Ruhrverband

Estimation of the Impact of Possible Climate Change on the Management of the Reservoirs in the Ruhr Catchment Basin

Gerd Morgenschweis, Georg zur Strassen (Ruhrverband Essen),
Simone Patzke, Dirk Schwanenberg (WL | Delft Hydraulics)

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10 Estimation of the Impact of Possible Climate Change on the Management of the Reservoirs in the Ruhr Catchment Basin

10.1 Introduction

During the period from July 2004 to February 2006, WL | Delft Hydraulics, a prominent research institute in the Netherlands, was commissioned by the Ruhr River Association (Ruhrverband), to develop a methodology for the analysis of long-term reservoir management that would be suitable for investigating the operational reliability and limit capability of the existing reservoir system (WL, 2006). To this end long time series of daily precipitation and air temperature were generated with stochastic models (up to 10 x 1,000 years) and served as the input data for the river basin models that have already been set up at the Ruhr River Association and used successfully to optimize the operation of the reservoir system for many years. From this starting point, calculations were performed with several variants to determine the effects of changed framework conditions – e.g. the expansion of the flood protection volumes, altered schemes for discharging water from the reservoirs based on ecological considerations, and the introduction of new thresholds for minimum runoff – on the capability of the existing system in order to quantitatively assess the feasibility of such changes in use. Chapter 10 of the Ruhrwassermenge 2005 [Ruhr Water Quantity Report 2005] (Ruhrverband, 2006) contains a detailed discussion of this topic.

During the same period of time, the Ruhr River Association analyzed the existing long time series of calculated areal precipitation with the aid of statistical methods to identify trends. The program TREND (Version 5.0) taken from the software package ZEITREIHEN [TIME SERIES] developed by the Institute for Water and River Basin Management (IWG, 2002) of the University of Karlsruhe was used for this purpose. Significant trends were noted in both the annual totals for the time series examined for the period 1927 – 2005 and, in particular, the totals for the winter half-year (November – April). The precipitation totals for the winter half-year are presented as an example in Fig. 17, this substantiates the increase in precipitation during the winter which has been confirmed with a statistical significance level of 98 %. In contrast, no trend was noted for precipitation during the summer half-year (May – October). On the whole, i.e. for the entire water year, the positive trend in the winter makes itself felt – albeit with a somewhat weaker significance of 95 % – in the figures for annual precipitation.

This is also substantiated by the results of the trend studies of monthly and annual areal precipitation depths summarized in table 13. The increased values recorded for the months of December and March (in particular) – as well as during the hydrological winter half-year and the meteorological winter – stand out by reason of their especially high statistical confidence.

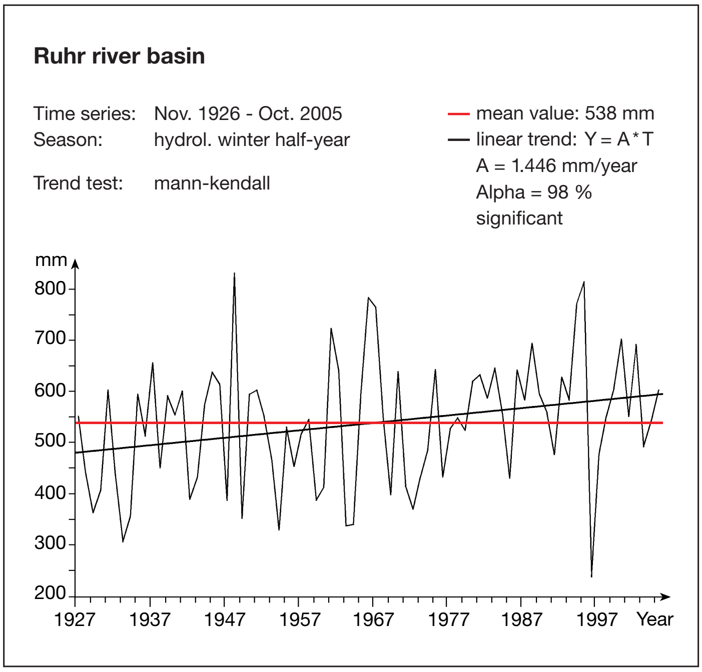

Fig. 17: Trend analysis of the areal winter precipitation of the Ruhr catchment basin from 1927 to 2005

Table 13: Trends in the mean annual precipitation depths of the Ruhr catchment basin from 1927 to 2005

time period	mean mm	significance	Alpha %
November	97	NO	50
December	104	YES	95
January	102	YES	80
February	81	NO	50
March	77	YES	99.5
April	77	YES	50
May	74	YES	50
June	91	NO	50
July	97	NO	50
August	91	YES	80
September	82	YES	80
October	86	NO	50
1st half-year (Nov. – April)	538	YES	98
2nd half-year (May – Oct.)	521	NO	50
water year (Nov. – Oct.)	1,059	YES	95
Meteorolog. winter (Dec. – Feb.)	287	YES	98
Meteorolog. spring (March – May)	228	YES	90
Meteorolog. summer (June – Aug.)	279	YES	50
Meteorolog. autumn (Sept. – Nov.)	265	YES	50

These results can be interpreted as evidence of an altered precipitation regime in the catchment basin of the Ruhr River.

In the autumn of 2006 new scientific findings on possible climate changes were discussed by the professional community and it was announced that regional climate change predictions generated by newly developed climate models would soon be forthcoming.
At this time the idea was put forward of conducting a prospective investigation, using the methodology of long-term analysis, of the impact of possible climate changes on the limit capability of the reservoir system in the Ruhr catchment basin. On 19 Dec. 2006 WL | Delft Hydraulics was commissioned to carry out this work.

The project team consisted of Dr.-Ing. Dirk Schwanenberg, Dipl.-Ing. Simone Patzke and Dr. Jaap Kwadijk. The project was carried out from February to July 2007.

The results of the investigation (WL, 2007) are now presented to the professional public in the form of this report.

10.2 Results of global climate change models

Because of the global significance of a possible climate change and the associated scientific questions, questions which can only be resolved internationally, the United Nations Environmental Program (UNEP) and the World Meteorological Organisation (WMO) jointly founded the Intergovernmental Panel on Climate Change (IPCC) in 1988. This international body, which is composed of the most prominent scientists in the scientific disciplines involved, collects and processes the latest scientific knowledge on this topic and in so doing supports further research and the necessary political action.

To date the IPCC has published four comprehensive reports, the most recent of which was published in the spring of 2007. The results contained in the Third Report (IPCC, 2001) and in the current reports (IPCC, 2007a and 2007b) constitute the basic foundation for the investigations presented here.

10.2.1 SRES emission scenarios

The calculations of current global climate models are based on the "SRES scenarios". In 2000 a group of scientists from IPCC derived these emission scenarios (**S**pecial **R**eport on **E**missions **S**cenarios [SRES], IPCC, 2000) from a number of possible assumptions on the future development of society and the resulting future climate development. The total of 40 SRES scenarios can be broken down into four "families": A1, A2, B1 and B2. Each family represents a different global strategy for dealing with resources. For the purpose of these scenarios various degrees of environmental awareness and knowledge transfer are combined (UBA, 2007).

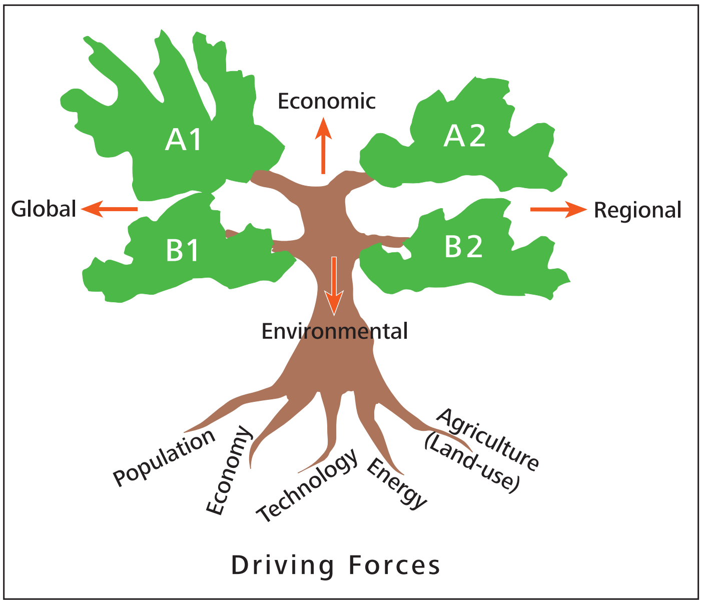

Fig. 18: Basic structure of the SRES scenarios (UBA, 2007)

The following explanations of the individual SRES families are taken from the IPCC Report (IPPC, 2001). The basis structure of the SRES scenarios is shown in figure 18.

A1 scenarios:

The A1 scenarios are based on the assumption of very strong economic growth in future. In these scenarios the world population reaches a maximum in the middle of the 21st century and then decreases. Moreover, new and more efficient technologies are introduced quickly. These scenarios assume that the world will become increasingly global with the result that regional differences in income, cultural and social background, and technological development will largely offset each other. The A1 scenarios are broken down further into three different subgroups. These differ with respect to the predominant use of energy sources:

- A1FI: intensive use of fossil energy sources
- A1T: intensive use of non-fossil energy sources
- A1B: balanced mixture of fossil and non-fossil energy sources

Accordingly, the A1 scenarios are characterized by a mainly economic and global approach. The A1B scenario can be viewed as a "global middle path".

A2 scenarios:

The A2 scenarios are based on the assumption that the world is heterogeneous in character. They rest on the basic premises that local differences are preserved, that birth rates continue to vary greatly from region to region, and that the world population therefore displays steady growth. Furthermore, they assume that economic development will be determined primarily by regional factors, and that the growth of gross national product and the development of technology will vary more from region to region and proceed more slowly on the whole than in the two other main groups.

Accordingly, the A2 scenarios proceed on the assumption of a world with a primarily economic orientation.

B1 scenarios:

The assumptions underlying the B1 scenarios are similar to those made for the A1 scenarios. The B1 scenarios assume that the world will develop with a global orientation – but with the difference that the present economic structure will rapidly be replaced by a service and information economy. Accordingly, material consumption will be reduced; at the same time cleaner and more resource-conserving technologies will be introduced. This scenario is based on the premise that development will head in the direction of a global solution for the problem of sustainability in the economic, social and environmental sectors, and that this sustainable solution will include a balanced distribution of prosperity.

The B1 scenarios are based on the assumption of an ecological and sustainable future development of the human race.

B2 scenarios:

The B2 scenarios are based on the assumption of local solutions for problems of sustainability in the economic, social and environmental spheres. It also assumes that the world population will grow steadily although at a somewhat slower pace than in the A2 scenarios. Economic development will be on a medium level and technological change will be less rapid and display more regional variations than in the A1 and A2 scenarios. On the local and regional levels importance will be placed on environmental protection and a balanced distribution of prosperity.

The B2 scenarios, like their B1 counterparts, proceed on the premise of primarily ecological development; however, this development takes place on the regional level.

10.2.2 Results of the global climate models for various SRES scenarios

Figure 19 shows the development of CO_2 emissions over time in the various SRES scenarios. CO_2 emissions are defined as total global emissions from the sources of energy, industry and land-use change. It is evident that, in the scenarios A1B and B1, CO_2 emissions rise up to the year 2050 and then decline. In scenario A2, in contrast, CO_2 emissions increase continuously.

In the further investigations the three SRES scenarios A1B, A2 and B1 are used.

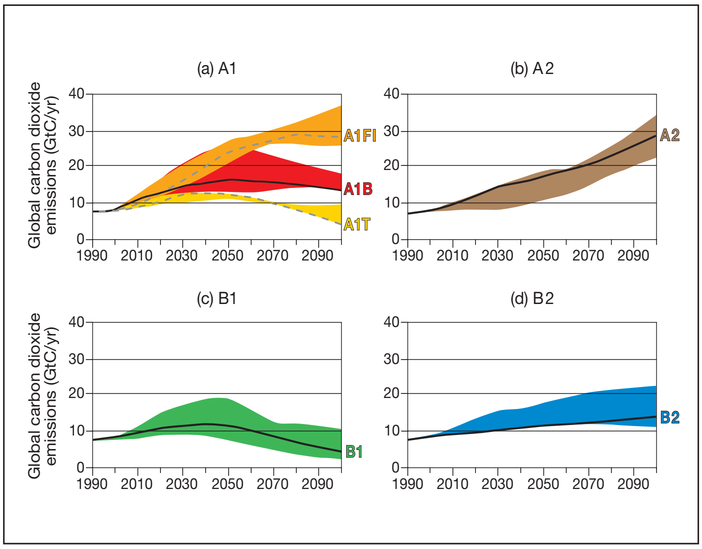

Fig. 19: Total global annual CO_2 emissions due to energy, industry, land-use change from 1990 to 2100 (in gigatonnes of carbon, Gt C/yr) for the four scenario families (IPCC, 2000)

The global temperature changes resulting from the individual scenarios are shown in figure 20.

The data on which figure 20, based reflect the latest research results presented in February 2007. Mean values and the corresponding ranges from all the climate models available worldwide have been plotted in this multi-model figure.

Comparing the scenarios depicted in figure 20, we see that, of the three selected scenarios, the scenario A2 embodies the strongest warming effect with a temperature change of +3.4 °C. The smallest warming effect, with a change of +1.8 °C, takes place in scenario B1. The temperature change of + 2.8 °C in scenario A1B lies between the corresponding figures for A2 and B1. In general it can be said that the climate scenario A2 is the most extreme scenario followed by the scenarios A1B and B1.

The predicted temperature increases have a far-reaching impact on various sectors which are relevant for human beings and the environment. The IPCC Working Group II (IPCC, 2007b) has now, for the first time, evaluated the consequences of climate change in combination with the expected increase in temperature for the following sectors:

- water and its availability (floods, low flow)
- ecosystems (animal and plant populations)
- agriculture and food production
- public health (heat waves, droughts, epidemics, etc.)

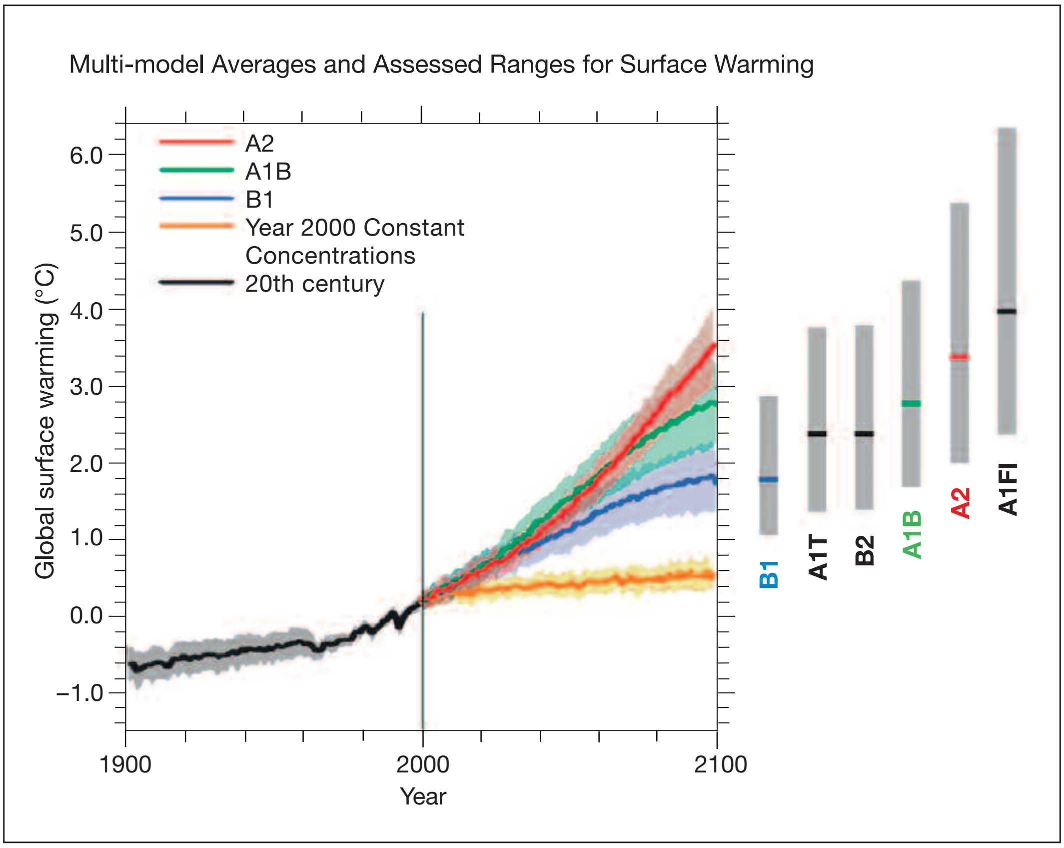

Fig. 20: Multi-model means for surface warming in the 20th- and 21th-century (compared with the 1980 – 1999 baseline period) for different SRES scenarios (IPCC, 2007a)

10.3 Results of the regional climate models simulating climate change in the Ruhr catchment basin

To estimate the future climate development and its regional impact as well, scientists have developed various models in recent years making it possible to derive climate scenarios with a higher regional resolution from the global climate models (and SRES scenarios).

Within the framework of the program "Klimaauswirkungen und Anpassungen in Deutschland" (Climate Effects and Adaptations in Germany), three climate projections were derived for Germany using the regional climate models REMO (Cf. Chapter 10.3.1) and WETTREG (Cf. Chapter 10.3.2). This work was commissioned by the Federal Environmental Agency (UBA). The necessary calculations are based on the results of the global climate model ECHAM5/MPI-OM developed by the Max Planck Institute for Meteorology (MPI-M) in Hamburg. The SRES scenarios A1B, A2 and B1 described in Chapter 10.2.1 constituted the basis for the three projections.

The results of the calculations performed for these climate projections were then used to evaluate the effects of possible climate changes on the reservoir system in the Ruhr River. The REMO and WETTREG data sets were made available by the Federal Environmental Agency (UBA) and can be obtained from the Climate and Environmental Data Retrieval and Archive (CERA) Database at the World Data Center for Climate (WDCC)[1].

Chapter 10.3.3 explores the question of how the two models, WETTREG and REMO, reproduce the three SRES scenarios A1B, A2 and B1 for the Ruhr catchment basin. The data sets serving as the basis for the models were analyzed with respect to changes in temperature and precipitation – in particular for the reference time period 1961–1995, which also served as the basis for the generation of synthetic data.

10.3.1 Regional climate model REMO

The regional climate model REMO (Regional Model) is a dynamic regionalization method developed by MPI-M (MPI, 2007). It reproduces the dynamic processes taking place in the atmosphere at a distinctly higher geographical resolution than the global models. The REMO model grid has a resolution of 10 x 10 km (fig. 21). This model has been described in detail by the Federal Environmental Agency (UBA) (2006) and the Max Planck Institute (MPI) (2007). The time frame for the modelling encompasses the period 1951–2100 (inclusive). The period from 1951 to 2000 served in this context as the control run performed to validate the model.

For the analysis of the temperature and precipitation data sets, the arithmetic means of all the grid points located in the Ruhr catchment basin were taken. The corresponding points are represented by white stars in figure 21.

[1] http://cera-www.dkrz.de/CERA/index.html

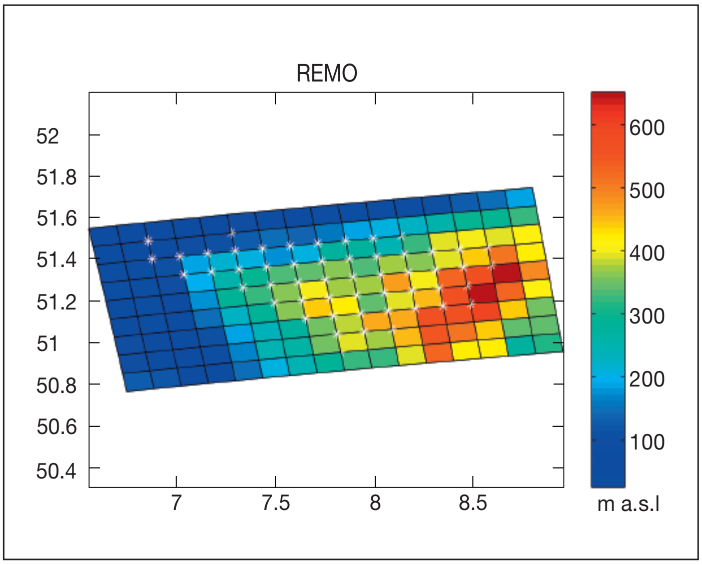

Fig. 21: Geographical resolution of the regional climate model REMO in the Ruhr catchment basin including topography

10.3.2 Regional climate model WETTREG

The WETTREG statistical model was developed by the company Climate & Environment Consulting Potsdam GmbH (CEC) in Potsdam. This model makes use of the statistical interrelationships between the observations on climate made to date – in particular, the effect of the general weather situation on local climate. WETTREG works with data from climate and precipitation stations. There is a 1:1 relationship between the geographical resolution and the number of measurement series available from these stations (UBA, 2007). The present time series covers the period 1961–2100 (inclusive) whereby the period 1961–2000 serves to validate the model using climate date. This model has been described in detail by the Federal Environmental Agency (UBA) (2007).

For the analysis of the WETTREG data the spatial interpolation of the station values was dispensed with during the calculation of mean values since no major spatial variations in the temperature and precipitation changes were noted between the stations in the area under investigation. A simple arithmetic method was used to calculate the mean values of the station data for the Ruhr catchment basin. For the parameter of temperature, data from the climate stations at Arnsberg, Brilon, Eslohe, Essen-Bredeney and Siegen are used; for the parameter of precipitation, data are taken from the stations at Brilon, Eslohe and Siegen.

10.3.3 Analysis of the results of REMO and WETTREG

This chapter examines the question of how the two regional models REMO und WETTREG reproduce the three selected SRES scenarios A1B, A2 and B1 (Chapter 10.2.1) with respect to changes in temperature and precipitation in the Ruhr catchment basin.

Change in temperature

The areal mean values for temperature change in the individual scenarios for the Ruhr catchment basin are shown in figure 22. The 10-year mean value was used for the analysis. Depending on the particular scenario, temperature increases as high as +2 and +3.5 °C have been predicted for the period up to the year 2100 in the Ruhr catchment basin.

Comparison of the REMO and WETTREG results:

- The control calculations for the period 1961–1995 display a good congruency.
- The temperature changes are predicted consistently in the individual scenarios. The results for scenario B1, in particular, display a good congruency.
- Starting in the year 2050 the REMO model results in temperature changes 0.5 to 1.0 °C higher than those generated by the WETTREG model. The reason for this discrepancy, according to the model developers, is that the weather situation concept used by WETTREG reaches its limits in the hot season toward the end of the century; this possibly results in a slight underestimation of the general temperature.

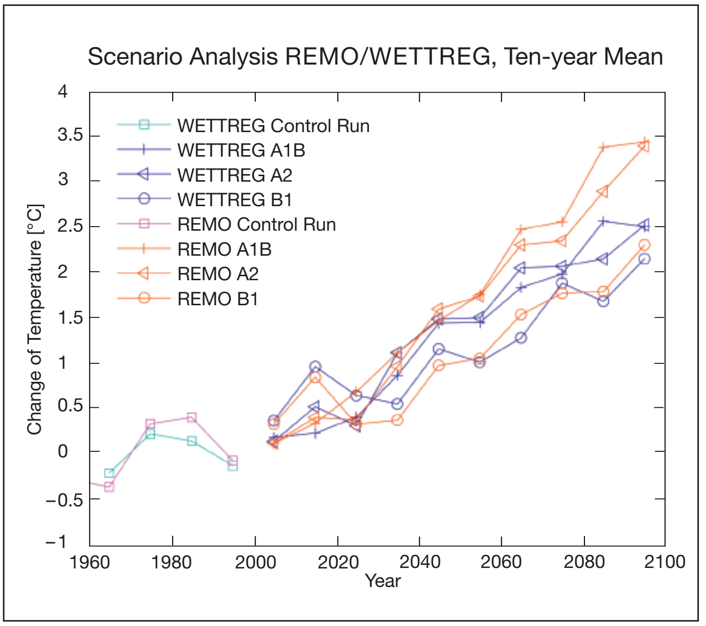

Fig. 22: Ten-year mean of mean annual temperature in the Ruhr catchment basin from 1960 to 2100: Results of the regional models WETTREG and REMO for the SRES scenarios A1B, A2 and B1

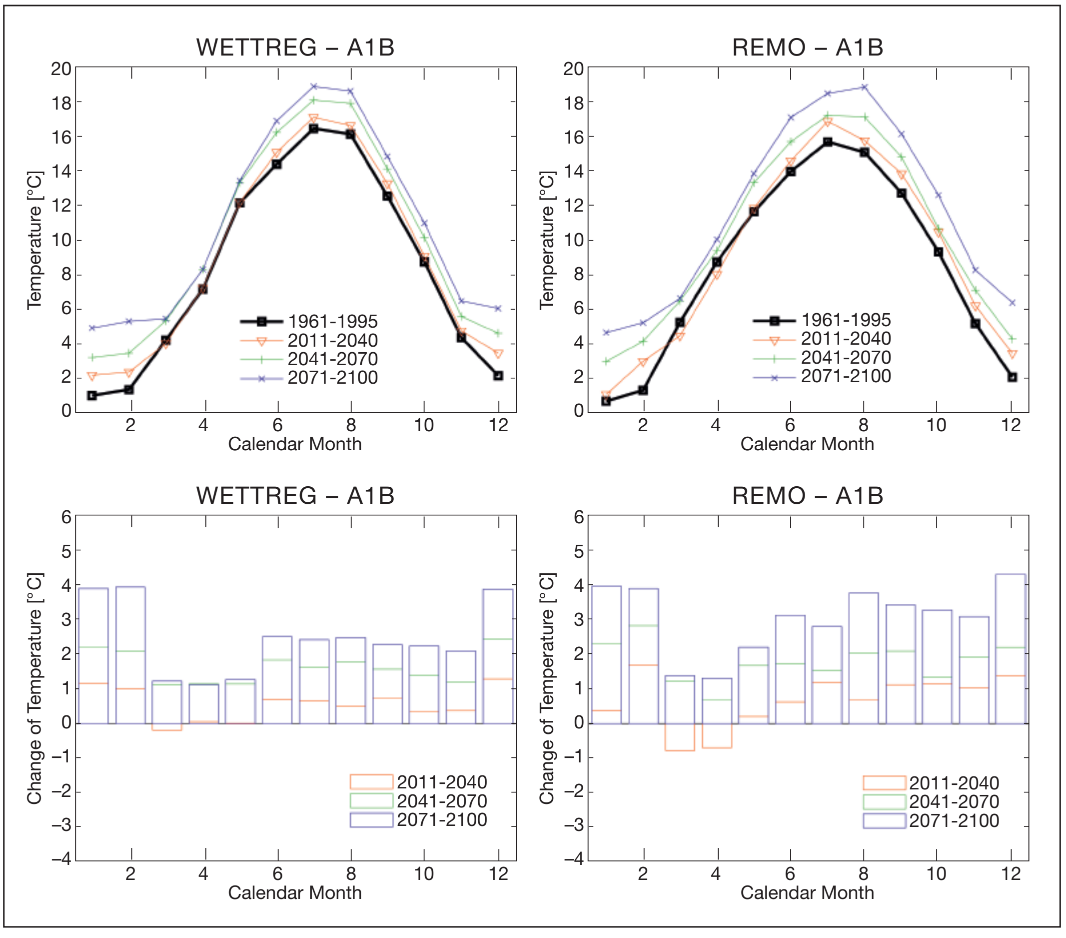

Fig. 23: Mean monthly temperature and changes of temperature in the Ruhr catchment basin taking the scenario A1B as an example

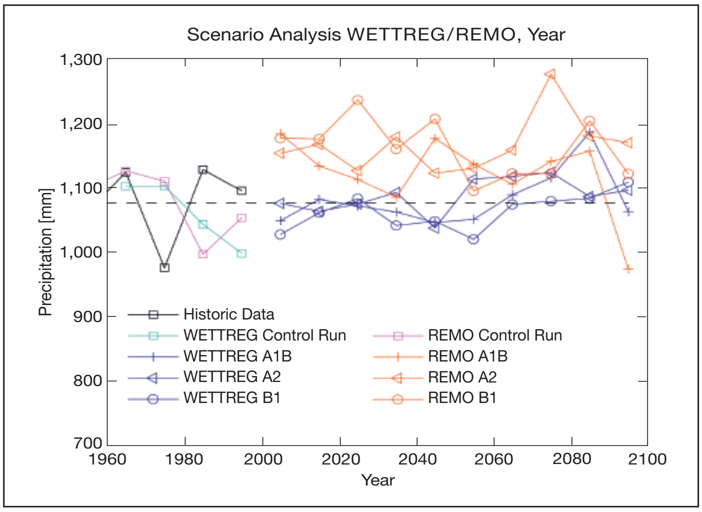

Fig. 24: Ten-year mean of annual precipitation depth in the Ruhr catchment basin of the regional climate models WETTREG and REMO for the scenarios A1B, A2 and B1

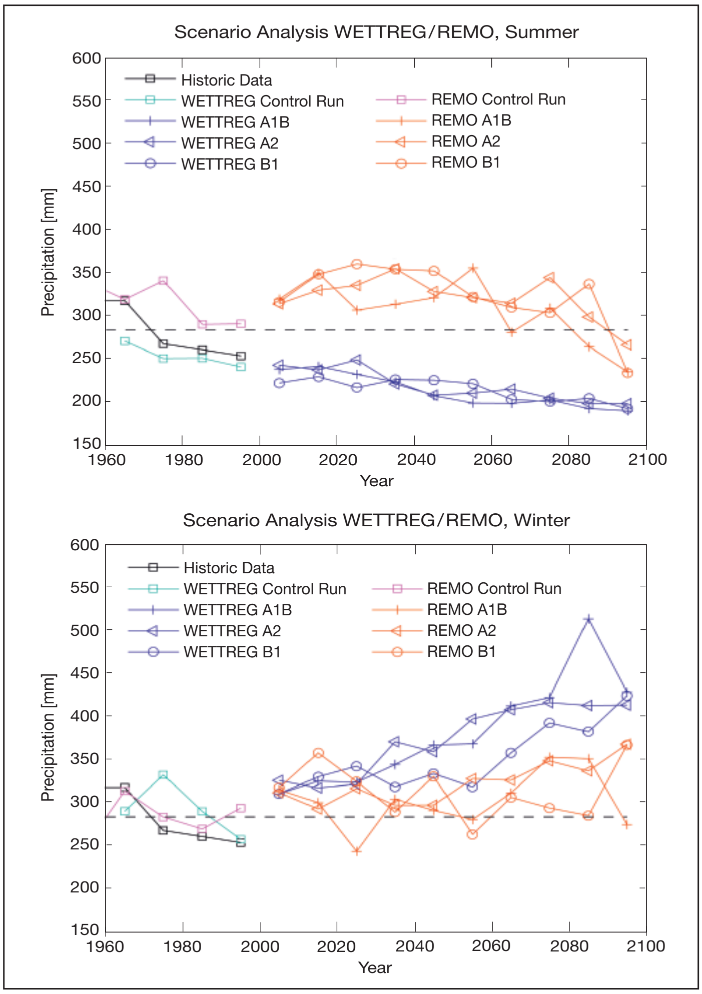

Fig. 25: Ten-year mean of precipitation depth during the summer (on top) and winter (at the bottom) as results of the regional models WETTREG and REMO

Figure 23 shows the results generated by WETTREG and REMO by calendar month for the scenario A1B. In the upper figure, the mean temperature values are plotted in the form of a hydrograph. In the lower figure, the temperature change values are plotted in comparison with the period 1961–1995. For the analysis the periods 2011–2040, 2041–2070 and 2071–2100 were used. These periods were chosen since the German Weather Service also employs a 30-year time period, e.g. as the reference period 1961–1990, for the analysis of its data.

Figure 23 confirms that, in both models, the highest rise in temperature occurs in winter and the lowest in spring. This is consistently reproduced by both models.

Change in precipitation

A basic remark to be made about the results of the analysis of the changes in precipitation is that precipitation is a meteorological element which can be modelled with far less precision than temperature. This is because precipitation is in general the weather element with the greatest spatial and temporal variation. Consequently, there is greater uncertainty with respect to precipitation in all the models.

This is reflected, moreover by the results presented in figure 24 and figure 25 for the precipitation depths projected for the Ruhr catchment basin. The 10-year mean annual precipitation depths shown in figure 24 thus differ – in some cases markedly – in the two models as early as the control runs.

Comparison of WETTREG and REMO results:

- On the whole the precipitation depths in the control calculations exhibit comparable values even if the differences are distinctly larger than for the matching temperature results (Cf. fig. 22).
- In the projections for the future in figure 24 the precipitation values generated by the WETTREG scenarios continue at about the level of the control runs and then rise slightly in the further course.
- The REMO totals, in contrast, are about 80 mm higher and display a discontinuity in comparison with the control run. Moreover, a distinct reduction of the precipitation depth of approx. 200 mm can be observed during the last decade (2091–2100) in the REMO A1B scenario.

According to these results, annual precipitation will remain roughly changed – regardless of the climate scenarios – in the Ruhr catchment basin until about the end of 2100.

If we view the changes in precipitation for summer and winter separately in figure 25 (the seasons are defined here according to the meteorological calendar, i.e. summer consists of the months of June, July and August and winter of the months December, January and February, we note a slight decline of precipitation in the summer and a marked increase in precipitation in the winter for the Ruhr catchment basin in general.

However, the marked differences between the precipitation depths predicted by the REMO and WETTREG models are also evident here. The increase in precipitation up to the year 2100 is approx. 50 mm in REMO and about 150 mm in WETTREG.

In the analysis of the monthly precipitation depths from scenario A1B a massive redistribution of precipitation from summer to winter can be observed in WETTREG (Cf. fig. 26). According to CEC (2007) this is consistent with the model logic of WETTREG, whereby there is a drastic increase in warm west-wind weather situations, and thus in precipitation as well, in the winter. In the summer, in contrast, warm weather situations are associated with frequent dry periods. In REMO a larger redistribution of precipitation from winter to summer occurs only during the reporting period 2071–2100.

10.4 Analysis of the impact of climate change on the Ruhr reservoir system

In the annual "Ruhr Water Report 2005" a methodology was presented for analyzing the operational reliability of the reservoir system in the Ruhr River. The long time series of precipitation totals (10 x 1,000 years) required for this purpose and the mean daily temperatures were generated on a daily basis with the aid of a stochastic model developed by the Koninklijk Nederlands Meteorologisch Instituut (KNMI). They were then used as input data for the water balance and water resource management model that has been used by the Ruhr River Association for reservoir management for many years (WL, 2006). The resulting long-term model adapted to actual conditions in the Ruhr catchment basin will now be used to analyze the impact of the predicted climate change on the security of the supraregional water supply.

As a first step simulations of the three REMO climate scenarios A1B, A2 und B1 are carried out for the Ruhr catchment basin for the period 1961–2100. The calculations are performed for the purpose of analyzing possible changes in the amount of water available in the Ruhr catchment basin. The existing hydrological

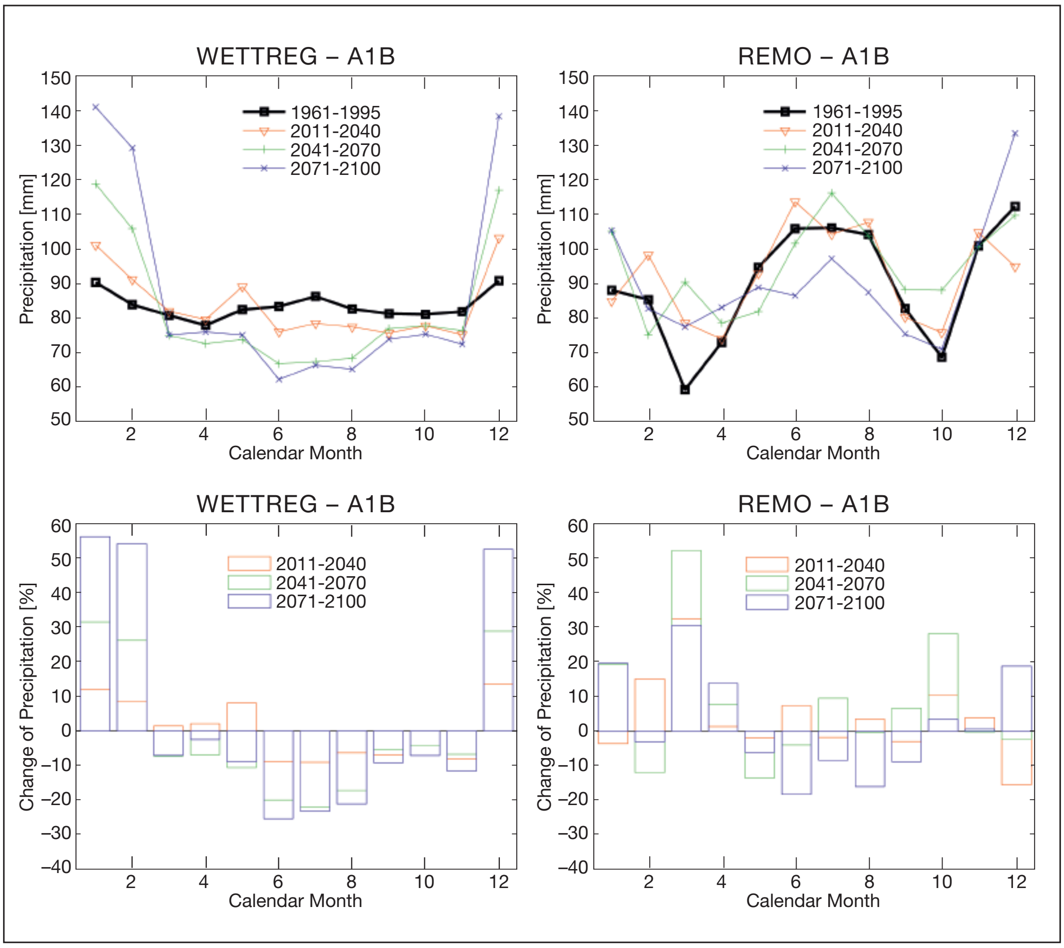

Fig. 26: Monthly precipitation totals and changes in these totals for scenario A1B from WETTREG (left) and REMO (right)

continuum model is used with the daily values for air temperature, specific air humidity and precipitation predicted with REMO as input data (Cf. Chapter 10.4.1).

In a second step regional climate scenarios are derived from the existing region al climate model REMO on the basis of the analysis of results presented in Chapter 10.3.2. For this purpose the synthetic time series (10 x 1,000 years) were transformed in such a way that they reproduced the effects of an assumed climate change (Chapter 10.4.3). With this as a starting point, the long-term simulations are carried out, in a last step, with the four selected synthetic time series of 1,000 years each for the scenarios defined above; the probability of a system failure is analyzed in each case in comparison with the scenario S0 representing the current state (Chapter 10.4.4).

10.4.1 Estimation of the impact of projected climate changes on runoff

To estimate the changes in the water resources in the Ruhr catchment basin, hydrological simulation calculations were performed on a daily basis with the river basin models of the Ruhr River Association for the period 1961 to 2100. The hydrological models were driven by the daily values for air temperature, precipitation and specific air humidity calculated by the REMO regional climate model for the SRES scenarios A1B, A2 and B1 (Chapter 10.3.1). The simulation calculations were performed for the period 1961–2100; however, the data for the period 1961–2000 were used for the control run and the data for the period 2001–2100 for the scenario calculations. The performance of the calculations with Delft-FEWS is described in detail in WL (2007).

The value of water losses is fixed at 8 m³/s for the entire simulation period. A possible change in water losses in the future has thus not been taken into account.

Results

As a major result of the simulation, the hydrological models yield runoff hydrographs for all the gauging stations in the Ruhr catchment basin discretised in the models. Since the relative changes in runoff due to climate change observed at all the gauging stations are roughly the same, we have confined the presentation of results to the total inflow to the six largest reservoirs Bigge, Verse, Ennepe, Möhne, Sorpe and Henne and to the Hattingen gauging stations – totals representing total runoff in the catchment basin.

By way of example only the results of the "middle" scenario A1B are presented graphically in the following; for the two other scenarios A2 and B1, the reader is referred to WL (2007). Figure 27 depicts (a) runoff at the Hattingen gauging station and (b) the total inflow to the reservoirs. The figures includes the mean annual values, the 10-year mean values and the mean values for the 30-year periods 2011–2040, 2041–2070 and 2071–2100, and the mean value of the synthetic data for the reference period 1961–1995.

Figure 28 shows (a) mean monthly runoff (lines) and changes in runoff (bars) at the Hattingen gauging station and (b) total inflow to the reservoirs for the periods being analyzed – 2011–2040, 2041–2070 and 2071–2100 – with respect to the reference period 1961–1995.

Comparing the 30-year mean values for **scenario A1B**, we see that runoff remains at roughly the same level during the period 2011–2070 as during the reference period (fig. 27). During the last period 2071–2100 the runoff at the Hattingen gauging station and the total inflow to the reservoirs decreases by approx. 5 m³/s in each case in comparison with the reference period. If we study the figures for monthly change in runoff shown in figure 28, we note a decrease in runoff of up to 40 % at the Hattingen gauging station in the autumn during this period. This is attributable, among

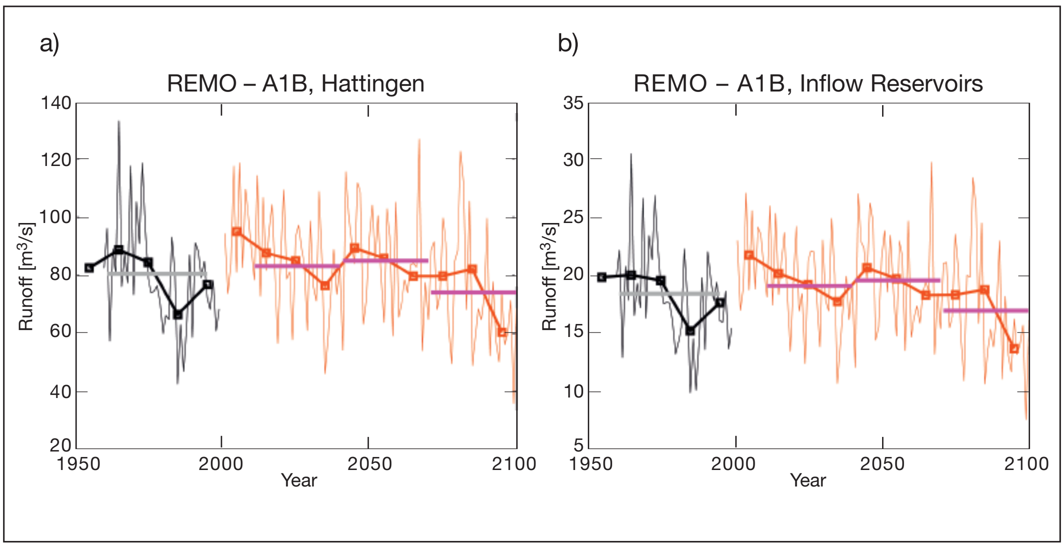

Fig. 27: Mean anual runoff at the gauging station at Hattingen (a) and total inflow to the reservoirs (b) for scenario A1B from REMO

other things, to the changes in precipitation already described in Chapter 10.3.3 and the simultaneous rise in temperature. Inflow to the reservoirs decreases by as much as 45 % in late autumn. The increase in runoff during the winter months is caused by the increase in precipitation of up to 20 % during this period.

For **scenario A2** a discontinuity can be noted in the values for the 30-year mean runoff for the control run and the scenario run, respectively; this discontinuity is also evident in the mean values for precipitation (Cf. Chapter 10.3.3). During the reference period mean runoff is 10 m^3/s lower at the Hattingen gauging station than during the period 2011–2040. In the scenario runs themselves no clear-cut trend can be observed either for the 30-year mean values at the Hattingen gauging station or for total inflow to the reservoirs. Studying the changes in monthly runoff, we see an increase of up to 45 % in runoff in most cases for the different periods in winter and spring. An increase in runoff of up to 30 % was recorded for the summer and the autumn for the period 2011–2040. For the two other periods, 2041–2070 and 2071–2100, monthly runoff is reduced by as much as 15 %.

For **scenario B1** as well, an increase in precipitation between the control run and the scenario run can be observed in the values for 30-year mean runoff. Mean runoff is approx. 15 m^3/s lower at the Hattingen gauging station. During the period 2041–2100 mean runoff declines from approx. 100 m^3/s to barely 90 m^3/s during the reference period. This trend can also be observed in the figures for total inflow to the reservoirs. Here the mean inflow has remained constant at approx. 20 m^3/s during the last 60 years. If we look at the monthly changes in runoff, we see an increase in runoff of up to 40 % over the entire year for the period 2011–2040. During the period 2041–2070 runoff is raised by as much as 25 % in all months. February was the exception here with a 10 % reduction in runoff. During the period 2071–2100 an increase in runoff of up to 30 % is observed in autumn, winter and spring. In the summer, in contrast, mean runoff deceases by as much as 20 %.

Discussion of results

The runoff calculated for the control period appears to be relatively high in comparison with the measurements made by the Ruhr River Association. If we look at the values for the individual months, we see that this is particularly true during the summer months. This observation is consistent with the analysis of the precipitation values calculated by REMO, which are considered too high (especially in the summer) in comparison with the measurements made by the Ruhr River Association (Cf. Chapter 10.3). A direct comparison with measured runoff values was not carried out since a com-

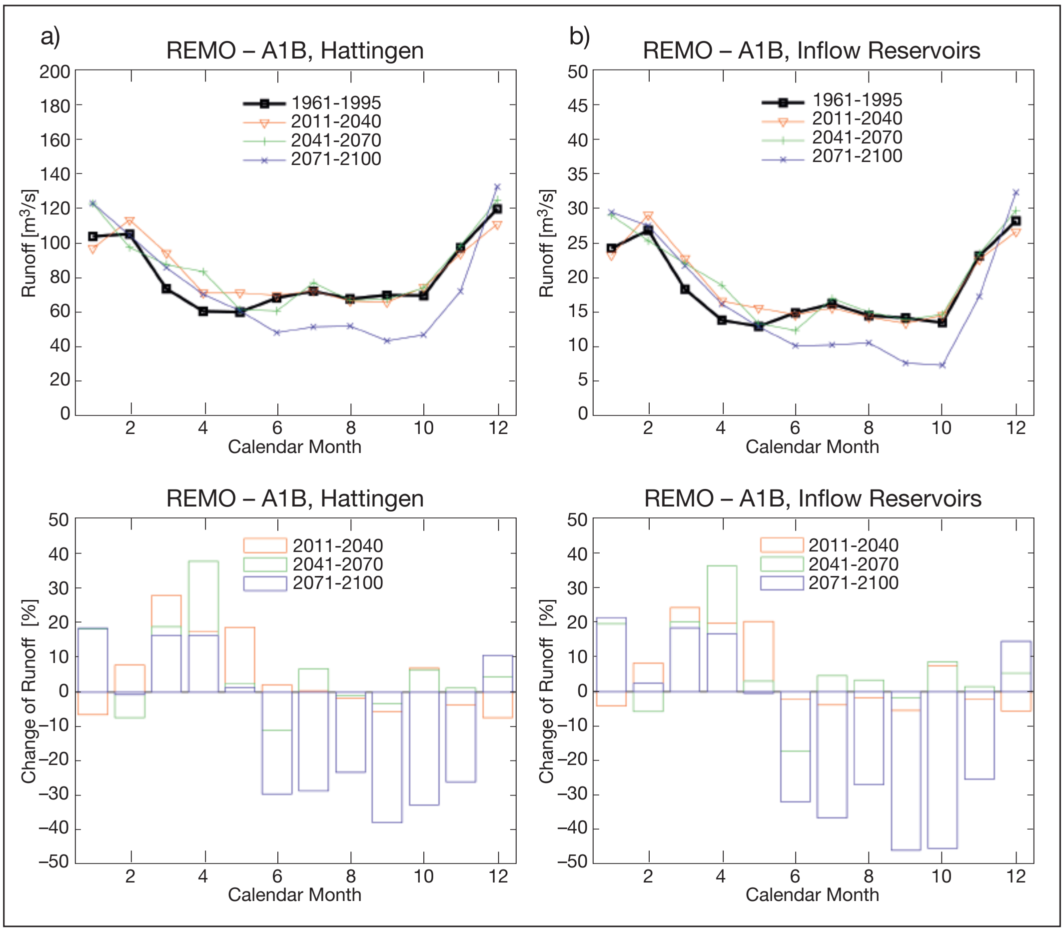

Fig. 28: Mean monthly runoff and changes in runoff at the gauging station at Hattingen (a) and mean monthly inflow to the reservoirs (b) resp. its percentual changes in this value for scenario A1B from REMO

parison of this kind would have to take account of the long-term trend in water losses. We have deliberately not done this in the interests of isolating the impact of climate change.

During the analysis of the scenarios it is generally remarked that a repeat increase in runoff is observed between the period 2011–2040 and the reference period 1961–1995. This increase is due to the rise in precipitation (Cf. Chapter 10.3.3) at the junction between the control calculation and the scenario calculations, an increase for which no logical explanation has been proposed to date and which may point to an inconsistency in the REMO model. In the further course of the scenario calculations up to the period 2071–2100, mean annual runoff declines only slightly in the scenarios A2 and B1 but displays a distinct reduction especially in the summer which may be due to the greater evaporation caused by the temperature increase. In scenario A1B runoff is substantially reduced during the period 2071–2100. A breakdown of runoff by month reveals that the seasons of summer and autumn are mainly responsible for this reduction, which is attributable to roughly an equal extent to the lower precipitation and the higher evaporation caused by the temperature increase.

10.4.2 Model scenarios for the long-term analysis

On the basis of the analyses explained in Chapter 10.3.3, four model scenarios are defined for the investigation of the impact of possible climate developments on the Ruhr reservoir system. These calculations were originally intended for the three SRES scenarios A1B, A2 and B1. On the basis of the analysis set forth above, however, it emerges that the variation between the WETTREG and REMO models is greater – especially for the parameter of precipitation – than the variation among the three scenarios. For this reason we have not differentiated between the individual emission scenarios. Instead we have taken the middle scenario A1B (which is in our opinion the most probable scenario) and used it for both the REMO and WETTREG models. To differentiate between the effect of the relatively certain temperature increase and the effect of the relatively uncertain development of precipitation on the limit capability of the reservoir system, we have defined the second and fourth regional climate scenarios, respectively, with only a temperature increase. This approach results in the following four scenarios:

K1: Change in precipitation and temperature from WETTREG

K2: Change in temperature from WETTREG, no change in precipitation

K3: Change in precipitation and temperature from REMO

K4: Change in temperature from REMO, no change in precipitation

With the regional climate scenarios K2 and K4, it is possible to estimate the impact of a change in temperature alone on the catchment basin. A comparison of K1 and K3, and of K2 and K4, provides, in addition, an estimation of the model uncertainties inherent in the regionalization methods REMO and WETTREG.

10.4.3 Transformation of climate data

For the calculation of the four regional climate scenarios, synthetic time series with a length of several thousand years were transformed so that they corresponded to possible climate changes in comparison with the reference period 1961–1995.

A method developed by Koninklijk Nederlands Meteorologisch Instituut (KNMI, 2006) was used for this purpose. This method is based on a relatively simple scaling of daily values for temperature and precipitation. The following parameters, or the change in these parameters in comparison with the reference period, are required:

ΔT_{50} Median temperature (°C)

ΔT_{90} 90th percentile of temperature (°C)

ΔT_{10} 10th percentile of temperature (°C)

ΔP_m Mean precipitation (%)

ΔW Frequency of wet days (%)

ΔP_{mwd} Mean precipitation (%) based on wet days

ΔP_{50wd} Median precipitation (%) based on wet days

ΔP_{99wd} 99th percentile of wet days (%)

The mean precipitation on wet days is the only parameter that is not required for the transformation since it is already reflected by the frequency of wet days and mean precipitation. This parameter can be used later to control the transformation. The KNMI transformation, applied to the REMO and WETTREG data, yields the statistical parameters described above.

The parameters were set up for the periods 1961–1995 and 2071–2100 and compared. The results of the analysis for the scenario A1B are presented in Table 14 broken down by season. The seasons correspond to the meteorological calendar, i.e. spring comprises the months March, April and May, summer the months

Table 14: Statistical parameters of the REMO-A1B scenario for the period from 2071 to 2100 in comparison to the period from 1961 to 1995

Parameter	Spring	Summer	Autumn	Winter	Annual Mean
ΔT_{50}	+1.61	+3.26	+3.03	+4.11	+3.00
ΔT_{90}	+2.10	+3.63	+3.73	+3.45	+3.21
ΔT_{10}	+2.26	+2.90	+3.74	+3.53	+3.11
ΔP_m	+9.85	−14.17	−1.74	+12.40	+0.86
ΔW	−0.51	−13.70	−4.58	+0.86	−4.64
ΔP_{mwd}	+10.43	−0.61	+2.97	+11.48	+5.82
ΔP_{50wd}	+17.68	−23.66	−2.47	+11.36	−0.52
ΔT_{99wd}	−11.12	+30.55	+9.25	+8.40	+9.95

Table 15: *Statistical parameters of the WETTREG-A1B scenario for the period from 2071 to 2100 in comparison to the period from 1961 to 1995*

Parameter	Spring	Summer	Autumn	Winter	Annual Mean
ΔT_{50}	+1.12	+2.50	+2.12	+3.88	+2.41
ΔT_{90}	+1.28	+2.10	+2.04	+3.46	+2.22
ΔT_{10}	+1.12	+2.14	+2.14	+4.30	+2.43
ΔP_{m}	−6.15	−23.09	−9.21	+54.07	+5.01
ΔW	−7.38	−22.89	−9.72	+21.02	−3.84
ΔP_{mwd}	+1.49	−0.26	+0.91	+27.03	+7.17
ΔP_{50wd}	+4.03	−19.14	−4.35	+35.21	+3.21
ΔT_{99wd}	+4.40	+13.47	−1.58	+5.37	+5.45

June, July and August, autumn the months September, October and November, and winter the months December, January and February.

A general increase in temperature is recorded in all of the seasons. The annual mean increase in temperature is approx. +3.0 °C. The largest increase in temperature, approx. +4.1 °C, is recorded in winter. An increase of +1.6 °C is predicted for spring, of approx. +3.3 °C for summer, and of approx. +3.0 °C for autumn. Mean precipitation declines by approx. 14.2 % in the summer and by approx. 1.7 % in the autumn; in contrast, a rise of 9.9 % is predicted for the spring and of 12.4 % for the winter.

The parameters have been analyzed using the method described above for WETTREG as well; the results are shown in table 15.

A general rise in temperature is recorded for all the seasons. The mean annual temperature rises by approx. +2.4 °C. The greatest increase, of approx. 3.9 °C, is recorded in the winter. An increase of +1.1 °C is predicted for the spring, of approx. +2.5 °C for the summer and of approx. +2.1 °C for the autumn. Mean precipitation declines by approx. 6.2 % in the spring, by approx. 23.1 % in the summer and by approx. 9.2 %, in the autumn; in contrast, an increase of 54.1 % is predicted for the winter. The mean annual precipitation rises by 5.0 %.

To provide an overview, the changes in the parameters for the four regional climate scenarios defined for the long-term analysis are summarized in table 16.

The transformation methodology described in the above is implemented as a new module in the existing analysis tool. Both historical and synthetic time series can be transformed in such a manner that they reproduce the effects of an assumed climate change. The climate change is described in this context with the changes of the statistical parameters for the corresponding climate scenarios by means of a configurable file. More detailed information on this subject can be found in WL (2007).

		ΔT_{50}	ΔT_{90}	ΔT_{10}	ΔP_{m}	ΔW	ΔP_{mwd}	ΔP_{50wd}	ΔT_{99wd}
Spring	K1	+1.12	+1.28	+1.12	−6.15	−7.38	+1.49	+4.03	+4.40
	K2	+1.12	+1.28	+1.12	0	0	0	0	0
	K3	+1.61	+2.01	+2.26	+9.85	−0.51	+10.43	+17.68	−11.12
	K4	+1.61	+2.01	+2.26	0	0	0	0	0
Summer	K1	+2.50	+2.10	+2.14	−23.09	−22.89	−0.26	−19.44	+13.47
	K2	+2.50	+2.10	+2.14	0	0	0	0	0
	K3	+3.26	+3.63	+2.90	−14.17	−13.70	−0.61	−23.66	+30.55
	K4	+3.26	+3.63	+2.90	0	0	0	0	0
Autumn	K1	+2.12	+2.04	+2.14	−9.21	−9.72	+0.91	−4.35	−1.58
	K2	+2.12	+2.04	+2.14	0	0	0	0	0
	K3	+3.03	+3.73	+3.74	−1.74	−4.58	+2.97	−2.47	+9.25
	K4	+3.03	+3.73	+3.74	0	0	0	0	0
Winter	K1	+3.88	+3.46	+4.30	+54.07	+21.02	+27.03	+35.21	+5.37
	K2	+3.88	+3.46	+4.30	0	0	0	0	0
	K3	+4.11	+3.45	+3.53	+12.40	+0.86	+11.48	+11.36	+8.40
	K4	+4.11	+3.45	+3.53	0	0	0	0	0

Table 16: *Summary of the statistical parameters of the four seasons for the regional scenarios K1, K2, K3 and K4*

Table 17: *List of regional climate scenarios*

Scenario	Remark
S0 – Current-state scenario	Reference calculation: current water resource management rules, water losses of 8 m^3/s
K1 – Regional climate scenario 1	SRES scenario A1B, parameters from WETTREG
K2 – Regional climate scenario 2	SRES scenario A1B, temperature change parameters only from WETTREG
K3 – Regional climate scenario 3	SRES scenario A1B, parameters from REMO
K4 – Regional climate scenario 4	SRES scenario A1B, temperature change parameters only from REMO

10.4.4 Results of the long-term simulation calculations

To estimate the consequences of a possible climate change for the Ruhr reservoir system, four long-term simulations were carried out. The four model scenarios used for these simulations are based on the SRES scenario A1B in combination with the results from the regional climate models WETTREG and REMO. Table 17 provides an overview of the calculated regional climate scenarios. For the purposes of comparison, the scenario S0 is also listed.

For the calculation of the scenarios the four synthetic time series R2, R3, R6 and R9 were used (Cf. WL, 2006). The simulation duration is thus 4,000 years in total. A reservoir is said to fail when the volume of water in the reservoir falls below 2 % of the available storage capacity.

The regional climate scenarios K1–K4 are based on the scenario S0 (Cf. Ruhrwassermenge 2005 [Ruhr Water Quantity Report]) and thus reflect the current state of the reservoir system with respect to reservoir management and water losses. A possible change in water losses or water exports due to future climate change is not taken into account. For the climate transformation the seasonal changes in the temperature and precipitation parameters for the SRES scenario A1B were used for the regional climate scenarios K1–K4 (Cf. table 16).

Table 18: *Failure statistics for regional scenario K1*

Reservoir	Duration of failure K1 (S0) in days	No. of system failures K1 (S0)	Recurrence interval K1 (S0) in years
Henne	567 (890)	9 (8)	444 (500)
Möhne	354 (703)	8 (8)	500 (500)
Sorpe	303 (739)	7 (7)	571 (571)
Ennepe	0 (0)	0 (0)	– (–)
Verse	0 (0)	0 (0)	– (–)
Bigge	0 (0)	0 (0)	– (–)

Regional climate scenario K1

The system failures occurring over a period of 4,000 years in comparison with the current-state scenario S0 are presented in table 18.

System failures occur only in the northern group of reservoirs. There is only a slight change in the number of failures. For the regional climate scenario K1 the Sorpe and Möhne reservoirs exhibit the same number of system failures, namely seven to eight, in comparison with the scenario S0. The recurrence intervals are 571 and 500 years, respectively. The Henne reservoir experiences nine failures, one more than in the scenario S0. The recurrence interval decreases from 500 to 444 years.

The duration of failure during the system failures, i.e. the time periods during which the reservoir is empty, is reduced by more than half for several reservoirs. For the climate scenario K1 the duration of failure is 567 days at the Henne reservoir. This is a decrease of approx. 36 % in comparison with scenario S0. The duration of the failure is thus reduced by about half to 354 days at the Möhne reservoir; at the Sorpe reservoir it is reduced by approx. 59 % to 303 days.

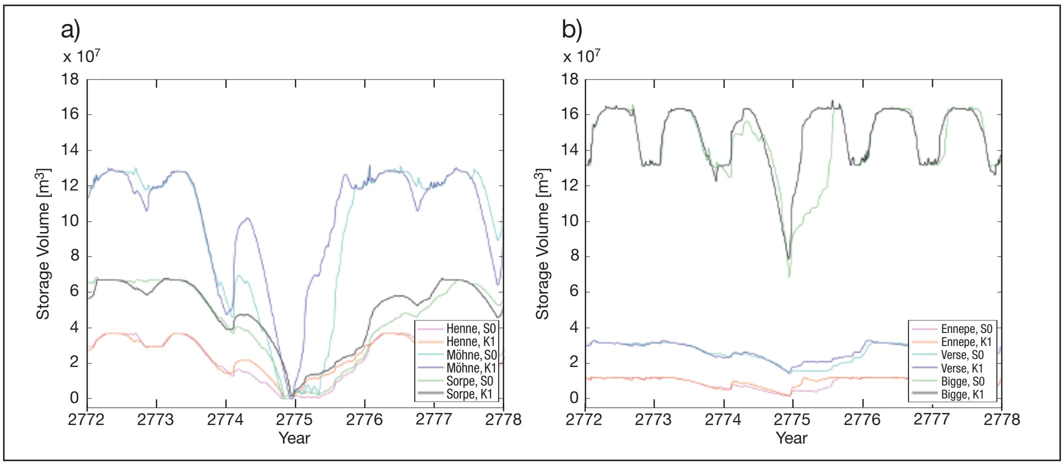

Fig. 29: *Regional scenario K1: Hydrographs showing the storage volume of the northern (a) and southern (b) group of reservoirs*

Table 19: Failure statistics for regional scenario K2

Reservoir	Duration of failure K2 (S0) in days	No. of system failures K2 (S0)	Recurrence interval K2 (S0) in years
Henne	3,009 (890)	17 (8)	235 (500)
Möhne	2,779 (703)	18 (8)	222 (500)
Sorpe	2,705 (739)	16 (7)	250 (571)
Ennepe	465 (0)	8 (0)	500 (–)
Verse	324 (0)	3 (0)	1.333 (–)
Bigge	340 (0)	4 (0)	1.000 (–)

Figure 29 shows the hydrographs for the storage volume of the reservoirs in the northern group (a) and in the southern group (b) for a failure event in the time series R9 around the year 2775 in comparison with the scenario S0.

It becomes evident that the reservoirs are faced with greater demands in the summer, owing to the changed distribution of precipitation over the year, and fill up again faster during the winter. This explains the lower duration of failures in comparison with the scenario S0 with about the same number of system failures. These trends are shown using the Möhne and Bigge reservoirs as examples in figure 30. As above one system failure in the time series R9 around the year 2775 (a) and one system failure in the time series R3 around the year 2244 (b) are studied. In both cases the vigorous refilling of the reservoirs in winter is evident.

Regional climate scenario K2

The system failures occurring over a period of 4,000 years during the scenario K2 in comparison with scenario S0 are summarized in table 19.

Failures occur in both the northern and southern group of reservoirs. In comparison with scenario S0, the number of failures has doubled. In scenario K2, the Henne reservoir has 17 system failures; the Möhne and Sorpe reservoirs have 18 and 16 system failures, respectively. The recurrence interval is reduced from 500 to 235 years for the Henne reservoir, from 500 to 222 for the Möhne reservoir, and from 571 to 250 years for the Sorpe reservoir. The duration of failure at each reservoir is about four times the corresponding duration of failure at the present time.

For the first time, system failures occur in the southern group as a result of the failure of the northern group. In the 4,000 simulated years, the Ennepe reservoir fails a total of eight times. This results in a recurrence interval of 500 years. The failure period amounted to 465 days. The Verse reservoir fails three times; this corresponds to a recurrence interval of 1,333 years. The failure duration is 324 days. The Bigge reservoir experiences four system failures. The recurrence interval is 1,000 years; the failure duration is 340 days. Figure 31 shows the storage volume hydrographs for the reservoirs in the northern group (a) and in the southern group (b) for the system failures already described in the preceding scenario for the time series R9 around the year 2775 in comparison with the scenario S0.

A marked increase in pressure is evident in both the southern and northern groups of reservoirs.

Regional climate scenario K3

The system failures occurring during a period of 4,000 years in comparison with scenario S0 are summarized in table 20.

System failures occur in both the northern and southern group of reservoirs. There are distinctly more failures in comparison with scenario S0. The Henne and Möhne reservoirs each experience 21 failures. In scenario S0, in contrast, eight system failures take place. The recurrence interval decreases from 500 to 190 years. The number of failures of the Sorpe reservoir rises from seven to 20; the recurrence interval thus decreases from 571 to 200 years. All of the reservoirs in the southern group display failures in the scenario K3. The Ennepe reservoir fails nine times and exhibits a recurrence interval of 444 years. The Verse reservoir fails three times; this results in a recurrence interval of 1,333 years. The Bigge reservoir fails five times; the recurrence interval is 800 years.

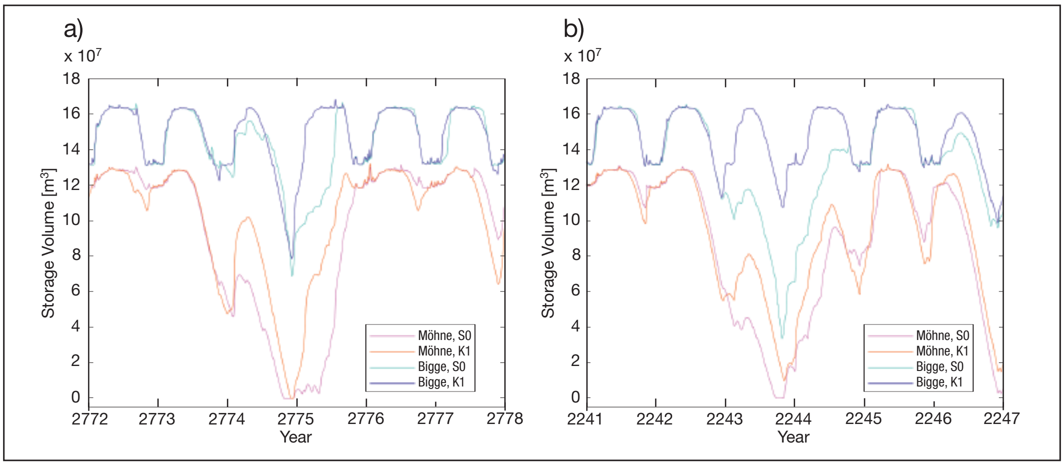

Fig. 30: Hydrographs of the storage volume during two system failures at the Moehne and Bigge reservoirs

Table 20: Failure statistics for regional scenario K3

Reservoir	Duration of failure K3 (S0) in days	No. of system failures K3 (S0)	Recurrence interval K3 (S0) in years
Henne	3,160 (890)	21 (8)	190 (500)
Möhne	2,716 (703)	21 (8)	190 (500)
Sorpe	2,734 (739)	20 (7)	200 (571)
Ennepe	564 (0)	9 (0)	444 (–)
Verse	473 (0)	3 (0)	1,333 (–)
Bigge	446 (0)	5 (0)	800 (–)

The failure period is also distinctly longer in comparison with scenario S0. A duration of 3,160 days results for the Henne reservoir; this represents an increase of approx. 355 %. The failure period due to the system failures at the Möhne reservoir is 2,716 days and is thus increased by approx. 386 % in comparison with scenario S0. At the Sorpe reservoir the duration of failure increases by approx. 370 % to 2,734 days. The Ennepe, Verse and Bigge reservoirs exhibit failure durations between 440 and 579 days. Figure 32 shows the storage volume hydrographs for the reservoirs in the northern group (a) and the reservoirs in the southern group (b) for the system failures already described for the time series R9 around the year 2775 in comparison with the scenario S0.

A marked increase in pressure is evident in both the northern and southern groups of reservoirs.

Regional climate scenario K4

The system failures taking place during a period of 4,000 years in comparison with the scenario S0 are presented in table 21.

System failures occur in both the northern and southern groups. In comparison with the scenario S0, the number of events in the northern group is almost tripled. In scenario K4 the Henne reservoir has 22 failures, the Möhne and Sorpe reservoirs 21 and 19, respectively. The recurrence interval is thus reduced from 500 to 182 years at the Henne reservoir, from 500 to 190 at the Möhne reservoir, and from 571 to 211 years at the Sorpe reservoir. The durations of failure at the reservoirs are five to six times the failure durations in the current-state scenarios.

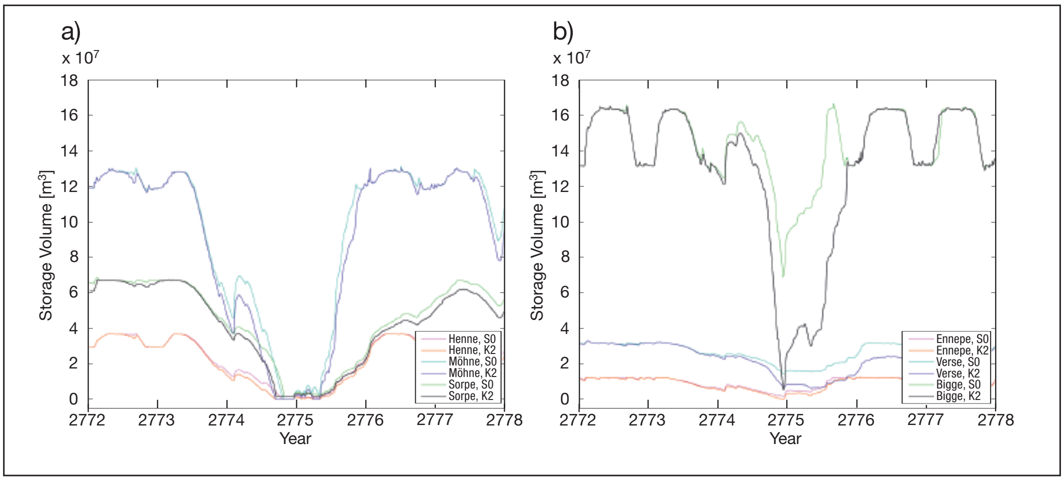

Fig. 31: Regional scenario K2: Hydrographs showing the storage volume of the northern (a) and southern (b) group of reservoirs

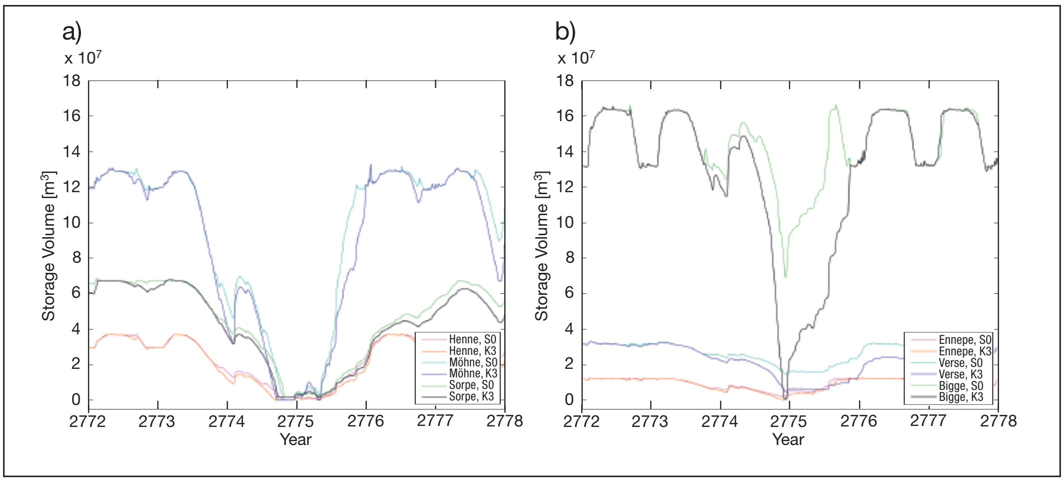

Fig. 32: Regional scenario K3: Hydrographs showing the storage volume of the northern (a) and southern (b) group of reservoirs

Table 21: *Failure statistics for regional scenario K4*

Reservoir	Duration of failure K4 (S0) in days	No. of system failures K4 (S0)	Recurrence interval K4 (S0) in years
Henne	4,373 (890)	22 (8)	182 (500)
Möhne	3,983 (703)	21 (8)	190 (500)
Sorpe	4,309 (739)	19 (7)	211 (571)
Ennepe	888 (0)	11 (0)	364 (–)
Verse	724 (0)	4 (0)	1,000 (–)
Bigge	709 (0)	10 (0)	400 (–)

In scenario K4 – as in scenario K2 – system failures take place in the southern group as a result of failures in the northern group. In the 4,000 simulated years the Ennepe reservoir fails a total of 11 times; this results in a recurrence interval of 364 years. The failure duration consists of 888 days. The Verse reservoir fails four times, corresponding to a recurrence interval of 1,000 years. The failure duration consists of 724 days. Ten system failures are noted for the Bigge reservoir. This corresponds to a recurrence interval of 400 years and a failure duration of 709 days. Figure 33 shows the storage volume hydrographs for the reservoirs in the northern group (a) and the southern group (b) for the system failures already described in the preceding scenarios for the time series R9 around the year 2775 in comparison with the scenario S0.

A market increase in pressure is noted in both the northern and the southern group of reservoirs.

10.4.5 Discussion of the results of the regional climate scenarios

Table 22 to table 27 present the system failures at all the reservoirs for the current state and the four regional climate scenarios. The results refer to the analysis of the time series R2, R3, R6 und R9, i.e. to a simulation period of 4,000 years. A system failure occurs when the storage volume of a reservoir falls below 2 % of the storage capacity.

Figure 34 presents a comparison of the two system failures for the time series R9 around the year 2775 (a) and for the time series R3 around the year 2244 (b) for the Möhne reservoir for the four regional climate scenarios and the scenario S0. Figure 35 shows the same events for the Bigge reservoir in the southern group of reservoirs.

The regional climate scenarios K2, K3 and K4 exert a distinctly more extreme impact on the Ruhr reservoir system than the scenario K1. In comparison with the scenario S0, the regional scenario K1 even has the effect of slightly alleviating the pressure on the reservoirs.

For the regional climate scenario K1 the precipitation and temperature change parameters were taken from the WETTREG results (table 16). Whereas precipitation decreases by as much as 23 % in the spring, summer and autumn, it is 54 % higher in the winter. The climate warming is highest in the winter at +4 °C. However, the warming has a smaller effect on evaporation during this season than in the summer. The shifting of precipitation from summer to winter, and the slight increase in annual precipitation, thus have the overall effect of increasing the amount of water available. Another effect of the shifting of precipitation from summer to winter is the higher pressure on the reservoirs in the summer and the quicker refilling in winter. This results in shorter system failures and reflects the more pronounced shortening of failure duration. The number of these shorter system failures is reduced only slightly.

In the regional climate scenarios K2 only the temperature change parameters from the WETTREG results are taken into account. The associated higher evaporation places greater pressure on the reser-

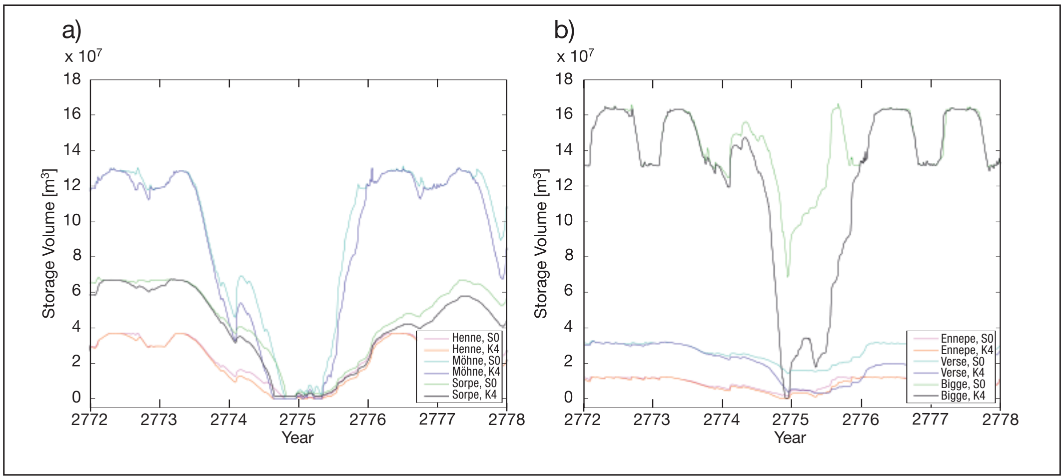

Fig. 33: *Regional scenario K4: Hydrographs showing the storage volume of the northern (a) and southern (b) group of reservoirs*

Table 22: Summary of the failure statistics of the Henne reservoir for all regional scenarios

Scenario	Description	Duration of failure in days	No. of system failures	Recurrence interval in years
S0	Current state	890	8	500
K1	WETTREG (N, T)	567	9	444
K2	WETTREG (T)	3,009	17	235
K3	REMO (N, T)	3,160	21	190
K4	REMO (T)	4,373	22	182

Table 23: Summary of the failure statistics of the Moehne reservoir for all regional scenarios

Scenario	Description	Duration of failure in days	No. of system failures	Recurrence interval in years
S0	Current state	703	8	500
K1	WETTREG (N, T)	354	8	500
K2	WETTREG (T)	2,779	18	222
K3	REMO (N, T)	2,716	21	190
K4	REMO (T)	3,983	21	190

Table 24: Summary of the failure statistics of the Sorpe reservoir for all regional scenarios

Scenario	Description	Duration of failure in days	No. of system failures	Recurrence interval in years
S0	Current state	739	7	571
K1	WETTREG (N, T)	303	7	571
K2	WETTREG (T)	2,705	16	250
K3	REMO (N, T)	2,734	20	200
K4	REMO (T)	4,309	19	211

Table 25: Summary of the failure statistics of the Ennepe reservoir for all regional scenarios

Scenario	Description	Duration of failure in days	No. of system failures	Recurrence interval in years
S0	Current state	0	0	–
K1	WETTREG (N, T)	0	0	–
K2	WETTREG (T)	465	8	500
K3	REMO (N, T)	564	9	444
K4	REMO (T)	888	11	364

Table 26: Summary of the failure statistics of the Verse reservoir for all regional scenarios

Scenario	Description	Duration of failure in days	No. of system failures	Recurrence interval in years
S0	Current state	0	0	–
K1	WETTREG (N, T)	0	0	–
K2	WETTREG (T)	324	3	1,333
K3	REMO (N, T)	473	3	1,333
K4	REMO (T)	724	4	1,000

Table 27: Summary of the failure statistics of the Bigge reservoir for all regional scenarios

Scenario	Description	Duration of failure in days	No. of system failures	Recurrence interval in years
S0	Current state	0	0	–
K1	WETTREG (N, T)	0	0	–
K2	WETTREG (T)	340	4	1,000
K3	REMO (N, T)	446	5	800
K4	REMO (T)	709	10	400

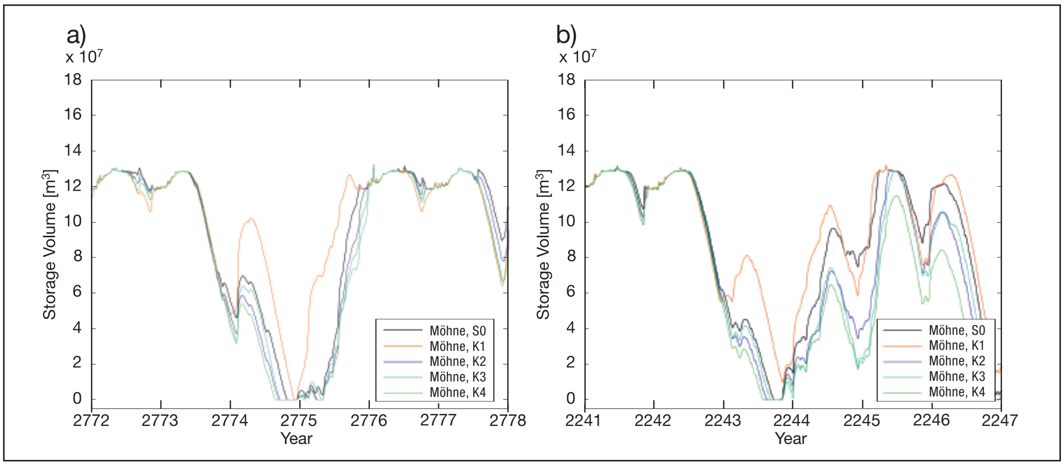

Fig. 34: Regional scenarios K1 to K4: Hydrographs showing the storage volume of the Moehne reservoir during two systems failures

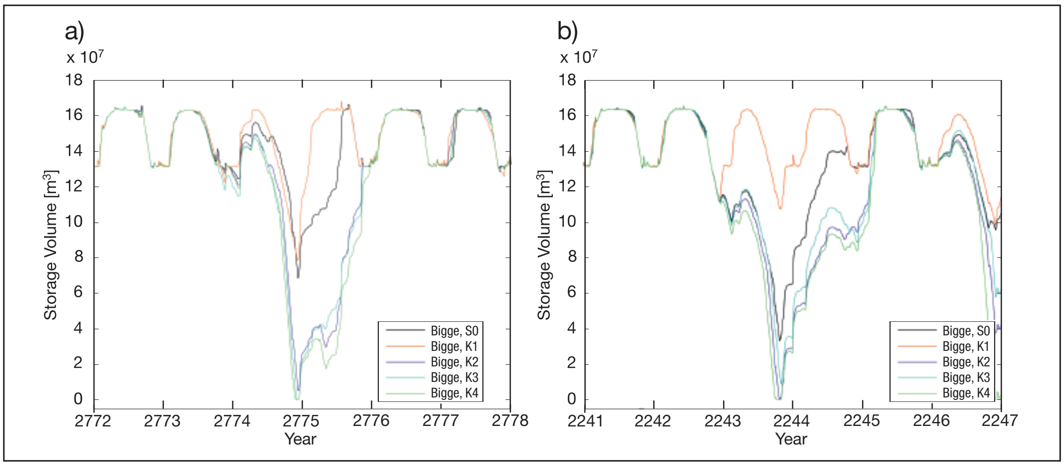

Fig. 35: Regional scenarios K1 to K4: Hydrographs showing the storage volume of the Bigge reservoir during two system failures

voir system. The alleviating effect of the increase in precipitation and the redistribution of precipitation are missing here. In this scenario 18 system failures occur at the Möhne reservoir in comparison with the scenario S0. For the first time failures are also recorded in the southern group of reservoirs.

The regional climate scenario K3 uses the precipitation and temperature parameters from the REMO results. It is more extreme than the comparable WETTREG scenario K1: there is a marked rise in system failures in both the northern and southern groups.

In the regional climate scenario K4 only the temperature change parameters from the REMO results are taken into account. As in the scenario K2 the alleviating effect of the redistribution of precipitation from summer to winter is missing. Since this redistribution takes place to a much lesser extent than in the WETTREG scenarios, however, the difference between K3 and K4 is relatively small. In comparison with the three other scenarios, K4 is the most extreme scenario. Both the number of system failures and the failure durations are increased markedly. This behaviour is attributable solely to the change in temperature and the associated higher evaporation.

10.5 Summary

In this study four different regional climate scenarios for the Ruhr catchment basin were defined on the basis of the SRES climate scenarios and the regional climate models WETTREG and REMO based on these scenarios; the impact of each of the four climate scenarios on the reservoir system was then analysed. For the calculation of the climate scenarios, synthetic time series with a length of several 1,000 years were transformed, using a method developed by KNMI, in such a way that they reflected the possible climate changes during the time period 2071 – 2100 in comparison with the reference period 1961 – 1995. The transformation methodology was integrated into the long-term analysis tool.

A long-term analysis was carried out with four synthetic time series of 1,000 years each for at least four regional climate scenarios. The analysis period thus encompassed a total of 4,000 years. The current-state scenario S0, which was already set up in the previous long-term analysis of the Ruhr reservoir system, served as a reference. A figure of 8 m³/s for current water losses in the Ruhr system is also used in the climate scenarios. Possible changes in water losses were not taken into account in this study.

The most important result emerging from this analysis with respect to the security of the supraregional water supply is that the probability of a failure of the Ruhr reservoir system may be distinctly higher in the future – as a result of climate changes – than it has been in the past. In three of the four climate scenarios calculated, the probability of system failure more than doubled. The increased probability of failure is based largely on the assumption that climate warming resulting in higher evaporation will take place in the future. This prediction is considered relatively certain. The prediction of precipitation change, and thus the prediction of its impact on the Ruhr reservoir system, remain uncertain, in contrast, and cannot be clearly evaluated with the present state of scientific knowledge. A marked shifting of precipitation from the summer to the winter – as predicted by the regional model WETTREG – would have a positive effect on the system. In this case the consequences of the temperature increase would be markedly attenuated. The precipitation changes calculated in REMO, on the other hand, are roughly neutral as regards their effect on the limit capability.

The most probable scenario is a distinct reduction of the present operational reliability of the reservoir system between now and the year 2100. The present recurrence interval of 500 years could drop to approx. 200 years. The maintenance of the present operational reliability can be achieved either by reducing minimum runoff at gauging stations (e.g. in Villigst) or by creating additional storage volume of about the magnitude of the Möhne or the Bigge reservoir.

Literature:

CEC (2007): E-Mail von Herrn Dr. Enke vom 10.5.2007.

IPCC (2000): Special Report on Emissions Scenarios, 2000, Nakicenovic, Nebojsa and Swart, Rob (eds.), Cambridge University Press, Cambridge 2000.

IPCC (2001): Climate Change 2001: The Scientific Basis. Summary for Policymakers and Technical Summary of the Working Group I Report, Cambridge 2001.

IPCC (2007a): Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC WGI), Cambridge 2007.

IPCC (2007b): Climate Change 2007: Climate Change Impacts, Adaption and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC WG II), Cambridge 2007.

IWG (2002): Softwarepaket Zeitreihen, Version 5.0, Institut für Wasser und Gewässerentwicklung der Universität Karlsruhe.

KNMI (2006): KNMI Climate Change Scenarios 2006 for the Netherlands, KNMI-publication: WR-2006-01, May 2006, pp82, De Bilt.

MPI (2007): REMO Homepage des MPI: http://www.mpimet.mpg.de/home.html.

Ruhrverband (2006): Jahresbericht Ruhrwassermenge 2005.

UBA (2006): Künftige Klimaänderungen in Deutschland – Regionale Projektionen für das 21. Jahrhundert. Hintergrundpapier gemeinsam mit Max-Planck-Institut für Meteorologie Hamburg, Sept. 2006.

UBA (2007): Neuentwicklung von regional hoch aufgelösten Wetterlagen für Deutschland und Bereitstellung regionaler Klimaszenarios auf der Basis von globalen Klimasimulationen mit dem Regionalisierungsmodell WETTREG auf der Basis von globalen Klimasimulationen mit ECHAM5/MPI-OM T63L31 2010 bis 2100 für die SRES-Szenarios B1, A1B und A2. Endbericht Umwelt Bundesamt, Januar 2007.

WL (2006): Langzeitbewirtschaftungsanalyse Ruhrtalsperrensystem. WL | Delft Hydraulics, Delft, Januar 2006.

WL (2007): Klimafolgenanalyse Ruhrtalsperrensystem. WL | Delft Hydraulics, Delft, Juni 2007.

Ruhrverband

Kronprinzenstraße 37, 45128 Essen
Postfach 10 32 42, 45032 Essen
Fon +49 (0) 201/178-0
Fax +49 (0) 201/178-14 25
www.ruhrverband.de