface Temperature
SWH	Significant Wave Height
TRI	Transport Direction Indicator
UQN	Environmental Quality Standards
WBM	Hydraulic Engineering Materials

11. Glossary

Abundance:
in ecology, refers to the number of individuals of a species, related to their habitat.

Adaptation options:
possible measures to minimise the effect on natural and human systems in the face of actual or expected impacts of climate change (based on the German Adaptation Strategy, 2008).

Additives:
additives, or admixtures, represent individual components with a proportion < 1 percent in the formulation of the product, they need not be declared.

Anthropogenic:
caused by humans.

ARA ports:
the ports of Amsterdam, Rotterdam and Antwerp.

Bias correction:
correction of systematic errors.

Blue-green algae (cyanobacteria):
part of the domain bacteria. Among all other bacteria this is characterised by its capability for oxygenic photosynthesis.

Bottleneck:
restriction in the usability of the waterway due to incorrect depths or breadths, unfavourable current conditions or insufficient structure or navigational aids.

Climate:
is a consequence of physical-chemical processes in the Earth's system as well as the external influences on this system and is characterised for a defined region by means of a statistical description of all relevant climate elements. This statistical description should apply for a sufficiently long period of time (usually 30 years, the so-called standard period) (Schönwiese, modified, 2003).

Climate model:
a numerical representation of the climate system that is based on the physical, chemical and biological characteristics of its parts, its interactions and feedback processes, and which considers all or some of its known characteristics.

Climate projection:
estimate of the climate with the help of models based on prescribed scenarios.

Climatology:
represents the climate in one location for a defined period of time by presenting selected variables (temperature, wind, radiation, currents, etc.).

Coenosis:
living community of animal or plant organisms.

Cold sum:
is the sum of the amounts of negative mean daily values of air temperature over a certain period of time. It is given without a unit.

Congeners:
chemical compounds, often with the same basic structure, but which, in contrast to isomer compounds, can differ in the molecular formula. Congener compounds can have different chemical, physical and toxicological characteristics. They often occur as a mixture.

Constriction:
area of restriction of channel breadth due to the depositing of sediments at the edge of the channel or in the lane.

Copernicus:
Earth observation programme of the European Union, previously Global Monitoring for Environment and Security (GMES), an initiative founded jointly in 1998 by the European Commission (EU) and the European Space Agency (ESA) with the objective of creating a sustainable and independent Earth observation system based on modern Earth observation and information technologies.

Desorption:
process in which particles leave the surface of a solid (e.g. sediment). It is the opposite of sorption.

Discharge (Q):
states the volume that flows through a certain section in a time unit and which is allocated to a catchment area. In the tidal reach of a river, “discharge” refers to the inflow of freshwater from the inner reach of that river, often measured at the inland gauge next to the entrance to the estuary.

Discharge year:
consecutive twelve-month period that is selected in such a manner that the total change in retention is minimal and the overflow is reduced to a minimum.

Downscaling:
method to derive local or regional information from large-scale models or data (e.g. global models). There are two main approaches: a) dynamic downscaling uses regional climate models b) statistical (or empirical) downscaling.

DPSIR scheme of the European Environmental Agency:
can be used to structure interactions between humans and the environment. The driver (D) indicators serve to present the causes or drivers of environmental changes. There are usually many causes that trigger a problem, but one cause can also have different impacts. The specific pressures created by these causes are represented as Pressure (P) indicators. State (S) indicators illustrate the current state, i.e. the quality of the local environment. The Impact (I) indicators represent the effects produced by the conditions that have arisen. But they only reproduce the impacts, they cannot make any statement about the causes. Finally, (counter) measures adopted and reactions to the environmental changes can be described with the Response (R) indicators. (EEA, 2003).

Effect:
the effect brought about by climate change. The term refers to the impact of climate change, which can be both positive and negative. Disadvantageous effects include the limited functionality or failure of infrastructure (e.g. locks, harbour facilities, sluice structures, etc.), increased security risks or higher maintenance costs. It covers the effects on individual people, groups and companies.

Estuary:
tidal-influenced mouth area of a river.

German Adaptation Strategy (Deutsche Anpassungsstrategie, DAS):
was passed by the federal government in 2008 and creates a framework for adapting to the consequences of climate change in Germany. It lays the foundation for a medium-term process in which risks are identified, possible needs for action are declared, the corresponding objectives are defined, and possible adaptation measures are developed and implemented.

Habitat:
here, the living space for a typical plant species.

Hazard:
state, condition or process from which damage can occur to a protected item.

Hot days:
days with a maximum air temperature of more than 30 °C.

Hysteresis:
the delay between the cause of an effect and the impact of that effect.

Indicator:
a knowledge-based instrument for diagnosis and action. It is a parameter or a value derived from parameters that describe the state or the dynamic of a phenomenon, a system or part of a system. The significance of the value need not comply with that of the parameter. The term “indicator” is frequently used in its broadest sense as a collective term for parameters, indicators and indices (Morosini et al., 2001; Girardin et al., 2000; OECD, 1994 und 1998).

Inner Elbe:
the part of the Elbe that is not influenced by the tide: from the source to the weir at Geesthacht at km 585.9.

IPCC Assessment Report:
assessment report of the Intergovernmental Panel on the scientific knowledge about climate change.

LC-Tandem-MS method:
Liquid Chromatography–Tandem Mass Spectrometry Method is a physical separation method with a combine procedure for measuring the mass of atoms or molecules.

Mesoscale structures:
dimensions of between some 10s to a few 100 km.

Monitoring:
long-term observation and recording of e.g. pollutant data in sediments or suspended solids at one station or in an observation area.

Neophytes:
plant species that have been introduced by humans, either deliberately or unintentionally, into an area in which they do not occur naturally, especially ever since the discovery of America in 1492.

Neozoa:
animals that have established themselves in an area in which they were not previously native.

No-regret measures:
here: adaptation measures that make economic, ecological and social sense, independently of climate change. They are taken as a preventative measure, in order to avoid or minimise negative impacts. Their social benefits are still felt even if the primary reason for adopting the strategy does not occur to its expected extent.

Nodal tide:
is a tidal cycle with a period of 18.6 years. This period dominates the climatology of high tide, low tide, mean tidewater levels and the tidal range.

Parameter:
numeric measurement size or value that measures or describes a characteristic of a system (Morosini et al., 2001), e.g. as a coefficient in formulas or hydrological models.

Range:
here: maximum difference between the smallest and largest value of an ensemble of projections at one point in time.

REACH Ordinance:
this obliges manufacturers and importers to register chemical substances with the EU chemicals agency ECHA if they manufacture or import these in volumes of ≥1000 kg per year.

Reanalysis:
model analysis data on the atmosphere, based on the assimilation of observation data from the past, and which are derived in a physically consistent manner with the help of a uniform model system and an assimilation method (e.g. European Centre for Medium-Range Weather Forecasts Re-Analysis ERA-Interim).

Regional climate model:
dynamic process that simulates with a high-resolution dynamic (numeric) model parameters for partial areas of the global model area, using input data from the global climate model.

Scale integration (upscaling):
high-resolution data are transferred to a larger area.

Scenario A1B:
emission scenario that takes account of a balanced use of fossil and non-fossil sources of energy.

Seiche (French):
standing wave in a body of water of lakes, inland seas, bays or harbour basins

Sorption:
process in which particles are concentrated on the surface of a solid (e.g. sediments). It is the opposite of desorption.

SRES scenarios:
SRES scenarios are emissions scenarios developed by Nakicenovic and Swart (2000) that are used as a basis for climate projections in this report.

Summer, hydrological:
Period from 1 May until 31 October of one year (see meteorological summer).

Summer, meteorological:
Period from 1 June until 31 August of one year (see hydrological summer).

Taxa:
a group of creatures recognised in biology as a systematic unit.

Tidal Elbe:
area of the Elbe that is influenced by the tide:
from Geesthacht weir at km 585.87 to km 727.2 (VV-WSV 1103).

Transformation products:
emerge as intermediate products during the biological degradation of a substance.

Value:
characteristic value that refers to a certain fact, identifying it. Example: m^3/s at Cologne gauging station.

Vibrio:
bacteria of the genus Vibrio, which occur naturally in seas and coastal waters. This bacterial genus has 12 human pathogenic species.

Winter, hydrological:
Period from 1 November until 30 April of the following year (see meteorological winter).

Winter, meteorological:
Period from 1 November until 28 or 29 February of the following year (see hydrological winter).

Winter cold sum of the air temperature:
sum of the amounts of negative mean daily values for air temperature in winter. The cold sum serves to assess the thermal conditions (cold) of a winter, and is therefore generally stated for the whole winter (in this case relating to the period November to March). Cold sum under 100 = mild; cold sum 100 to 199 = moderately warm; cold sum 200 to 299 = moderately cold; cold sum 300 and higher = severe.

12. Literature

The literature listed below refers only to the literature cited in this document. A comprehensive list of the publications, posters, etc., that have emerged from KLIWAS, may be found in the publications list on www.kliwas.de.

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13. Concluding reports of the KLIWAS projects

Research Task 1:

Validation and evaluation of climate projections – provision of climate scenarios for the application on waterways and navigation

1.01
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1.02
PLAGEMANN, S., IMBERY, F., NAMYSLO, J. (2014): Validierung und Bewertung von Klimaprojektionen – Bereitstellung von Klimaszenarien für den Binnenbereich. Schlussbericht KLIWAS-Projekt 1.02. KLIWAS-29/2014. DWD/BfG, Koblenz. DOI: 10.5675/Kliwas_29/2014_1.02, URL: http://doi.bafg.de/KLIWAS/2014/Kliwas_29_2014_1.02.pdf

1.03
K. BÜLOW, A. GANSKE, S. HÜTTL-KABUS, B. KLEIN, H. KLEIN, P. LÖWE, J. MÖLLER, N. SCHADE, B. TINZ, H. HEINRICH, G. ROSENHAGEN (2014): Ozeanische und atmosphärische Referenzdaten und Hindcast-Analysen für den Nordseeraum. Schlussbericht KLIWAS-Projekt 1.03. KLIWAS-30/2014. BSH/BfG, Koblenz. DOI: 10.5675/Kliwas_30/2014_1.03, URL: http://doi.bafg.de/KLIWAS/2014/Kliwas_30_2014_1.03.pdf

Research Task 2:

Changes in the hydrological system of coastal waters

2.01
K. BÜLOW, A. GANSKE, S. HÜTTL-KABUS, B. KLEIN, H. KLEIN, P. LÖWE, J. MÖLLER, N. SCHADE, B. TINZ, H. HEINRICH, G. ROSENHAGEN (2014): Entwicklung gekoppelter regionaler Modelle und Analyse von Klimawandelszenarien für die Nordseeregion. Schlussbericht KLIWAS-Projekt 2.01. KLIWAS-31/2014. BSH/BfG, Koblenz. DOI: 10.5675/Kliwas_31/2014_2.01 URL: http://doi.bafg.de/KLIWAS/2014/Kliwas_31_2014_2.01.pdf

2.02
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2.03
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2.04
See Project 3.02 (Projects 2.04 and 3.02 created a joint concluding report)

Research Task 3:

Changes and sensitivity of the water body state (morphology, quality, ecology) and adaptation options for navigation and waterways

3.01

K. BÜLOW, A. GANSKE, S. HÜTTL-KABUS, B. KLEIN, H. KLEIN, P. LÖWE, J. MÖLLER, N. SCHADE, B. TINZ, H. HEINRICH, G. ROSENHAGEN (2014): Klimabedingte Auswirkungen auf Schifffahrt, Küsten und Meeresnutzung in der Nordseeregion. Schlussbericht KLIWAS-Projekt 3.01. KLIWAS-35/2014. BSH/BfG, Koblenz. DOI: 10.5675/Kliwas_35/2014_3.01, URL: http://doi.bafg.de/KLIWAS/2014/Kliwas_35_2014_3.01.pdf

3.02

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WINTERSCHEID, A., GEHRES, N., CRON, N. (2014): Einfluss von klimabedingten Änderungen auf den Sedimenthaushalt der Nordsee-Ästuare. Schlussbericht KLIWAS-Projekt 3.03. KLIWAS-37/2014. BfG, Koblenz. DOI: 10.5675/Kliwas_37/2014_3.03, URL: http://doi.bafg.de/KLIWAS/2014/Kliwas_37_2014_3.03.pdf

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3.05

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3.06

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See Project 5.04 (Projects 3.07 and 5.04 created a joint concluding report).

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3.09
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Research Task 4:

Changes in the hydrological system: Sediment budgets, morphology and adaptation options for inland waterways and navigation

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4.03
SCHRÖDER, M., WURMS, S. (2014): Verkehrswasserbauliche Regelungs- und Anpassungsoptionen an klimabedingte Veränderungen des Abflussregimes. Schlussbericht KLIWAS-Projekt 4.03. KLIWAS-45/2014. BAW/BfG, Koblenz. DOI: 10.5675/Kliwas_45/2014_4.03, URL: http://doi.bafg.de/KLIWAS/2014/Kliwas_45_2014_4.03.pdf

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4.05
HATZ, M., MAURER, T. (2014): Prozessstudien über die Eisbildung auf Wasserstraßen und mögliche klimabedingte Änderungen. Schlussbericht KLIWAS-Projekt 4.05. KLIWAS-47/2014. BfG, Koblenz. DOI: 10.5675/Kliwas_47/2014_4.05, URL: http://doi.bafg.de/KLIWAS/2014/Kliwas_47_2014_4.05

Research Task 5:

Impacts of climate change on structure, ecological integrity and management of inland waterways

5.01

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5.02

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5.07

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14. The KLIWAS team

German Meteorological Service (DWD)

Dr. Claudia Frick, Project 1.01
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Dr. Florian Imbery, Project 1.02
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Joachim Namyslo, Project 1.02, Project Manager
Sabrina Plagemann, Project 1.02
Dr. Monika Rauthe, Project 1.01
Ulf Riediger, Project 1.01
Gudrun Rosenhagen, Projects 1.03, 2.01 and 3.01, Project Manager
Dr. Bruno Rudolf, Programme Officer
Dr. Nils Schade, Projects 1.03, 2.01 and 3.01
Heiko Steiner, Project 1.01
Dr. Birger Tinz, Projects 1.03, 2.01 and 3.01

Federal Waterways Engineering and Research Institute (BAW)

Dr.-Ing. Annette Büscher, Projects 2.04 and 3.02
Benjamin Fricke, Projects 2.04 and 3.02
Lucia Hahne, Project 4.04
Fred Hesser, Projects 2.04 and 3.02
Dr. Harro Heyer, Programme Officer
Ingrid Holzwarth, Projects 2.04 and 3.02
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WSA Stralsund, Sachbereich 2, Gewässerkunde (Project 3.04)

Imprint – KLIWAS Synthesis Report for Decision-Makers

Published by

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Edited by

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Status
March 2015

Design
Federal Institute of Hydrology
Department C Controlling / Public Relations
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Layout
Michael Spitzer, Federal Institute of Hydrology / Weißensee Verlag, Berlin (English version)

Translated by
Übersetzungsbüro Schnellübersetzer GmbH, Köln in cooperation with authors
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Print
Federal Ministry of Transport and Digital Infrastructure, Bonn

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BfG Federal Institute of Hydrology, DWD German Meteorological Service, BSH Federal Maritime and Hydrographic Agency, BAW Federal Waterways Engineering and Research Institute (eds.) (2015): KLIWAS Impacts of Climate Change on Waterways and Navigation in Germany – Development of Adaptation Options. Synthesis report for decision-makers. KLIWAS-57/2015.
DOI: 10.5675/Kliwas_57/2015_Synthese_ENG

Imprint

Published by
Federal Ministry of Transport and Digital Infrastructure
Invalidenstraße 44
10115 Berlin

Edited by
Federal Ministry of Transport and Digital Infrastructure
Division WS 14 – Climate Change Mitigation and Environmental Protection in the Waterways Sector;
Hydrology; Federal Institute of Hydrology
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Status
March 2015

Design
Federal Institute of Hydrology
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Layout
Michael Spitzer, Federal Institute of Hydrology
Weißensee Verlag, Berlin (English version)

Translated by
Übersetzungsbüro Schnellübersetzer GmbH, Köln in cooperation with authors
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Print
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