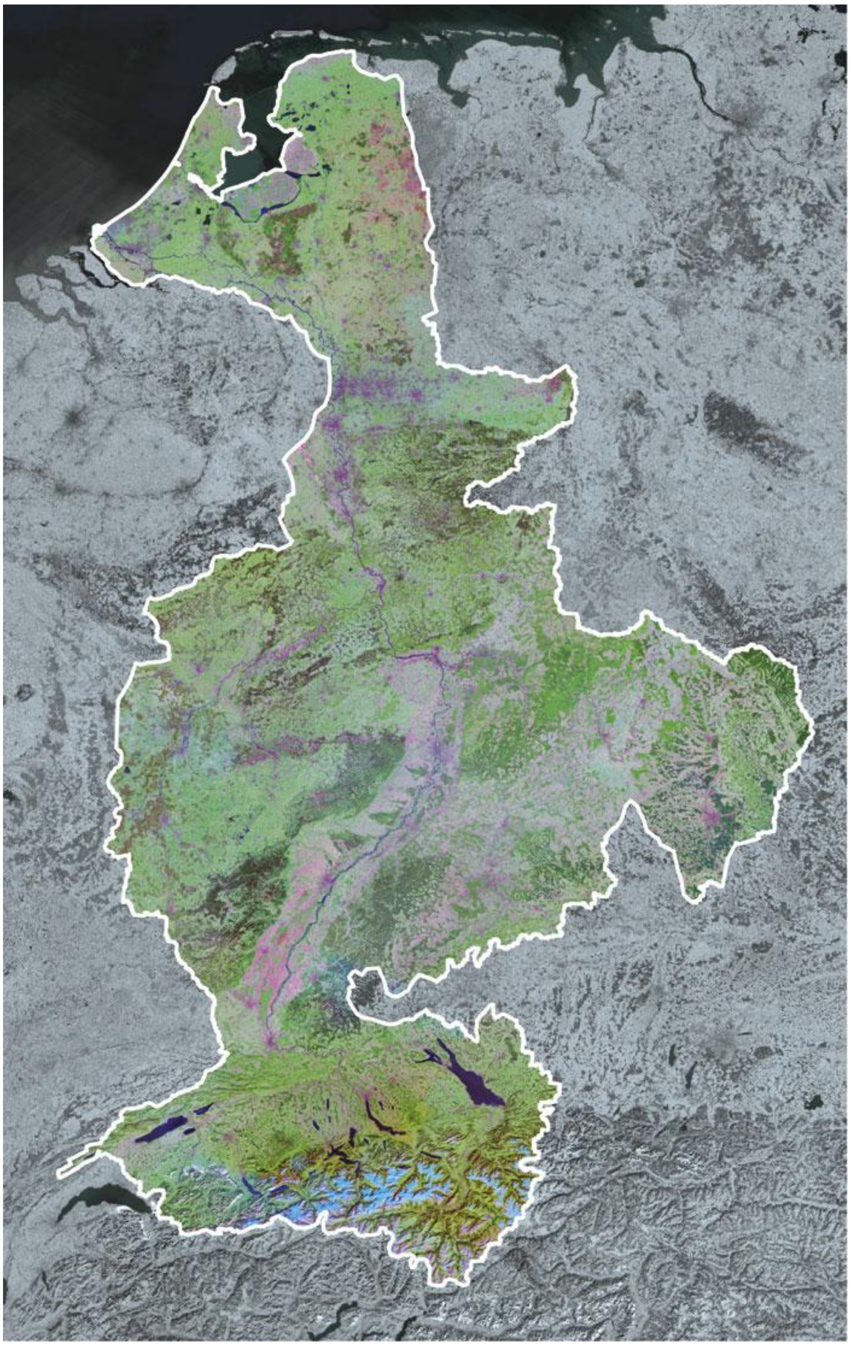
Impacts of climate change on low flows in the Rhine basin

Low flows for the Rhine basin



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Low flows for the Rhine basin

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Summary

Climate change is an important issue for water management in the coming decades and it is expected that problems will occur due to climate change. This research will be about the amount of low flows which is expected to increase as a consequence of climate change.

For the determination of a low flow, two indicators are used; the total summer deficit and the threshold for navigation purposes. The threshold for navigation is set at a 1000 m^3/s at Lobith, the Netherlands. These indicators are based on the LCW values.

Based on the two indicators the severity of low flows can be determined. For the simulation of the discharge at Lobith, a standalone version of the HBV model is used (FEWS). This model has a NS of 0.92, NSLOG of 0.92 and a RVE of 2% for a simulation with observed climate data for 1962-1992. This is a good simulation. The effects of the different climate change scenarios have been assessed with this model.

In the research four different steps have been conducted. One of the steps is to assess the effects of the HBV model on the different low flow indicators. The other step is to assess the effect of the RCM driven with GCM data for the control run on the different indicators; the final step is to assess the effect of climate change. This will be done by comparing the period 1962-1992 with 2070-2100 for a certain RCM driven with GCM data as input to the HBV model.

Low flow indicator for the HBV model with observed values

For the assessment of the different indicators, first the HBV model with observed data as input has been compared with the observed discharge. Hereby the following results were given. The simulation with observed values has 22.29 days annually with a flow below 1000 m^3/s for the period 1962-1992; the observed discharge shows an average of 21.32 days. The simulated average yearly deficit for the period 1962-1992 is 134 million m^3 compared with an observed deficit of 128 million m^3. For both indicators there is a small overestimation in the simulation compared with the observed discharge at Lobith.

The correlations between the observed and simulated values are 0.93 for the deficit. However, if the highest value is left out the correlation for the observed and simulated deficit is 0.77, the standard deviation is 358 million m^3. The correlation between the observed and simulation values are 0.87 for the amount of days below 1000 m^3/s, the standard deviation is 33.2 days. Based on the comparison of the indicators, it could be concluded that the different indicators have been simulated accurately by the HBV model.

In the observed discharge, the probability of a year with a flow below 1000 m^3/s is 54%, in the simulation with observed values in the HBV model it is 45%. For the deficit the probability of a deficit is 29% in both the simulation with observed values and the observed discharge.

Low flow indicators for the control period (1962-1992) with climate data

To investigate the effect of a choice of a certain RCM driven by GCM on the different indicators, the control period (1962-1992) is compared with the observed values as input for the hydrological model.

For the indicator of days below 1000 m^3/s, only the Racmo Echam 5 as input to the HBV model is underestimated. In the other scenarios the difference can be explained within the variability. Hereby this indicator, number of days below 1000 m^3/s, can be seen as a good indicator because this indicator is quite robust.

The deficit is only simulated in a representative way in the Aladin Arpege scenario. In the Racmo Echam 5 and Remo Echam 5 as input to the HBV model the deficit was underestimated. In the Hirham 5 Arpege as input to the HBV model the deficit was overestimated.

Overall it can be concluded that low flows are represented in a different way by the different scenarios, especially the amount of deficit is simulated differently in the control run than in the observed values. The indicator of the number of days with a discharge below 1000 m^3/s is simulated quite well in the control run. The bandwidth for the amount of days annually with a discharge below 1000 m^3/s is 12.2 days to 22.7 days in the climate scenarios compared with 22.3 days for the simulation with observed values. The bandwidth for the yearly average deficit is 16 to 360 million m^3 compared to 134 million m^3.The bandwidth for the probability of a flow below 1000 m^3/s in a year is between 41% and 67%, for the probability of a deficit in a year the probability is between 10% and 32%.

Low flow indicators with the effects of climate change

The four different climate scenarios have been run to assess how the two indicators will develop.

In the Aladin Arpege the average deficit decreases, but this can be explained because an extreme event has occurred in the period 1962-1992. This influences this indicator quite a lot. The changes of the number of days with a discharge below 1000 m^3/s are within the variability of the climate. This can be explained because this data series is only to 2050, by then the effects are not quite visible; the effects are the most visible in the period 2050-2100.

For the three climate scenarios with a runtime to 2100, the annual deficit increases with 460% to 2810% if the period 1962-1992 is compared with the period 2070-2100. Hereby it is questionable whether such an increase is realistic; a part of the increase can be explained by low starting values. In the number of days with a discharge below 1000 m^3/s a year the increase fluctuate from 112% to 249% if the period 1962-1992 is compared with the period 2070-2100, this is more realistic than the increase of the deficit. The indicator of the number of days below 1000 m^3/s is more robust than the indicator of the deficit.

The probability on a deficit during a year increases from 80% to 87% in the different scenarios for the period 2070-2100. The probability that a flow below 1000 m^3/s will occur in a specific year is between 80% and 96% in the period 2070-2100. This is quite high and it looks like a yearly event.

It can be concluded that the amount of low flows will increase in the future in 3 out of 4 scenarios which have been assessed.

Preface

Last February I started with my pre package for the master thesis. In May I started with the thesis itself. During this thesis I have learned a lot about doing research work. During my research I did encounter some setback; for example regarding the choice of the hydrological model. First I had a Matlab script, but almost on the end I shifted to a FEWS model.

My research is about low flows in the Rhine basin. The question being asked, whether the amount and severity of low flows will increase or decrease in the future. It is expected that the amount of low flows will increase in the different climate change scenarios.

The magnitude of changes of low flows depending on different climate change scenarios is the issue for this research.

I would like to express my thanks to some people who helped me during the research. First of all, I would like to thank my supervisors. Apart from my supervisors I would like to thank Albrecht Weerts for the FEWS model and answering so many of my questions. I would also like to thank Sander van de Tillaart for his HBV model in Matlab.

Finally I would like to thank my former and present roommates of the graduation room for all the coffee breaks and lunches together, and their support during my thesis.

At last I would like to thank my parents for their support and motivation.

Jasper Bisterbosch

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1 Introduction

In the chapter of the introduction, first the background will be presented. Next the problem analysis, objective, research question and finally the outline will be presented.

1.1 Background

The occurrence of low flows is a natural phenomenon, due to variability of the climate and the weather. Society is adapted to a significant variability in flows, but still extreme low and high flows cause severe damage. This thesis will focus on the low flows in the Rhine basin.

This study is about the impacts of climate change on low flows in the Rhine River. Currently, more research is being done towards the occurrence of high flows than low flows.

It is expected that in the future, climate change will cause more extreme low flows than in the current situation. Hurkmans et al. (2009) describe an expectation that the hydrological regime of the Rhine basin will shift from a combined snowmelt-rainfall regime, to a more rainfall-dominated regime because of climate change, leading to more extreme flood peaks and low flows. It is also expected that climate change will cause an increase in the frequency of low flows in the Rhine River. This results in an increase in the number of days with low flows.

The negative effects of low flows are that they cause some damage. The damage is in the agricultural sector, for navigation and other damage. Because a low flow can cause some damage it is important to identify the level and frequency of low flows which can occur. By doing this there can be assessed what can be expected. This can help to create support for taking adaptive measures against low flows.

Low flow events have occurred in the Rhine River in the past. Examples of this are the summers of 1969, 1976, 1985 and in 2003. Due to these events, the focus of attention with regards to the low flow phenomena has increased. Because of the damage which can be caused by a low flow. Low flows are important, so that adaptive measures may be taken when deemed necessary. An example of this is adapting management strategies towards low flows, reducing the amount of damage suffered. This could be implemented for shipping navigation or the cooling management of energy plants. If more low flows occurs the shipping occurs due to climate change, this is quite important to handle the problem.

In order to assess climate change in the future, various climate change scenarios have been developed. These scenarios are based on expected greenhouse gas emissions, which give a certain warming of the globe. The scenarios can serve as input for different GCM's (General Circulation Models), which in turn may be downscaled to RCM's (Regional Climate Model). This results in input data for the different runs in the hydrological model to assess the effects of climate change.

The main focus of this MSC thesis is to assess the impacts of climate change on low flows in the Rhine River. To this extent, output of climate models provided by the KNMI, will be used as input to a hydrological model.

1.2 Problem analysis

The hydrological cycle is expected to be intensified in the future. This will cause more extreme events. Due to the temperature rise it is more likely that the precipitations will fall in the form of rain instead as of snow, and the winter snowpack will melt earlier in spring. Snow melt is at the moment an important component for the base flow of the river.

Literature shows that the discharge will mainly decrease in the summer (Hurkmans et al.,2009; Kwadijk and Rotmans, 1995; Middelkoop et al. ,2001). A decrease of the discharge in summer will cause more days with a discharge below 1000 m^3/s. This threshold is used for navigation purposes.

Kwadijk and Rotmans (1995) studied the discharge changes upstream of Basel. They discovered that the winter discharge will increase and the summer discharges will decrease according to all six scenarios. The chosen climate scenarios are BaU-Best, BaU-HIGH, BaU-LOW, AP-BEST,AP-HIGH and AP-LOW. Those scenarios have been chosen to get the upper and the lower limit of the effects of climate change; these scenarios range from a temperature increase of 1.2 ^oC to 3.4 ^oC. These changes are due to an increasing winter temperature that leads to increased melt water volumes, combined with an increasing winter precipitation. According to all scenarios the winter precipitation, presently stored as snow, will have a direct impact as stream flow. This water will not be available in the following seasons and the result will be a lower summer discharge.

Middelkoop et al. (2001) have used a set of models, to assess the effects of climate change on the discharge regime in different parts of the Rhine basin using the results of UKHI and XCCC GCM-experiments. All models indicated similar trends regarding the observed values: higher winter discharge as a result of intensified snow melt and increased winter precipitation, and low summer discharge due to the reduced winter snow storage and an increase of evapotranspiration. Both climate models indicate a shift of the hydrological regime in the entire Rhine basin. In the upper Alpine area the intra-annual difference between a low winter flow and a high summer flow decreases (and even may be inverted), while in the lower parts the existing summer-winter differences are amplified. The average annual number of days with a Rhine discharge at Lobith is below 1000 m^3/s may increase from 19 (under present day conditions) to 26 according to the XCC2050 scenario and 34 according to the UKHI2050 scenario for the year 2050; both scenarios have used the IPCC emission scenario IS92a with a global climate sensitivity of 2.5 ^oC. (Middelkoop et al.,2001)

The main focus of this research is about low flows for the Rhine basin and about the possible effects of climate change on the low flows for navigation purposes, on this topic there is a small research gap. Based on this aim to investigate the objective of the research has been made.

1.3 Objective

The objective of this thesis is to determine:

Possible changes in the frequency and severity of low flows in the Rhine River over the 21st century due to climate change, by using a hydrological model with data from different GCM with RCM output provided by the KNMI.

1.4 Research questions

In this chapter the main question will be presented. Based on this question a few sub questions will be presented. Those sub questions will be answered, before the main question can be answered.

Main question:

How much can low flows change due to climate change with respect to low flow durations, the amount of the summer deficit as well as the frequency?

There will be the following research questions:

1. What is the frequency of occurrence and severity of a low flow in the period 1962 to 1992 according the observed discharge at Lobith?
2. What is the frequency of occurrence and severity of low flows simulated in the HBV model from 1962-1992 with observed climate data?
3. What is the frequency of occurrence and severity of a low flow simulated in the HBV model with the GCM and RCM model output for 1962-1992?
4. How will the frequency of occurrence and severity of a low flow change in the future with climate change, by using simulations of the HBV model with the GCM and RCM model output of the period 2020-2050 and the period 2070-2100?
5. What is the effect of different RCM scenarios on low flows?

1.5 Outline

The second chapter of the report is about the area of investigation and the data to be used. In this chapter the data is described.

The third chapter will be about the hydrological model which is used. In this chapter there will be explained how the model works and which parameters are used.

The fourth chapter is about the definition of low flows and the research model. Hereby the different steps of the research will be presented.

In chapter five, the results are presented. The first paragraph of chapter five is about the amount of low flows based upon the observed discharge at Lobith and the simulation with the hydrological model with observed climate data as input for the model. Next the different climate change scenarios will be discussed when the simulation with observed climate data is compared with the simulation with climate change data as input for the hydrological model for the period 1962-1992. This is done to determine the effects of the climate models on low flows.

Next the effects of climate change are assessed; hereby the different time spans for the different scenarios will be compared with each other, 1962-1992; 2020-2050 and 2070-2100. Based on this comparison it is possible to determine the effects of climate change on low flows. The severity of the deficit and the amount of days annually below the threshold for navigation purposes is investigated.

Finally, in chapter five the effects of a certain RCM are investigated; the two scenarios with the same GCM will be compared with each other. This is done to assess the effects of a certain RCM on the different indicators.

In chapter six the discussion is presented. In chapter seven the conclusions are given and some recommendations for further research are presented.

2 Study area and data

In this chapter a short description of the study area will be given. Next is described how the observed values for the precipitation, the evaporation and the temperature have been gathered. Next a description of the climate change data which is used is given.

2.1 Study area

The River Rhine (length 1320 km; catchment area 185 000 km^2) originates in the Swiss Alps, flows north along the border with France, and then passes through Germany and the Netherlands, before discharging into the North Sea. At Lobith, near the Dutch–German border, the daily river discharge for the period 1950–1999 varied between 665 m^3/s and 11885 m^3/s, the mean discharge is 2200m^3/s. (Vervuren et al., 2003)

A map of the Rhine river basin can be found in appendix A. In this map the study area is divided in multiple sub catchments. The southern part of the basin (Schweiz) is the Alps. The Alps are responsible for most of the snow melt and have a size of 30.000 km^2; the catchment area upstream of Lobith is 160.000 km^2.

2.2 Observed climate data

In this section, firstly there will be described under which conditions the observed precipitation and temperature values have been acquired. The potential evaporation is calculated internally in the HBV model, this is explained in chapter 3.2.

2.2.1 Precipitation

The precipitation has been measured 1 meter above the earth's surface at randomly distributed points (observation stations) in the study area.

However, for many applications the spatial distribution of the precipitation is needed. Precipitation data has been made available on a geographical grid for the whole area of Germany with a spatial resolution of 60 geographical seconds longitude parallel and 30 geographical seconds latitude parallel (Deutsche Wetterdienst, 2010). Data resulted from interpolation of station data, based on:

- Elevation
- Geographical longitude and latitude

2.2.2 Temperature

Station data of air temperature and sunshine duration have been obtained from the International Commission for the Hydrology of River Rhine Basin (CHR), the German Meteorological Service (DWD). For each sub basin, there were user defined input stations and station weights as well as an altitude correction of 0,6°C/100 m to the mean elevation of the sub basin. (Eberle, 2009)

2.3 Data from climate models

The research involves several climate change scenarios. One of the boundary conditions of climate change scenarios is that it needs to be bias corrected to get reliable data series. Based on these boundary conditions a selection is made. This selection of scenarios can be found in table 1 on page 19. The different scenarios will be compared with each other; this will be done to assess the effects of a certain GCM and RCM on low flows.

The Regional Climate Model (RCM) is derived from General Circulation Models (GCM) by downscaling the model. The global climate models are used to diagnose the global temperature rise and circulation. Regional climate models and local observations are used to construct regional climate scenarios. (KNMI, 2006)

The regional climate data grids depend in size from 10 km to 25km. The RCM data are used to determine the climate data of the sub-basins by using the average value for the whole sub basin of the temperature and the precipitation (Rheinblick, 2010). Those climate data will be used as input for the hydrological model.

2.3.1 Different climate change scenarios

The projections of global mean warming by year 2100, as a consequence an anthropogenic emission of greenhouse gases to the atmosphere, range from 1.8 to 4.5 C increase with the current climate. (IPCC, 2007). The global change would be a sum of regional changes scattered over both sides of the global mean. There is a serious short coming in simulations on the regional and local scales where the most detailed impact analyses are made. Various techniques exist to add details to the large-scale global climate model results, known collectively as downscaling or regionalization.

Different climate change scenarios were constructed in the context of the IPCC assessment (IPCC, 2007). This has to do with the global emissions scenarios, which are based on population and economical growth models. Those which are ranked from highest to lowest in terms of global average emissions at mid-century are A1F1, A2, A1B, A1T, B1 and B2. The different scenarios which are available in the current data set, is the A1B scenario. The C20 scenario is the control run, representing the historic climate. The C20 and A1B scenario will briefly be described on page 18.

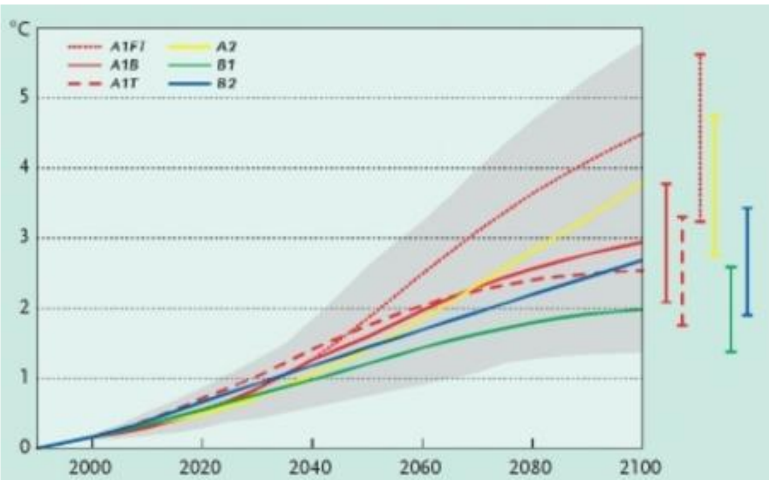

Figure 1: Temperature increase due to climate change for different scenarios including uncertainty (IPCC, 2007)

Figure 1 visualizes the increase of the temperature due to climate change. Figure 1 shows that some scenario's have a smaller temperature increase than other scenarios.

2.3.1.1 Which assumptions have been made for the climate scenarios?

There are made some assumptions based on the CO_2 emissions around the globe. The CO_2 emissions have been described as plausible, representations of the future emissions of greenhouse gases and with the understanding of the effect of increased atmospheric concentration of the gases on global climate.

The different scenarios have got distinguished input on the greenhouse gas emissions. These scenarios have got different growth models of the population and economical factor. This influences the amount of greenhouse gasses which is expelled and brings some uncertainty with it.

2.3.1.2 Which uncertainties are present in the different climate scenarios?

For climate projections, the following uncertainties are present (Webster, et al., 2003; Prudhomme, et al., 2003). This has to do with:

- Uncertainty about the future growth of the population and the economic, technological and social development. Those have influence on the greenhouse emissions.
- Restricted knowledge about the complex processes in the climate system. The influence of the solar radiation on vapor and clouds and the temperature has not been qualified appropriately. Some processes are not included in the climate runs.
- There are limitations on the possibility of predictions of a complex system like the climate system.
- It is hard to predict any extreme events, or to model sudden changes.
- There is a natural variability of the climate
- Average conditions can be modeled in a fair way, but extreme events still hard to model. This makes the results for extreme events even more uncertain.

For smaller areas like Western Europe or the Netherlands, the uncertainty is even larger. The air flow is very important for a smaller region. Those air flows are different above Western Europe in the different climate models. (KNMI, 2009)

2.3.1.3 Available climate change scenarios

In this research the C20 scenario is used for the control run, and the A1B scenario for climate change. Those scenarios will be briefly described.

2.3.1.3.1 C20 scenario

This is the actual climate of the 20th century using the observed greenhouse gas concentrations to drive the global and regional climate model. This gives a realization of the current climate.

2.3.1.3.2 A1B scenario

The A1B scenario describes a possible future world of very rapid economic growth, global population peak in mid-century, and rapid introduction of new and more efficient technologies. A balance between energy sources is assumed. (Sander & Dotzek, 2009)

The global average temperature is estimated to increase about 2,8 degree Celsius in the period 2090-2099 relative to 1980-1999. The likely range, as assessed by different climate models, is between 1,7 and 4,4 degree Celsius. (IPCC, 2007)

2.3.2 The data series used

First of all multiple climate scenarios were available, see table 1. Based on the available scenarios; 4 scenarios were chosen. A requirement was that it would be possible to do a comparison of the effects of the RCM's, so only four scenarios were left over. So it would be possible to assess the effects of a RCM on the different indicators.

For the first comparison on the effects the GCM ARPEGE will be assessed. Hereby the RCM's ALADIN and HIRHAM will be compared. For the second comparison, the GCM ECHAM5 will be assessed, and the RCM's RACMO and REMO will be used. The first comparison will be for the time periods of 1962-1992 with 2020-2050. The second comparison will be for the time periods of 1962-1992, 2020-2050 and 2070-2100. There is a difference in the comparison periods because the Aladin Arpege is from 1961-2050, and the other data sets periods are from 1961-2100.

Table 1: Different available scenarios

RCM Comparison	INSTITUTE	GCM	RCM	Period	Scenario	Period
1	CNRM	ARPEGE	ALADIN	1961-2000	A1B	2001-2050
	ETHZ	HADCM3_Q0	CLM	1961-2000	A1B	2001-2100
	HC	HADCM3_Q16	HADRM3	1961-2000	A1B	2001-2100
	HC	HADCM3_Q3	HADRM3	1961-2000	A1B	2001-2100
1	DMI	ARPEGE	HIRHAM	1961-2000	A1B	2001-2100
2	KNMI	ECHAM5	RACMO	1961-2000	A1B	2001-2100
2	MPI	ECHAM5	REMO	1961-2000	A1B	2001-2100
	UBA	ECHAM5	REMO	1961-2000	A1B	2001-2100

2.3.3 Bias correction on precipitation in climate change scenarios

After the generation of the climate change data sets by a combination of GCM and RCM, a bias correction has been done to get a reliable data series (Rheinblick, 2010). A bias correction has been done by Rheinblick (2010) on the data series, to rule out the undesired effects of obvious climate biases. In Rheinblick (2010) the different steps for the bias correction are explained. There is chosen for a non-linear correction, so the bias in the mean and in the extreme daily precipitation is removed.

Rheinblick (2010) shows that the bias was -10% to 50% before the bias correction for the precipitation, after the bias correction, the bias was only between 5%. This can be assumed to be accurate. The correction is quite large, but after the correction the data series are made reliable.

3 HBV model

First different hydrological models have been compared with each other. Based on a comparison of the different hydrological models, there is chosen to work with the HBV model. The HBV model was chosen because the HBV model is known to simulate the discharge of the Rhine sub basin quite well and the calibrated parameters were available (Eberle, 2009).

This chapter will explain the model which has been used for the hydrological modeling of the Rhine sub basin. It will be explained how the model works, what parameters are calibrated and how well the model performs.

The HBV-model is a conceptual hydrological model for the calculation of a runoff. It was originally developed at the Swedish Meteorological and Hydrological Institute (SMHI) in the early 70´s to assist hydropower operations by providing hydrological forecasts. The first operational forecasts by the HBV model were carried out for basins in the northern part of Sweden in 1975. Since then the model has been applied in more than 50 countries. (Eberle, 2009)

3.1 HBV model description

The HBV model is a rainfall-runoff model. The input data for the model are the rainfall and the temperature, based on the temperature the potential evaporation is calculated internally. The HBV model consists of subroutines for snow accumulation and snowmelt, a soil moisture accounting procedure, a upper response box and a lower response box. A schematic sketch of the HBV-model is shown in figure 2.

Within a sub basin with a considerable elevation range a subdivision into elevation zones can also be made. This subdivision is made for the snow and soil moisture routines only. Each elevation zone can further be divided into different vegetation zones, like forested and non-forested areas. (Eberle, 2009)

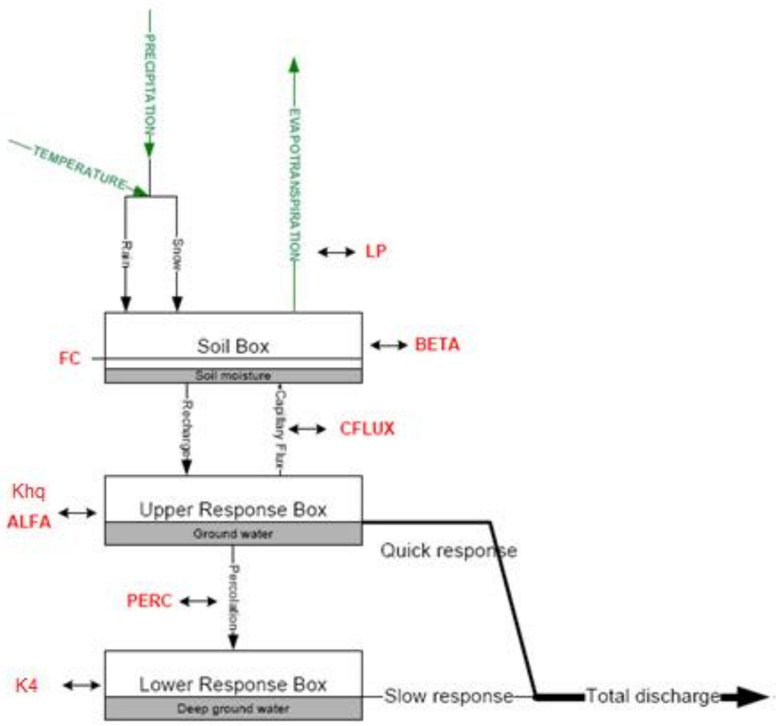

Figure 2: Schematization of the HBV model (Tillaart, 2010)

Model description
Figure 2 shows the schematization of the model for one sub basin (Tillaart, 2010). This schematization is based on the HBV model, which is described in Lindström et al. (1997) and Bergström (1976).

The schematization consists of three routines: the precipitation routine, the soil moisture routine and the runoff generating routine, which can be divided into quick and slow runoff. Next the routing and the transformation will be discussed.

Precipitation Routine
The precipitation is divided in the model as rainfall or snow. If the temperature is above a certain threshold, rainfall will fall. Below this threshold, the precipitation consists of snowfall. Also the melting and refreezing processes are taken into account in this routine (Tillaart, 2010).

Evapotranspiration
The parameter LP describes the limit of water storage for potential evapotranspiration. Above this limit, the actual evapotranspiration (EA) [mm/day] will be equal to the potential evapotranspiration (E_{pot}) [mm/day]. The potential evapotranspiration is calculated internally in the HBV model, this is explained in chapter 3.2 .

If the soil moisture (SM) is lower than the LP, the following formula is used:

$$EA = \frac{SM}{LP} * E_{pot} \qquad (1)$$

Soil Moisture Routine
The soil moisture routine controls which part of the precipitation is evaporated or stored into the soil. The ratio of actual soil moisture (SM) and the maximum water storage capacity of this routine controls, which part of precipitation is stored in the soil. The ratio of actual soil moisture (SM) and the maximum water storage capacity of the soil (FC) and the soil routine parameter (BETA) together assess the runoff coefficient. With this runoff coefficient, the part of the precipitation P which forms the recharge R to the upper response box can be calculated, by using equation (2). When the soil is saturated (SM=FC), then the recharge is equal than the precipitation (Tillaart, 2010).

$$R(t) = \left(\frac{SM}{FC}\right)^{beta} * P(t) \qquad (2)$$

The parameter CFLUX [*mm/day*] represents the maximum capillary flux from the runoff routine into the soil.

Runoff Generation Routine (quick and slow runoff)
The runoff generation routine is the response function that transforms excess water from the soil routine to runoff. The runoff generation routine consists of two reservoirs. The first one, the upper response box, is a non-linear reservoir which represents quick runoff. K_{hq} [day-1] is a recession parameter in the upper or fast response box. ALFA[-] is a measure for non-linearity of the quick runoff (Tillaart, 2010).

The second reservoir is the linear lower response box. This box represents the slow response (with recession coefficient K_4 [day-1], i.e. the base flow is fed by groundwater. The fast (Qf[mm/day], equation (3) and slow (Qs[mm/day]), equation (4)) response can be characterized by the following equations, in which S_f [mm] and S_s [mm] represent the storage in respectively the fast and slow response box.

$$Q_f(t) = k_{hq} * S_F(t)^{(1+alfa)} \tag{3}$$

$$Q_s(t) = k_4 * S_s(t) \tag{4}$$

Groundwater recharge is ruled by a maximum amount of water that is able to penetrate from soil to groundwater (parameter *PERC* [mm day-1]) through the upper response box.

Routing routine

The different sub basins are connected with each other to simulate a good discharge, therefore are the parameter LAG and DAMP used. For the inflow to another sub catchment, the inflow from an upstream catchment is added. Hereby there parameter LAG indicates the delay in the discharge (Huisjes, 2006).

The DAMP factor is a modified version of the Muskingum equation which is used for computation. This equation simulates the attenuation of the wave amplitude of the discharge through the sub catchment. If the DAMP has a value of zero, the outflow from a segment equals the inflow to the same segment during the preceding time step, so that the shape of the hydrograph is not changed. If DAMP is not zero the shape will be changed as an outflow at the preceding step (Huisjes, 2006). This is shown is equation (5).

$$Q_{out}(t) = Q_{out}(t-1) * C_1 + Q_{in}(t) * C_1 + Q_{in}(t-1) * C_2 \tag{5}$$

Where t is the current time step and t-1 is the previous time step. The coefficients C_1 and C_2 are determined by the equations (6) and (7).

$$C_1 = \frac{DAMP}{1+DAMP} \tag{6}$$

$$C_2 = \frac{1-DAMP}{1+DAMP} \tag{7}$$

3.2 Determination of the potential evapotranspiration

The Rhine river has been divided in 134 sub basins. Hereby the evaporation is calculated internally in the HBV model for each of the 134 sub basin separately (Eberle, 2009). This is done using equation (8):

$$E_{pot} = E0\,(1 + etf \cdot \partial t) \tag{8}$$

E_{pot}= potential daily evaporation	(mm/day)
E0= daily evaporation in the month	(mm/day)
etf =correction factor for the potential evaporation	(-/^{o}C)
∂t = deviation of temperature from the normal	(^{o}C)

The basic idea behind the equation is that the temperature is an important factor in explaining the day to day variations of the evaporation, not only directly but also because it is an indicator of the general weather condition.

The temperature normal is calculated from a long period, depending on the availability of data. There is one value for each day of the year and each sub basin. Based on this normal data the evaporation is calculated for each day and each sub basin. (Eberle, 2009)

3.3 Implementation Rhine basin in HBV

The Rhine River has been simulated in the HBV model. A stand alone model of the HBV has been used, called FEWS (Deltares, 2010). In this model the catchment of the Rhine upstream of Lobith has been divided in 134 sub catchments. This map can be found in Appendix A.

FEWS is a HBV model, which is used for flood early warning (Deltares, 2010). In this model it is possible to load in a climate data series and to simulate the discharge for each point of the sub catchment at a certain time step.

3.4 Calibration

The calibration of the different parameters has been done by Elberle (2009). In this chapter his calibration approach will be described.

Elberle (2009) did derive some parameters from previous calibrations by the SMHI, like the soil moisture *Fc* and the response box parameter *hq*. Those have been estimated from land use and other physical properties in the sub catchment. Also the travel time along the river from the outlet of one sub catchment to the next was kept unchanged from the previous calibration.

Based on long experience there are some model parameters that have been given default values. Those values are given in table 2. The parameters effecting snow build up and snow melt condition (*sfcf, cfmax* and *tt*) were calibrated in the catchments where snow was found during the calibration period. If there was no snow, there have been given default values.

Often an adjustment is required to the precipitation input to avoid a systematic underestimation or overestimation of runoff. The option of different correction for the rainfall and the snowfall were used (*rfcf* and *sfcf*). (Eberle, 2009) The average correction for the rainfall is 0.995 and for the snowfall 0.935. For the rainfall there have been made corrections in three sub basins in the sub catchment of Mosselle. For the snowfall there haven't been made correction in the Alps, but only in other sub basins. This is kind of strange if there is used climate change data, because it is supposed that this data is generates the right amount of precipitation and does not need a correction factor. The correction is used in the FEWS model, and will be used for that reason.

Parameter	Unit	Values
Etf	-/°C	0.1
Epf	-	0.02
Ered	-	0
ecorr	-	0.1
ecalt	-	0
cevpfo	-	1
icfi	-	1
icfo	-	1.5
pcorr	-	0.01
pcalt	-/100m	0.1
tcalt	-/100m	0.06
ttint	-	2
dttm	-	0
fosfcf	-	1
focfmax	-	0.6
cfr	-	0.05
whc	-	0.1
cflux	-	0
lp	-	0.9
alfa	-	1
resparea	-	1

Table 2: Fixed values

Parameter	Unit	Start	Lower values	Upper value
rfcf	-	1	0.8	1.3
sfcf	-	1.1	0.7	1.4
cfmax	mm/day °C	3.5	2	5
tt	°C	0	-2	2
Khq	day^{-1}	0.2	0.005	0.5
k4	day^{-1}	0.05	0.001	0.1
perc	mm/day	2	0.01	5
beta	-	2.5	1	4
maxbaz	day	0.5	0	7

Table 3: Calibration parameters

The calibration criteria used by Eberle was:

$$crit = 0{,}5R^2 + 0{,}5R_{log}^2 + 0{,}1 * relaccdif \qquad (9)$$

R^2 = the efficiency criteria according to Nash and Sutcliffe (1970).
R^2_{log}= as R^2 but using the logarithmic discharge values (gives more weight to low flows).
relaccdif = the accumulated difference between simulated and observed discharge

The starting parameter values for the automatic calibration as well as the upper and lower limits are found in table 2. The parameters have been calibrated by using an automatic calibration routine described in Lindström et al. (1997).

Whenever possible, the calibration was done on the local outflow of a sub-catchment. It was done for all upstream catchments, but for some of the downstream sub catchments the recorded local inflow was too unreliable. In such case several sub-catchments were calibrated together or model parameters were taken from a neighboring catchment and then verified against the total discharge. The results of the calibration values for each sub basin can be found in Elberle (2009).

The calibration was done for the period 1-11-2000 to 1-11-2007 and the verification period was 1-11-1996 to 1-11-2000. (Eberle, 2009).

4 Research approach

In this chapter first the different possible definitions of a low flow will be given. Connected to this, a definition will be given for the indicators which determine the severity of the low flow. After the indictors have been chosen, the different steps of the research model will be described.

4.1 Low flow definition

For the identification of the occurrence of low flows, there are several possible indicators which can be used. The indicators which could be chosen are:

- The LCW values (low critical values). This norm is determined by Rijkswaterstaat (2009) for the Netherlands.
- The flows within the range of 70-99% time exceedance are usually most widely used as design low flows. Some common example indices are: one- or n-day discharge exceeded 75, 90, 95% of the time. – e.g. Q75(7), Q75(10),Q90(1) (Smakhtin, 2001)
- In the USA, the most widely used indices are 7-day 10-year low flow (7Q10) and 7-day 2-year low flow (7Q2), which are defined as the lowest average flow that occur for a consecutive 7-day period at the recurrence intervals of 10 and 2 years. (Smakhtin, 2001)
- Peters (2004) describes the hydrologic drought as a water flow below a certain threshold. In the Netherlands there is a deficit below 1800 m^3/s for the Rhine River during the period of the 1th of April to the 1th of October. This period has been chosen because this is the most important timeframe for the agricultural sector. This definition was used by the RIZA. (Peters, 2004)
- However in the report of Peters (2004) is also another definition of 1000 m^3/s used as a critical condition. This definition is used for navigation and in this thesis for the threshold for navigation.

The LCW values (low critical value) are used as thresholds, because this norm has been determined for the Netherlands and is used by Rijkswaterstaat at the moment.

4.1.1 LCW values

For the LCW values the following guidelines are used.

- Shipping needs a discharge of at least 1000 m^3/s at Lobith
- There is a discharge shortage if the demand for water exceeds the availability, this changes from April to September. Water can be demanded in the agricultural sector, household water, etc.. Because the demands for water are different throughout the year, the norms are different throughout the year.

The LCW values are presented in Table 4.

Table 4: LCW values for the Rhine River at Lobith

Month	Rhine river discharge at Lobith
January	
February	
March	
April	1000 m^3/s
May	1400 m^3/s
June	1300 m^3/s
July	1200 m^3/s
Augustus	1100 m^3/s
September	1000 m^3/s
October	
November	
December	

A low occurs when the flow is less than the LCW-value for the Rhine at Lobith. (Rijkswaterstaat, 2009)

The LCW values from Rijkswaterstaat are currently used and made for the current conditions in the Netherlands. It is possible that values will change in the future due to changes in demand in the Netherlands, but this is not taken into account in this study.

The severity of low flows will be determined by using two different indicators:

- Determining the annual total deficit of water, this is done by summing the discharge deficit below the LCW values from the 1th of April till the 30th of September. (Rijkswaterstaat, 2003)
- The number of days that the discharge is below 1000 m^3/s during a year. This threshold is important for shipping.

4.2 Research model

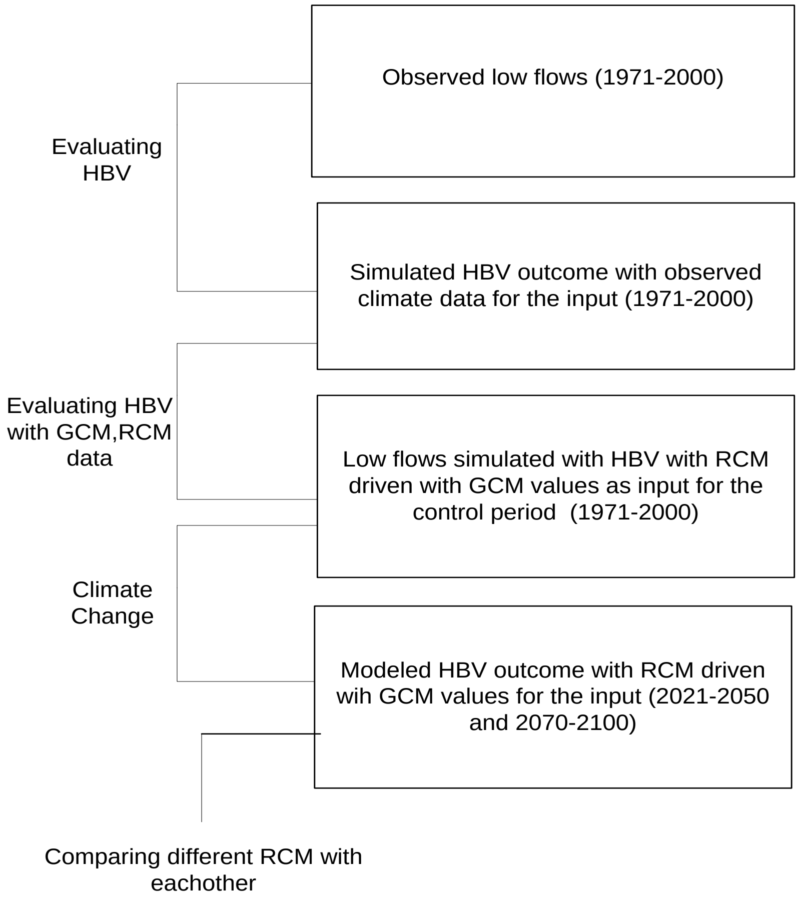

Figure 3: Research model

In the research four comparisons will be made to assess the effects of the HBV model, the effects of the RCM and the effects of climate change. In this paragraph the different steps will be described.

4.2.1 Evaluation of the HBV model based on the two indicators

In the first comparison the effects of the HBV model will be investigated. Here the two indictors will be compared. Hereby there can be found out whether the indicators are simulated quite well and the indicators will be assessed.

4.2.2 Determination of the effects of the RCM driven with GCM output on the simulation results

The second comparison will be the comparison of the climate change runs with the observed values in the HBV model for the time period of 1962-1992. Hereby the effects on the indicators by the run with RCM driven with GCM output as input for the hydrological model on the different indicators will be determined.

4.2.3 Identification of the future climate impacts on low flows

The third comparison will be about the effect of climate change using RCM data driven by GCM data, hereby the period 1962-1992 will be compared with the period 2020-2050 and 2070-2100. This will be done to assess the effects of climate change by taking a look at both indicators for the different time periods.

4.2.4 Comparing different RCM with each other

To assess the influence of a certain RCM the different climate change scenarios with the same GCM but another RCM will be compared, so that the effects of the RCM will be identified on the two indicators.

5 Results

Firstly in this chapter the results of the simulation run with observed values are described. By doing this the first step of my research model is executed. This is the comparison between the observed discharge and the simulation with observed climate data values. Hereby the difference between the values of both indicators will be investigated.

After the first step has been executed, the different RCM driven by GCM runs will be explained. Hereby a comparison will be made between the indicators of the outcome of the HBV model with observed values and the HBV model with climate change data as input for 1962-1992. This will be done to assess the effects of the RCM driven with GCM output as input for the HBV model. Next the development of climate change will be assessed. This will be done for four different scenarios; Aladin Arpege, Hirham Arpege, Racmo Echam5 and Remo Echam5.

Hereafter the results for climate change for the different scenarios will be presented. Hereby the period 1962-1992 will be compared with 2020-2050 and 2070-2100. By doing this the effects of climate change on the different indicators can be determined.

Finally the scenarios with the same GCM will be compared; this will be done to assess whether the effects of a certain RCM on the different indicators can be determined.

5.1 Evaluation of the HBV model based on the two indicators

This chapter will describe the output of the HBV model with the observed values for the precipitation and the temperature as input compared with the observed discharge for the different indicators. In this chapter firstly the hydrograph will be presented, and then the amount of deficit, finally the number of days will be presented. At the end of this chapter a short overview table of the results will be presented.

Table 5: Temperature and precipitation

Period	Average Temperature (°C)	Average Temperature Alps (°C)	Average Precipitation (mm/year)	Average Precipitation Alps (mm/year)
1962-1992	8,4	6,0	947	1382

Table 5 shows the average temperature and precipitation for the Rhine basin and for the Alpine sub basin. The Alpine sub basin is added here, because a significant part of this sub basin originates.

5.1.1 Hydrograph

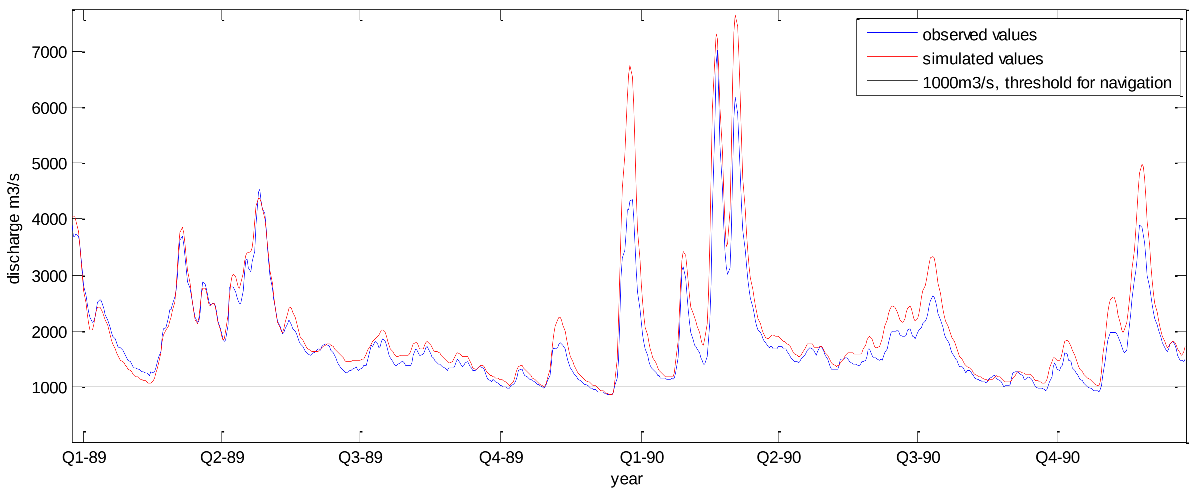

Figure 4: Hydrograph for 1989-1991 of HBV model with observed precipitation and temperature and the observed discharge

Figure 4 shows the hydrograph of the HBV model with the precipitation and the temperature as input for the HBV model, as well as the observed values for the period 1989-1991.This period has been chosen to give an expression of the simulated values. The black line is the threshold for navigation purposes. If the discharge falls below this threshold, the navigation is hindered. The hydrograph for 1961-1996 can be found in appendix B.

The simulated discharge has an RVE of 2%, the NS of 0.92 and the NSlog of 0.92 for the period 1962-1995. According to common practice simulation results are considered to be good for values of a NS of 0.75 or higher (Motovilov et al., 1999), so there can be concluded that NS value is good. Figure 4 shows a good simulation for the year 1989, in the year 1990 the discharge is overestimated. However the peaks discharges are overestimated.

5.1.2 Deficit

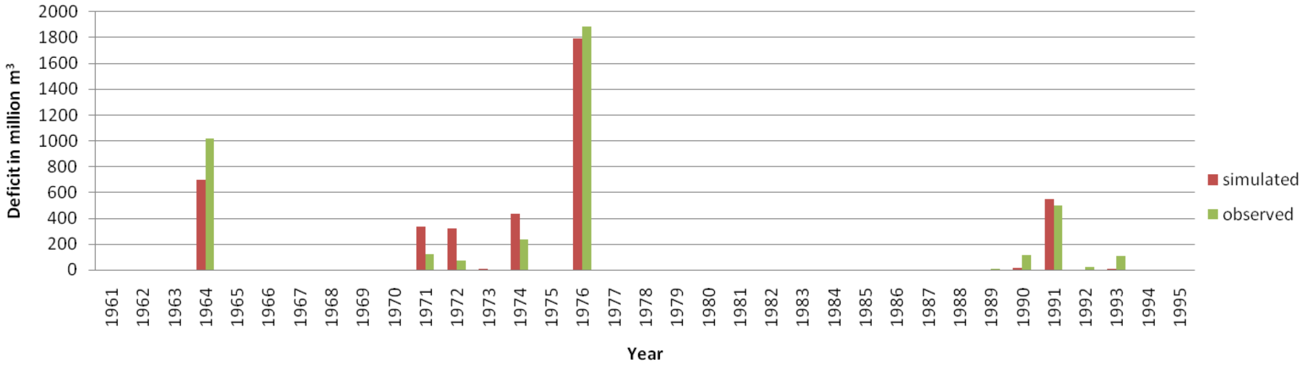

Figure 5: Annual deficit for observed P and T as input for the HBV model and the observed values

Figure 5 shows the annual deficit for the HBV model with observed precipitation and temperature and the observed discharge at Lobith. Table 6 shows that the deficits are overestimated within the simulation.

A short summary of the results is given in table 6. This table gives the average yearly deficit and the maximum deficit which has been found. The average annual deficit is overestimated with 5%, the maximum deficit in the period is underestimated with 5%.

Table 6: Overview of the deficit for the HBV model with observed P and T and the observed values

	Average annual deficit (million m^3)	Maximum deficit (million m^3)
Observed discharge		
1962-1992	128	1883
HBV model with observed P,T		
1962-1992	134	1794

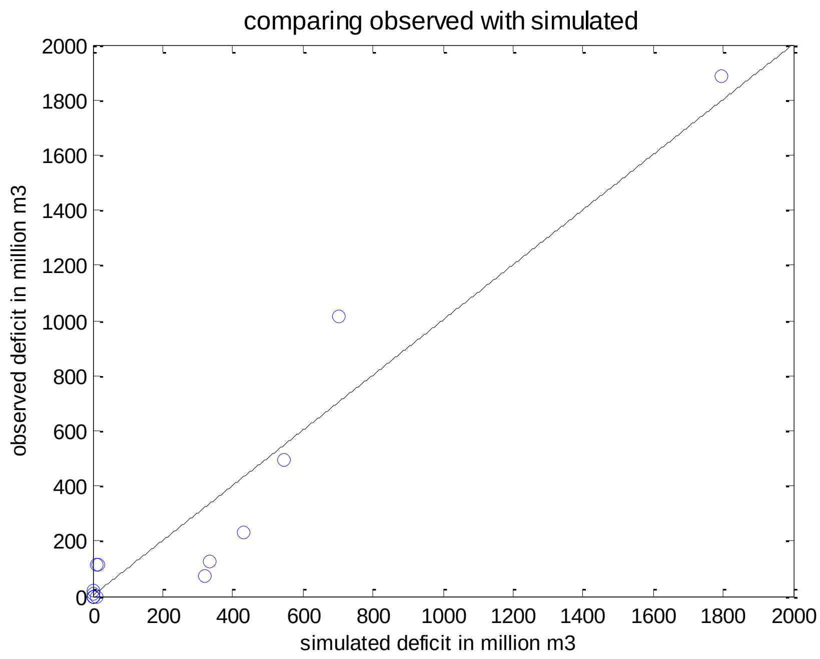

Figure 6: Comparing observed with simulated deficit

Figure 6 shows the observed values plotted against the simulated values. In figure 6 it is possible to assess whether or not the values are overestimated. The correlation between the simulations and the observed deficit is 0.93 and the standard deviation is 358 million m^3. This is quite a good correlation. If, however the highest point is removed the correlation becomes 0.77. So it can be concluded that the high correlation depends on one point and this gives some remarks on how good this indicator is simulated. It is quite hard to assess the quality of the simulation with the few points available and the standard deviation corresponds to a large percentage of the deficit for most historical events.

5.1.3 Days with flow below the threshold for navigation

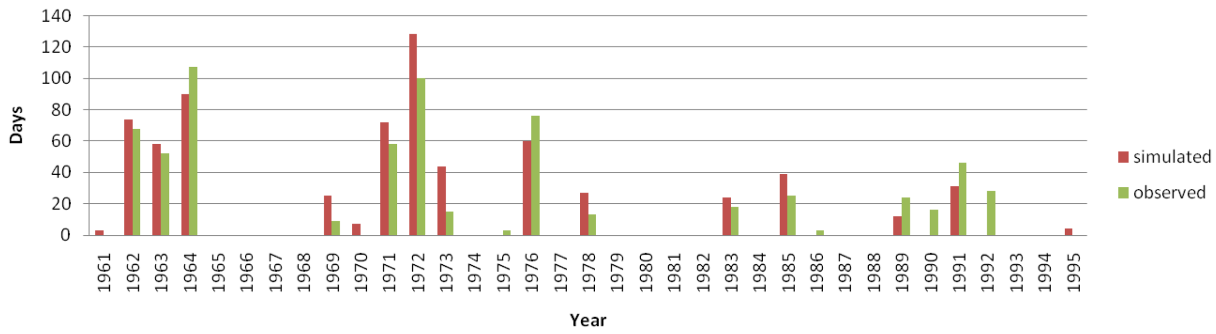

Figure 7: Days below 1000 m^3/s for the HBV model with observed P and T

Figure 7 shows the number of days with a flow below 1000 m^3/s. The simulation shows some more number of days below 1000 m^3/s than in the observed values. However the difference is small and the pattern is quite well simulated. For that reason there can be said that the model performance for this criteria is quite well for this indicator.

Table 7 gives a short overview of the model about the discharge below 1000 m^3/s, the threshold for navigation. Table 7 shows an overestimation of 5% of the average days below 1000 m^3/s annually. This is acceptable.

Table 7: Days below 1000 m^3/s for the HBV model with observed precipitation and temperature and for the observed discharge

	Average number of days annually with flow below 1000 m^3/s	Maximum number of days during a year with flow below 1000 m^3/s
Observed discharge		
1962-1992	21.3	107
HBV model with observed P,T		
1962-1992	22.3	128

5.1.3.1 Correlation between observed and simulated values for the amount of days below 1000 m³/s

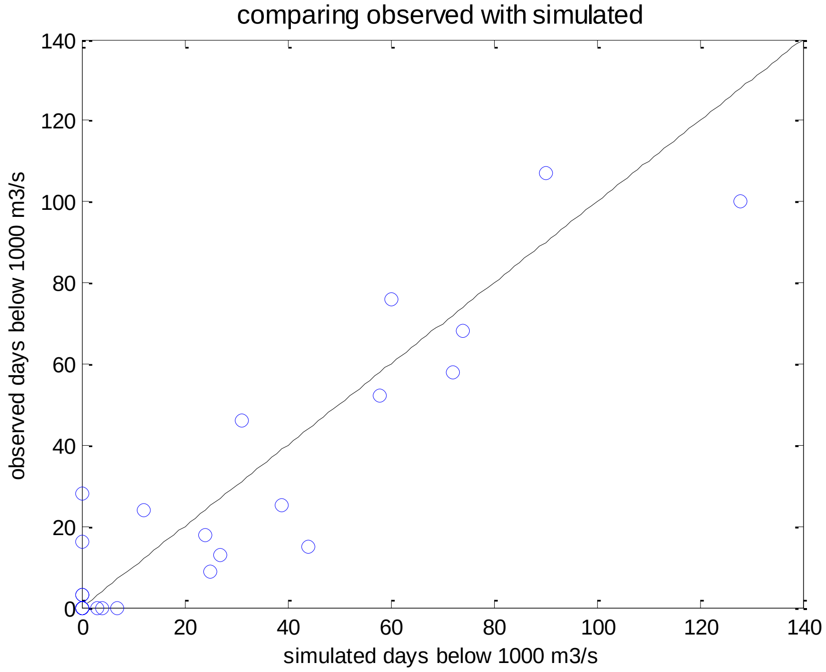

Figure 8: simulated and observed values

Figure 8 shows the observed values plotted against the simulated values. In figure 8 it is possible to assess whether or not the values are overestimated. The correlation between the simulations and the observed number of days below 1000 m^3/s is 0.87 and the standard deviation is 33.2 days. This is quite a good correlation. In figure 8 there no systematic over or underestimation is found.

5.1.4 Conclusion

For the different indicators used, the simulated and the observed values give a fair match. The correlation between the observed and the simulated values for the deficit is 0.92, however if the highest values is left out the correlation is 0.77. The correlation between the observed and the simulated values for the amount of days below 1000 m^3/s annually is 0.87. The standard deviation is 358 million m^3 for the deficit and 33.2 days for the amount of days below 1000 m^3/s.

Summarizing, it may be stated that the results for the different indicators are simulated quite well because of the small difference between the simulation and the observed values for the different indicators. The indicator of days below 1000 m^3/s is simulated better, then the deficit.

5.2 Determination of the effects of the RCM with GCM data output on the simulation results

This section presents the results of the effects of the chosen RCM with GCM data on the results of climate change. Hereby there will be given a discussion about the three different aspects for the time span 1962-1992: an overview of the temperature and precipitation, an overview of the deficit and the amount of days below a 1000 m^3/s. Hereby the effect of the RCM with GCM data output on the simulated results can be assessed.

Table 8: Temperature and precipitation for different scenarios

Scenario	Period	Average Temperature (^oC)	Average Temperature Alps (^{o} C)	Average Precipitation (mm/year)	Average Precipitation Alps (mm/year)
Observed values	**1962-1992**	8,4	6,0	947	1382
Aladin Arpege	**1962-1992**	8,3	5,4	960	1525
Hirham Arpege	**1962-1992**	8,4	5,3	954	1665
Racmo Echam5	**1962-1992**	8,3	6,6	972	1448
Remo Echam5	**1962-1992**	8,3	6,5	971	1436

Table 8 shows the temperature and precipitation of the different scenarios. The average temperature over the Rhine basin is about the same. However there is a difference in the region of the Alps as well as for the temperature. Hereby the Arpege scenarios have a lower temperature than the observed values, and the Echam 5 scenario has a higher temperature. The precipitation is overestimated in all the scenarios, but within 5%.

The overestimation of the precipitation is the most in the Echam 5 scenarios, for that reason the low flows in this scenarios are expected to be the less severe.

Table 9: Deficit due to certain scenario

	Scenario	Average annual deficit (million m^3)	Maximum deficit (million m^3)
Observed discharge	**1962-1992**	128	1883
Simulated discharge Deltares (FEWS; HBV)	**1962-1992**	134	1794
Aladin Arpege +HBV model	**1962-1992**	119	2615
Hirham5 Arpege + HBV model	**1962-1992**	360	2046
Racmo Echam5 +HBV model	**1962-1992**	16	245
Remo Echam 5 +HBV model	**1962-1992**	28	545

Table 9 gives an indication of the deficit; the average deficit is quite well simulated by the Aladin Arpege scenario. In the Hirham5 Arpege scenario the deficit is overestimated by 200 percent. This is quite a lot and there can be questioned how realistic the Hirham5 Arpege scenario is.

Table 10: Overview of days below 1000 m^3/s

	Scenario	Average number of days annually with flow below 1000 m^3/s	Maximum number of days annually with flow below 1000 m^3/s a year
Observed discharge	**1962-1992**	21,3	107
Simulated discharge Deltares (FEWS; HBV)	**1962-1992**	22,3	128
Aladin Arpege	**1962-1992**	18,3	98
Hirham5 Arpege	**1962-1992**	22,7	131
Racmo Echam 5	**1962-1992**	12,2	95
Remo Echam 5	**1962-1992**	20,0	84

Table 10 shows the amount of days below 1000 m^3/s. Table 10 shows that the Hirham5 Arpege scenario simulates the amount of days below 1000 m^3/s quite well. The difference with the observed values is within the variability of the results. The largest underestimation is for the Racmo Echam 5 scenario, this can be explained because the precipitation is overestimated quite a lot in this scenario.

5.2.1 Discussion

The over- or underestimation of the deficits could be explained by the following reasons:

- **The climate change data is randomly generated**

The different climate data is randomly generated for a period of 30 years. The climate has an internal variability because of deviations in averages and frequency of occurrence of events for a long term period. For that reasons there could be outliers in. It is possible that an extreme event would occur in the control run; this would affect the indicators quite a lot. For the amount of days with a discharge below 1000 m^3/s, this effect could be about 5 days extra for this indicator. This represents 155 days above the average amount number of days with a flow below 1000 m^3/s in a year. For the deficit it is quite hard to determine, because it is quite hard to predict the maximum deficit.

- **Different amount of rain simulated**

In the different climate runs, different amounts of rain are simulated. Another amount of rain would lead to another amount of discharge, so the amount of low flows can change.

- **Different results for the different indicators**

The different indicators which are used have different characteristics. The indicator of days with a discharge below 1000 m^3/s is better simulated than the indicator of the deficit.

5.3 Overall trends in different climate change scenarios

In this section the different aspects of the climate change scenarios will be discussed, first of all the temperature and precipitation will be discussed, next the deficit, then the amount of days below 1000 m^3/s. Next a conclusion about the different trends will be presented.

Table 11: Temperature and precipitation in climate change scenarios

Scenario	Period	Average Temperature (^oc)	Average Temperature Alps (^oc)	Average Precipitation (mm/year)	Average Precipitation Alps (mm/year)
Observed values	**1962-1992**	8,4	6,0	947	1382
Aladin Arpege	**1962-1992**	8,3	5,4	960	1525
	2020-2050	9,7	8,2	967	1480
Hirham5 Arpege	**1962-1992**	8,4	5,3	954	1665
	2020-2050	9,4	8,0	940	1374
	2070-2100	10,6	9,3	795	1151
Racmo Echam5	**1962-1992**	8,3	6,6	972	1448
	2020-2050	9,7	7,7	976	1463
	2070-2100	11,5	9,8	1020	1495
Remo Echam5	**1962-1992**	8,3	6,5	971	1436
	2020-2050	9,4	7,7	966	1445
	2070-2100	11,6	10,1	983	1409

Table 11 shows the developments of the temperature and the precipitation in the different scenarios. Overall the temperature increases over the whole sub basins. The increase of temperature is even more in the Alps than in the other parts of the Rhine basin.

An increase of the temperature would lead to a river which is more a rainfall-runoff river than the current snowfall-rainfall river; this would shift the hydrological regime. (Hurkmans et al., 2009) So it can be expected that the severity of low flows would increase.

The precipitation increases in the Racmo Echam 5 scenario, in the Hirham Arpege scenario the precipitation decreases. In the Aladin Arpege and the Remo Echam5, the change of the precipitation is within the natural variability.

Table 12: Deficits in the different scenarios

	Scenario	Average annual deficit (million m^3)	% Increase with 1962-1992	Maximum deficit (million m^3)	% Increase with 1962-1992
Observed discharge	**1962-1992**	128		1883	
Simulated discharge Deltares (FEWS; HBV)	**1962-1992**	134		1794	
HBV with Aladin Arpege	**1962-1992**	119		2615	
	2020-2050	31	-74%	346	-87%
HBV with Hirham5 Arpege	**1962-1992**	360		2046	
	2020-2050	462	+28%	2819	+38%
	2070-2100	2018	+460%	6892	+237%
HBV with Racmo Echam5	**1962-1992**	16		245	
	2020-2050	87	+443%	1469	+500%
	2070-2100	755	+4618%	6544	+2571%
HBV with Remo Echam 5	**1962-1992**	28		545	
	2020-2050	76	+171%	758	+30%
	2070-2100	815	+2810%	5614	+931%

Table 12 shows the deficits for the different scenarios. Overall there could be concluded that the deficit will increase in the future. It is expected that the smallest increase is in 2020-2050 for 3 of the 4 scenarios. In 2070-2100 the increase will be quite large.

For the Hirham 5 Arpege scenario the deficit will reach the highest level, this could be explained because the precipitation is also going to decrease. However for the Aladin Arpege scenario the deficit decreases. For the GCM of Echam 5 the increase is about the same in absolute terms.

The overall view of the ranking of the deficits can be found in appendix C.

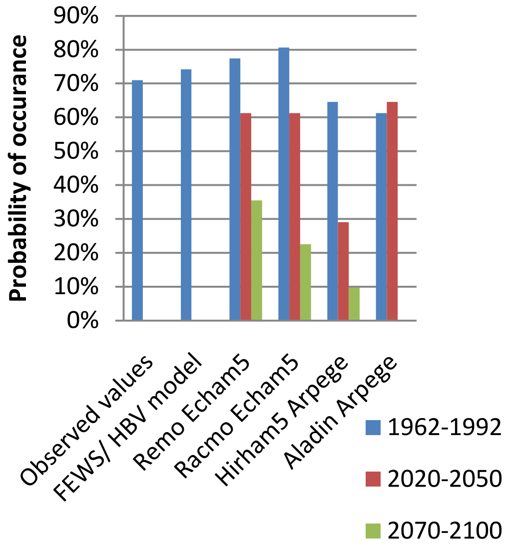

Figure 9a: Probability of no deficit annual

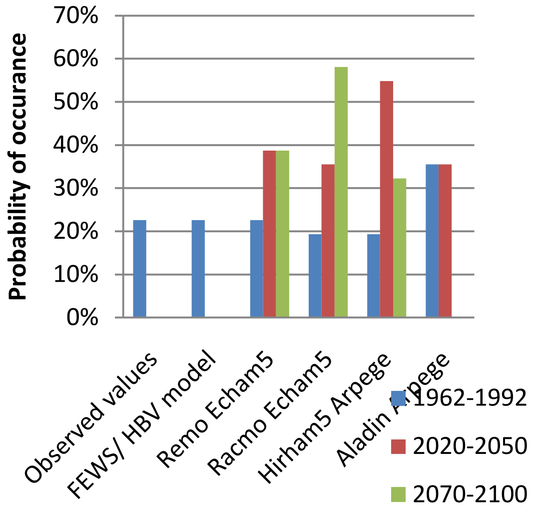

Figure 9b: Probability of a deficit between 1 and 1000 million m^3 annual

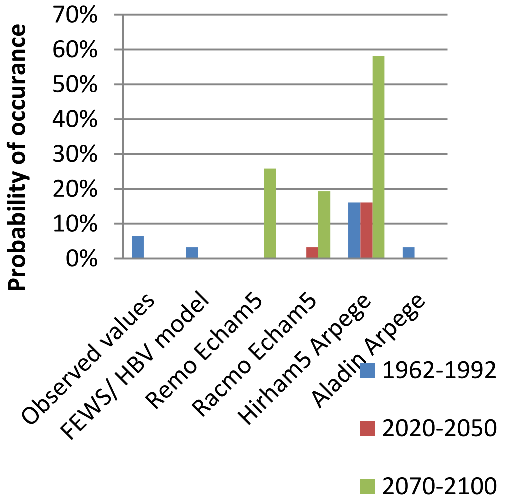

Figure 9c: Probability of a deficit large than a billion m^3 annual

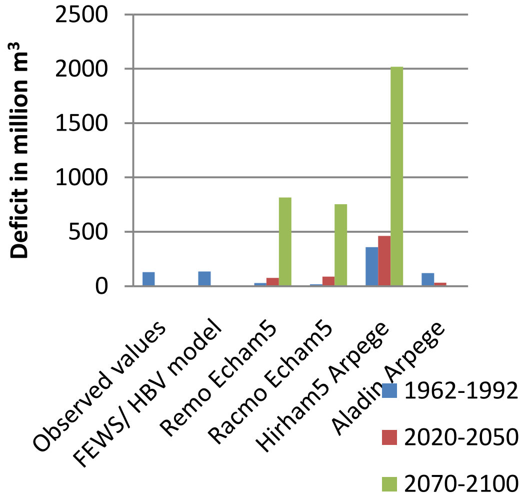

Figure 10: Average annual deficit

Figure 9 shows the trends of the probability of a certain deficit. For the deficit there have been made three categories; no deficit, a deficit from 1-1000 million m^3 and a deficit over a billion m^3. For the several deficits, the amount of the deficit will increase over the years. Only in the Aladin Arpege scenario the deficits will decrease, in all the other scenarios they will increase. For the Hirham5 Arpege scenario the change of a severe deficit will be the largest in 2070-2100.

Figure 10 shows that the average annual deficit for 3 of the 4 scenarios increases. The further in the future the more severe the deficit will be for most models.

Table 13: Days below 1000 m^3/s in the different scenarios

	Scenario	Average days annual with flow below 1000 m^3/s	% Increase with 1962-1992	Maximum days annual with flow below 1000 m^3/s a year	% Increase with 1962-1992
Observed discharge	**1962-1992**	21,3		107	
Simulated discharge Deltares (FEWS; HBV)	**1962-1992**	22,3		128	
HBV with Aladin Arpege	**1962-1992**	18,3		98	
	2020-2050	17,5	-5%	79	-19%
HBV with Hirham5 Arpege	**1962-1992**	22,7		131	
	2020-2050	32,5	+43%	188	+44%
	2070-2100	110,3	+185%	274	+109%
HBV with Racmo Echam5	**1962-1992**	12,2		95	
	2020-2050	18,6	+52%	88	-8%
	2070-2100	41,5	+240%	148	+56%
HBV with Remo Echam 5	**1962-1992**	20,0		84	
	2020-2050	19,5	-2.5%	88	+5%
	2070-2100	42,3	+112%	158	+88%

Table 13 shows the number of days below 1000 m^3/s. For this indicator an increase is found in the results. In the Echam 5 scenarios the increase in the number of low flows days is about the same in the different scenarios. Results for both RCMs agree an increase of days with an amount of days below 1000 m^3/s. For the Aladin Arpege a small decrease is simulated, variability can be a reason for this. For the Hirham 5 Arpege scenario the increase of the average amount of days below 1000 m^3/s is expected to be the largest, this is due to a decrease of precipitation.

The overall view at the ranking of the amount of days below 1000 m^3/s can be found in appendix D.

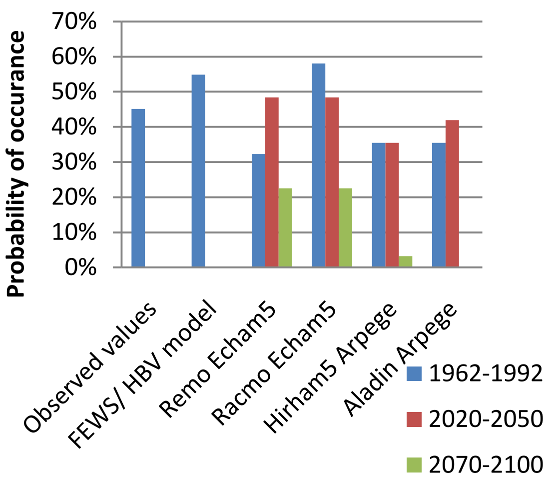

Figure 11a: Probability of 0 days below 1000 m^3/s a year

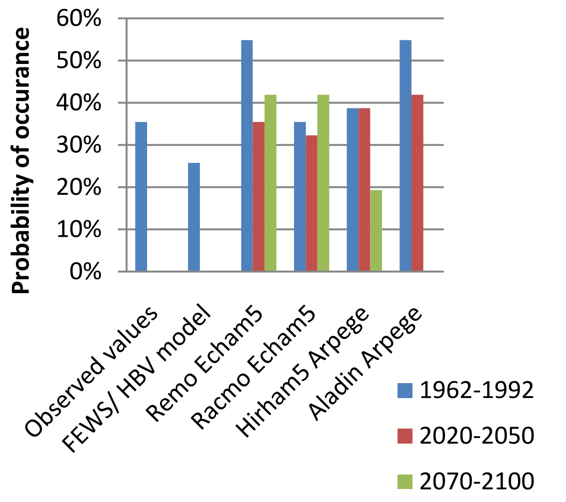

Figure 11b: Probability of 1 to 50 days below 1000 m^3/s a year

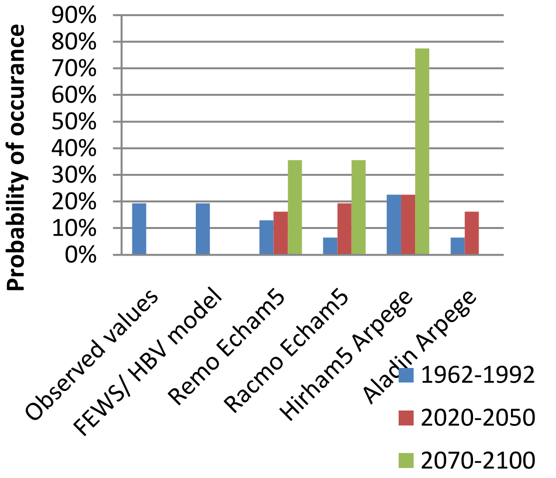

Figure 11c: Probability of over a 50 days below 1000 m^3/s a year

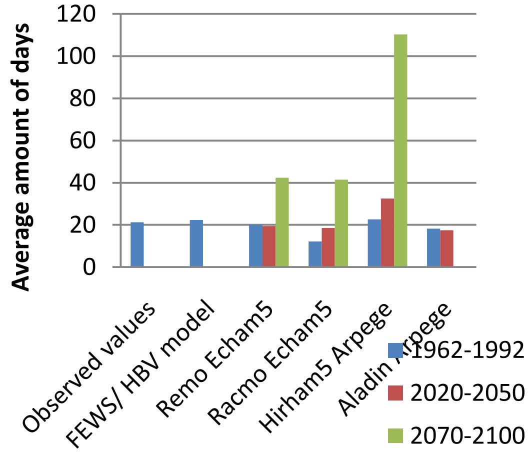

Figure 12: Average amount of days below 1000 m^3/s annual

Figure 11 shows the probability of a certain amounts of days with a discharge below 1000 m^3/s, this threshold is used for navigation. There have been made three categories: 0 days below 1000 m^3/s, 1 to 50 days below 1000 m^3/s and over 50 days below 1000 m^3/s a year. Figure 11 a-c shows that the frequency of a year without a day with a discharge below 1000 m^3/s will decrease for the Remo Echam5, the Racmo Echam5 and the Hirham5 Arpege scenario, for the Aladin Arpege scenario the amount of days will increase. The probability of a year with an amount of days of 1 to 50 with a discharge below 1000 m^3/s will first decrease for the several scenarios in 2020-2050 compared to 1962-1992, the amount of days will increase if 2070-2100 is compared with 2020-2050. The probability of a year with over 50 days with a discharge below 1000 m^3/s will increase in three of the four scenarios. The increase will be small in 2020-2050 compared to 1962-1992. In 2070-2100 the increase will be quite large.

Literature indicates that it is expected that the amount of days with a low flow will increase (Hurkmans et al., 2009; Kwadijk and Rotmans., 1995; Middelkoop et al., 2001). Figure 12 shows that the average amount of days below 1000 m^3/s increases.

5.4 Comparing different RCM with each other

In this section first of all the climate change scenarios will be compared, hereby the climate change scenarios with the same GCM will be compared. So it becomes possible to identify the possible effects of the choice of a certain RCM on the development of the different indicators.

First of all the two different RCM scenarios for the GCM Arpege will be compared with each other. Hereby the results will be compared with each other. A comparison will be given of temperature and precipitation. Next the different indicators will be compared; the amount of days annual below 1000 m^3/s and the deficit. Finally a conclusion will be given about the influence of a RCM on the indicators.

The first comparison will be made between the Hirham Arpege and the Aladin Arpege; the second comparison will be made between the Remo Echam5 and the Racmo Echam5.

5.4.1 Comparison 1: Hirham Arpege vs. Aladin Arpege

Table 14: Overview table temperature Hirham Arpege vs. Aladin Arpege

Period	Average Temperature (c)	Average Temperature alps (c)	Average Precipitation (mm/year)	Average Precipitation alps (mm/year)
Hirham Arpege				
1962-1992	8.4	5.3	954	1665
2020-2050	9.4	8.0	940	1374
2070-2100	10.6	9.3	795	1151
Aladin Arpege				
1962-1992	8.3	5.4	960	1525
2020-2050	9.7	8.2	967	1480

Table 14 shows the average temperature and precipitation for the Rhine basin. The average temperature in the two scenarios increases in the same way. The difference between those two scenarios is small. With respect to the development of the precipitation there is a lot of difference between them. For this reason it is expected that the different indicators will behave differently for those two scenarios. This can be explained because different runs for the GCM of Arpege have been used; because of randomness those scenarios behave differently.

Table 15: Overview table deficit Hirham Arpege vs. Aladin Arpege

Scenario	Average annual deficit (million m^3)	Maximum annual deficit (million m^3)
Hirham Arpege		
1962-1992	360	2046
2020-2050	462	2819
2070-2100	2018	6892
Aladin Arpege		
1962-1992	119	2615
2020-2050	31	346

Table 15 shows the developments of the deficits between those two scenarios. In the Hirham Arpege scenario the average annual deficit increases from 360 million m^3 annual in 1962-1992 to 462 million m^3 annual in 2020-2050. In the Aladin Arpege scenario the deficit is decreased from an average annually of 119 million m^3 in the period 1962-1992 to 31 million m^3 in the period 2020-2050. This can be explained because there is one year with an extreme value in the period 1962-1992, in the period 2020-2050 there is no such an event.

Table 16: Overview table days below 1000 m^3/s Hirham Arpege vs. Aladin Arpege

Scenario	Average number of days annually with flow below 1000 m^3/s	Maximum number of days annually with flow below 1000 m^3/s
Hirham Arpege		
1962-1992	22.7	131
2020-2050	32.5	188
2070-2100	110.3	279
Aladin Arpege		
1962-1992	18.3	98
2020-2050	17.5	79

Table 16 shows the average amount of days with a discharge less than a 1000 m^3/s. The developments of the two different scenarios for the average amount of days below 1000 m^3/s are different. In the Hirham Arpege scenario the average amount of days below 1000 m^3/s increases from 22.7 days to 32.5 days annually. In the Aladin Arpege scenario the average amount of days below 1000 m^3/s decreases from 18.3 days to 17.5 days. Hereby there can be concluded; that the two scenarios behave differently for the indicator of the amount of days below a 1000 m^3/s.

5.4.2 Comparison 2: Remo Echam 5 vs. Racmo Echam 5

Table 17: Overview table temperature Remo Echam5 vs. Racmo Echam5

Period	Average Temperature (^{o}c)	Average Temperature alps (^{o}c)	Average Precipitation (mm/year)	Average Precipitation alps (mm/year)
Remo Echam 5				
1962-1992	8,3	6,5	971	1436
2020-2050	9,4	7.7	966	1445
2070-2100	11,6	10,1	983	1409
Racmo Echam 5				
1962-1992	8.3	6.6	972	1448
2020-2050	9.7	7.7	976	1463
2070-2100	11.5	9.8	1020	1495

Table 17 shows the average temperature and precipitation for the Rhine basin. The average temperatures between the two scenarios do increase a bit the same. The difference between those two scenarios is small. The precipitation is also developing in the same way. Hereby there can be concluded; that the indicators will probably behave in the same way for both of the scenarios.

Table 18: Overview table deficit Remo Echam5 vs. Racmo Echam5

Scenario	Average annual deficit (million m^3)	Maximum annual deficit (million m^3)
Remo Echam 5		
1962-1992	28	545
2020-2050	76	758
2070-2100	815	5614
Racmo Echam 5		
1962-1992	16	245
2020-2050	87	1469
2070-2100	755	6544

Table 18 shows the deficits for both scenarios. In both scenarios the average annual deficit is developing in the same way. In the Racmo Echam 5 scenario the deficit increases the most. In the Remo Echam 5 scenario the average deficit increases from 28 million in 1962-1992 to 815 million in 2070-2100. In the Racmo Echam5 scenario the deficit increases from 16 million m^3 in 1962-1992 to 755 million m^3 in 2070-2100.

Table 19: Overview table days below 1000 m^3/s Remo Echam5 vs. Racmo Echam5

Scenario	Average number of days annually with flow below 1000 m^3/s	Maximum number of days annually with flow below 1000 m^3/s
Remo Echam 5		
1962-1992	20	84
2020-2050	19.5	88
2070-2100	42.3	158
Racmo Echam 5		
1962-1992	12.2	95
2020-2050	18.6	88
2070-2100	41.5	148

Table 19 shows the amounts of days below a 1000 m^3/s. The developments of the two different scenarios for the average amount of days below 1000 m^3/s are in the same direction. For the Remo Echam 5 scenario the average amount of days with a flow below 1000 m^3/s increases form 20 days in 1962-1992 to an average of 42.3 days in 2070-2100. The average amount of days for the Racmo Echam 5 scenario increases from 12.2 days in 1962-1992 to an average of 41.5 days in 2070-2100. Hereby there can be concluded that the two scenarios do behave in the same direction, however the indicators for the Racmo Echam5 scenario increases stronger than the indicators for the Remo Echam5 scenario do.

5.4.3 Conclusion

It can be concluded that the temperature development is dominated by the GCM, the different RCM's yield very similar results for the temperature. For the precipitation, there can be found a difference between the two RCM's for the GCM Arpege. The Aladin Arpege scenario has a small increase in precipitation and the Hirham Arpege scenario has a decrease in precipitation. This can be explained because two different runs with Arpege model have been used to make the climate change scenario and the difference between those two runs can be explained due to variability in the climate. In the GCM Echam 5 for the different RCM's the precipitation is developing in the same direction. In the Hirham Arpege scenario the severity of a low flow increases, in the Aladin Arpege scenario the severity decreases. This can be explained because different GCM runs for the Arpege scenario have been used. In the Echam 5 scenarios the development for the severity of a low flow are about the same.

6 Discussion

In the discussion, the climate change data, the model, the definition of a low flow and finally the time frame will be discussed.

Climate change data series

There have been made some assumption of climate change based on the CO_2 emissions and there are some limitations on the possibility of prediction of a complex system like the climate system. Another aspect of the different climate data is the uncertainty in the CO_2 emissions (KNMI, 2009). The assumptions of the emissions are based on economical and population growth model. This resulted in different climate change scenarios, A1B, A2, B1 and B2 (IPCC, 2007). Only the A1B scenario was available, so this scenario is used in this research. By taking more climate change scenarios are taken into account, it is possible to give a better impression of the bandwidth of the results.

Another aspect of the climate change data series is the variability of the climate. For this reason there could be a lot of outliers in the data, which could affect the different indicators. This could be solved by taking more ensembles of the same scenario into account.

Finally only a few RCM and GCM scenarios have been investigated. If more scenarios are taken into account, it becomes possible to determine a wider range of the results.

The last aspect is the bias correction method which is chosen. By using different bias correction methods, the results could be different because the data is corrected for another purpose. Before the bias correction was applied to the data series, the bias was -10% to 50% for the precipitation. After the correction the bias was only 5%. This correction was done to make the data series reliable.

Model

A standalone HBV model, FEWS, is used for the simulations. The calibrated parameters from Eberle (2009) are used in this model. If another hydrological model would have been chosen, the results could be different.

In the model a rainfall and snowfall correction is used; hereby there is simulated a bit more or less precipitation than there falls. The average correction for the rainfall is 0.995 and for the snowfall 0.935. For the rainfall there have been made corrections in three sub basins in the sub catchment of Mosselle. For the snowfall there haven't been made correction in the Alps, but only in other sub basins. This is kind of strange if there is used climate change data, because it is supposed that this data is generates the right amount of precipitation and does not need a correction factor.

Definition of a low flow

The LCW values (Rijkswaterstaat, 2009) are used because this norm is used in the Netherlands. There can be asked how the results of the increase of climate change data would be if a different indicator would have been chosen. The different indicators which are chosen behave different due to climate change. For example indicator of the amount of days below 1000 m^3/s increases less than indicator of the deficit. Based on other indicators the conclusions could be different.

For example, in Rheinblick (2010) it is described that the 90th percentile flow has decreased with 0% to 20% in 2071 to 2100. The difference between the results of (Rheinblick, 2010) and the results of this thesis can be explained because the indicator of 90^{th} percentile flow has been used for the determination of a low flow.

Time frame

The uncertainty in the results are due to a timeframe of 30 years for the determination of the different indicators. One extreme event in the time series could have huge influence on the results, by taking more ensembles of the same GCM with RCM scenario into account. It is possible to rule out those events.

7 Conclusions and recommendations

In this chapter the answers on the different research questions are presented and the conclusions are drawn. After the answering of different research questions, the main question can be answered. Based on the discussion and the conclusions some recommendations will be given.

7.1 Conclusions

The research is done to assess the effects of climate change on low flows. Hereby there has been made use of four different RCM's driven by two different GCM: Aladin Arpege, Hirham Arpege, Racmo Echam5 and Remo Echam5.First the different research questions will be answered; furthermore by the objective.

Low flow indicators for the observed discharge at Lobith

In the period 1962-1992 an average of 21.3 days a year with a flow below 1000 m^3/s has occurred, and a yearly average deficit of 128 million m^3 has occurred.

Low flow indicators for the HBV model with observed values

The simulation of the HBV model with observed climate values shows an average of 22.3 days annually with a flow below 1000 m^3/s for the period 1962-1992 and an average deficit of 134 million m^3.For both indicators there is a small overestimation in the simulation with observed values compared with the observed discharge. But the correlation between the observed and simulated deficit are 0.93. However, if the highest value is left out the correlation for the observed and simulated deficit is 0.77, the standard deviation is 358 million m^3. The correlation between the observed and simulation amount of days below 1000 m^3/s is 0.87, the standard deviation is 33.2 days. Based on the comparison of the indicators, it could be concluded that the different indicators have been simulated very accurately by the HBV model and thereafter it is possible to determine the different indicators for low flows.

In the observed discharge, the probability of a year with a flow below 1000 m^3/s is 54%, in the simulation with observed values in the HBV model it is 45%. For the deficit the probability of a deficit is 29% in both the simulation with observed values and the observed discharge.

Low flow indicators for the control period (1962-1992) with climate data

To investigate the effect of a choice of a certain RCM driven by GCM on the different indicators, the control period (1962-1992) is compared with the observed values as input for the hydrological model.

For the indicator of days below 1000 m^3/s, only the Racmo Echam 5 as input to the HBV model is underestimated. In the other scenarios the difference can be explained within the variability. Hereby this indicator, number of days below 1000 m^3/s, can be seen as a good indicator because this indicator is quite robust.

The deficit is only simulated in a representative way in the Aladin Arpege scenario. In the Racmo Echam 5 and Remo Echam 5 as input to the HBV model the deficit was underestimated. In the Hirham 5 Arpege as input to the HBV model the deficit was overestimated.

Overall it can be concluded that low flows are represented in a different way by the different scenarios, especially the amount of deficit is simulated differently in the control run than in the observed values. The indicator of the number of days with a discharge below 1000 m^3/s is simulated quite well in the control run. The bandwidth for the amount of days annually with a discharge below 1000 m^3/s is 12.2 days to 22.7 days in the climate scenarios compared with 22.3 days for the simulation with observed values. The bandwidth for the yearly average deficit is 16 to 360 million m^3 compared to 134 million m^3.The bandwidth for the probability of a flow below 1000 m^3/s in a year is between 41% and 67%, for the probability of a deficit in a year the probability is between 10% and 32%.

Low flow indicators with the effects of climate change

The four different climate scenarios have been run to assess how the two indicators will develop.

In the Aladin Arpege the average deficit decreases, but this can be explained because an extreme event has occurred in the period 1962-1992. This influences this indicator quite a lot. The changes of the number of days with a discharge below 1000 m^3/s are within the variability of the climate. This can be explained because this data series is only to 2050, by then the effects are not quite visible; the effects are the most visible in the period 2050-2100.

For the three climate scenarios with a runtime to 2100, the annual deficit increases with 460% to 2810% if the period 1962-1992 is compared with the period 2070-2100. Hereby it is questionable whether such an increase is realistic; a part of the increase can be explained by low starting values. In the number of days with a discharge below 1000 m^3/s a year the increase fluctuate from 112% to 249% if the period 1962-1992 is compared with the period 2070-2100, this is more realistic than the increase of the deficit. The indicator of the number of days below 1000 m^3/s is more robust than the indicator of the deficit.

The probability on a deficit during a year increases from 80% to 87% in the different scenarios for the period 2070-2100. The probability that a flow below 1000 m^3/s will occur in a specific year is between 80% and 96% in the period 2070-2100. This is quite high and it looks like a yearly event.

Effect of a certain RCMs on the low flow indicators

A comparison between the Aladin Arpege and the Hirham Arpege is made; another comparison is made between the Racmo Echam5 and the Remo Echam5 scenario. By comparing those scenarios it is possible to determine the effects of a certain RCM.

It can be concluded that the temperature and precipitation development in the Rhine basin is dependent on the chosen GCM for the same emission scenario. The Aladin Arpege scenario has a small increase in precipitation and the Hirham Arpege scenario has a decrease in precipitation. A reason for this difference is that two different GCM runs for the Arpege scenarios are used. For the GCM Echam 5 the precipitation is developing in the same direction, in both RCM scenarios.

The developments in the precipitation amount can be the reason why there is a difference in the development of the different indicators for the GCM of Arpege. In the Hirham Arpege scenario the severity of a low flow increases, in the Aladin Arpege scenario the severity decreases. In the Echam 5 scenario the development of the severity of a low flow is about the same for both RCM's.

The differences in the low flow indicators are therefore not only due to different RCM's, but also influenced by the differences between these GCM runs, resembling the natural variability of climate.

Objective

The objective of the research is to determine:

Possible changes in the occurrence of low flows in the Rhine River over the 21ste century due to climate change, by using a hydrological model with data from different GCM with RCM output provided by the KNMI.

The severity of a low flow increases due to climate change in 3 out of 4 RCM with GCM scenarios. The increase is both for the amount of days below 1000 m^3/s and for the total deficit.

Four climate change scenarios have been investigated: Aladin Arpege, Hirham Arpege, Racmo Echam5 and Remo Echam5. Only the Aladin Arpege was available for 1961-2050, the three other scenarios are available for 1961-2100. With respect to the different scenarios only the Aladin Arpege shows a slight decrease in the severity and in the amount of low flows. When 1962-1992 is compared with 2020-2050; the decreases are for both of the indicators, the deficit and the amount of days with a discharge below 1000 m^3/s. This can be explained by the fact that an extreme event occurred in the period 1962-1992, which had quite some influence on the different indicators. However this change can be explained by the variability of flows, so no firm conclusion can be given on this scenario.

With respect to the other three scenarios, Hirham Arpege, Racmo Echam5 and Remo Echam5, the amount of low flows will increase when the period 1962-1992 is compared with the period 2020-2050 and the increase will even be larger in the period 2070-2100. The increase occurs for both indicators: the deficit and the amount of days with a discharge below 1000 m^3/s.

The probability on a deficit during a year increases from 80% to 87% in the different scenarios for the period 2070-2100 compared to a probability of 10% to 32% for the period 1962-1992. The probability that a flow below 1000 m^3/s will occur during a year is between 80% and 96% in the period 2070-2100 for the different scenarios, compared to a probability between 41% and 67% for the period 1962-1992. The increases are quite high.

The yearly deficit increases from 460% to 2810% if the period 1962-1992 is compared with the period 2070-2100, hereby it is questionable whether such an increase is realistic; a part of this increase can be explained by the low starting values in the reference period. With respect to the amount of days with a discharge below 1000 m^3/s a year; this increases from 112% to 249% if the period 1962-1992 is compared with the period 2070-2100. This is more realistic than the increase of the deficit. The indicator of the number of days below 1000 m^3/s is more robust than the indicator of the deficit.

Summarized it can be assumed that the severity and probability of occurrence of low flows will increase in the future. This is described in the literature (Hurkmans et al.,2009; Kwadijk and Rotmans,1995; Middelkoop et al.,2001).

7.2 Recommendations

Based on the results several recommendations are given for further research. These recommendations are:

Sensitivity of the model

- The research could be conducted with different hydrological models. This could be done because different hydrological models can give different results.

Definition of a low flow

- There could be investigated how a low flow behaves if other indicators are used. The different indicators behave different.

Climate change data

- Sensitivity analysis: especially because data is randomly generated, hereby there can be asked what would be the results if 5% more precipitation falls, or if 5% less precipitation falls.
- Further investigation could be done on the effects of different bias correction methods on the effects of the indicators.
- The research could be done with some more climate change scenarios. Hereby a wider range of the results can be expected. Hereby are the A1B, A2 scenario and different RCM and GCM scenarios can be used as input.

Research based on my research

- Other research could be done on the variability of the low flows of occurrence.
- At what period the low flows do occur, do the low flow mostly occur in the winter or in the summer.

Prevent the effects of a low flow

- A research can be done on which measures can be taken upstream to prevent low flows, so that the amount of a low flows will be reduced.
- After the determination of the magnitude of a low flow, an investigation can be done to assess which adaptive measures could be taken to reduce damage due to low flows.

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Appendix A: A map with different sub basins of the Rhine River

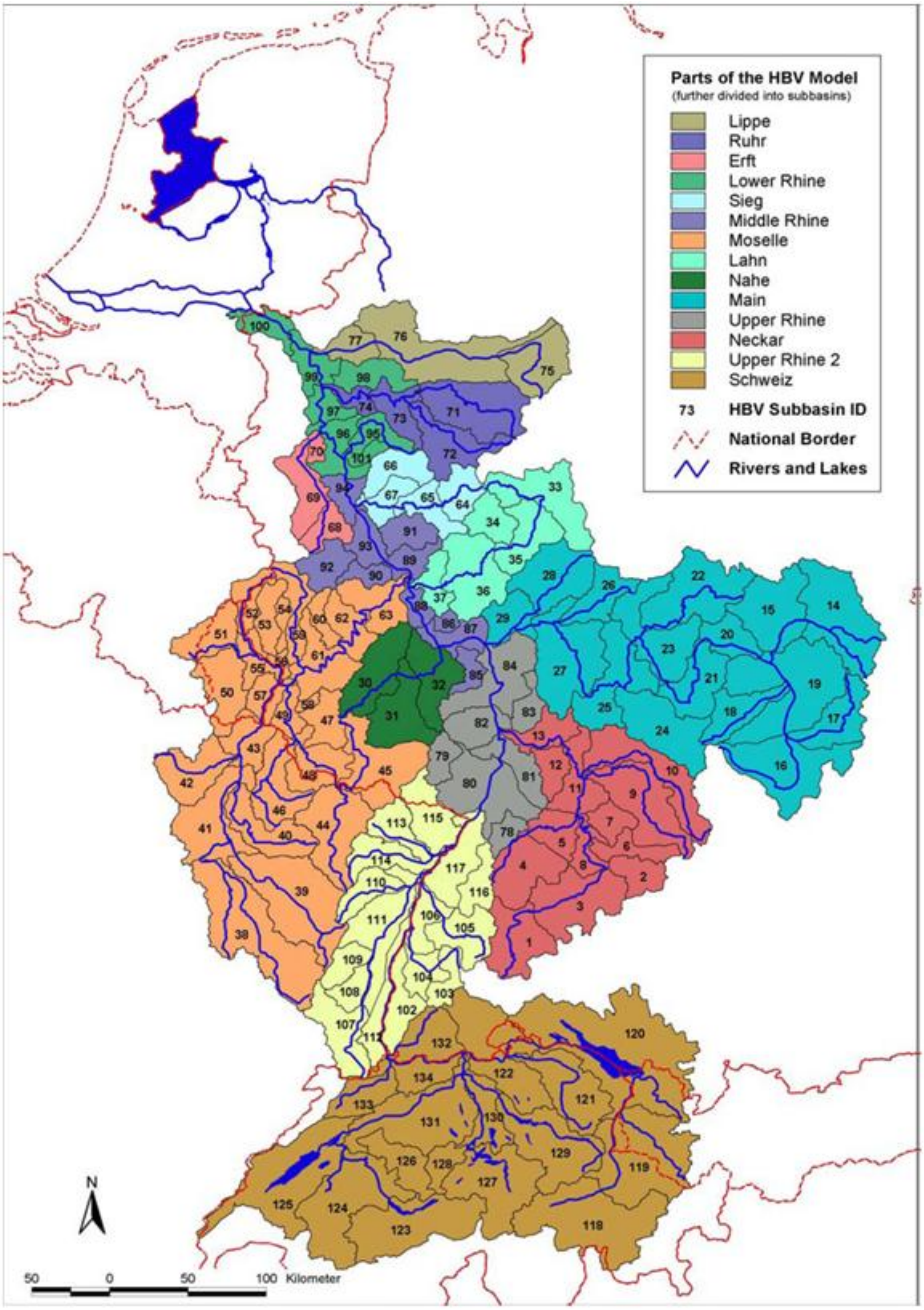

Figure 13: Different sub basins of the Rhine River

Figure 13 shows the map with the different sub-basins of the Rhine River. (BFG & RIZA, 2005)

Appendix B: Hydrograph for simulation with observed values

In this appendix the different hydrographs for the observed values will be presented.

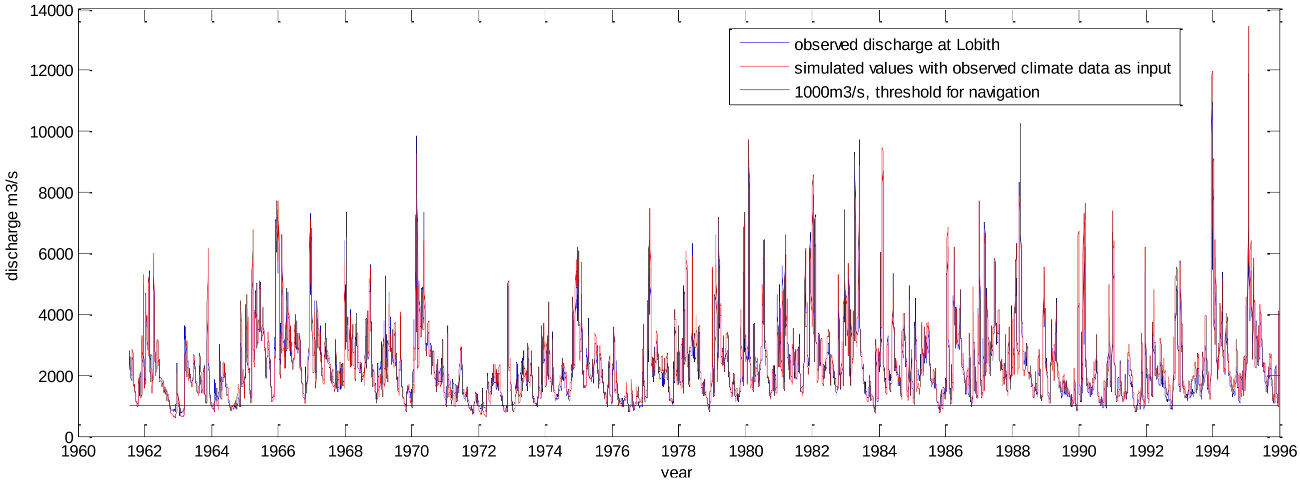

Figure 14: Hydrograph of HBV model with observed precipitation and temperature data

Appendix C: Ranking the deficit

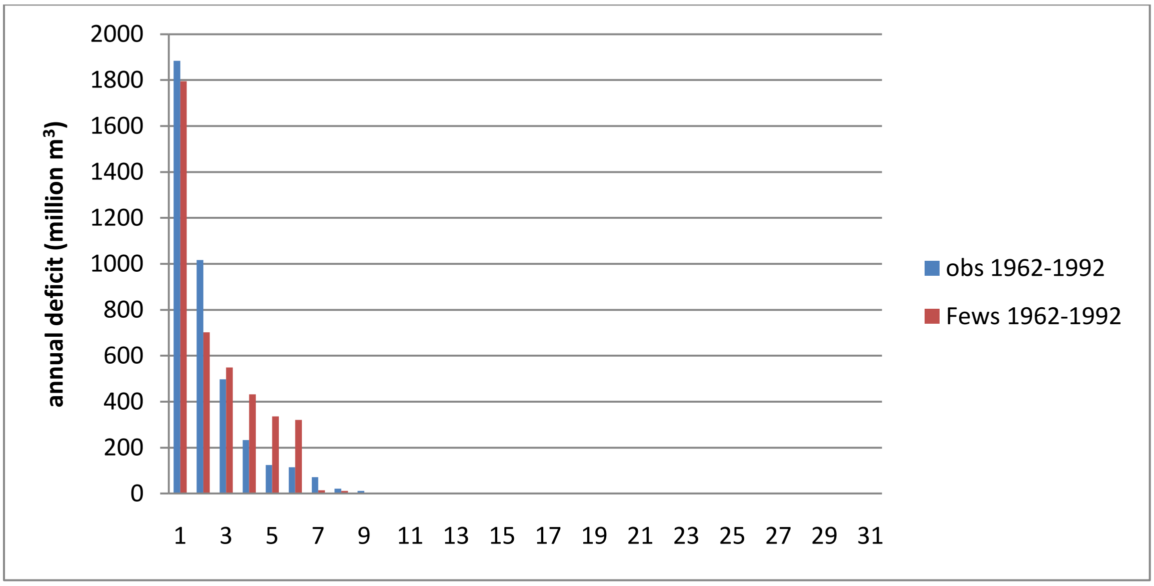

Figure 15: Ranking the deficit for the observed discharge and the output of the HBV model with observed climate data

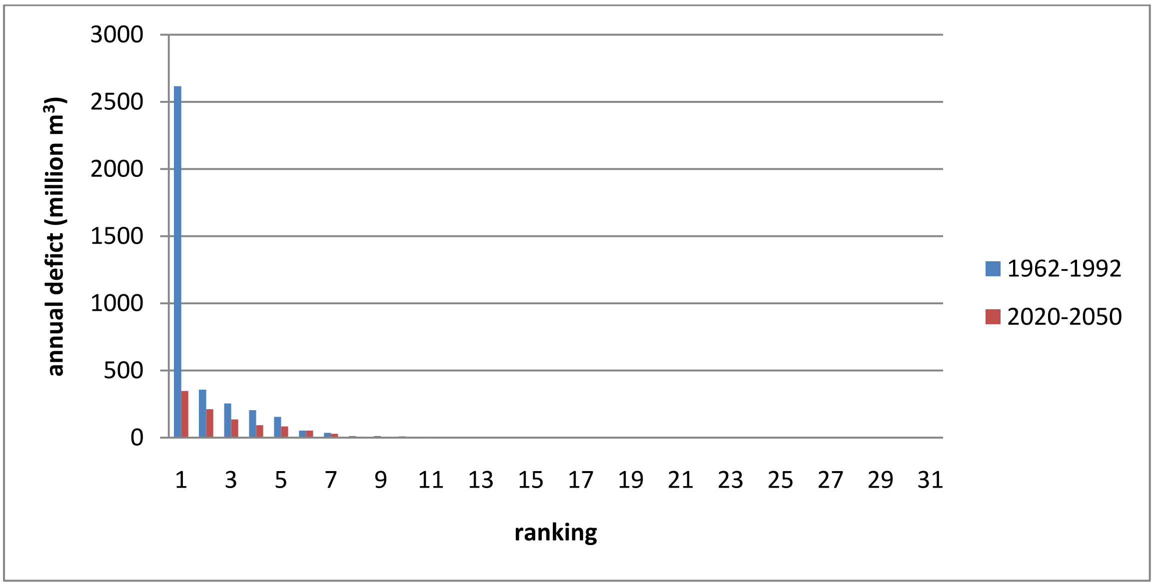

Figure 16: Ranking the deficit for the Aladin Arpege scenario

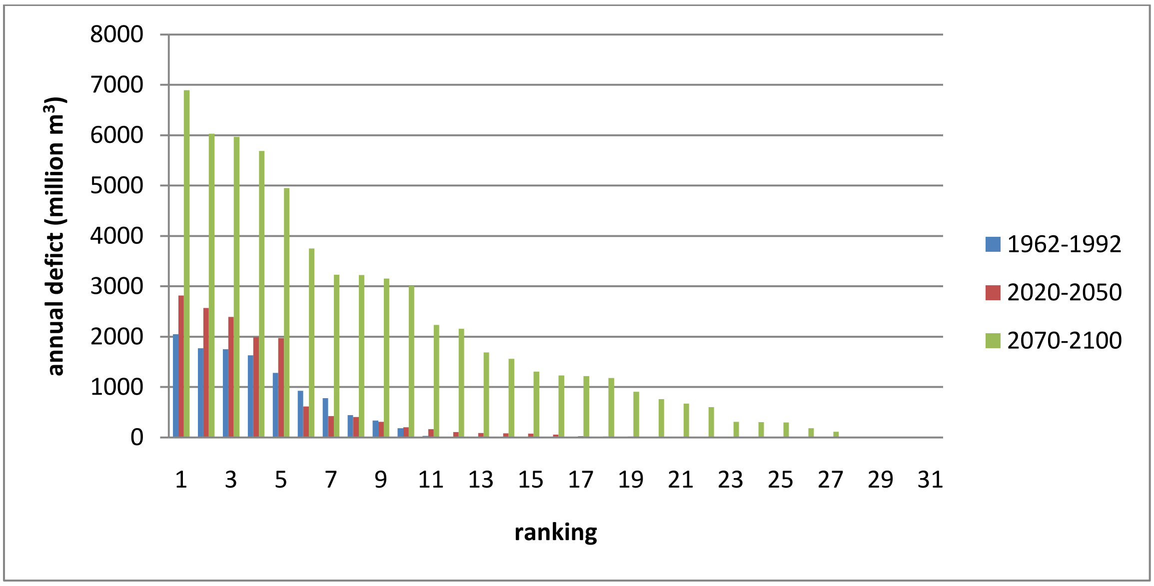

Figure 17: Ranking the deficit for the Hirham 5 Arpege scenario

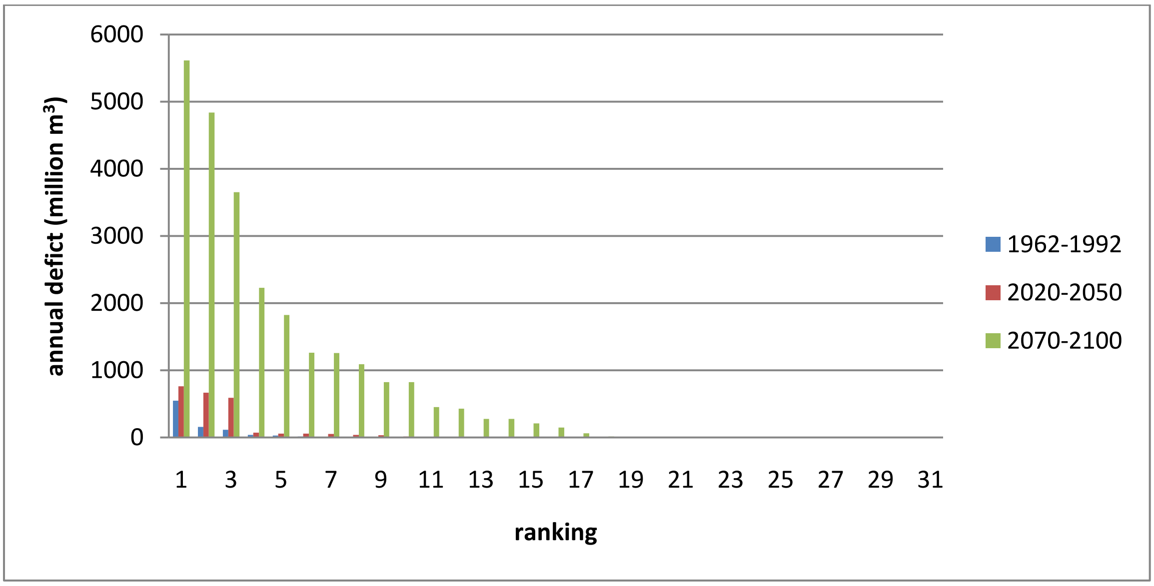

Figure 18: Ranking the deficit for the Remo Echam5 scenario

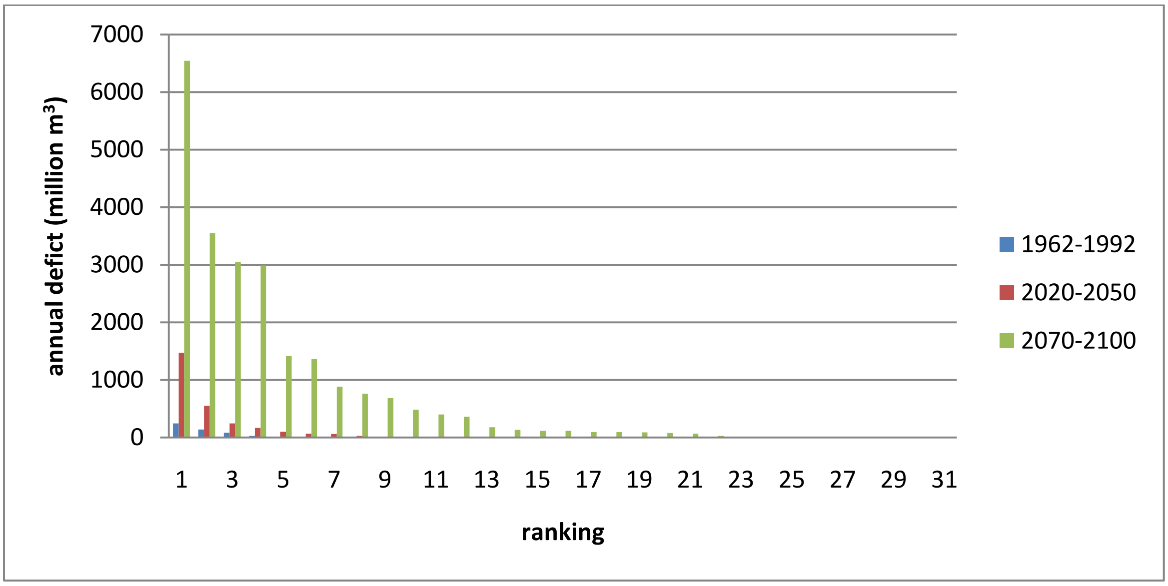

Figure 19: Ranking the deficit for the Racmo Echam5 scenario

Appendix D: Ranking the amount of days below 1000 m³/s

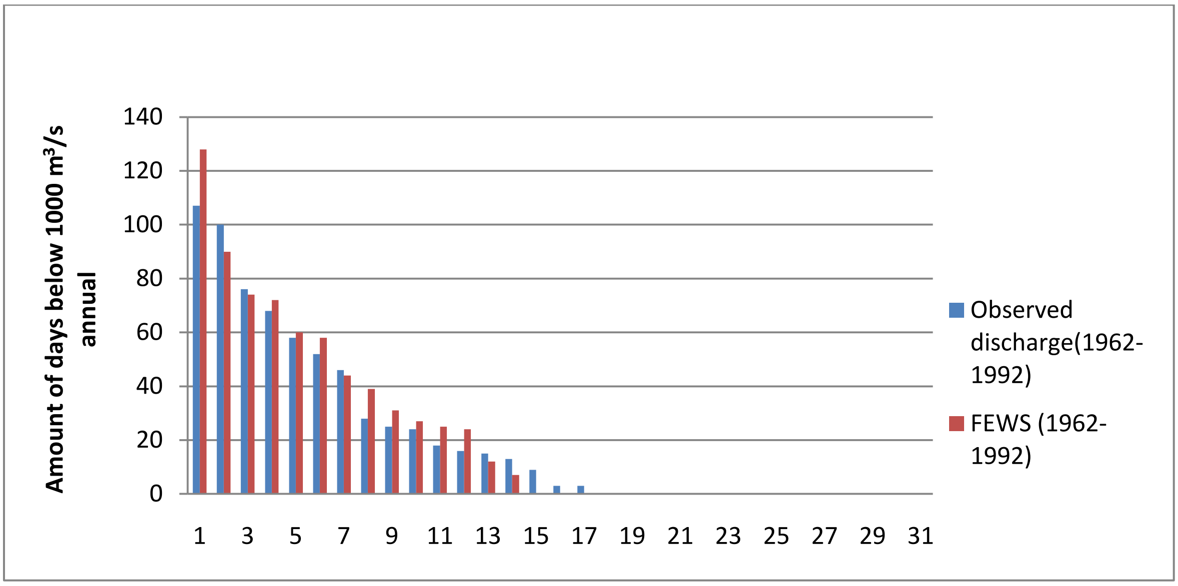

Figure 20: Ranking the amount of days below 1000m³/s annual for the observed discharge and the output of the HBV model with observed climate data

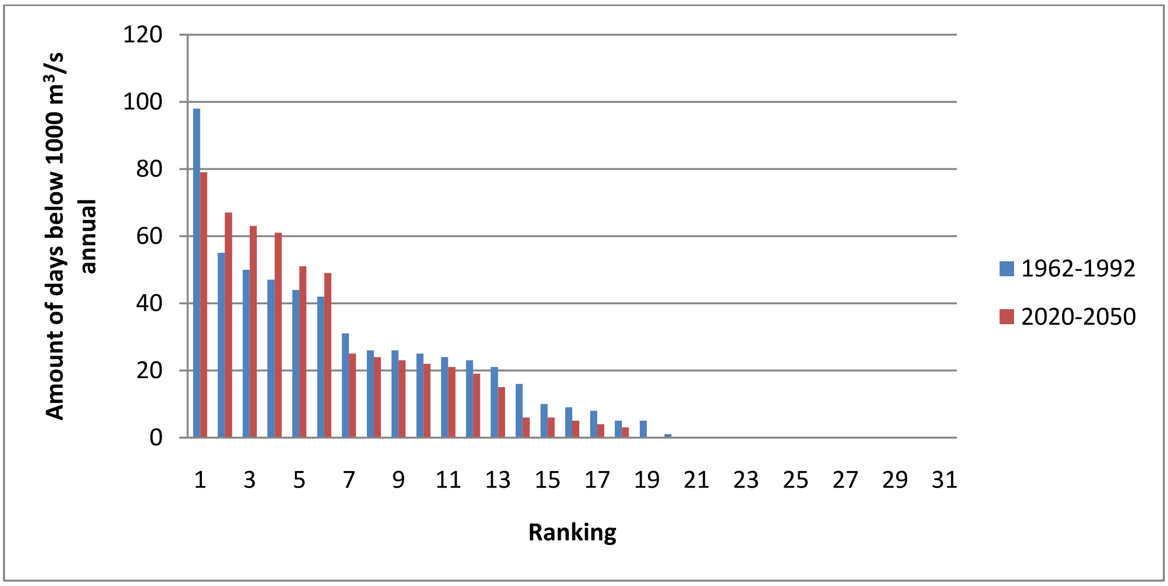

Figure 21: Ranking the amount of days below 1000 m³/s annual for the Aladin Arpege scenario

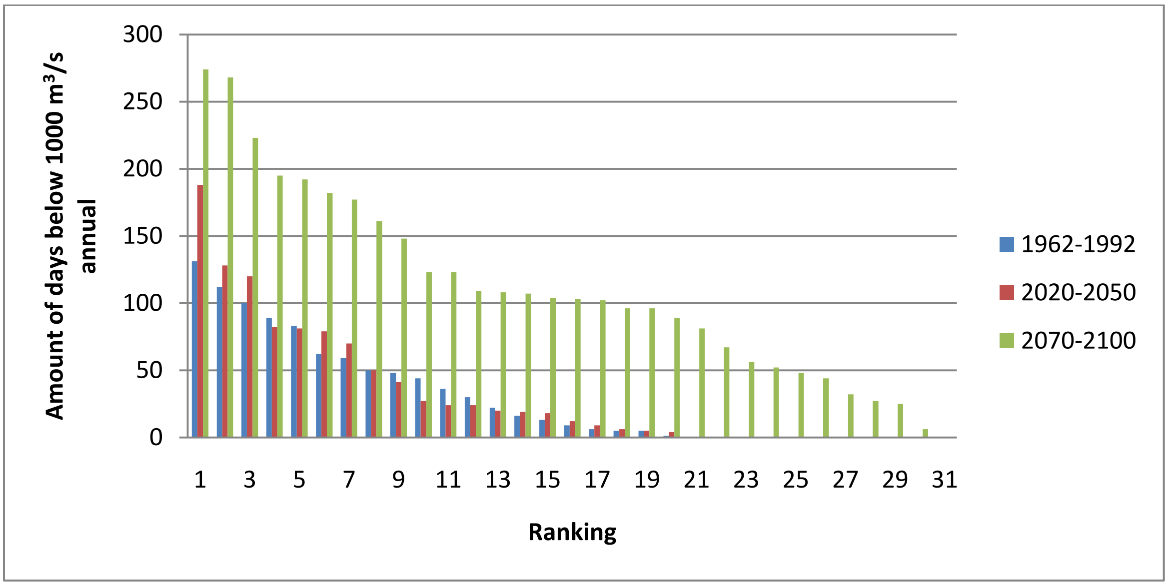

Figure 22: Ranking the amount of days below 1000 m^3/s annual for the Hirham Arpege scenario

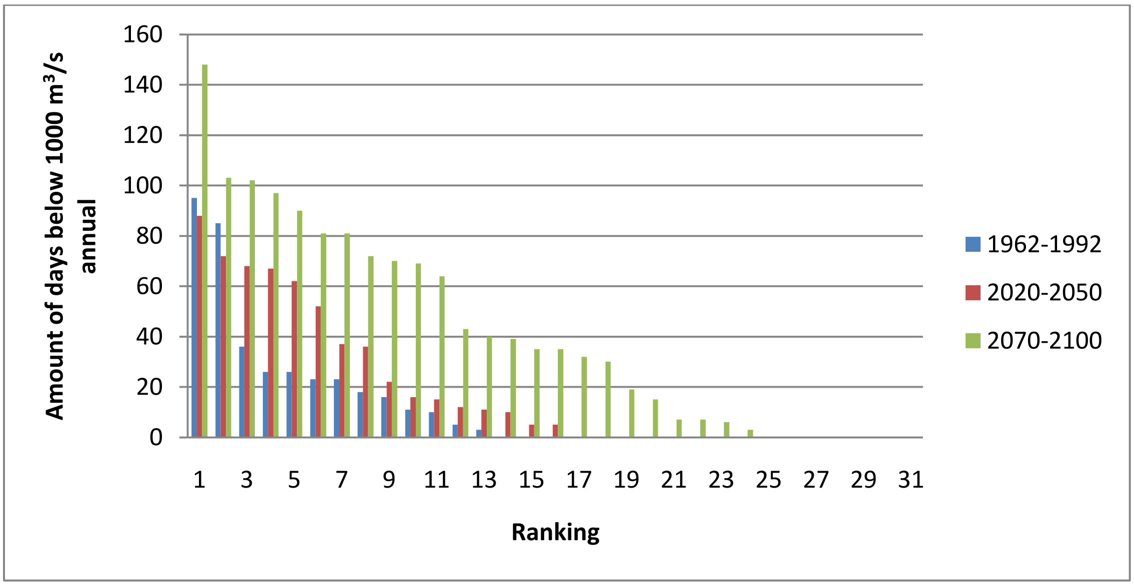

Figure 23: Ranking the amount of days below 1000 m^3/s annual for the Racmo Echam5 scenario

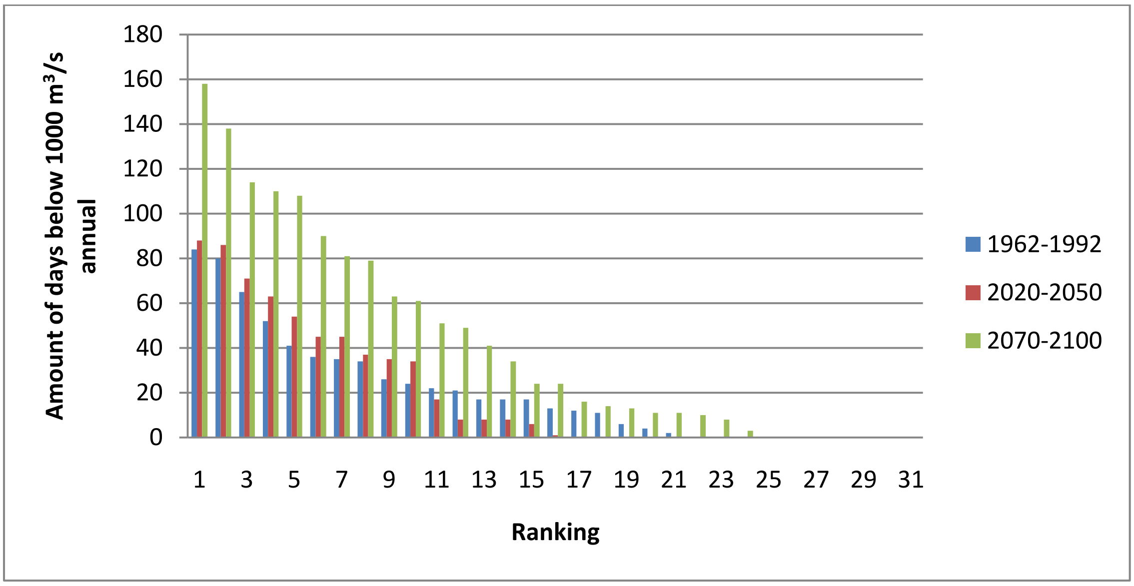

Figure 24: Ranking the amount of days below 1000 m^3/s annual for the Remo Echam5 scenario