Impacts of Climate Change on Navigation

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ABSTRACT

Climate Change and its impacts are widely discussed in science community and in the public. However, the discussion about the impact of climate change on inland and marine navigation is still at its beginning. Against this background PIANC has set up a task group on climate and navigation to bring the available knowledge together and give an outlook about the necessary actions to support sustainable navigation. Results of the PIANC task group on climate change and navigation will be given with a deeper look to possible consequences of climate change on inland navigation exemplified for the river Rhine in Germany, the busiest inland waterway in Europe.

1. INTRODUCTION

The key drivers of change, directly influencing the navigation on waterways, are the meteorological parameters, i.e. precipitation and air temperature, since they determine the water supply and the probability of occurrence of extreme hydrological conditions. An indirect driver of change to inland navigation is the river morphology, since changes in river morphology are driven by changes of river hydrology, i.e. driven by the key drivers of change. The influence of climate change on the hydrology is exemplified for the River Rhine in chapters 2 to 4, presenting results of ongoing research projects. The impacts of the presented hydrological changes on inland navigation are discussed in chapter 5. Adaptation options are finally summarized in chapter 6.

2. HYDROLOGY OF THE CATCHMENT OF THE RIVER RHINE

The basin area of the River Rhine (Fig. 1) represents 185,300 km² and the 1,320 km long course of the river starting at the outlet of Lake Toma in Switzerland is divided into six major stretches. Lake Toma, located in the northern high cirque of Piz Badus (2,928 m) is regarded as the source of the “Vorderrhein” (eng. Frontal Rhein). The “Hinterrhein” (eng. Rear Rhine) rises from the Paradies Glacier at the Mascholhorn (Adula Range) in the Rhine Forest area. The source rivers join in Reichenau, near Chur. Downstream of the unification up to the outlet of Lake Constance the river course is called “Alpenrhein” (eng. Alpine Rhine). The “Alpenrhein” is a high

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mountain river. The basin area up to the inflow in Lake Constance amounts to 6,122 km². Below Lake Constance, from Stein am Rhein, the river flows west as the “Hochrhein” (eng. High Rhine) over a distance of 142 km until Basle. From the mouth of the Aare onwards, the discharge rate of the Rhine is affected by numerous glacier and high mountain streams, whose unbridled drainage patterns compensate for three alpine fringe lakes.

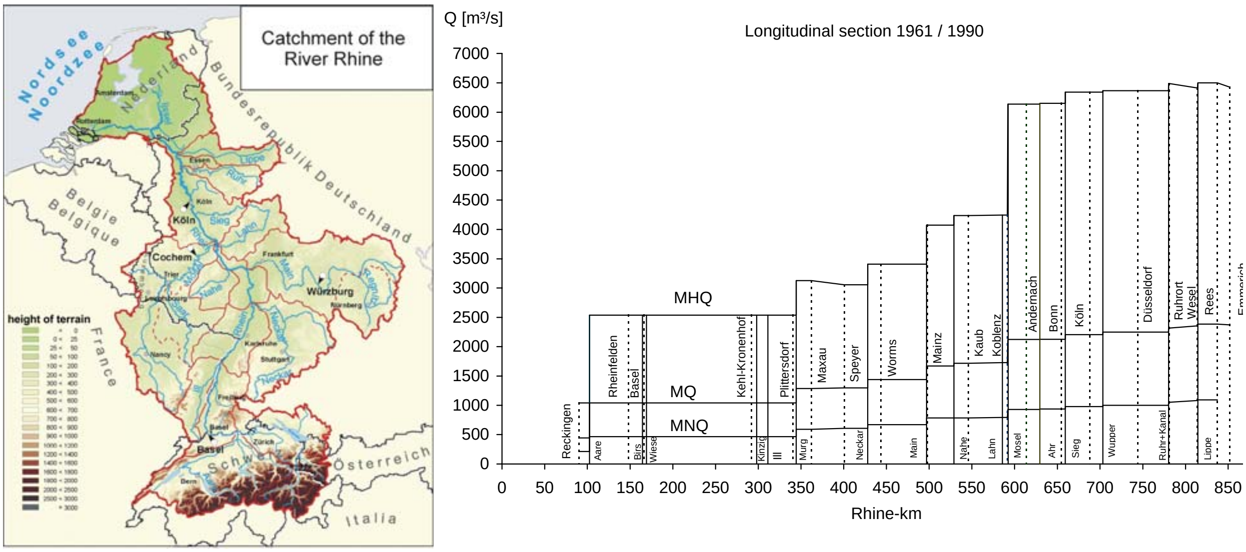

Fig. 1: Terrain height within the catchment of the River Rhine (left), longitudinal section of the River Rhine downstream of Rekingen up to the German-Dutch border: Annual average of maximum discharge (MHQ), mean discharge (MQ) and minimum discharge (MNQ) (right)

The Alpine Rhine and High Rhine are marked by the influence of more than 16,000 km² of high mountain area, of which about 400 km² are covered by glaciers. Downstream Basle, the “Oberrhein” (eng. Upper Rhine) flows through the approx. 300 km long and, on average, 35 km wide Upper Rhine Graben, a tectonic rift. The lowland plain with a markedly flatter gradient than the High Rhine caused over the centuries a network of channels (furcation zone). Numerous river training works have been undertaken there since the beginning of the 19th century. With the exception of the Neckar area, only relatively minor catchment areas follow; however, they have high runoff levels due to the high precipitation and the relief. In Mainz the tributary with the largest surface, the Main, joins the Rhine after a distance of 524 km. Downstream up to Bingen only small secondary rivers flow into the Rhine. The section of the Rhine that extends from Bingen to south of Cologne is called the “Mittelrhein” (eng. Middle Rhine). Its meanders have cut 200 to 300 m down into the rock, and at the narrowest point the valley bottom is merely 200 m wide. The largest tributaries along this stretch are the Nahe, Moselle, Lahn, and Sieg Rivers, and of these the Moselle, which is 545 km long and rises on the western slope of the Vosges, represents the main one. South of Cologne the Middle Rhine discharges into the “Niederrheinische Bucht” (eng. Lower Rhine Bight). The Lower Rhine flows like a typical lowland river in wide meanders. At the western Lower Rhine the watershed of the Maas is close to the Rhine. Since the water level of the Maas is lower than that of the Rhine, subterranean drainage towards the Maas is easy. The average annual minimum, mean and maximum discharge from the end of the High Rhine to the Lower Rhine is given in Fig. 1, right.

Immediately after the German-Dutch border, the Rhine Delta begins, the area where the Rhine and the Maas dovetail; that is why the catchment area of the Maas might also be regarded as belonging to the Rhine. The flow regime in River Rhine is dominated by melt water and precipitation runoff from the Alps in summer months and by precipitation runoff from the uplands in winter. Further downstream, the influence of the uplands grows more and more, and over the year the discharge becomes much more homogeneous. More detailed description of the hydrological regime of the River Rhine is given in the following chapter.

3. DISCHARGE REGIME OF THE CATCHMENT OF THE RIVER RHINE

In general “regime” is used in a hydrological sense to refer to the relative or absolute variations of one element of the water cycle within a particular time period (LHG/BWG 2002). “Discharge regime” is often used to designate the general hydrological behaviour of a river. The long-term average seasonal variations of discharge will be referred to as “regime” in accordance with the classical use of the term. These regimes can be described in terms of the dimensionless Pardé coefficients (PKi), defined as the ratios of monthly and yearly runoff or by long-term average monthly values. There is a long tradition of research dealing with characterisation of rivers using runoff regimes. Pardé (1933) in France, Keller (1968) in Germany, Grimm (1968), Aschwanden and Weingartner (1986) in Switzerland, or Mader et al. (1996) in Austria studied the flow characteristics of rivers. The runoff regime is a product of the temporal variation of the water balance in a catchment area and is, therefore, influenced by all the factors that control runoff. Runoff regimes take into account the periodical discharge behaviour during the year, maximum and minimum flow periods, extreme flows over an extended observation period, and the frequency distribution of characteristic hydrological discharge values. For example, the knowledge of periodical occurrences of high or low-flows, or the reliability of a specific discharge for a given time or season, might be of special interest in water resources management (power stations, dilution of discharges etc.). The given runoff regime is moulded by the natural boundary conditions and can be modified by anthropogenic influences in the river basin (e. g., weirs, bypasses). Year diagrams composed of the twelve monthly values (Fig. 2) show characteristic curves that can conventionally be classified by the influence of, e. g., dry periods and/or number of maxima. According to Keller (1961), nival regimes are dominated by snow storage and snow melt, in nivo-pluvial regimes the snow melt peak is higher than the peak resulting from rainfalls, in pluvio-nival regimes rainfall peaks exceed the snow melt peak, and pluvial regimes are only influenced by rainfall. Glacial regimes are dominated by storage of water in glaciers and runoff of glaciers. In glacial regimes the discharges depend on the seasonal temperature variations with a minimum in winter and maximum in summer. The daily variations in summer are dominated by the daily temperature regime in this regime type.

A detailed classification and a regionalization of discharge regimes can be found in LHG/BWG (2002) and BMU (2003). An initial classification of regimes in Switzerland reveals distinctive alpine and midland-Jurassic, which differ from one another in their respective number of maxima. For example regimes with a single maximum are found on the north side of the Alps above an average of catchment altitude of 1550 m, whereas below this altitude regimes with several maxima occur. The natural flow conditions are depicted, but it is important to note that many rivers have been changed by human influences, especially in the Alps. Generally, the flow regime in River Rhine is dominated by melt water and precipitation runoff from the Alps in summer months and by precipitation runoff from the uplands in winter. Therefore, the dominating regimes which can be found upstream of Basle are nival and nivo-pluvial regimes. There is a slightly decrease in the summer maximum which is caused by a reservoir storage of 1.9 x 109 m^3, taken in summer and consumed in winter for power production. This volume corresponds to a mean runoff of about 50 mm in Rhine basin upstream of Basle. Also the retention in the Alpine border lakes should be considered: his cause smoothing of the discharge trends.

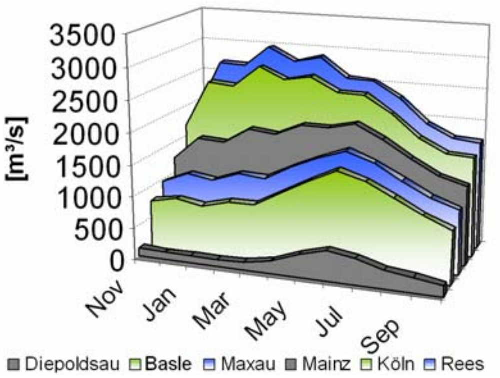

Fig. 2: Monthly averaged discharges in the River

Further downstream the influence of the uplands grows more and more, and over the year the discharge becomes even compensated. The pluvial regime with a maximum in the winter months gradually becomes the dominating one. This can be illustrated by annual hydrographs of selected gauges along the Rhine (Fig. 3). It can be seen, that the discharge components from the high mountains and those from the hilly country complement each other nearly ideally. Pluvio-nival regimes are restricted to the higher parts of the tributaries mentioned. At the Moselle confluence the discharge maximum moves to the winter season, maintaining however a considerable discharge in summer thanks to the water supply from the Alpine regions. On the one hand the winter maximum can be characterised by evapotranspiration during the growing season in summer exceeding the contribution of the precipitation to the runoff, in spite of the precipitation maximum in this period. On the other hand, winter-precipitation falls in the lower parts of the basin predominately as rain, while casual snowfall melts quickly. Going downstream the declining contribution of the tributary basins to the mean yearly runoff is mainly caused by regression of precipitation in the lower parts of the basin.

4. OVERVIEW ON THE IMPACTS OF CLIMATE CHANGE AT CATCHMENT SCALE
4.1 GLOBAL CLIMATE CHANGE

The global climate change, which is expected due to the anthropogenic-caused emissions of the so-called greenhouse gases, as well as an assessment of its possible effects are described in detail in the third and fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2001, 2007). In the 20th century the global average temperature rose around approx. 0.6°C and precipitation over land in middle and high latitudes of the northern hemisphere clearly increased. The largest part of the global warming over last 50 years can be probably attributed to the human activities. For 21st century the Global warming is expected to continue at an accelerated rate and that will clearly change precipitation region specifically. Depending upon the accepted emission scenarios climate models predict a rise in the mean global near-surface temperature of around 1.4°C to 5.8°C (ProCliM 2002). In the IPCC "Special Report on Emission Scenarios" (Nakicenovic et al. 2000) emission scenarios - the so called SRES scenarios – were published. From these the B2 scenario was selected for the study within the River Rhine basin. B2 is a "dynamics-as-usual" scenario, where differences in the economic growth across regions are gradually reduced and concerns for environmental and social sustainability at the local and regional level rise gradually along the time horizon up to the year 2100. It is expected that the probability and the spatial distribution of extreme events will gradually shift with the climatic change. The extent and the character of the changes will be different depending upon the place and the kind of extreme events. Recently, throughout the world an accumulation of natural disasters has been registered, from which those in Central Europe, for example the flood events in the Elbe and Danube area in August 2002, cannot be exempted. This accumulation could be coincidental, caused by natural long-term climatic variations or as a consequence of the anthropogenic influences on climate. For reasons of principle it is difficult or even impossible to prove or exclude statistically a trend in the frequency from rare extreme events. It is conceivable that long-term changes of extreme events can only be proved when they have reached a considerable magnitude and caused great damage (OcCC 2003). The aim of regional climate impact research is to transfer future prospects forecast on a global scale to a regional scale and identify sensitive regions (Schär 2000). Furthermore, in terms of sustainable development and according to the principle of precaution, the need for action and action strategies should be devised to minimise possible harmful events. In order to study the impact of climate change on hydrology and to develop strategies for the protection and adjustment of water resources, it is necessary to consider in terms of river catchment areas. In the following selected statements about changes in the past as well as prospects for the future for the catchment area of the Rhine up to the German/Netherlands border (A_{Eo}= 159,500 km²) have been made. Whereby emphasis is on estimations of the Rhine itself. Studies at sub-basin level are at present being carried out in the project Climate Change and Consequences for Water Management (KLIWA), a joint project of the states Baden-Württemberg and Bavaria as well as the German Weather Service (Bartels et al. 2004b).

4.2 OBSERVED TRENDS OF HYDROMETEOROLOGICAL AND HYDROLOGICAL VARIABLES IN THE RIVER RHINE

On the basis of the analysis of long time series of air temperature, station and areal mean precipitation as well as discharge, the long-period fluctuation behaviour can be studied. Different statistic characteristic values, such as, for example, the average values of the hydrological half-years of winter (November to April) as well as summer (May to October), are considered. A large portion of this fluctuation behaviour is related to the decade variability, i.e. for periods of approx. 10 years duration weather periods of a certain kind frequently occur.

This fluctuation shows a trend behaviour that, however particularly for precipitation and for discharge, is region-specifically strong pronounced. During the interpretation of trend analyses the dependence of the selected time period has to be considered. For example in Fig. 3 time series from 1891 to 2002 of air temperature, areal mean precipitation and discharge for the gauge Cologne are depicted for the hydrological winter (and/or concerning the temperature representatively for the area of Central Europe, supplement after Baur (1975)). In the temperature series of Central Europe the positive trend, as determined for the global air temperature, clearly appears. High winter temperatures arise since 1990 in a more frequent manner. The trend of the winter precipitation likewise exhibits an increase. The analyses of precipitation changes show stronger positive trend since around 1970 (break-point analysis). These general tendencies are also supported by station related statistical investigations. Krüger (2002) determined for stations from North Rhine-Westphalia in the summer a decrease of the precipitation depth and in the winter an increase. This trend is significant in summer at 26 % and in winter at 32 % of the stations. Also the trends of precipitation found by Bardossy and Caspary (1990), Schönwiese et al. (1997), Widmann and Schär (1997) as well as KLIWA (2003a) confirm this tendency as far as possible. High-correlated with the long-term fluctuations of precipitation is the discharge of the winter half-year. Since around 1980 an increase of high winter discharges can be registered. This trend is regional-specifically differently strong pronounced even in smaller river catchments (KLIWA 2002 and 2003b, Pfister et al. 2000). Generally, an accumulation of discharge-rich winters can be stated, in particular in the higher altitudes of the low mountain ranges aligned to the west. As a cause for the observed trend behaviour of the hydrometeorological and hydrological time series a changed occurrence in the frequency and in the maximal duration of westerly atmospheric circulation patterns is regarded (Caspary 2004).Thus the positive winter precipitation trend is confirmed by an increase of zonal weather conditions for Central Europe (Bardossy and Caspary 1990, Caspary 2004, Günther 2004, Pfister et al. 2004).

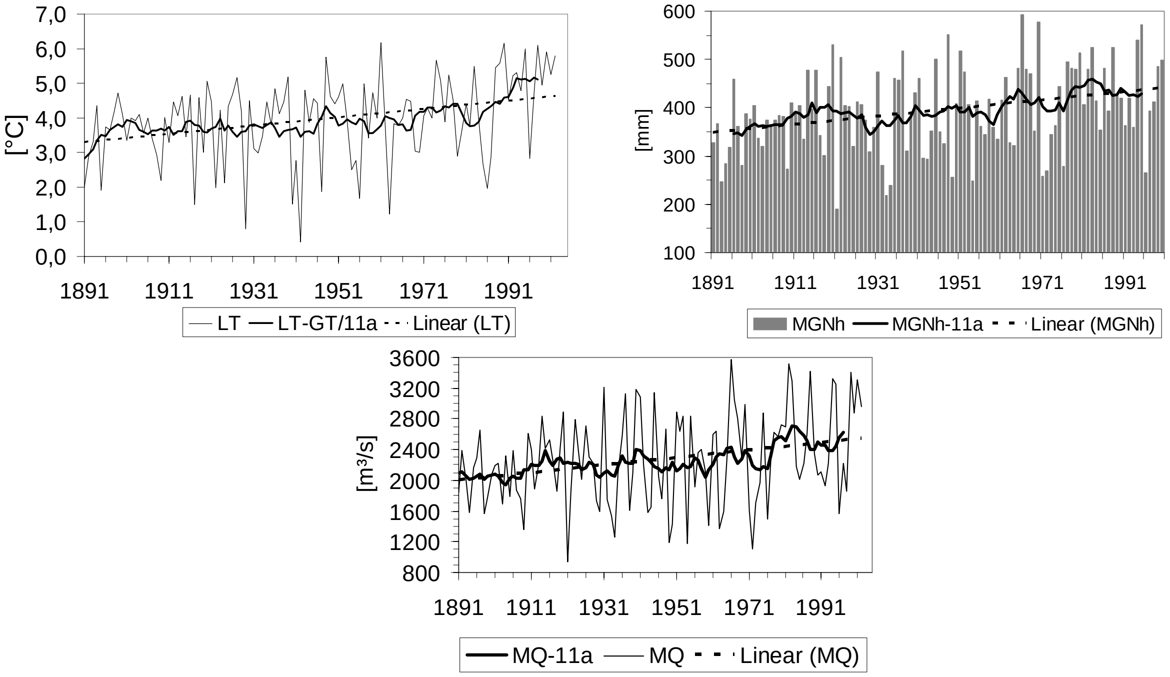

Fig. 3: Decadal variability and linear trend of air temperature (LT) in Central Europe (top,left), of areal precipitation depth (MGNh) for the River Rhine basin up to gauge Cologne (top, right), and of discharge (MQ) at gauge Cologne (bottom) for the hydrological winter half-year

Table 1: Results of trend analyses of air temperature of Central Europe areal precipitation depths, and discharge at gauge Cologne of hydrological half-years and years of time period 1891/2002

	Mean 1961/90	Standard-deviation 1961/90	Trend/ noise ratio*	Deviation from 10-year-average 1990/99**	
				Min.	Max.
Air temperature					
Hydrol. year	9.4 °C	0.64 °C	2.1	-1.2 °C	-0.2 °C
Winter half-year	4.1 °C	1.19 °C	1.4	-1.6 °C	-0.7 °C
Summer half-year	15.2 °C	0.62 °C	1.6	-1.5 °C	-0.3 °C
Areal precipitation					
Hydrol. year	918 mm	134 mm	0.7	-10 %	7 %
Winter half-year	428 mm	88 mm	0.9	-19 %	9 %
Summer half-year	489 mm	76 mm	0.2	-8 %	12 %
Discharge					
Hydrol. year	2205 m³/s	499 m³/s	0.6	-12 %	19 %
Winter half-year	2415 m³/s	640 m³/s	0.9	-18 %	13 %
Summer half-year	1998 m³/s	472 m³/s	0.0	-13 %	26 %

* Trend/noise-ratio = (11a-average at the end of time series - 11a-average at the begin of the time series / standard deviation of time period 1961/90

** Time series 1891-1989, for time period 1990-1999 results of REMO control run are available (s. b.)

Widmann and Schär (1997) do not attribute the trend for Switzerland to a significant change of frequency of weather conditions, but still see it as part of the natural variability with normal frequency of the weather conditions. In Table 1 characteristics of air temperature, areal mean precipitation and discharge at the gauge Cologne specified for the hydrological year and the hydrological half-years are listed. For the characterisation of the decadal variability the smallest and the largest deviation of the 10-annual average-value from the average value of the time series 1990/99 is used.

4.3 ESTIMATION OF THE EFFECT OF CLIMATE CHANGE ON THE DISCHARGE REGIME OF THE RIVER RHINE

The effects of climate changes on hydrology and implications for water resources in general have been investigated in the River Rhine basin by applying various climate scenarios and hydrological models (Kwadijk and Rotmans 1995, Middelkoop, et al. 2001, Menzel et al. 2002, Kleinn 2002). Results obtained by these scenario simulations mostly suggest higher winter discharges, as a consequence of an increase in winter rainfall and a slightly decrease in summer runoff, due to an increase of evaporation. But it has to be noted that Zehe et al. (2004) have found a general decrease of precipitation and discharge in their 2xCO2-scenario experiment in the River Rhine basin. This indicates that the scenario techniques in use so far are accompanied with large uncertainties. In order to be able to create a basis for the definition of water management action strategies, it is necessary, to assess the changes of the hydrometeorological variables in the Rhine area for the next decades with the help of suitable regional climatic scenarios and to convert these results to discharge scenarios, using water balance models. Fig. 4 shows schematically this procedure in principle (changed after Andréasson et al. 2004).

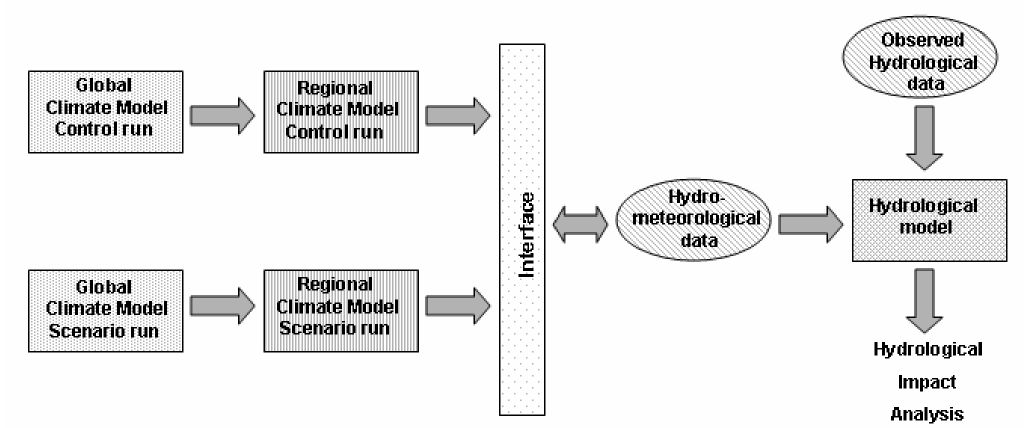

Fig. 4: Methodology of coupling results of global and regional climate models in hydrological impact analysis of climate change

All regional climate models and statistical procedures of today exhibit for different reasons uncertainties and process-determined pros and cons. The selection of a suitable model or procedure depends in the long run on the application purpose and is therefore to be evaluated in each case of concrete application. In the project KLIWA different regionalization procedures were used therefore, in order to get a bandwidth of possible results (Bartels et al. 2004a). The respective results were made comparable by defining appropriate defaults in advance in order to be able to relate them to past knowledge level of the analysis of the long-term behaviour of the hydrometeorological variables. Changes of precipitation, especially in the hydrological winter half-year, are of particularly interest. The results of the climate scenarios are used as input for water regime computations, covering the following variables precipitation, air temperature, relative humidity, air pressure, global radiation or duration of sunshine, and wind velocity. The substantial steps of the conversion of the regional climate scenarios to the hydrological models are shown in Fig. 4. Statements for changes of the hydrometeorological variables which can be expected in the future (e.g. precipitation and air temperature) can be made best by the comparison of future scenario results with the simulated actual condition (control run), because existing biased errors of the climatic model are at least partly eliminated thereby. The resulting assessments of hydrological changes form the basis for an estimation of the effects on the water management.

The comparability of the regional climate scenarios in the project KLIWA was reached by the following defaults:

All regional models use results of the global climatic model ECHAM4 of the Max-Planck-Institute for Meteorology in Hamburg (MPI) for the emission scenario B2. The quality of regional simulations is examined by comparison along and adjustment at measuring and observation data from 1971 to 2000. Thus, changed conditions of the recent past are considered. In the control run, which has to be accomplished in parallel, the influence of the global climatic model (ECHAM4) for the same time series becomes visible. With help of the control run the differences to the intended scenario period have to be determined, whereby biased errors of the ECHAM4 will be partially balanced. For the period 1951 to 2000 examined complete and homogenized data records are made available of approximately 75 climate stations. For verification and validating runs statistic characteristic numbers are fixed for middle, extreme and persistence behaviour of the hydro-meteorological variables, specified above. For comparison of the regional models a uniform, in the more near future lying time horizon is specified from 2021 to 2050. The results of model calculations are to be made available as daily values. Exception is the modelling of the MPI, which can supply hourly values.

The point results (station values) of the two statistic procedures (Gerstengarbe et al. 2002; Enke 2003) to determine climate scenarios for 2021-2050 were not yet used for the Rhine-far modelling, since station density in the foreign catchment area portions does not permit a scenario production. It is however intended to use these scenarios for selected tributaries of the Rhine in order to arrive at an estimation of the uncertainties. The results of the regional dynamic model REMO (Jacob and Podzun 1997) are available as time series of hourly values in the form of raster value files (1/6° x 1/6°, about 18 km x 18 km, Jacob et al. 2003).

The meteorological variables precipitation, air temperature, humidity, wind velocity, and radiation simulated with REMO serve as input for the water balance models LARSIM and HBV-SMHI. Comparative simulations for present climate and the climate scenario permit the quantification of possible hydrological effects. For the Rhine basin the calibrated and well established water balance model LARSIM (Bremicker 2000; Ebel et al. 2000) and the precipitation-runoff model HBV-SMHI (Bergström 1996, Eberle et al. 2001) are used.

The water balance model LARSIM (Large Area Runoff Simulation Model) computes on a raster of 18 km x 18 km the processes interception, actual evapotranspiration, snow accumulation, -setting and -melting, soil water and groundwater storage, lateral water transportation to water bodies (runoff concentration) as well as translation and retention in water bodies. Anthropogenic measures (e.g. water conduits as well as discharge regulations by retention basins and dams) can be modelled, too. The raster is co-ordinated with the regional climatic model REMO. The model was calibrated on the basis of measured hydrological and meteorological data for the period 1992/97 and verified for the period 1987/92.

The model HBV (Hydrologiska Byråns Vattenbalansavdelning) is a development of the Swedish Meteorological and Hydrological Institute (SMHI). The hydrological computation unit is the sub-basin, within which height zones are defined in order to improve simulation of snow processes. Each height zone is further subdivided into forested and non-forested areas to take into account the different hydrological behaviour of these land use units. Originally the model has been developed as a long-term simulation model working on daily value basis. For the modelling in the Rhine area sub-basins are used, which usually exhibit a surface size between 500 km² and 2000 km². Continuous simulations of time series of e.g. 30 years can be accomplished so far. The daily time step can be reduced if necessary to 1 hour, e.g. for special applications of floods. In this case, an adjustment of the hydrological model is necessary.

As an example for discharge scenarios for the Rhine area, the results of the model LARSIM, driven by the REMO control and scenario data, are presented. For the interpretation of the model results it has to be noted that the model climates (control and scenario run) differ still clearly from the observed climate. Observed climate is delineated from observed data as well as of data generated by REMO by the so-called validation run. In the validation run REMO is driven by data set of observed atmospheric global reanalysis data. Thus for example the deviation between the REMO control and validation run in the hydrological summer half-year is 14% and in the winter half-year 35% (Fig. 5). As deviation between control and scenario run a uniform increase results in both half-years of approximately 5%. The strongest increases are found to the months January and November.

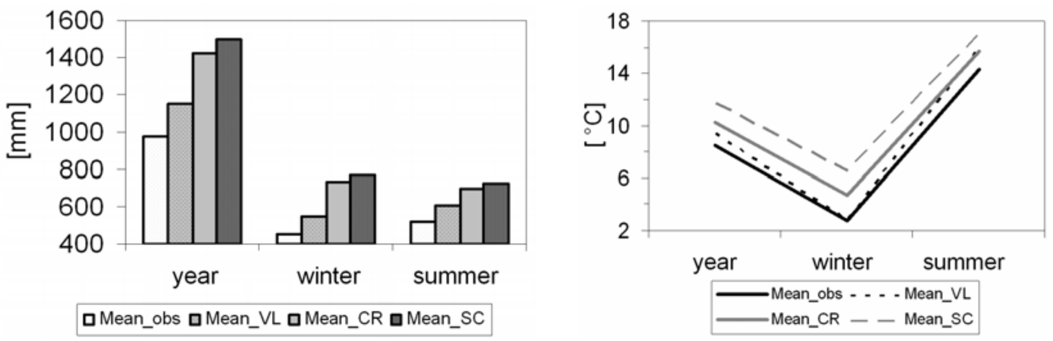

Fig. 5: Mean half-yearly and yearly areal precipitation depths of River Rhine basin up to gauge Cologne (observed data, validating run (VL), REMO control (CR) and scenario run (SC)) (left), mean half-yearly and annual averages of areal air temperature of River Rhine basin up to the level Cologne (measured values, validating run (VL), REMO control (CR) and scenario run (SC)) (right)

For the discharge changes represented in the Fig. 6 exemplarily for four important gauges the depicted results relate to the hydrologic half-years when direct using these scenarios. Also the scenario calculations exhibit a clear variability between the regarded decades. Perhaps with exception of the gauge Cochem there is constantly a strong increase of the discharge in the winter half-year.

For the discharge changes represented in the Fig. 5 exemplarily for four important gauges the depicted results relate to the hydrologic half-years when direct using these. The precipitation increase simulated with REMO in the winter results in a substantially stronger discharge increase. This occupies the sensitivity of hydrological systems in relation to changes in the precipitation. Precipitation can be predicted most with difficulty in numerical weather forecast and climate models but it is the most important variable for the hydrological water resources related climate change impact estimation.

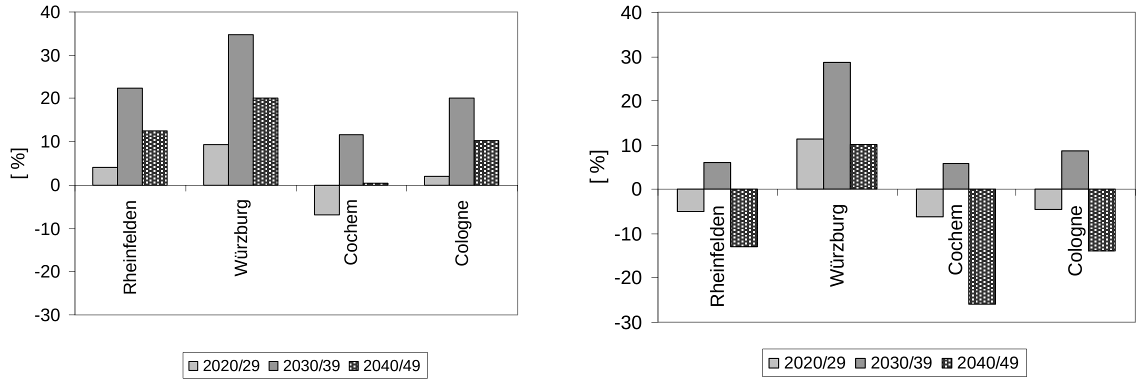

Fig. 6: Discharge changes of hydrological winter half-year for selected gauges of the River Rhine and its tributaries by direct use of results of the regional climatic model REMO as averages for time periods 2020/29, 2030/39, and 2040/49 (left), discharge changes of hydrologic summer half-year for selected gauges of the River Rhine and its tributaries by direct use of results of the regional climatic model REMO as averages for time periods 2020/29, 2030/39, and 2040/49 (right)

4.4 CLIMATIC CHANGES AND HYDROLOGIC EXTREME VALUES

Climate is defined as average weather conditions at a place or in an area. This is described statistically with averages and variabilities of meteorological variables. Extreme events are episodes, in which the weather deviates strongly from its long-temporal means and the fluctuations typical for a certain place and a certain season. They belong to the climate of a region and influence landscape and living conditions. Extreme events can lead however to devastating damage to cultures and social mechanisms. Knowledge of their frequency and intensity is important for our society, therefore. They are considered in today's tasks of water resources planning and preventive measures.

In the knowledge around the rise of the global temperature the question about the correlation between extreme events and climate change is asked again and again: “Did extreme events become more frequent as consequence of the climatic change (OcCC 2003)?”

Present knowledge is that the global climate change will affect also the frequency and intensity of extreme events. There are indications that the frequency of extreme events could react particularly sensitively to a climate change. Responsible for this are on the one hand physical feedback mechanisms. On the other hand there are also statistical effects, by which the climate change in the frequency of extremes could manifest itself even more strongly than in "normal" weather events. With a rise of probability of occurrence and an increase of the variability more frequent and higher extreme values have to be expected.

4.5 EVALUATION OF RESULTS

The results of the hydrologic climate impact research obtained so far suggest that the water resources management should argue with the described system-dependent fluctuations and change potentials in a more extensive way, despite the still existing large methodical uncertainties strengthened. The existing water resources action goals should be examined and new concepts for the consideration of the existing uncertainties be compiled. This refers both to measures of flood protection management and to the safety device of the water availability.

The water resources management should give increased attention to the recommendations of the advisory committee for questions of the climate change in Switzerland (OcCC). The most important recommendations are in part:

- The possibility of a high hydrological sensitivity (means and extreme values) together with the sensitivity of the modern civilization requires a scientifically based estimation of possible future developments of extreme events, an evaluation of its meaning for humans and environment and realizations of improved protection and adaptation strategies.

- In the last decade the hydrological extreme events pointed out that action is still given without climate change to the protection from extreme events due to the increasing value concentration, damage vulnerability and the rising protection need. In the consciousness of the climate change the endangerment pictures, protection goals, and the residual risks taken in purchase should be periodically adapted to the changing conditions and solutions with as large a flexibility as possible should be aimed at. Medium-term it is to be foreseen that new calculation and planning methods must be developed, which are able to quantify the endangerments in a changing climate.

- Already today a sufficient knowledge basis is present, in order to seize measures against climate change and to the protection from extreme events. The research will still continue to increase in addition the knowledge conditions in the future to reduce the uncertainties, and to be used itself as a more direct planning instrument.

The modelling of the water balance components actual evaporation, ground-water recharge, soil moisture, water equivalent of snow and finally the discharge get in the last years a greater importance in the operational hydrology and water resources management. For the estimation of design values and the enterprise of water-resources plants the appropriate hydrological models were usually provided for small (< 500 km², lower meso-scale) to medium-sized catchment areas (< 5000 km², upper meso-scale), so far. Meanwhile investigations step to the consequences of the wide changes of our landscape and to the effects of climate change in addition. Thus also the demand strengthens on hydrological modelling of large rivers and basins (> 10,000 km², macro scale).

Integrated river basin management is called the challenge today. It aims to the safety device of the water availability at the improvement of the flood protection and the flood precaution, in addition, especially in low water periods. Besides this the maintenance of the various uses of waters, like e.g. water supply and power supply, navigation as well as the guarantee of ecological minimum requirements are important tasks of water resources management.

5. IMPACT OF CLIMATE CHANGE ON INLAND NAVIGATION

The effects of climate change exemplary described for the River Rhine in the previous chapters will impact inland navigation primarily in terms of water depth and velocity, resultant changes in sedimentation and the presence and absence of ice. General areas of impact are shown in Table 2.

The most crucial aspect of climate change, causing a wide range of impacts on inland navigation, is the change in water supply in the navigable river sections. The change in water supply relates to increased and decreased water level and velocity and resultant changes in sedimentation processes such as bank failure, local scour, and locations of aggradation and degradation. Changes in water levels that impact the movement of sediment and hence channel maintenance activities will require increased or decreased dredging, depending on the locations and specific impacts. In addition the changes in water level and velocity can also impact manoeuvrability and operational efficiency of navigation structures. Navigation structures may also experience loadings different from design loading, affecting stability and resiliency. Higher water levels could require modifications to existing ports and mooring areas or reduce their potential for expansion.

Table 2: Drivers and Impacts of Climate Change to Inland Navigation

Drivers	**Impacts**	**Rivers, Channels, Canals, Lakes**	**Locks, Dams, and Infrastructure**	**Operational Control**	**Vessels**
Water supply: increased precipitation Extreme conditions: more extreme floods	Increased water level and velocity	x	x	x	x
	Changes in sedimentation processes (bank failure, local scour, locations of aggradation, degradation)	x	x	x	
	Manoeuvrability		x		x
	Increased loads on structures		x		
	Decreased land area available for development		x		
	Reduced regularity of the port		x	x	
	Reducing the capacity of natural systems to recover	x			
Water supply: decreased precipitation Extreme conditions: more extreme droughts	Decreased water level and velocity	x	x	x	x
	Reduced regularity of the port		x	x	
	Changes in sedimentation processes (locations of aggradation, degradation)	x	x	x	
	Reducing the capacity of natural systems to recover	x			
Water supply: changes in form and quantity of seasonal precipitation	Change in timing of seasonal high water and seasonal low water	x	x	x	x
	Changes in sedimentation processes (locations of aggradation, degradation)	x	x	x	x
Water temperature increases	Ecosystem impacts affecting habitat	x		x	
	Oxygen depletion	x		x	
	Reducing the capacity of natural systems to recover	x			
River Morphology	Changes in sedimentation processes (locations of aggradation, degradation)	x	x	x	x
	Ecosystem impacts affecting habitat and lifecycle				
	Reducing the capacity of natural systems to recover	x			
Changes in ice cover	Shorter duration of river ice	x	x	x	x
	Changes in locations of ice jams	x	x	x	

Besides that the changes in the timing of seasonal high water and seasonal low water may impact shipping and maintenance schedules. These issues are already being observed in the North American Great Lakes, where falling lake levels due to changes in precipitation reduces ship clearance in channels and harbors and increases demand for dredging (Kling et al. 2003). The changes in the occurrence of more extreme floods and droughts will exacerbate these impacts. Increased flood levels may result in the need for reengineering infrastructure design (Caldwell et al. 2002). Despite of the needs for reengineering of waterways infrastructure the changes in sediment load, as exemplarily given for a barrage in the River Rhine, will cause changes in river bed erosion, river dune development as well as in floodplain sedimentation and therefore will require an adaptation of sediment management, i.e. dredging or artificial sediment supply. Changing erosion, scour, and sedimentation patterns will also impact ecosystem structure and functioning. In addition to that the riverine ecosystems are also affected by the expected increase of water temperature, causing already a shift in the abundance of species. Navigation will be primarily affected by an increase of water temperature through regulations to protect and enhance riverine ecosystems. Warmer water temperatures resulting in increased occurrence of oxygen deficits for the same nutrient loading will adversely impact theses ecosystems. Since oxygen deficits are often compensated by discharging water over spillweirs, the water depth in navigable rivers could be reduced. Although climate trends indicate higher mean temperatures and therefore shorter periods of ice cover, a high degree of variability in local climatic conditions is still expected to cause ice impacts to inland navigation in many years. Warmer early winter air temperatures followed by rapid decrease in air temperature can result in thicker or rougher than normal ice cover formation or freeze-up jamming. While reducing the period of ice cover, earlier breakup can coincide with higher than normal ice strength, resulting in midwinter ice jams that freeze in place or jams that occur in different locations than expected. However in Germany, decreased duration of ice cover may be beneficial, resulting in extended navigation seasons, especially in the River Elbe and the Main-Donau canal.

6. RESPONSE OPTIONS OF INLAND NAVIGATION TO CLIMATE CHANGE

Climate change impacts to rivers, channels and canals may be mitigated through changes in operational control of flow or by modifications to channel maintenance. Because water supply for inland navigation is intimately connected to and competing with other water users such as domestic water supply, industrial and agricultural demand, and ecosystem requirements, operational changes to water control will require legal and environmental analyses. However, control of water flow to improve navigation may well be in line with the principles for flood mitigation (IKSR, 1998). Similarly, changes to existing maintenance practices such as channel and bank stabilization and dredging, will also require legal and environmental analyses before proceeding. Navigation system operation may benefit from increased use of automation, queuing procedures and the application of River Information Services (PIANC, 2002). Extension of the time range of water level forecasts, increased data sharing regarding unexpected hazardous conditions or conditions requiring restrictions and lessons learned from response successes and failures will also improve system operation in the face of climate changes. Impacts of climate change relevant for inland navigation, such as low water levels or floods, are well known phenomena in many parts of the world. The users of the navigation systems, the operators of the vessels, try to respond to these phenomena in a way that assures the reliability of inland navigation. Thus possible responses of the inland navigation sectors to the impact of climate change are already known and often applied (Middelkoop and van Deursen, 1999). Changes in transport management and operation of the vessels are short term responses addressing situations, when navigation is inhibited for a short period of time. If navigation conditions are altered over longer periods of time, adaptation of the fleet and new vessels of different design seem to be inevitable.

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