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Comparison of CMIP5 climate model projections and preliminary KNMI'14 scenarios with earlier climate assessments for the Rhine and Meuse

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1209424-002

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Client	**Project**	**Reference**	**Pages**
Rijkswaterstaat, WVL	1209424-002	1209424-002-ZWS-0001	50

Keywords
Rhine, Meuse, CMIP5 climate projections, KNMI'14 scenarios, climate impact assessment

Summary
In this study we assessed potential changes in discharge for the Meuse and Rhine using (1) a selection of 191 simulations from the recently developed Coupled Model Intercomparison Project (CMIP5) datasets and (2) a preliminary version of the KNMI’14 scenarios for the Rhine and Meuse basins. A final version of the latter is still under development. To generate discharge projections, the HBV models for the Meuse and Rhine were run with the climate datasets which were down-scaled to the HBV sub-catchments by KNMI. The results of the discharge change analysis were compared with existing discharge change projections i.e. those based on KNMI’06 and the results from the AMICE and RheinBlick2050 projects. The analysis focussed on monthly mean discharge cycle, minimum and maximum flow. It should be noted that the comparison may be influenced by the use of different hydrological model versions, climate bias-correction / down-scaling methods and potential evaporation in the different scenario analysis.

Results indicate that for both rivers there is a general tendency towards increasing spring discharge and decreasing late summer discharge. For the Meuse mean and maximum discharge are projected to increase whereas minimum discharge is projected to decrease. For the Rhine maximum discharge is also consistently projected to increase and minimum flow is projected to decrease. Mean annual discharge will clearly increase according to most (preliminary) KNMI’14 scenarios and the CMIP5 projections.

Comparison of the new projections with the existing scenarios resulted in the following conclusions:

- The new climate change scenarios (KNMI’14 and CMIP5) for the Meuse basin are overall in agreement with the existing scenarios datasets (KNMI’06 and RheinBlick2050). Except that according to this analysis the majority of CMIP5 scenarios project a decrease instead of increase in annual mean flow and more specifically a large decrease for late summer.
- For the Rhine, projected discharge changes are overall smallest in the KNMI’14 scenarios and the scenario band-with is often relatively narrow compared to the other scenario sets.
- According to the new scenario sets annual mean discharge for the Rhine will increase for all locations, with a smallest increases at Trier. Large late summer discharge decreases are projected by part of the CMIP5 models, whereas the KNMI’14 scenarios project relatively moderate decreases compared to all other scenario datasets.

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Version	Date	Author	Initials	Review	Initials	Approval	Initials
	sept. 2014	Frederiek Sperna Weiland		Erik Ruijgh		Gerard Blom	
		Laurene Bouaziz					
		Jules Beersma					

State
final

This is an intermediate rather than a final report on the impact of new climate change scenarios on the discharge characteristics of the Rhine and the Meuse. It is mainly intended for discussion purposes. Since this study made use of preliminary KNMI'14 scenarios for the Rhine and Meuse the results (and conclusions) in this report may *not* be relied upon.

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1 Introduction

Background
As part of the KPP program Transnational Cooperation – which focuses on studies and knowledge development in the transboudary river basins Rhine and Meuse – RWS requested Deltares and KNMI to perform a comparison of the newly available KNMI'14 scenarios and CMIP5 climate model projections with the existing climate projections for the Rhine and Meuse. These are (1) the Delta scenarios based upon the KNMI'06 scenarios developed for the Dutch Delta Program, (2) the international AMICE project and (3) the RheinBlick2050 project. These comparisons should give an impression of the validity of the existing climate scenario projections and an indication of the quality and impact of the new scenarios. The release of the final KNMI'14 scenarios has been delayed. The current report contains the work done in 2013 – 2014 and here the preliminary KNMI'14 scenarios are presented. The report will be finalized in 2015.

Scenario comparison
Within the current study the impact of (1) the preliminary set of KNMI'14 scenarios for the Rhine and Meuse (recently developed by KNMI) and (2) the recently released CMIP5 climate model datasets are presented and compared with discharge projections based on:

(1) the earlier KNMI'06 climate scenarios,
(2) results of the RheinBlick2050 project for the Rhine and
(3) results of the AMICE project for the Meuse.

The HBV model has been used to model river discharges for all climate model datasets.

Climate datasets used for the IPCC 5th assessment report
In 2013 the IPCC 5th assessment report was published (IPCC, 2013) and new climate model datasets (CMIP5) became available. For many of these datasets a new, and ideally improved, generation of climate models was used and the scenario philosophy changed. KNMI developed an efficient method to down-scale these datasets to the Meuse and Rhine sub-catchments (Van Pelt et al., 2012; Kraaijenbrink et al., 2013). This enabled Deltares to perform a large number of HBV simulations based on an ensemble of climate datasets from the IPCC 5th assessment report in order to assess changes in discharge extremes and their uncertainties for both the Rhine and Meuse rivers.

KNMI'14
KNMI has recently published the new set of climate scenarios for the Netherlands – KNMI'14 - the follow up of the KNMI'06 scenarios. In contrast to KNMI'06, KNMI planned to construct sets of (four) climate scenarios that are specifically designed for the Rhine and the Meuse basins. These KNMI'14 climate scenarios for the river basins should be consistent with the KNMI'14 climate scenarios for the Netherlands and with the CMIP5 climate model projections for the river basins. In contrast to KNMI'06, the KNMI'14 climate scenarios will have spatial gradients (of the changes) over the river basins. In this report a first (preliminary) set of four KNMI'14 scenarios for the river basins is used to assess the hydrological impact in the Rhine and Meuse basins. For the river basins the definitive set of KNMI'14 climate scenarios is not ready yet. The 'driest scenario in summer' in the preliminary set (the W_H scenario) turned out (in comparison with CMIP5) not dry enough.

This set of KNMI’14 scenarios for the river basins will therefore in the (near) future be replaced by KNMI by a definite set. For the W_H scenario in summer it is expected that the difference will be considerable. For all the other individual scenarios (and the individual seasons) it is impossible to say if and how much it may change. The only thing KNMI can say now is that the changes are expected to be small and definitely smaller than for the W_H scenario. The KNMI’14 discharge results presented here are thus not the definitive KNMI’14 discharge results and an update will follow.

Previous climate impact assessments for the Rhine and Meuse

RheinBlick2050
Over the period 2008-2010 an international climate impact assessment was made for the Rhine river basin within the project RheinBlick2050 (Görgen et al., 2010). The project was initiated by the international Commission for the Hydrology of the Rhine Basin (CHR) and project partners came from research institutes and governmental organizations from all Rhine countries. A thorough assessment was made based on climate model projections from the EU FP6 ENSEMBLES database which contains dynamically (=RCM) down-scaled GCM runs from the IPCC 4th assessment report. In the uncertainty analysis of the projected climate changes it was tried to fully assess uncertainties in climate models, scenarios, down-scaling / bias-correction techniques and hydrological models.

AMICE
Over the period 2009-2012 an international climate impact assessment was made for the Meuse river basin. This assessment was executed by research institutes and water managers from all Meuse countries and was part of the INTERREG-IVB project AMICE - ***A****daptation of the* ***M****euse to the* ***I****mpacts of* ***C****limate* ***E****volution*. RWS was one of the project partners and Deltares conducted the hydrological analysis for RWS (Drogue et al., 2010).
Similar to the RheinBlick2050 project, the AMICE project strengthened the relation and the international co-operation between the Meuse countries and resulted in a number of scientific reports as well as successful pilot climate adaptation projects. Yet, due to time and budget limitations some simplifications have been made in the climate analysis. Future climate scenarios have been derived using a delta approach, consisting of one delta for the dry season and one delta for the wet season. The deltas have been derived by weighted-averaging the changes from national climate impact assessment. Weights were derived from the basin area within each country.

Objectives

The objectives of this study are:

(1) To assess the hydrological impacts of climate change on the Rhine and Meuse rivers based on the preliminary KNMI’14 scenarios and the CMIP5 climate model projections for the river basins.
(2) To compare the hydrological changes from (1) with the results of the KNMI’06 based hydrological projections, RheinBlick2050 results (for the Rhine) and the AMICE results (for the Meuse).

Organization of the report

In this report we first summarize the climate scenarios/climate model projections and methods applied within RheinBlick2050, AMICE and the KNMI'06 scenarios. We then describe the scenarios/projections and methodology used for the CMIP5 and (preliminary) KNMI'14 assessments. Finally we compare the results of these new assessments with the results of the earlier assessments and draw conclusions. In the Appendix an analysis is made of the applicability of the HBV method to derive potential evaporation.

2 Earlier climate impact assessments for Meuse and Rhine

2.1 General

2.1.1 KNMI’06 scenarios -Method

The KNMI’06 scenarios consist of four distinct climate change scenarios for 2050 and 2100. The scenarios were designed for The Netherlands and include seasonal and monthly changes in temperature and precipitation. The scenarios have been constructed using information and statistics derived from GCM simulations that are part of the IPCC 4th assessment report (AR4), see for more information Hurk et al. (2006). The precipitation and temperature changes from KNMI’06 were used to transform historical observed time-series for the Rhine (for 134 HBV sub-basins for the period 1961-1995, i.e. the so-called CHR-OBS data) and Meuse (for 15 HBV sub-basins for the period 1961-1995; Leander et al., 2005) with the classical Delta Change method (Gellens and Roulin, 1998). Within this method only changes in the means are taken into account. The HBV model has been run with both the historical observed time-series and the transformed precipitation and temperature time-series to assess potential future changes.

The KNMI’06 dataset provide 4 scenarios for both 2050 and 2100:

Scenario	Global Temperature increase in 2050	Change of atmospheric circulation
G	+1°C	weak
G+	+1°C	strong
W	+2°C	weak
W+	+2°C	strong

The relevant results of the KNMI’06 scenarios are presented in Chapter 4 together with the corresponding results for KNMI’14, CMIP5 and RheinBlick2050 / AMICE climate datasets.

2.2 Rhine

2.2.1 RheinBlick2050 - Method

Within the RheinBlick2050 project (Görgen et al., 2010) an ensemble of 20 dynamically down-scaled bias-corrected regional climate simulations were used to force the hydrological HBV134 model at a daily time-step over all Rhine sub-catchments.

The regional climate datasets were mainly obtained from the EU FP6 ENSEMBLES database, the selection existed of the A1B scenario and runs which were mainly forced by the GCMs HadCM3 and ECHAM5. Multiple bias-correction techniques were applied and compared. For the assessment of changes in extreme high flows the rainfall generator methodology of KNMI was used to extend the 30-year RCM time slices to 3000-year time series.
From the resulting ensemble of hydrological model simulations, changes in mean discharge, high and low flows have been assessed both for the near (2021-2050) and far (2071-2100) future.

Deltares contributed to the RheinBlick2050 project by conducting the hydrological simulations with the HBV134_Deltares model under future climate conditions. This version of the HBV model applied was calibrated based on the CHR-OBS (1961-1995) dataset by Eberle et al. (2005). For details see Görgen et al. (2010), section 2.4. The results of the analysis of changes in extreme high flows are presented in chapter 7 of Görgen et al. (2010). For this, an ensemble of 7 bias-corrected RCM model projections was used (for details see Görgen et al. (2010), section 3.2).

The most relevant results of RheinBlick2050 are presented in Chapter 4 of this report.

2.3 Meuse

2.3.1 AMICE – Method

Within the AMICE project pre-existing national climate scenarios, based on climate datasets from meteorological institutes and national and EU research projects, were used. This was done because many datasets were already available and the AMICE project was too short to run new simulations. All scenarios were based on climate models used for the IPCC 4th assessment report. They provided projected changes in summer and winter precipitation and temperature for a number of IPCC emission scenarios.

To generate international scenarios for the Meuse basin each country selected a wet and a dry projection from its national projections. Subsequently, from these national projections each country individually derived, for the two future time-horizons, two deltas; one for the wet season and one for the dry season.
Due to the large heterogeneity between the projections available for the different countries it was decided to derive basin wide transnational seasonal deltas. These basin wide deltas were derived by straightforward weighted averaging of the national delta values. Here the weights we derived based upon the area of the Meuse basin located in each country. This resulted in four basin average delta values, for the future time horizons 2050 and 2100 one delta for the wet and one for the dry season (for more information see Drogue et al., 2010).

The resulting deltas were applied to the historical E-OBS 0.25 gridded dataset (Haylock et al., 2008) to obtain future time-series. Hydrological simulations were conducted to assess the impacts of climate evolutions on high- and low-flow discharges during the 21st century (focussing on 2021-2050 and 2071-2100). Each AMICE-partner used his own hydrological model.

For Deltares this was the HBV-Meuse model calibrated by Van Deursen (2004). Unfortunately, for this HBV model the results derived with the meteorological E-OBS dataset, that was used by the other AMICE project partners, were not satisfactory. This might be due to the fact that in the E-OBS dataset, fewer weather stations are included than in the dataset the HBV-Meuse model was calibrated with. Therefore a historical dataset of precipitation and temperature timeseries for the 15 HBV basins for the period 1961-1998 constructued by KNMI was used. The same dataset had also been used for the calibration of the HBV model (Leander et al., 2005; Keizer and Kwadijk, 2009; Van Deursen et al., 2009).

3 Methodology: Generation of discharge projections for the Rhine and Meuse based on CMIP5 datasets and preliminary KNMI'14 scenarios

3.1 CMIP5

In 2013 the 5th IPCC assessment report has been published (IPCC, 2013). The climate simulations of this report have been conducted with climate models that were part of the fifth phase of the Coupled Model Intercomparison Project (CMIP5). Compared to the scenarios of the 4th assessment report, the definition of the climate forcing is new (Van Vuuren et al., 2010; IIASA, 2013). Previously, the climate models were forced with greenhouse gas concentrations which were prescribed by the IPCC SRES emission scenarios. Within the 5th assessment report, four Representative Concentration Pathways (RCPs) are prescribed that are used as climate model forcing. These RCPs each follow a pre-defined path of radiative forcing (W/m^2) that belongs to certain emission scenarios:

- RCP 2.6: In this pathway the radiative forcing peaks around 2050 after which there is a modest decline towards 2100 due to a declining use of oil and an overall decrease in energy use;
- RCP 4.5: In this pathway the radiative forcing stabilizes before 2100 due to the introduction of technologies and strategies that reduce greenhouse gas emissions;
- RCP 6.0: Here a stabilization, due to the introduction of technologies for greenhouse gas emissions, is reached after 2100;
- RCP 8.5: In this pathway there is a continuously increasing radiative forcing.

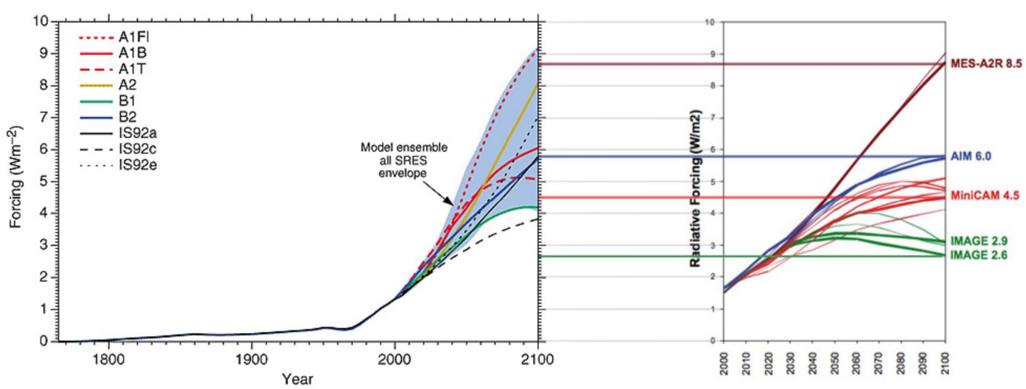

Figure 3.1 Comparison between radiative forcing according to the earlier IPCC scenarios IS92 and AR4 (left) and the new RCPs (right) after (IPCC, 2001; Moss et al., 2008; Taylor et al., 2012; Vecchi, 2012)

KNMI decided to exclude the RCP 2.6 as it is relatively conservative and maybe too optimistic on the reduction of radiation forcing, therewith inducing relatively small changes in temperature and precipitation patterns. Note that near 2100 the radiative forcing in the low RCP scenarios (green lines in the right panel of Fig 3.1) is much lower than in the IPCC 4th assessment report (left panel of Fig. 3.1.

3.1.1 The Advanced Delta Change method for down-scaling the CMIP5 datasets

KNMI has developed an Advanced Delta Change method (ADC-method; Van Pelt et al., 2012) where the climate responses of GCMs are used to modify historical observed precipitation and temperature time series. In addition to changes in temporal means, this method also takes changes in variability and extremes into account, thereby allowing for an analysis of the effects of changes in future precipitation extremes. In this report the method is applied to precipitation and temperature time-series for the HBV-catchments of the Meuse and Rhine. The method generates future precipitation and temperature time-series for 191 CMIP5 datasets, containing multiple RCP's, GCM's, time-horizons and varying initial conditions.

In 2012–2013 a software package was developed which makes it easy to apply the ADC method for each of the CMIP5 GCM simulations to historical datasets anywhere in Europe. Below follows a short description of the ADC method, a detailed description of the application of this method to CMIP5 climate model simulations can be found in Ruiter (2012) and Kraaijenbrink (2013).

Historical data

Meuse

For the Meuse basin the historical precipitation and temperature data from French and Belgium meteorological surveys were interpolated to the 15 HBV-Meuse sub-basins (Buishand and Leander, 2011; Leander, 2009). The resulting historical meteorological dataset covers the period 1967-2007. For AMICE and the KNMI'06 scenarios the same dataset is used as reference, yet the time-series reached up to 1998 at that time.

Rhine

Precipitation: For precipitation in the Rhine basin version 2 of the HYRAS dataset prepared by the German Weather Service (DWD) is used (Rauthe et al., 2013). HYRAS is a gridded daily dataset with a spatial resolution of 1 km^2, which covers the period 1951 to 2006. It has been obtained by linear regression and inverse distance weighting based on 6200 precipitation stations (Rauthe et al., 2013). The gridded time-series have been aggregated to the 134 HBV catchments of the Rhine based on Thiessen's method.

Temperature: The temperature time-series for the 134 HBV sub-basins have been obtained by spatial aggregation (Thiessen's method) of the European gridded E-OBS 0.25 gridded dataset (Haylock et al., 2008). The E-OBS dataset used a daily times-step. The temperature grids have been obtained by spatial interpolation of station data of approximately 2316 stations. The exact number varies over time and the station density is relatively high in Switzerland and the Netherlands (Haylock et al., 2008).

For RheinBlick 2050 and the KNMI'06 scenarios the CHR-OBS dataset has been used as reference.

Global climate model data

From the available CMIP5 runs (IIASA, 2013) the 191 runs with both daily precipitation and temperature data for the time-slices 1961-1995, 2021-2050 and 2071-2100 have been selected. Figure 3.2 lists the GCMs used together with the number of model runs per GCM (= runs with different initial conditions that represent natural climate variability) and the number of runs per RCP.

Model (n=31)	Model runs	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5	Total
ACCESS1-0	1	-	1	-	1	2
ACCESS1-3	1	-	1	-	1	2
bcc-csm1-1	1	1	1	1	1	4
bcc-csm1-1-m	1	1	1	1	1	4
BNU-ESM	1	1	1	-	1	3
CanESM2	5	5	5	-	5	15
CCSM4	3	3	3	3	3	12
CMCC-CESM	1	-	-	-	1	1
CMCC-CM	1	-	1	-	1	2
CMCC-CMS	1	-	1	-	1	2
CNRM-CM5	1	1	1	-	1	3
CSIRO-Mk3-6-0	10	10	10	10	10	40
FGOALS-s2	3	1	3	1	3	8
GFDL-CM3	1	1	-	1	1	3
GFDL-ESM2G	1	1	1	1	1	4
GFDL-ESM2M	1	1	1	1	1	4
GISS-E2-R	1	-	1	-	-	1
HadGEM2-CC	3	-	1	-	3	4
HadGEM2-ES	4	4	4	4	4	16
inmcm4	1	-	1	-	1	2
IPSL-CM5A-LR	4	4	4	1	4	13
IPSL-CM5A-MR	1	1	1	1	1	4
IPSL-CM5B-LR	1	-	1	-	1	2
MIROC-ESM	1	1	1	1	1	4
MIROC-ESM-CHEM	1	1	1	1	1	4
MIROC5	3	3	3	1	3	10
MPI-ESM-LR	3	3	3	-	3	9
MPI-ESM-MR	3	1	3	-	1	5
MRI-CGCM3	1	1	1	1	1	4
NorESM1-M	1	1	1	1	1	4
EC-EARTH-v2.3	8	-	-	-	8	8
Total	69	46	57	30	66	**199**

Figure 3.2 Overview of GCMs used in this study (excl EC-EARTH) together with the number of available runs and the number of specific RCPs available for those runs (Kraaijenbrink, 2013)

ADC method

Figure 3.3 summarizes the ADC method which will be described below.

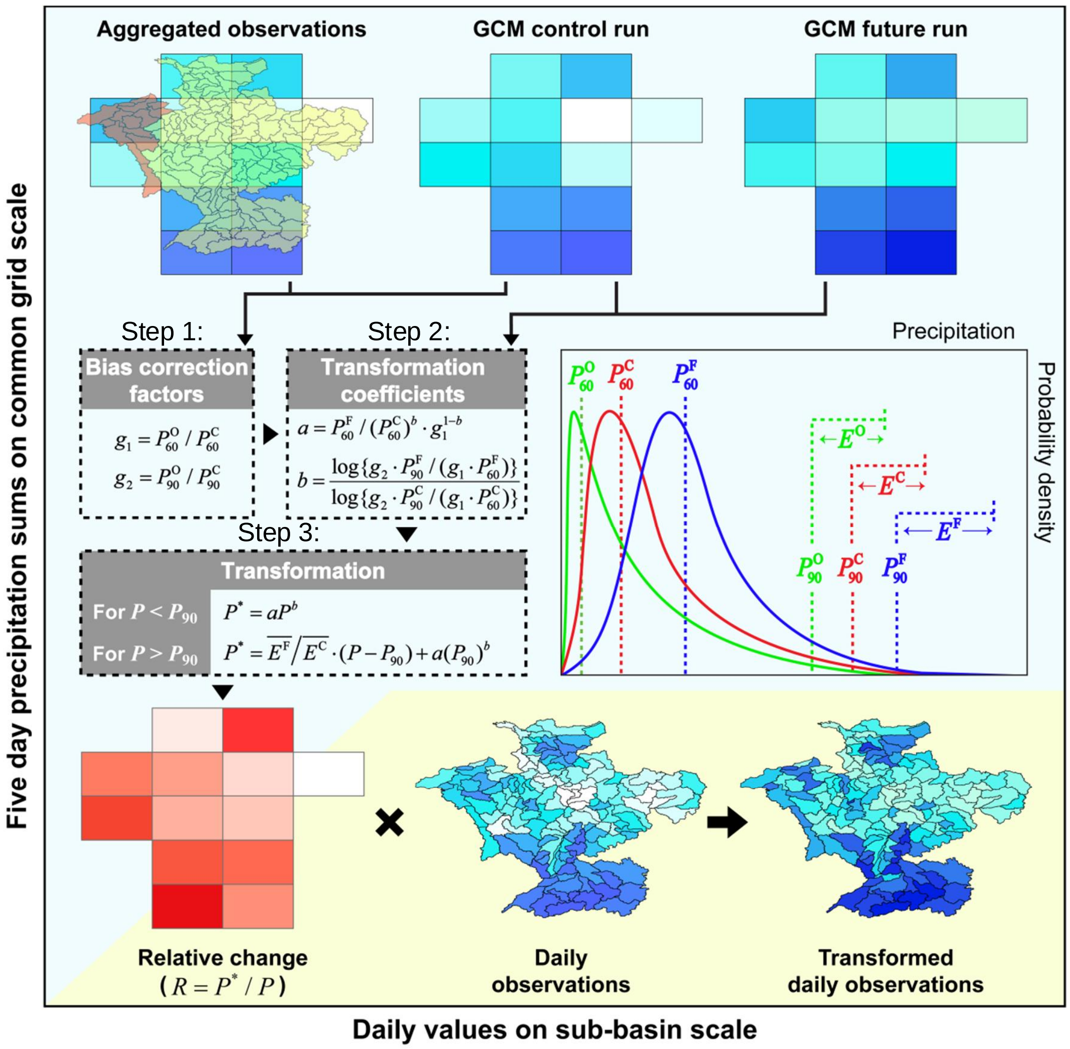

Figure 3.3 *Schematic overview of the Advanced Delta-Change method (source: Kraaijenbrink, 2013; after Van Pelt et al., 2012)*

Spatial aggregation

In the first step of the ADC method all GCM datasets are interpolated to a common grid with a resolution of 1.25 degrees latitude and 2.0 degrees longitude (top row Fig. 3.3). For each grid cell within the Rhine / Meuse basin, the cell specific values are smoothed by averaging the cell’s value with the values of its eight-neighboring cells of the larger European grid and assigning the average value to the center cell.

Temporal aggregation

Extreme discharge events are a result of extreme rainfall lasting for several days. Therefore the future transformation should also be based on a period of several days. A representative rain event period of 5-days has been selected and the daily time-series are aggregated to time-series of 5-day sums. The transformation exists of (step 1) calculation of bias correction factors, (step 2) calculation of transformation coefficients and (step 3) calculation of future precipitation amounts and is applied to these 5-day sums. The transformed 5-day sums are disaggregated to daily sums, by applying the relative change of the 5-day sum to the individual days (for a detailed description see Kraaijenbrink, 2013; after Van Pelt et al., 2012).

3.2 KNMI14 + ADC method

The KNMI'14 climate scenarios for the Rhine and Meuse basins, described and applied here, are a preliminary set of KNMI'14 scenarios for the river basins. The most obvious shortcoming of this preliminary set is that the driest scenario in summer (i.e. the W_H scenario) is over the whole Rhine and Meuse domain not dry enough in comparison with the CMIP5 climate model projection for these river basins. This is the reason why these KNMI'14 climate scenarios for the Rhine and Meuse basins are called 'preliminary' and why they will be updated.

Here we describe how these preliminary KNMI'14 scenarios for the river basins were constructed. Note that for all KNMI'14 scenarios the CMIP5 climate model projections are considered as the reference and that each KNMI'14 scenario should 'fit well' within the range spanned by the CMIP5 projections. For each of the four KNMI'14 scenarios for the Netherlands 8 simulations with the KNMI climate models EC-Earth and RACMO2 were selected. The total of 4 × 8 = 32 simulations covers (at least for the Netherlands) the most relevant part of the range of changes of the CMIP5 climate model projections. So each of the four KNMI'14 scenarios is represented by 8 simulations with EC-Earth-RACMO2.
The same 32 EC-Earth-RACMO2 simulations that are used for the KNMI'14 scenarios for the Netherlands are used for the KNMI'14 scenarios for the river basins. As for the CMIP5 climate model projections (in the previous section) the ADC method is applied to each of these 8 EC-Earth-RACMO2 simulations. The transformation coefficients that come out of the ADC method are averaged over these 8 simulations, resulting in one set of transformation coefficients for each of the four KNMI'14 climate scenarios. The only difference between applying the ADC method to the CMIP5 climate model projections and the EC-Earth-RACMO2 simulations (the latter of which are the basis for KNMI'14) is that the spatial resolution of the EC-Earth-RACMO2 simulations (which is a RCM) is (much) larger than that of the CMIP5 climate model projections (which are GCMs) and that in the case of EC-Earth-RACMO2 (i.e. KNMI'14) the transformation coefficients are averaged. Note that the ADC method automatically accounts for the difference in spatial resolution. In both cases the transformation is applied to the same historical data (which has a spatial resolution corresponding to the sub-basins in the HBV model, see next section).

3.3 Modelling the hydrological impacts of climate change

For both the Rhine and Meuse river discharges have been modelled using the lumped rainfall runoff model HBV. To facilitate efficient model running of the multitude of scenarios the HBV models have been implemented in the Delft-FEWS system (Werner et al., 2013).

As model input the HBV sub-catchment specific historical observed meteorological time-series (CHR-OBS and Leander et al. (2009)) were used. For the simulations of the future climate, CMIP5 and KNMI14 scenarios, these times-series were transformed according to the above methods. Below follows a specification of the applied HBV models.

3.3.1 Meuse

Although Deltares recently derived new parameter sets for the HBV model of the Meuse river basin following the GLUE procedure (Kramer et al. (2008); it was decided to use the older Van Deursen model calibration (van Deursen, 2004) that was also used within the AMICE project. The motivation being that the recent calibration is a ‘high flow calibration’ and this study also focuses on changes is low flows. Kramer et al. (2008) already stated that the Van Deursen’s calibration gave reasonable to good fits for ‘low’ and ‘middle low’ discharges. The selected calibration thus performs better for low flows, but possibly slightly worse for high flows, although the model was optimized using the Nash-Sutcliffe criterium.

3.3.2 Rhine

Several HBV model parameterizations exist for the Rhine river basin. Yet, none of these are optimized specifically for low flows. Ideally the HBV model used in this climate impact assessment should perform well for both high and low flows. Therefore the possibility for model optimization, focussing on both high and low flow criteria, was explored (Bouaziz, 2013). From this analysis it was concluded that an optimization of the HBV-Rhine model for both high and low flow criteria does not perform better in terms of low flows than previous calibrations which focussed on high flows. This is probably due to spatial aggregation of hydrological processes within HBV. It turned out that the GRADE 50% model optimization, based upon high flow criteria only, also performed relatively well for low flows compared to the new parameterization. For GRADE 50% for the minimum flow criterium, a percentage difference from observed of -9.8 was obtained, whereas this difference was slightly more (-10.1) for the calibration based upon high and low criteria (see Bouaziz (2013) for more information). Therefore, and for the consistency, it was decided to use the HBV model with the GRADE 50% parameter set for both high and low flow impact assessment.

NB: The HBV Rhine model version without extractions for high flows has been used (see for more info Hegnauer and Becker (2013).

3.4 Potential evaporation in HBV

Here we provide an overview of the methods applied to estimate HBV sub-catchment specific potential evaporation from the different climate datasets for the Rhine and Meuse. The HBV model can either calculate daily potential evaporation from daily temperature time-series or the model can be forced with external potential evaporation. Within the HBV model potential evaporation is reduced to actual evapotranspiration depending on water availability in soil and open water.

In principle HBV uses its build-in method to derive potential evaporation from daily temperatures and long-term average climatologies of temperature and evaporation. We here refer to this method as the *etf* method. Within this method the following formula is used to estimate daily potential evaporation at time *t* from climatological mean potential evaporation:

$$E_{p,t} = E_{p,mean} * (1 + etf\ (T_t - T_{mean}) \qquad \text{Eq. 1}$$

Where:

$E_{p,t}$ potential evaporation on day t (mm/day)
$E_{p,mean}$ long term mean monthly potential evaporation from a historical time series (mm/day)
etf correction factor of potential evaporation for long term means for actual temperature (1/°C)
T_t temperature on day t (°C)
T_{mean} long term mean daily temperature from historical time series on day t (°C)

A sensitivity analysis of the *etf* method is given in Appendix 1. e*tf* values are varied to explore the effect on modelled discharges. Moreover the temperature and potential evaporation profiles, that have been present in the HBV models for years, are compared with similar profiles derived from the currently available temperature and evaporation time-series to see if the old data is still representative. Results of this analysis are presented in Appendix 2.

A drawback of the *etf* method is that this method is not supposed to integrate the systematic impact of climate change (temperature change). Within the *etf* method $T_t - T_{mean}$ is originally used to calculate the effect of historical day-to-day temperature variability on potential evaporation. Therefore KNMI derived an alternative regression to obtain potential evaporation to force HBV with external potential evaporation (Leander et al., 2009). Using externally calculated potential evaporation also enables the incorporation of systematic climate change.

In the section below we describe for all climate scenario / model datasets which method has been applied to incorporate potential evaporation.

3.4.1 Rhine

CMIP5, KNMI'06 and RheinBlick2050 (Deltares contribution)

For the hydrological model runs, based on the CMIP5, KNMI'06 and RheinBlick2050 datasets the HBV internal *etf* method is used. The, for the Rhine default, *etf* value of 0.05 was used for all basins. For each HBV sub-basin the mean evaporation for each calendar month and mean temperature for each calendar day were derived by Eberle et al. (2005) from the CHR dataset.

KNMI'14

For the KNMI'14 scenarios for the Rhine, KNMI used a method to estimate potential evaporation that considers the influence of temperature variation caused by both natural variability and climate change on potential evaporation.

In a first step the monthly average change in potential evaporation is derived from radiation and temperature data from the KNMI'14 scenarios using Makkink's equation.

$$\Delta Ep = \Delta R + \Delta T\left(\frac{dEp}{dT}\right) \qquad \text{Eq. 2}$$

Where ΔR is the change in radiation (%) and ΔT is the change in temperature (°C) from the scenario. dEp is the relative change in Ep per °C temperature increase obtained with the Makkink equation. ΔEp is the resulting change in potential evaporation (%) corresponding to the global radiation and temperature change in the scenario.

In the second step the potential evaporation is calculated. For the current climate Eq. 1 applies. For the future climate:

$$Ep' = Ep_{mean}(1 + \frac{\Delta Ep}{100})(1 + etf(T' - T'_{mean})) \qquad \text{Eq. 3}$$

Where T', Ep' and T'_{mean} refer to respectively daily temperature, daily Ep' and monthly mean temperature in the future climate.

This two-way calculation of daily potential evaporation for the future climate was implemented and calculated within Delft-FEWS and used as ‘external’ forcing for HBV. It thus avoids the misuse of the *etf* factor to account for the systematic change of *PET* due to climate change.

3.4.2 Meuse

KNMI’06
For the KNMI’06 scenarios, potential evaporation has been calculated outside HBV and is used as forcing of HBV overruling the *etf* method.

AMICE
The external daily potential evaporation time-series used within the AMICE project are based on historical sub-catchment specific daily potential evaporation time-series (Leander, 2009) which are adjusted with 4% per °C air temperature increase.

KNMI’14
For the KNMI’14 scenarios for the Meuse, KNMI prepared potential evaporation time-series for the current and future climate. The same two-way procedure as for the Rhine was used. Except that KNMI applied this two-way procedure and calculated the evaporation time series rather than that this two-way procedure was implemented in and calculated by Delft-FEWS (as for the Rhine). The monthly *etf* values and the monthly mean evaporation (per calendar month and sub-basin) according to Leander (2009) were used.

CMIP5
For the CMIP5 projections the *etf* method was implemented in Delft-FEWS to make potential evaporation time series available to HBV. In this implementation the monthly *etf* values and the mean evaporation and mean temperature (per calendar month and sub-basin) from Leander (2009) were used. In these simulations the *etf* factor is thus misused to account for the systematic effect of temperature change on potential evaporation. Since the *etf* factor for the Meuse is relatively large, in particular in projections with large temperature increases the resulting increase in potential evaporation may lead to a systematic overestimation.
The two-way procedure could not be used because of lack of information on ΔR (same argument as for CMIP5 projections for the Rhine).

3.5 Overview of scenarios and methods applied:

Several differences exist between the earlier and new scenario projections. Table 3.1 summarizes the most relevant differences present in the generation of discharge projections. Differences in projected discharge changes for the individual scenarios sets may not only result from differences in projected climate change. The projections may also be influenced by differences in the in Table 3.1 listed components. This should be kept in mind while reading the results and conclusion chapters. At the same time one should realize that for the projections relative changes are calculated, in each case the same methods have been applied for both the historical and future time period and changes are likely comparable. Because of the variety of differences, a transparent evaluation of their individual influences is not feasible.

Table 3.1 Most relevant differences in the discharge projections for the Rhine

	Rhine					
	Historical time-slice	*Historical data source*	*Future time-slice / horizon*	*Downscaling / Correction Method*	*HBV model version*	*Potential evaporation method*
KNMI'06	1961-1995	CHR-OBS	2050 2100	Classical Delta Change	*Eberle et al. 2005*	*Etf* method
KNMI'14	1951-2006	HYRAS / E-OBS	2050 2085	ADC-method	Glue50%	External constructed by KNMI
CMIP5	1951-2006	HYRAS / E-OBS	2021-2050 2071-2100	ADC-method	Glue50%	*Etf* method
RheinBlick2050	1961-1990	CHR-OBS	2021-2050 2071-2100	Bias-Correction RCM	*Eberle et al. 2005*	*Etf* method

Table 3.2 Most relevant differences in the discharge projections for the Meuse

	Meuse					
	Historical time-slice	*Historical data source*	*Future (time-slice)*	*Downscaling / Correction Method*	*HBV model version*	*Potential evaporation method*
KNMI'06	1961-1995	Leander (2005)	2050 2100	Classical Delta Change	Van Deursen (2004)	External
KNMI'14	1967-2007	Leander (2005)	2050 2085	ADC-method	Van Deursen (2004)	External constructed by KNMI
CMIP5	1967-2007	Leander (2005)	2021-2050 2071-2100	ADC-method	Van Deursen (2004)	Etf method implemented in Delft-FEWS with monthly profiles
AMICE	1961-1990	Leander (2005)	2021-2050 2071-2100	Seasonal Delta Change	Van Deursen (2004)	Seasonal Delta Change

4 CMIP5 and preliminary KNMI’14 results compared with earlier assessments

Overview of change statistics applied in the current analysis

Climate change induced changes in the following statistical quantities have been derived for all climate scenario datasets for a number of representative locations along the Rhine and Meuse. Statistics have been calculated for the period nov-oct as October is assumed to be the end of the low flow period at which the *hydrological* year for the Rhine and Meuse ends.

MQ: Long term mean annual discharge (nov-oct)

MAMQ7: Long term mean annual lowest seven day flow (nov-oct).

MHQ: Long term average annual maximum flow (nov-oct)

Monthly discharge:

(1) Regime curves
(2) Average monthly discharge changes

Locations Rhine:

Maxau, Worms, Kaub, Köln, Lobith, Raunheim, Trier

Locations Meuse:

Borgharen, Chooz, Chaudfontaine

4.1 Meuse

4.1.1 Monthly discharge cycle – Regime curves

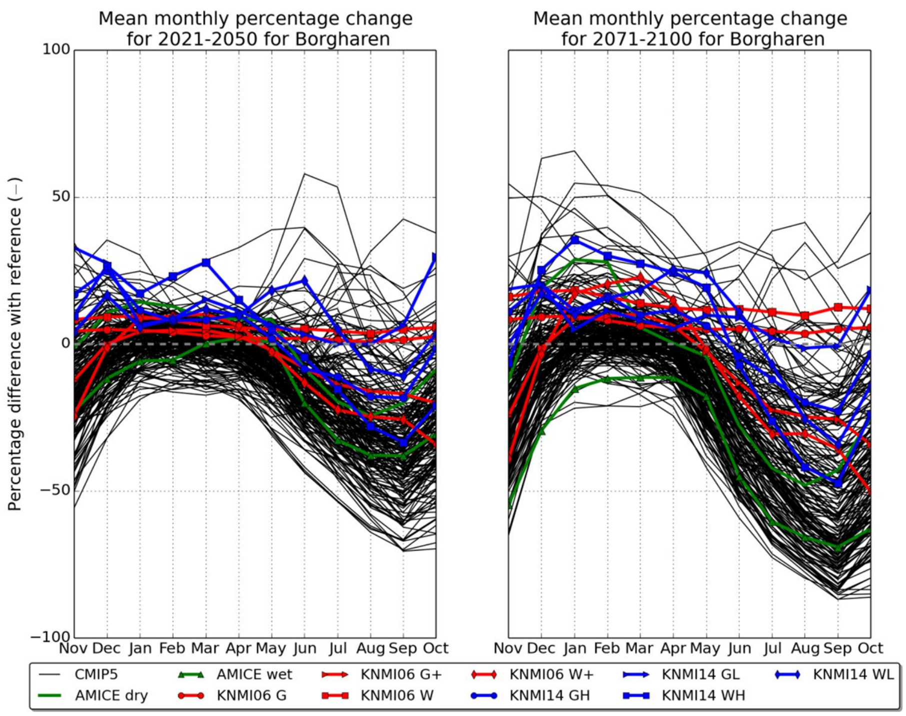

Figure 4.1 Percentage change (%) in average monthly discharge cycle for Borgharen for all climate model / scenario sets

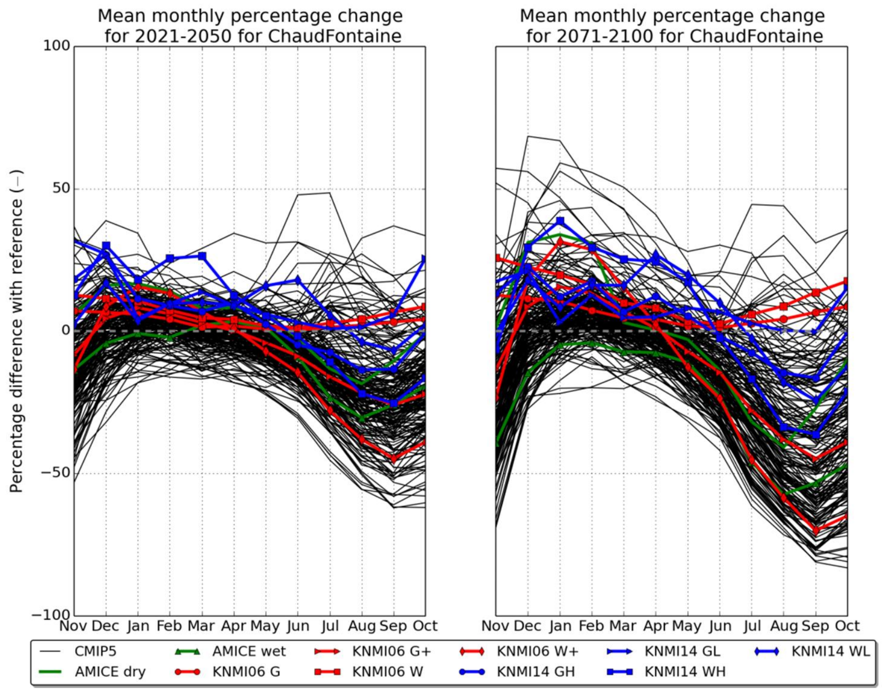

Figure 4.2 Percentage change (%) in average monthly discharge cycle for Chaudfontaine for all climate model / scenario sets

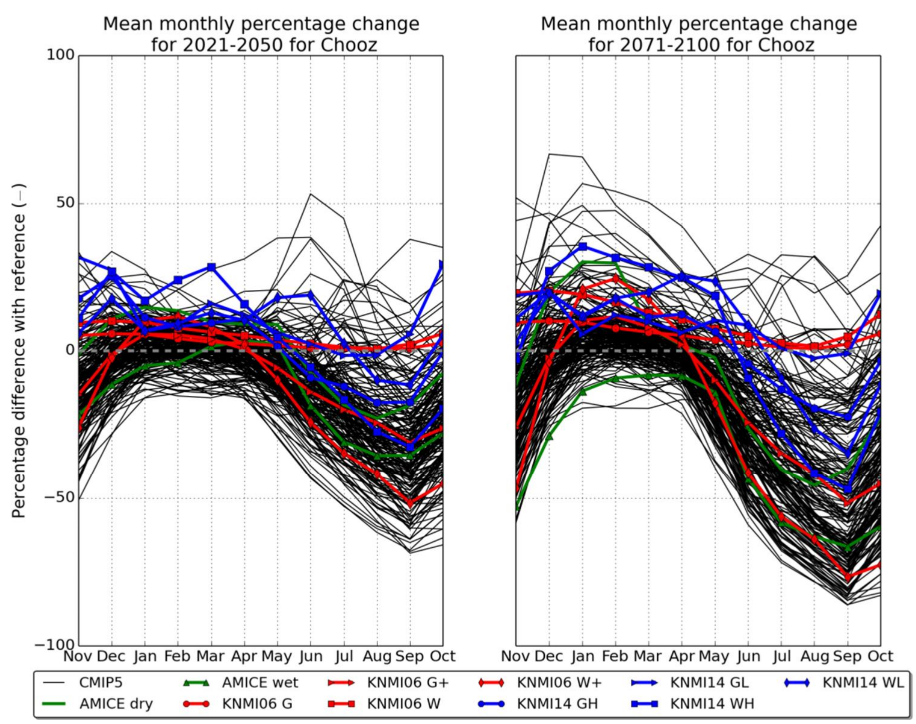

Figure 4.3 Percentage change (%) in average monthly discharge cycle for Chaudfontaine for all climate model / scenario sets

For all scenario sets there is a general tendency towards increasing spring discharge and decreasing late summer discharge, except for the moderate KNMI'06 G and W and the KNMI'14 GL scenarios that tend to project an increase throughout the year.

The spread in the CMIP5 projections is large and not fully covered by the KNMI'14 scenarios, which give a slightly smaller decrease for late summer and autumn for both 2071-2100 and 2021-2050. Yet, the large spread in CMIP5 scenarios may also be caused by the use of the *etf* method with *etf* values of 0.07 – 0.08 per degree Celcius for the summer. With these *etf* values a large increase in temperature will induce a very large increase in potential evaporation. Therefore the here obtained CMIP5 discharge projections may not be a reliable reference for summer discharge and the MAMQ7. The dry KNMI'14 projections for the Meuse compare well with the dry KNMI'06 scenarios. At Borgharen, the dry AMICE scenario is much drier than the KNMI scenario sets.

4.1.2 Change in annual mean discharge

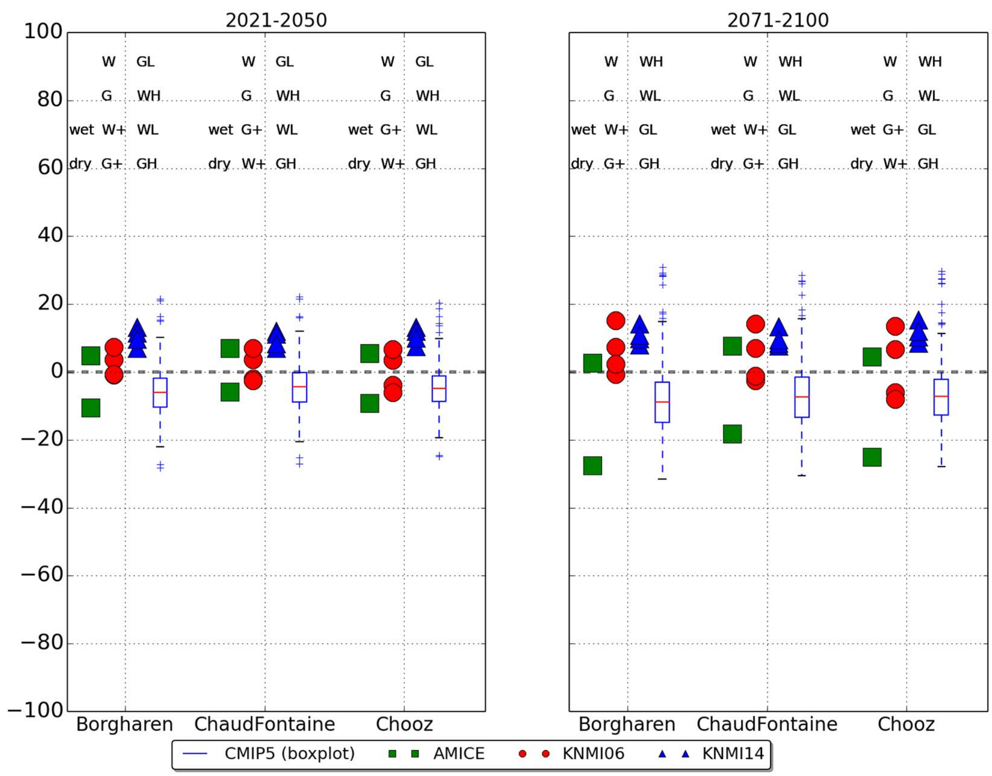

Figure 4.4 Percentage change in mean discharge (MQ) for the Meuse for all climate model / scenario sets. The color / symbol coding and boxplots represent the scenario sets. On top of the graphs the ordering of scenarios is given

The annual mean discharge is projected to increase for most KNMI'06, the wet AMICE scenario and all KNMI'14 scenarios for all selected locations along the Meuse. Exceptions are (1) the dry AMICE scenario which projects decrease for all locations along the Meuse and (2) the KNMI'06 projections for Chooz. Moreover, the majority of CMIP5 model-scenario combinations (i.e. the centre of the boxplot) project a decrease in average discharge for all locations, whereas the KNMI'14 scenarios project a slight increase. Here the KNMI'14 scenarios deviate from the CMIP5 scenarios. Again this may partly result from the overestimation of potential evaporation in summer by the CMIP5 models because of the use of the *etf* method with relatively high *etf* values.

4.1.3 Change in long-term average annual maximum flow

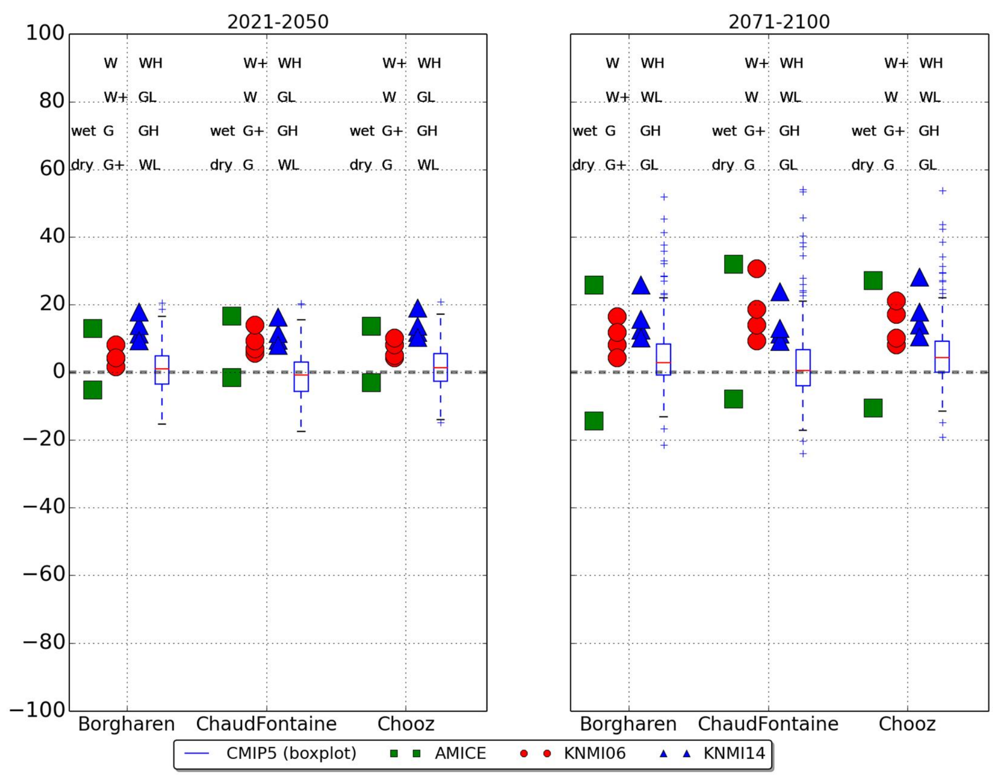

Figure 4.5 Percentage change in annual maximum discharge (MHQ) for the Meuse for all climate model / scenario sets. The color / symbol coding and boxplots represent the scenario sets. On top of the graphs the ordering of scenarios is given

Annual maximum discharge (MHQ) is likely to increase. The dry scenario of the AMICE project is the only scenario that projects decreases for all locations. For the CMIP5 models the median projected change is close to zero.

4.1.4 Change in long-term average annual minimum 7-day flow

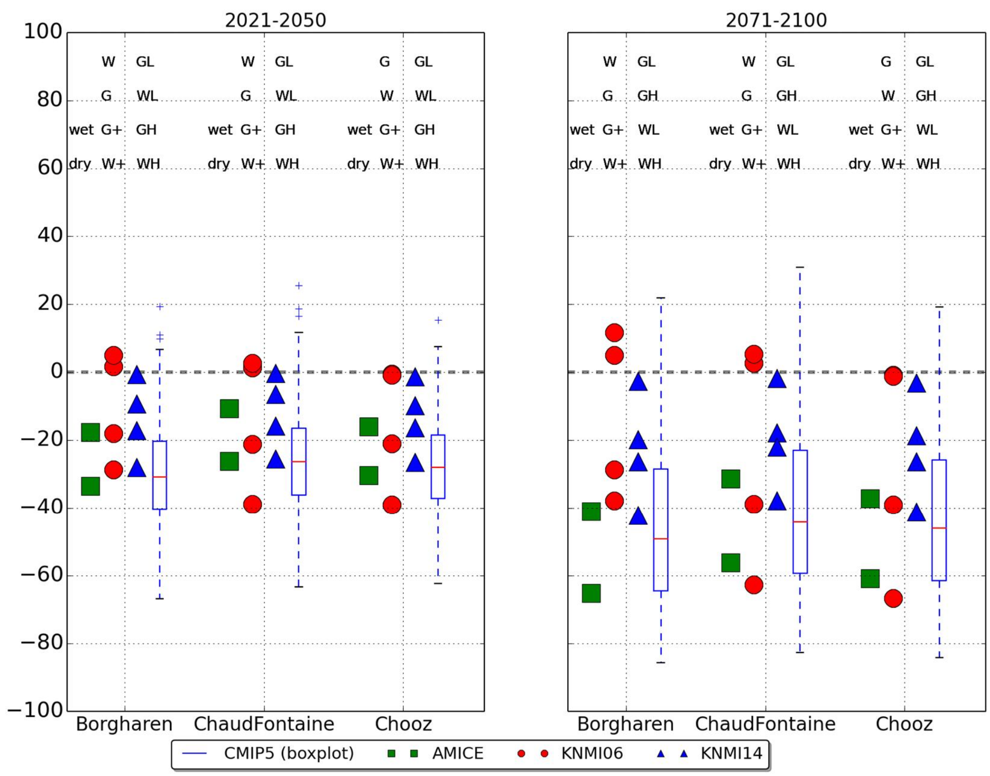

Figure 4.6 Percentage change in annual minimum discharge (MAMQ7) for the Meuse for all climate model / scenario sets. The color / symbol coding and boxplots represent the scenario sets. On top of the graphs the ordering of scenarios is given

In general the scenarios project a decreasing trend for the 7-day minimum flow sum for all selected locations along the Meuse. Exceptions are the KNMI'06 G and W scenarios and the KNMI'14 G_L scenarios which project small increases. Decreases are large (up to 60%) in the AMICE dry and KNMI'06 W+ scenario and the spread in projected changes is large for the CMIP5 scenarios (again this may be an artefact caused by the *etf* method).

4.1.5 Summary statistics

Table 4.1 and 4.2 provide an overview of the main change statistics for the Meuse for all scenarios.

Table 4.1 Change statistics Meuse – Projected mean change

			KNMI'06	AMICE	KNMI'14	CMIP5
Borgharen	*MQ*	2050 2100	2 6	-3 -12	10 11	-6 -8
	MHQ	2050 2100	5 10	4 6	13 16	1 5
	MAMQ7	2050 2100	-10 -13	-26 -53	-14 -23	-30 -47
Chooz	*MQ*	2050 2100	2 4	-2 -10	11 12	-5 -6
	MHQ	2050 2100	7 14	5 8	14 18	2 6
	MAMQ7	2050 2100	-16 -27	-23 -49	-14 -22	-28 -44
Chaudfontaine	*MQ*	2050 2100	0 2	1 -5	10 10	-4 -6
	MHQ	2050 2100	9 18	8 12	11 14	-1 3
	MAMQ7	2050 2100	-13 -22	-18 -44	-12 -20	-26 -44

Table 4.2 Change statistics Meuse – Range of projected changes

			KNMI'06	AMICE	KNMI'14	CMIP5 *
Borgharen	*MQ*	2050	-1 to +7	-11 to +5	+7 to +13	-22 to +10
		2100	-1 to +15	-27 to +3	+8 to +14	-32 to +15
	MHQ	2050	+2 to +8	-5 to +13	+9 to +18	-15 to +17
		2100	+4 to +16	-14 to +26	+10 to +26	-13 to +22
	MAMQ7	2050	-30 to +5	-33 to -18	-28 to -1	-62 to +7
		2100	-41 to +12	-65 to -44	-42 to -3	-84 to +19
Chooz	*MQ*	2050	-6 to +7	-9 to +5	+8 to +13	-19 to +1-
		2100	-8 to +14	-25 to +4	+9 to +15	-28 to +11
	MHQ	2050	+4 to +10	-3 to +14	+10 to +19	-14 to + 17
		2100	+8 to +21	-11 to +27	+11 to +28	-11 to +22
	MAMQ7	2050	-41 to +0	-30 to -16	-27 to -1	-62 to + 7
		2100	-69 to +0	-61 to -37	-41 to -3	-84 to +19
Chaudfontaine	*MQ*	2050	-3 to +7	-6 to +7	+7 to +12	-21 to +12
		2100	-3 to +14	-18 to +8	+8 to +13	-30 to +16
	MHQ	2050	+6 to +14	-1 to +17	+8 to +16	-17 to +15
		2100	+9 to +31	-8 to 32	+9 to +24	-17 to +21
	MAMQ7	2050	-39 to +5	-26 to -11	-25 to 0	-63 to +12
		2100	-64 to +9	-56 to -31	-38 to -2	-83 to +31

*) For CMIP5 min and max are the values at the end of the whiskers, outliers are excluded

4.2 Rhine

4.2.1 Monthly discharge cycle – Regime curves

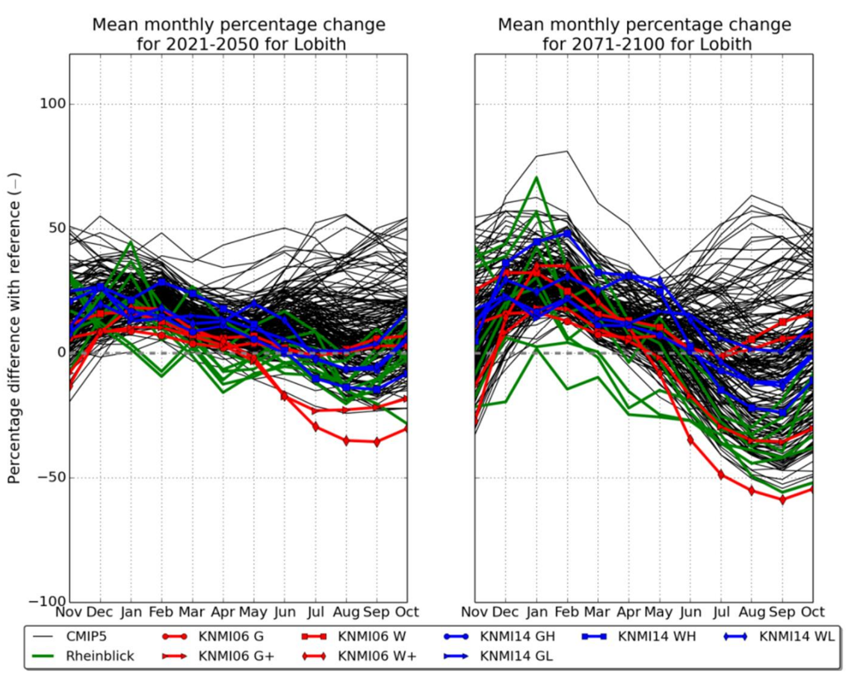

Figure 4.7 Percentage change (%) in average monthly discharge cycle for Lobith for all climate model / scenario sets

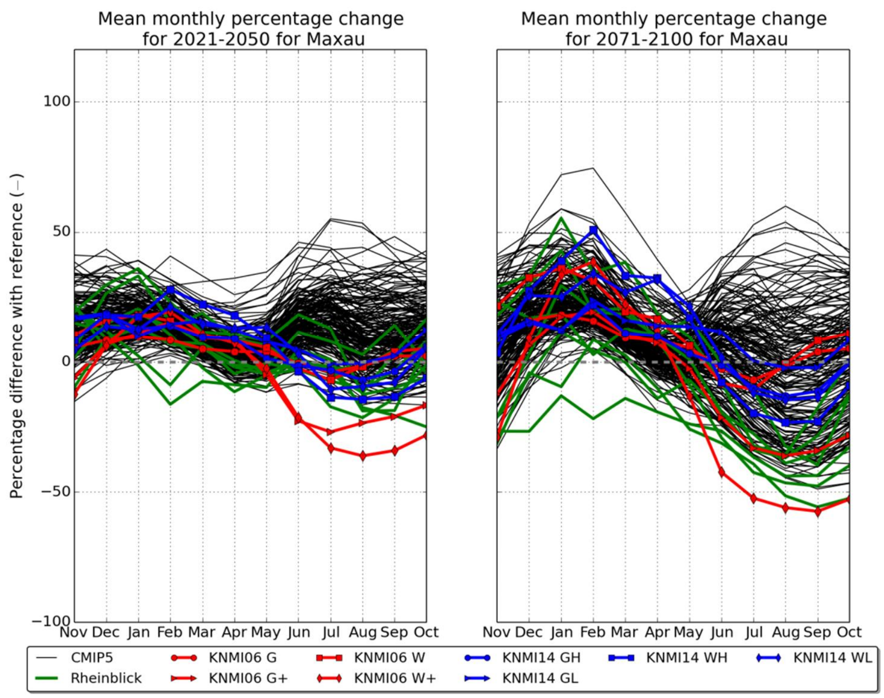

Figure 4.8 Percentage change (%) in average monthly discharge cycle for Maxau for all climate model / scenario sets

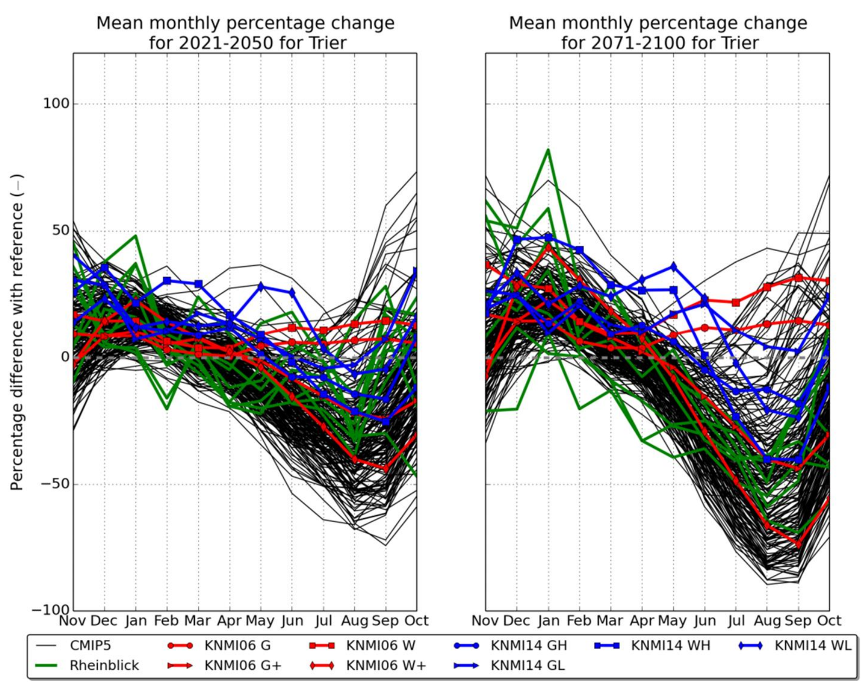

Figure 4.9 Percentage change (%) in average monthly discharge cycle for Trier for all climate model / scenario sets

For Lobtih and Trier the scenarios project in general an increase in winter discharge and a decrease in late summer / autumn discharge. This change is more pronounced at the end of the century but can already be observed in 2035. The moderate KNMI'06 G and W scneario project (slight) discharge increases for late summer. The changes projected by the new KNMI'14 scenarios are not as large as changes projected by the CMIP5 model set. For the CMIP5 models the summer discharge decrease in the Rhine is less pronounced than the decrease projected for the Meuse – likely because of the smaller *etf* value of 0.05.

At Maxau a clear winter/spring discharge increase and large late summer decrease can be found in most scenario sets, except for the CMIP5 scenarios. For 2035 the majority of CMIP5 scenarios project a year round discharge increase. For 2085 approximately half of the scenarios project increases in late summer discharge whereas the other half project decreases. Maxau is located upstream of Trier and Lobith and here the influence of temperature increases may be relatively large. More precipitation will fall as rain instead of snow, resulting in more fast runoff and less snow accumulation.

4.2.2 Change in annual mean discharge

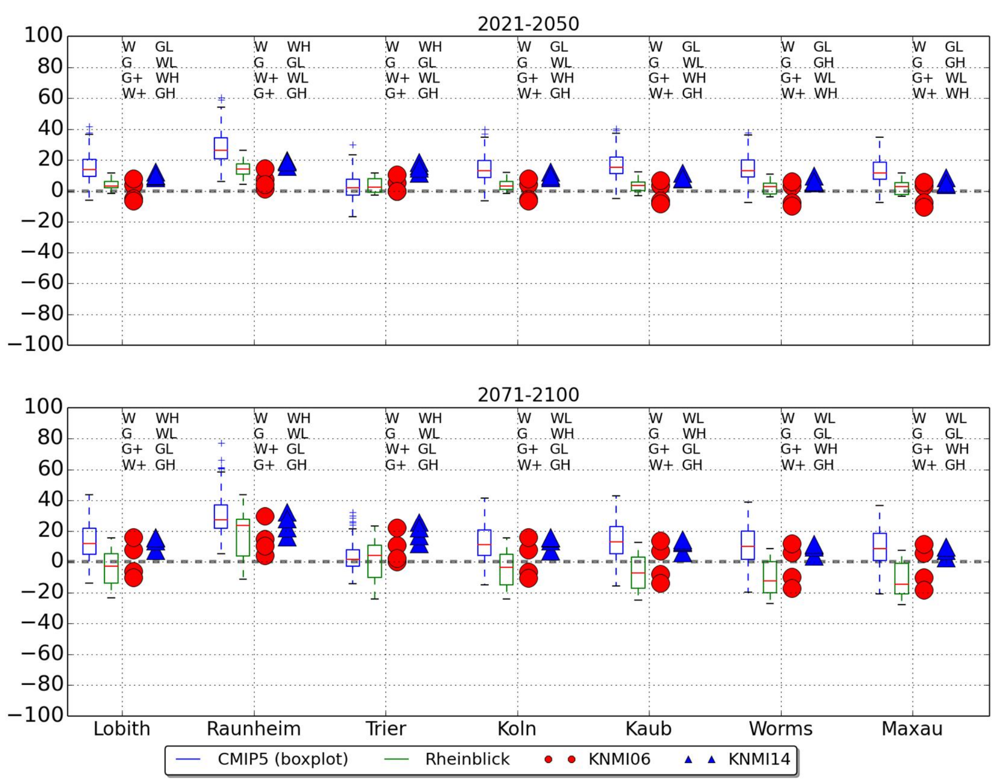

Figure 4.10 Percentage change in annual mean discharge (MQ) for the Rhine for all climate model / scenario sets. The color / symbol coding and boxplots represent the scenario sets. On top of the graphs the ordering of scenarios is given

Changes in annual mean flow are +/- 20%. Both the KNMI'14 scenarios and the majority of CMIP5 scenarios project mean discharge increases throughout the basin. Similar to RheinBlick2050 and KNMI'06 the largest increase is projected for Raunheim. Yet, for all other locations the dry KNMI'06 scenarios and the main part of the RheinBlick2050 projections for 2100 project discharge decreases.

4.2.3 Change in long-term average annual maximum flow

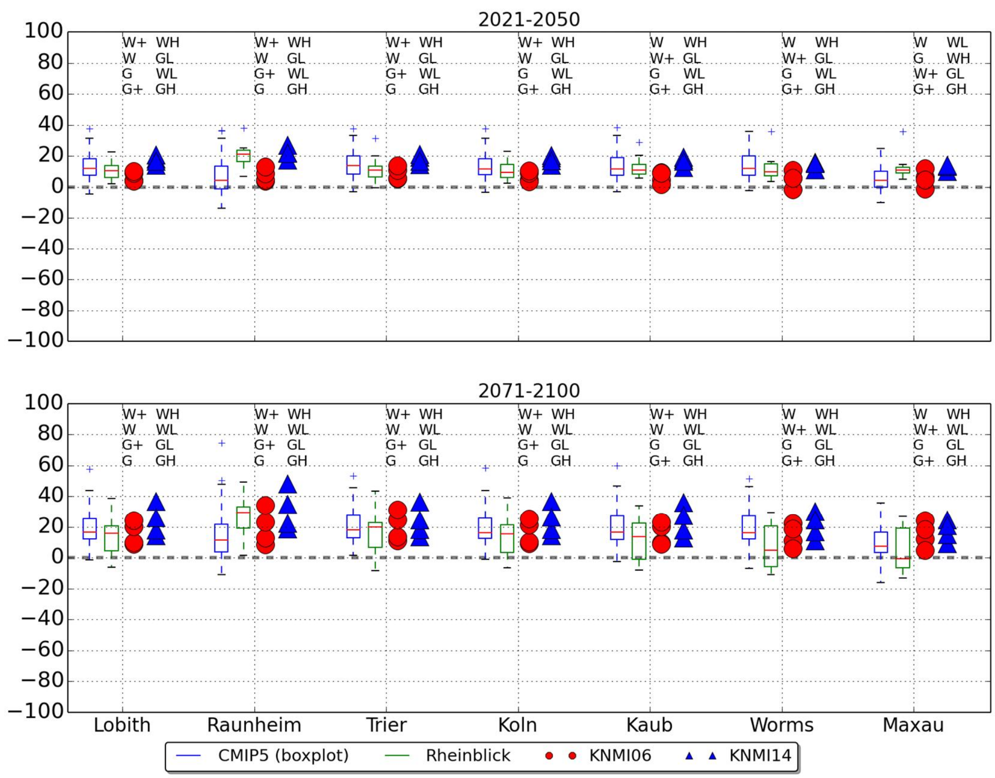

Figure 4.11 Percentage change in annual maximum discharge (MHQ) for the Rhine for all climate model / scenario sets. The color / symbol coding and boxplots represent the scenario sets. On top of the graphs the ordering of scenarios is given

All scenarios dominantly project increases in maximum discharge throughout the basin. Projected changes range approximately from +10 to +30%. In the CMIP5 dataset changes for Maxau are small.

4.2.4 Change in long-term average annual minimum 7-day flow

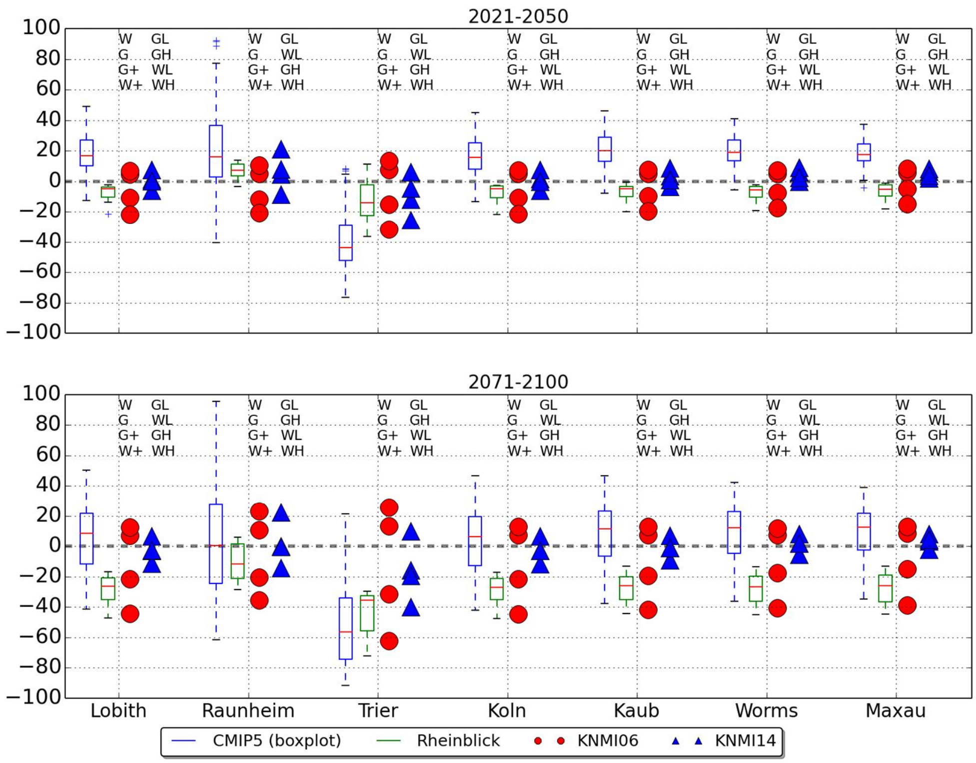

Figure 4.12 Percentage change in given7-day minimum flow (MAMQ7) for the Rhine for all climate model / scenario sets. The color / symbol coding and boxplots represent the scenario sets. On top of the graphs the ordering of scenarios is given

The RheinBlick2050 scenarios and the more extreme KNMI'06 and KNMI'14 scenarios project decreases in the 7 day low flow value for all locations. Decreases projected by the dry KNMI'14 scenarios are relatively small. This may be because the KNMI'14 scenarios are based on the CMIP5 scenarios which tend to project increases in 7 day low flow values except for Trier.

4.2.5 Summary statistics

Table 4.3 and 4.4 provide an overview of the main change statistics for the Rhine for all scenarios.

Table 4.3 Change statistics Rhine – Projected mean change

		KNMI'06	RheinBlick 2050	KNMI'14	CMIP5
Lobith *MQ*	*2021-2050* *2071-2100*	0 +2	+4 -4	+10 +13	+ 15 + 12
MHQ	*2021-2050* *2071-2100*	+7 +16	+11 +14	+18 +24	+ 12 + 18
MAMQ7	*2021-2050* *2071-2100*	-5 -12	-8 -29	+1 -2	+ 17 + 5
Raunheim *MQ*	*2021-2050* *2071-2100*	+7 +15	+15 +17	+19 +25	+ 27 + 29
MHQ	*2021-2050* *2071-2100*	+7 +20	+21 +26	+22 +31	+ 5 + 13
MAMQ7	*2021-2050* *2071-2100*	-4 -6	+7 -10	+6 +2	+ 17 + 1
Trier *MQ*	*2021-2050* *2071-2100*	+4 +9	+3 +1	+15 +19	+ 2 + 2
MHQ	*2021-2050* *2071-2100*	+9 +20	+12 +16	+18 +23	+ 13 + 19
MAMQ7	*2021-2050* *2071-2100*	-6 -14	-12 -45	-9 -16	- 42 - 56
Köln *MQ*	*2021-2050* *2071-2100*	0 +2	+4 -5	+10 +13	+ 14 + 11
MHQ	*2021-2050* *2071-2100*	+7 +17	+11 +14	+18 +24	+ 12 + 18
MAMQ7	*2021-2050* *2071-2100*	-5 -11	-8 -29	+1 -3	+ 16 + 13
Kaub *MQ*	*2021-2050* *2071-2100*	-1 0	-7 +4	+9 +12	+ 16 + 13
MHQ	*2021-2050* *2071-2100*	+6 +16	+13 +12	+17 +24	+ 13 + 18
MAMQ7	*2021-2050* *2071-2100*	-4 -10	-7 -28	+2 -1	+ 20 + 8
Worms *MQ*	*2021-2050* *2071-2100*	-2 -2	+2 -10	+7 +9	+ 14 + 10
MHQ	*2021-2050* *2071-2100*	+5 +15	+13 +8	+15 +21	+ 13 + 18
MAMQ7	*2021-2050* *2071-2100*	-3 -10	-8 -28	+4 +2	+ 8 + 19

		KNMI'06	RheinBlick 2050	KNMI'14	CMIP5
Maxau	*2021-2050*	-2	+3	+6	+ 12
MQ	*2071-2100*	-3	-11	+7	+ 8
	2021-2050	+6	+13	+13	+ 5
MHQ	*2071-2100*	+15	+5	+18	+ 9
	2021-2050	-1	-7	+5	+ 19
MAMQ7	*2071-2100*	-8	-28	+4	+ 8

Table 4.4 Change statistics Rhine – Range of projected changes

		KNMI'06	Rheinblick 2050	KNMI'14	CMIP5
Lobith	*2021-2050*	-6 to +8	-1 to +12	+7 to +12	-6 to +35
MQ	*2071-2100*	-10 to +16	-24 to +16	+7 to +16	-14 to +39
	2021-2050	+4 to +10	+2 to +23	+14 to +21	-4 to +31
MHQ	*2071-2100*	+9 to +24	-6 to +39	+15 to +37	-1 to +39
	2021-2050	-22 to +7	-14 to -2	-6 to +7	-12 to +48
MAMQ7	*2071-2100*	-44 to +13	-47 to -17	-11 to +7	-41 to +50
Raunheim	*2021-2050*	+1 to +15	+4 to +26	+16 to +20	+6 to +51
MQ	*2071-2100*	+4 to +30	-11 to +44	+16 to +32	+5 to +54
	2021-2050	+4 to +13	+7 to +25	+17 to +27	-14 to +31
MHQ	*2071-2100*	+9 to +34	+1 to +49	+19 to +48	-11 to +43
	2021-2050	-20 to +11	-3 to +14	-9 to +21	-41 to +72
MAMQ7	*2071-2100*	-35 to +23	-29 to +6	-14 to +23	-62 to +95
Trier	*2021-2050*	0 to +11	-3 to +12	+12 to +18	-17 to +21
MQ	*2071-2100*	0 to +22	-25 to +12	+12 to +26	-14 to +21
	2021-2050	+6 to +14	-1 to +20	+14 to +21	-3 to +33
MHQ	*2071-2100*	+11 to +31	-8 to +43	+14 to +36	+2 to +42
	2021-2050	-31 to +13	-37 to +11	-25 to +6	-76 to +1
MAMQ7	*2071-2100*	-62 to +26	-72 to -30	-40 to +10	-91 to +1
Köln	*2021-2050*	-6 to +8	-2 to +12	+9 to +13	-3 to +33
MQ	*2071-2100*	-11 to +16	-24 to +15	+7 to +16	-15 to +40
	2021-2050	+4 to +10	+3 to +23	+14 to +21	-3 to +31
MHQ	*2071-2100*	+9 to +25	-7 to +39	+14 to +37	-1 to +41
	2021-2050	-21 to +7	-22 to -2	-6 to +7	-13 to +45
MAMQ7	*2071-2100*	-45 to +13	-48 to -17	-12 to +7	-42 to +47
Kaub	*2021-2050*	-8 to +7	-3 to +12	+8 to +12	0 to +36
MQ	*2071-2100*	-14 to +14	-25 to +12	+6 to +14	-16 to +43
	2021-2050	+2 to +9	+6 to +20	+13 to +19	-3 to +33
MHQ	*2071-2100*	+9 to +23	-8 to +34	+13 to +36	-2 to +43
	2021-2050	-20 to +8	-20 to -1	-4 to +9	-8 to +46
MAMQ7	*2071-2100*	-42 to +13	-44 to -13	-9 to +7	-38 to +47
Worms	*2021-2050*	-10 to +6	-4 to +11	+5 to +10	-2 to +32
MQ	*2071-2100*	-17 to +12	-27 to +8	+4 to +12	-20 to +39
	2021-2050	-1 to +11	+3 to +16	+11 to +16	-2 to +36
MHQ	*2071-2100*	+6 to +23	-11 to +29	+11 to +30	-7 to +43

		KNMI'06	**Rheinblick 2050**	**KNMI'14**	**CMIP5**
MAMQ7	*2021-2050* *2071-2100*	-18 to +7 -41 to +12	-19 to -2 -45 to -13	0 to +9 -5 to +8	-6 to +41 -36 to +42
Maxau *MQ*	*2021-2050* *2071-2100*	-10 to +6 -18 to +11	-4 to +12 -28 to +7	+4 to +9 +3 to +10	-3 to +32 -21 to +37
MHQ	*2021-2050* *2071-2100*	-1 to +12 +5 to +24	+5 to +15 -13 to +27	+10 to +14 +9 to +25	-10 to +23 -8 to +30
MAMQ7	*2021-2050* *2071-2100*	-15 to +8 -39 to +13	-18 to -1 -45 to -13	+2 to +8 -2 to +8	0 to +37 -35 to +39

5 Summary and conclusions

Meuse

<u>Summary:</u>
- There is a general tendency towards increasing spring discharge and decreasing late summer discharge. The late summer discharge decrease is slightly less in the KNMI'14 scenarios than in the driest CMIP5 projections.
- All scenario sets dominantly project increases in annual mean discharge, except for the CMIP5 scenarios where the centre of the boxplots are below zero and mainly discharge decreases are projected.
- All scenario sets dominantly project (small) increases in annual maximum discharge. The dry AMICE scenario is an exception, projecting decreases for all locations.
- Overall the 7-day minimum flow is projected to decrease. Decreases projected by the KNMI'14 scenario are slightly less than decreases projected by the CMIP5 scenarios.
- The CMIP5 projections may be biased because the *etf* method is used with relatively high summer values ranging between 0.07 and 0.08. This will result in large increases in potential evaporation with increasing temperature.

<u>Conclusion:</u>
- The updated climate change scenarios (KNMI'14 and CMIP5) for the Meuse basin are overall in agreement with the existing scenarios datasets (KNMI'06 and RheinBlick2050).

Rhine

<u>Summary:</u>
- For the Rhine there is a general tendency towards increasing spring discharge and decreasing late summer discharge as well.
- In the CMIP5 projections, summer discharge decrease is larger for the locations Lobith and Trier, than for the upstream location Maxau. At Maxau only half of the CMIP scenarios project summer discharge decreases for 2085. This is likely due to the impact of temperature increases on snowfall and accumulation.
- Maximum discharge is consistently projected to increase.
- Mean discharge is projected to increase by the KNMI'14 and CMIP5 scenarios. The older scenarios show more variation and tend towards discharge decreases especially for 2100.
- 7-day minimum flow is projected to decrease according to most scenarios except for the CMIP5 scenarios. As a consequence, in the KNMI'14 scenarios (which are based on the CMIP5 scenarios) projected decreases are smaller than in the KNMI'06 scenarios.
- Changes projected by the KNMI'14 scenarios are relatively moderate.
- For the CMIP5 models the summer discharge decrease in the Rhine is less pronounced than the decrease projected for the Meuse – likely because of the smaller *etf* value of 0.05 applied in HBV

Conclusion:

- According to the new scenario sets, both KNMI14 and CMIP5, mean discharge for the Rhine is likely to increase.
- For the Rhine the KNMI'14 scenario band-with is often narrow compared to the projections of the other scenario sets for the Rhine and late summer discharge decreases are relatively moderate.

6 Literature

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A On the influence of the etf parameter on actual evaporation and discharges

A.1 Introduction

In the current set-up of the HBV model in Delft-FEWS the *etf* method can be applied to estimate potential evaporation. The discussion on how potential evaporation is calculated in the HBV model is a returning point of concern in the RheinBlick2050 and GRADE projects, because of the difference which exists between the Meuse and the Rhine river basins. Besides, the introduction of a seasonal *etf* parameter is desirable (as the relation between temperature change and evaporation change varies per season) but cannot directly be implemented in HBV and would require the external input of potential evaporation instead of using the above described method. In order to make a founded decision on how to best deal with potential evaporation in the Rhine and the Meuse models, it was decided to once again evaluate the influence of the parameter *etf* on discharges. In this Appendix we investigate the sensitivity of the model (modeled actual evapotranspiration and discharge) towards the value of the *etf* coefficient.

Within the *etf* method the following formula is used to evaluate potential evaporation at time *t*:

$$E_{p,t} = E_{p,mean} * (1 + etf\ (T_t - T_{mean})$$

Where:

$E_{p,t}$ potential evaporation on day t (mm/day)

$E_{p,mean}$ long term mean potential evaporation from historical time series (mm/day)

etf correction factor of potential evaporation for long term means for actual temperature (1/°C)

T_t temperature on day t (°C)

T_{mean} long term mean temperature from a historical time series on day t (°C)

In the current models for the Rhine and the Meuse, a value of 0.05 (1/°C) and 0.17 (1/º C) is respectively used. In a previous study by Lineke Woelders, it was found that the influence of this *etf* factor lies within 1% for 7-days minimum discharges and maximum annual discharges when *etf* values of 5% and 10% were compared.

A.2 Analysis

The HBV model (GRADE configuration with Glue50% parameter set – Winsemius et al. (2013)) for the Rhine was run with the following values of *etf*:

- 0.025
- 0.05
- 0.10
- 0.17
- 0.20
- 0.25
- 0.50

Analyses were made based on:

- Discharge regime at Lobith
- Statistics at Lobith
- Extreme values at Lobith
- Flow duration curve (aug-nov) at Lobith
- Visual hydrograph inspection at Lobith during high and low flow
- Visual inspection of actual evaporation at Aare 2 and Ruhr 3

a) Discharge regime at Lobith
The discharge regime curves found at Lobith for the different *etf* values are shown in Figure A.1

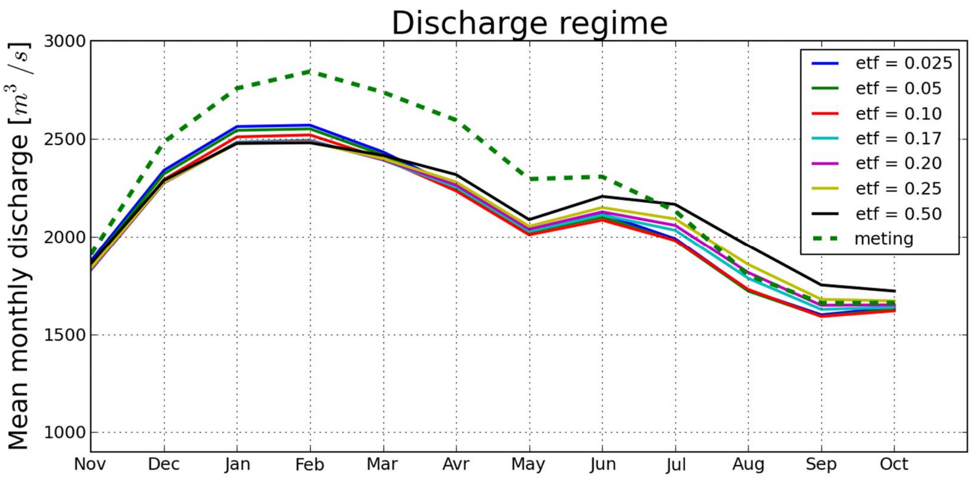

Figure A.1 Discharge regime for different values of etf at Lobith

Lower mean discharges are obtained from December to March with higher *etf* values. The opposite is true from April to November.

b) Statistics at Lobith
Figure A.2 depicts mean (MQ), mean maximum annual (MHQ) and mean 7 days minimum (MAMQ7) discharges at Lobith for different values of *etf*.

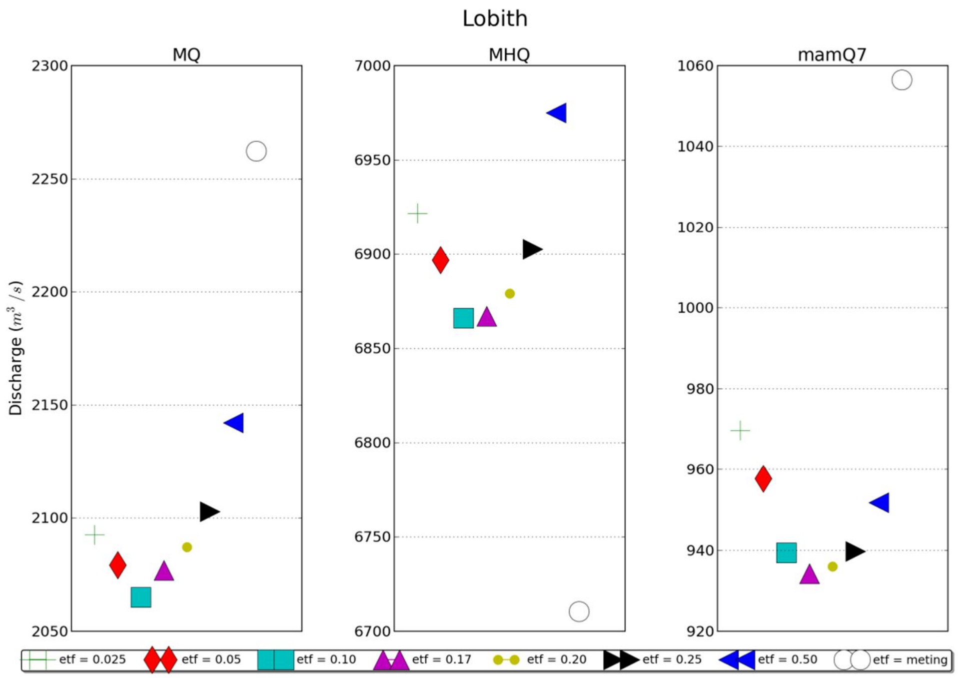

Figure A.2 Mean, mean maximum annual and mean 7 days minimum discharges at Lobith for different values of etf

There is no linear relation between the *etf* value and the mean, mean maximum and mean minimum discharges.

The differences between observed and modelled statistics are outlined in the Tables below and a comparison with what was found by L. Woelders is also added.

	MAM7 Memo Woelders	MHQ Memo Woelders	MAM7 (Glue50%)	MHQ (Glue50%)
Gemeten afvoer	1064.47	6499	1056	6710
afvoer (m3/s) bij etf 5%	1003.7	6734.63	958	6897
afvoer (m3/s) bij etf = 10%	1004.8	6751.13	939	6866

	MAM7 Memo Woelders	MHQ Memo Woelders	MAM7 (Glue50%)	MHQ (Glue50%)
procentuele afwijking bij etf 5%	94.3	103.6	90.7	102.8
procentuele afwijking bij etf = 10%	94.4	103.9	98.1	99.6

The difference found between an *etf* of 5% and 10% is slightly larger than what was previously found by L. Woelders. A possible explanation for this is the difference in time period investigated which we could unfortunately not find within the study of Woelders.

c) Extreme values at Lobith
An extreme value analysis was made using a Gumbel distribution, results are shown in Figure A.3.

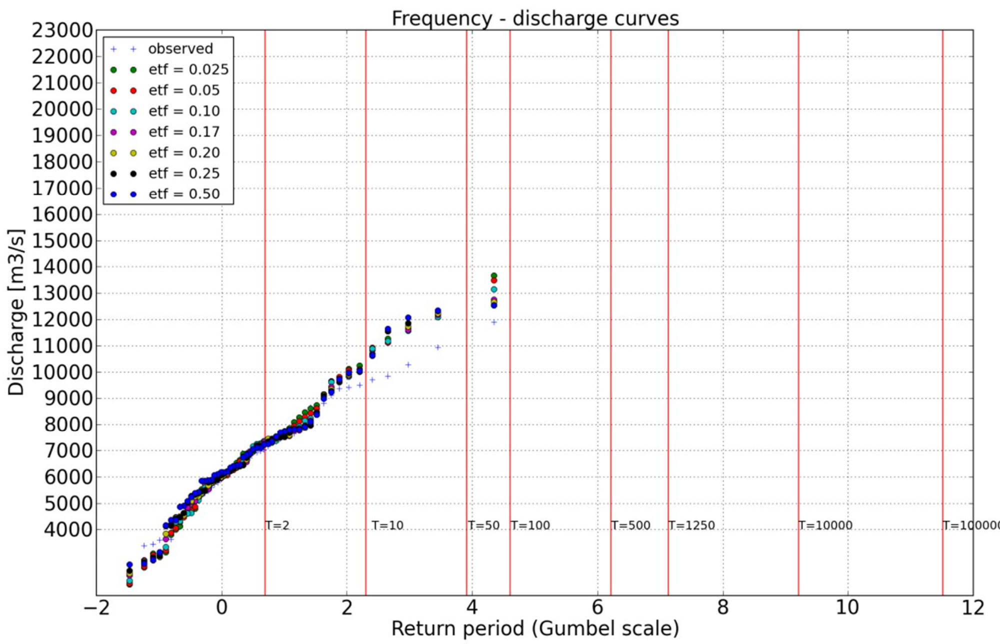

Figure A.3 Extreme value analysis with Gumbel distribution based on different values of etf

Extreme values are also influenced by the value of *etf*. Lower values of *etf* lead to higher extreme flows for a return period of 100 year. Yet, the spread between discharge realizations varies for different return periods, there is no visible trend.

d) Flow duration curve during low flows
Assessing the impact of *etf* values on low flows was done plotting the flow duration curve of flows between august and November, as shown in Figure A.4.

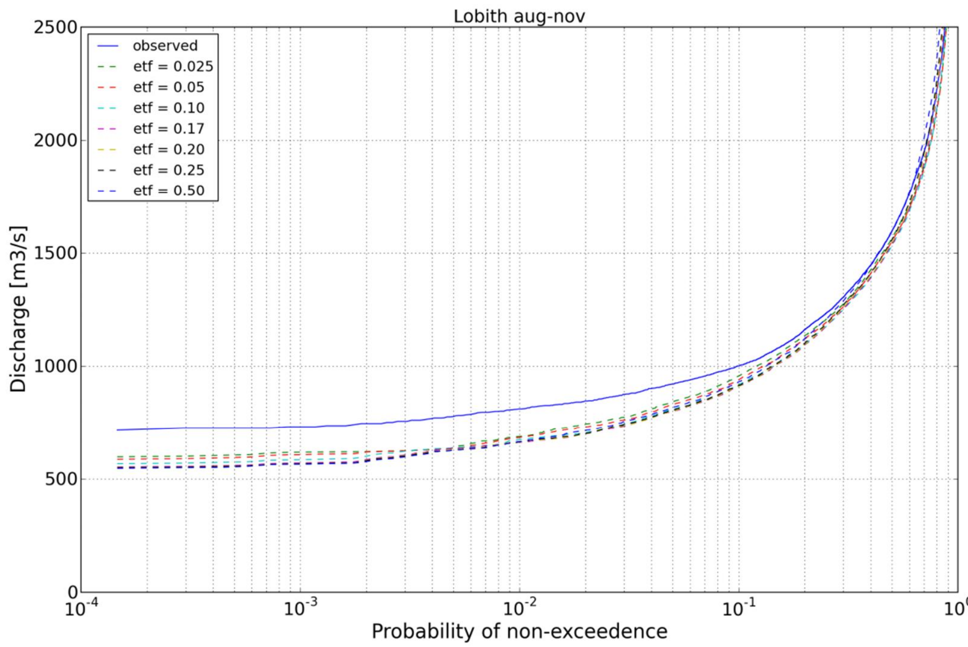

Figure A.4   Flow duration curve of flows between August until November at Lobith

The lowest flows are found when *etf* values are large. Yet, it should be noted that for low flows the model bias from observed is also largest.

e) Hydrograph at Lobith during low and high flows
The influence of using different values for *etf* during the simulations of summer 2003 is shown in Figure A.5 and the high flows of 1995 are shown in Figure A.6.

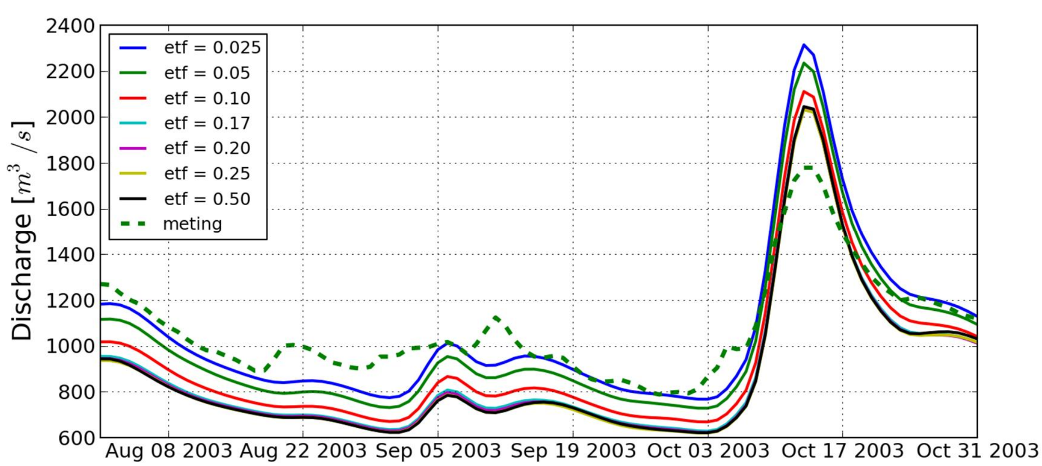

Figure A.5   Hydrograph at Lobith during the summer of 2003 for different values of etf

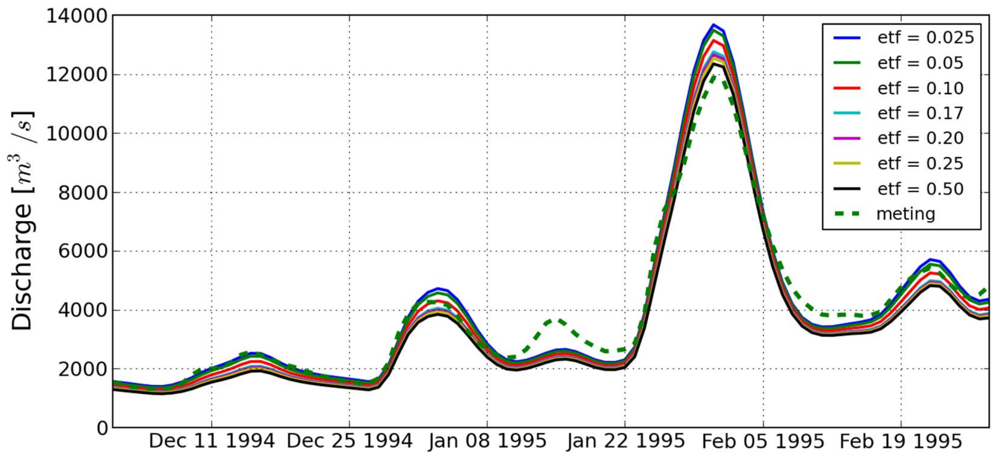

Figure A.6 Hydrograph during the high flows of 1995 at Lobith for different values of etf

Both during the summer of 2003 and the high peaks of 1995, lower discharges are found with higher values for *etf*.

f) Actual evaporation
The influence of different values of *etf* on actual evaporation is shown for the Aare2 sub-catchment in Figure A.7 (during summer) and in Figure A.8 (during winter). Actual evaporation during summer 2003 in the Ruhr 3 catchment is shown in Figure A.9.

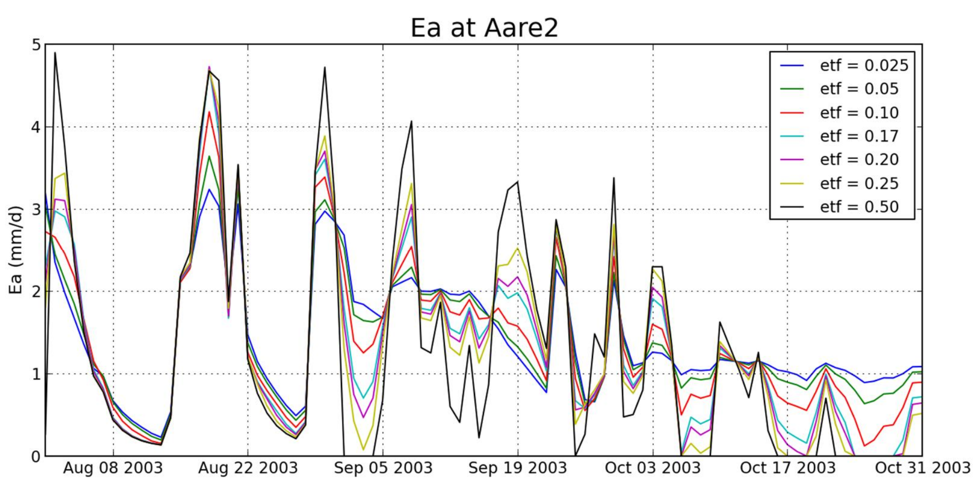

Figure A.7 Simulated actual evaporation at Aare 2 during summer 2003

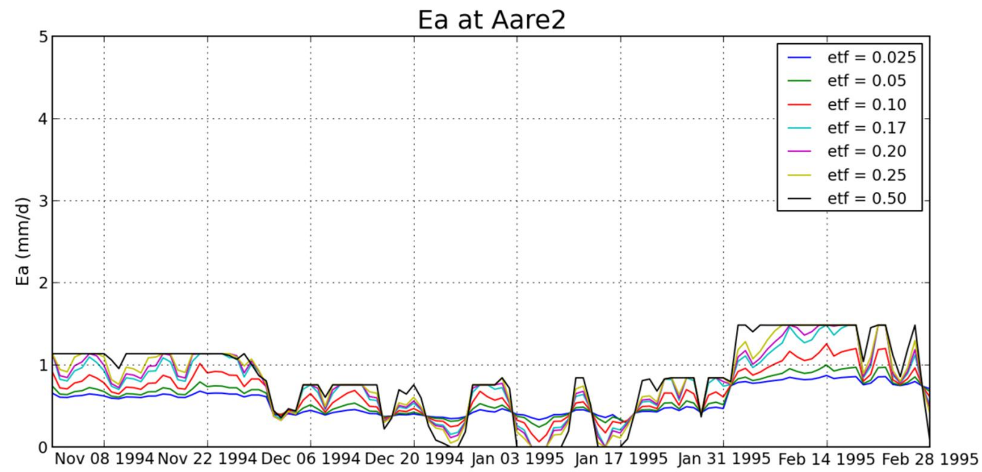

Figure A.8 Simulated actual evaporation at Aare 2 during winter 1995

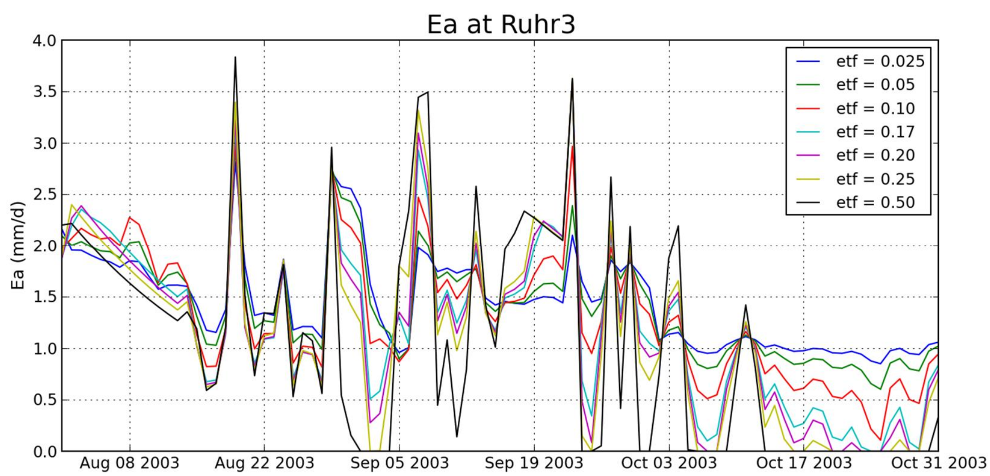

Figure A.9 Simulated actual evaporation at Aare 2 during summer 2003

There is no clear relation between the value of *etf* and the actual evaporation. The *etf* factor is used to adjust the monthly evaporation profile according to the temperature difference between the long-term average temperature profile and the temperature for the given day. This difference can either be positive or negative leading to an in- or decrease of the evaporation profile. A larger *etf* value will lead to a larger adjustment, but throughout the year this can either be positive of negative. However, it is clear that as potential evaporation is lower during winter, the relative importance of *etf* during winter is less.

A.3 Conclusion

The influence of the value of *etf* on mean, low and high discharges is relatively large. Introducing seasonal variability of the *etf* factor might therefore be relevant and this can only be achieved if external potential evaporation is used as input into HBV instead of using the HBV build in *etf* method. From this analysis, it therefore seems favourable to use external time series for potential evaporation instead of using the *etf* method.

B Evaluation of HBV temperature and evaporation profiles

As described in Appendix A, the HBV model calculates potential evaporation for each day based on long term means of potential evaporation and temperature derived from historical time series. In this Appendix we assess whether the mean daily temperature and evaporation profiles for the Rhine and the Meuse included in HBV match mean daily and monthly profiles of historical data sources, i.e. HYRAS / E-OBS for the Rhine and Leander et al., (2005) for the Meuse. With this comparison we evaluate whether the existing profiles in HBV are still representative for the historical climate up until 2008. For the Meuse the long term average temperature profiles (norm.dat) are not present in the HBV model and are therefore missing in this comparison.

The following profiles are available and will be compared.

<u>Temperature:</u>
- Mean monthly temperature based on E-OBS (1967-2008) and mean monthly temperature profiles implicitely contained in HBV (1968-1986) for the Meuse. The latter was provided by Beersma (January 15th of 2014) and prepared by Leander (2009)
- Mean monthly temperature of the HYRAS dataset (1951-2007) and mean monthly profiles in HBV for the Rhine, as derived by Eberle et al. (2005)

<u>Evaporation:</u>
- Mean monthly evaporation profiles for each sub-catchment of the Meuse as provided by Jules Beersma by email (January 15th of 2014) and prepared by Leander (2009) and the mean monthly evaporation profiles as present in HBV

Furthermore, a comparison of the temperature was made for the Meuse and the Moselle based on the following products:
- Mean monthly temperature of the Moselle based on HYRAS
- Mean monthly temperature of the Moselle as derived by Eberle et al. (2005) and contained in HBV
- Mean monthly temperature of the Meuse based on E-OBS
- Mean monthly temperature based on the profiles derived by Leander (2009).

Finally a comparison of the evaporation for the Meuse and the Moselle was made based on the following data;
- For each sub-catchment within the Moselle, a weighted average of evaporation based on station data was calculated with the weights as given in HBV and a weighted average of the entire catchment of the Moselle was calculated based on sub-catchment areas
- For the Meuse, a basin wide evaporation was determined based on a areal weighted average of the evaporation in the sub-catchments.

B.1 Comparison temperature profiles Meuse

The mean monthly temperature profiles as in HBV and based on a historical time series from 1968 to 1986 were provided by Jules Beersma by email on January 15th of 2014 (and created by R. Leander in 2009) – T_HBV-. These are here compared with E-OBS data (1967-2008) – T_EOBS- for each of the sub-catchments of the Meuse.

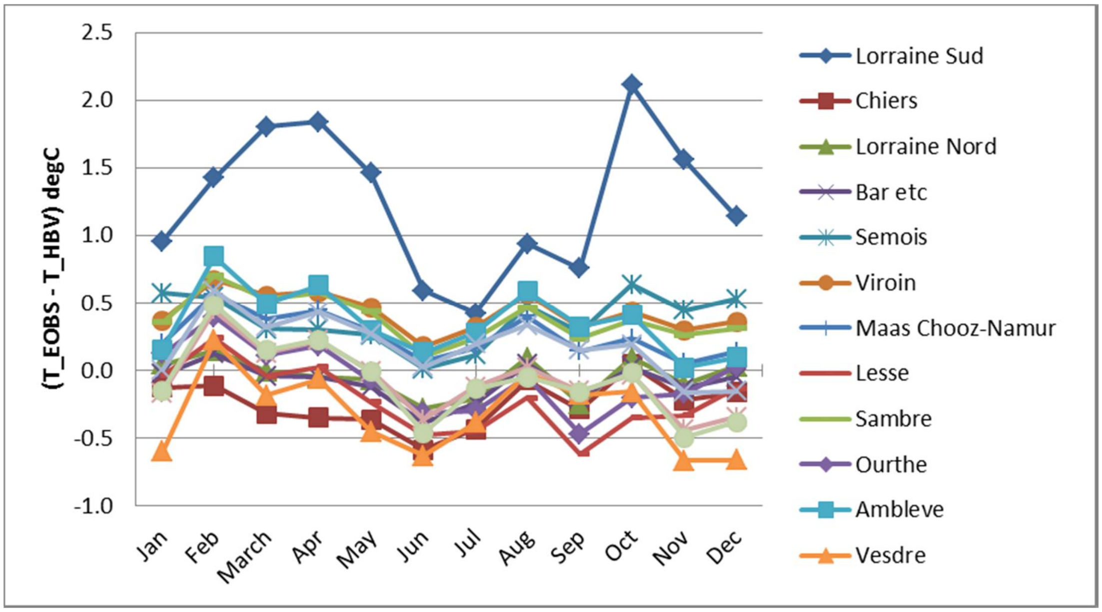

Figure B.1 Differences in mean monthly temperature (E-OBS and HBV profile) for sub-catchments of the Meuse

It can be seen from Figure B.1, that difference between the temperature of E-OBS and of HBV ranges between -0.6°C and approximately 2°C. The largest differences are observed for the Lorraine Sud catchment.

B.2 Comparison temperature profiles Rhine

The difference between the HYRAS (1951-2007) mean monthly temperature – T_HYRAS- and the temperature profiles included in HBV (as derived by Eberle et al., 2005) –T_HBV- for a few sub catchments in Switserland (Aare2), Main (Main2), Moselle (Alzette) and the Rurh (Ruhr3) are shown in Figure B.2.

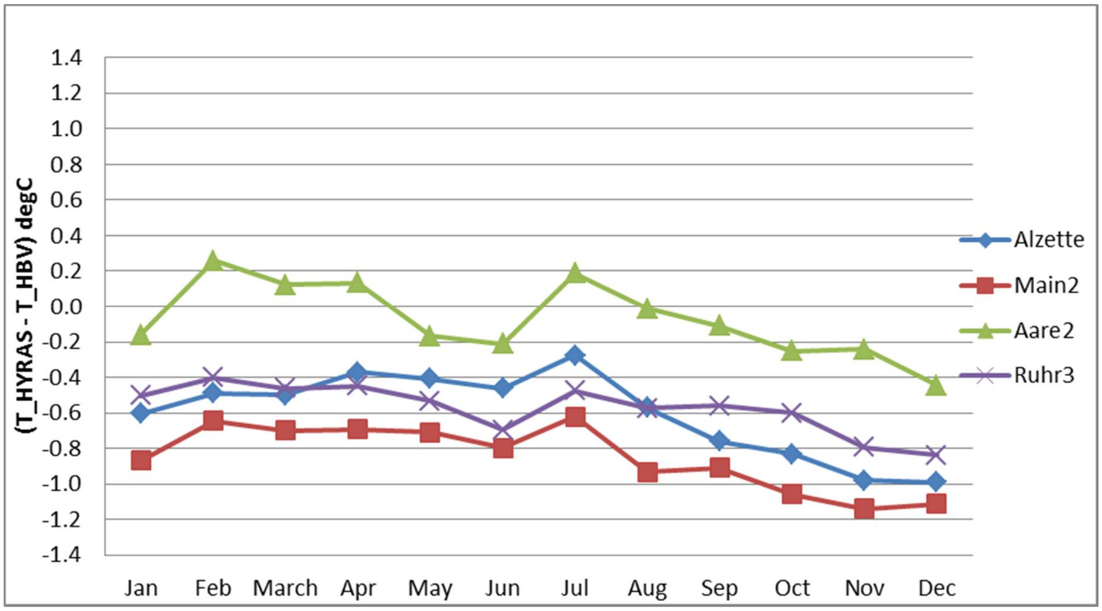

Figure B.2 Differences in mean monthly temperature (of HYRAS and HBV profile) for several Rhine sub-catchments

For the assessed sub-catchments, which are spread in the Rhine Basin, the differences between the HYRAS dataset and the temperature profiles within HBV range between -1.20 and 0.40°C.

B.3 Comparison potential evaporation profiles Meuse

The potential evaporation profiles for the different sub-catchments of the Meuse as included in HBV were compared to evaporation profiles as created by R. Leander (2009).

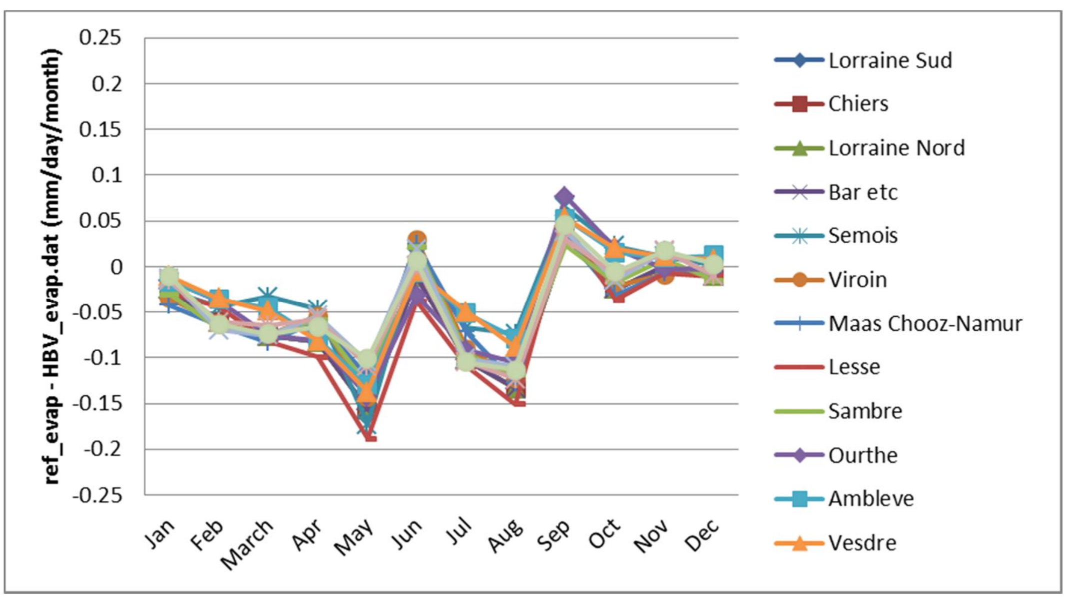

Figure B.3 Differences in mean daily potential evaporation per month (reference and HBV profiles) for the sub-catchments of the Meuse

Reference and HBV mean daily evaporation per month varied within a range of -0.2 mm/day to 0.1 mm/day for the different sub-catchments of the Meuse. The monthly bias seems to be similar for all sub-catchments.

B.4 Comparison of temperature and potential evaporation in the Moselle and the Meuse

Temperature

Because the HBV model for the Meuse does not contain a long-term average temperature profile we included the Moselle HBV profile in the current comparison. The Moselle is considered representative for the Meuse as both climate and hydrological conditions are comparable between the Meuse and the Moselle.
The basin wide mean monthly temperature of the Moselle and Meuse was determined based on the following data sources:

- HYRAS for the Moselle
- HBV profile as derived by Eberle et al. (2005) for the Moselle
- E-OBS for the Meuse
- Reference profile (as created by R. Leander in 2009) for the Meuse

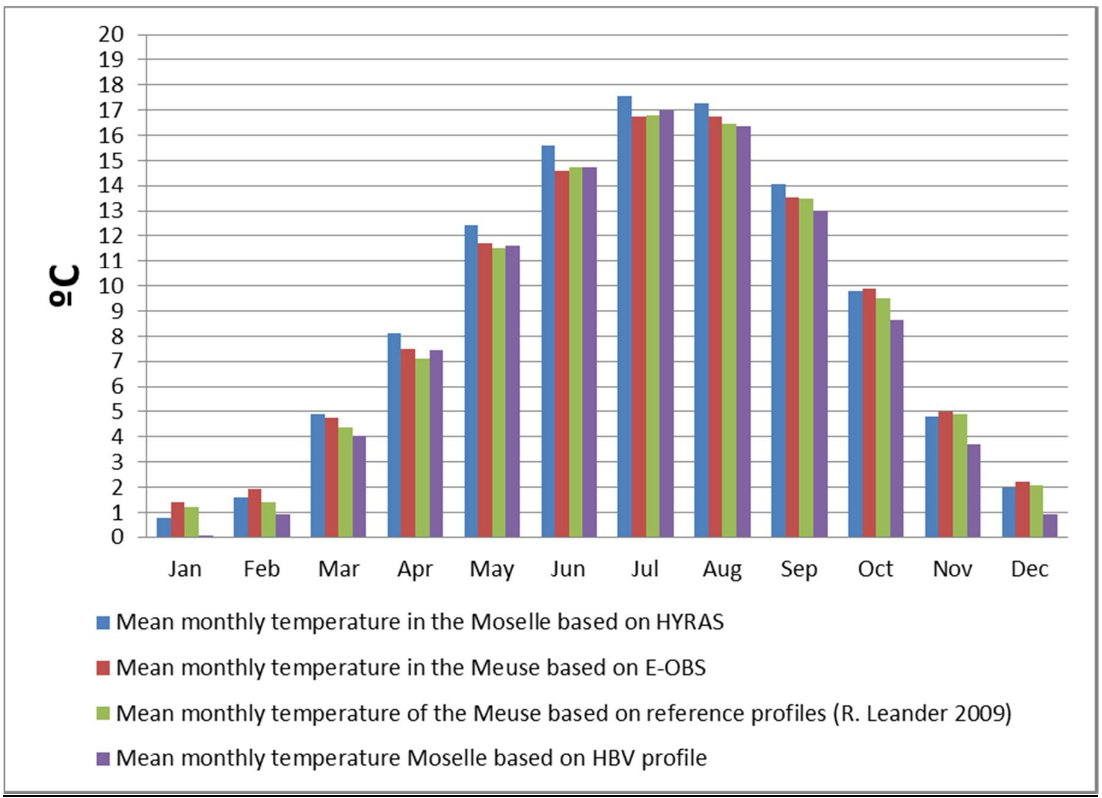

Figure B.4 Comparison of mean monthly temperature in the Meuse and in the Moselle catchments

As depicted in Figure B.4, the difference in mean monthly temperature in the Meuse and the Moselle based on different sources of profiles are approximately never higher than 1°C.

Evaporation
Mean daily potential evaporation per month for the Meuse and the Moselle was assessed by comparing data from the following profiles:

- Areal weighted average of sub-catchment potential evaporation based on weights of stations as calculated in HBV for the Moselle
- Areal weighted average of the potential evaporation of the sub-catchments of the Meuse as in the HBV profiles
- Areal weighted average of the sub-catchment of the Meuse based on the reference profiles as created by R. Leander (2009)

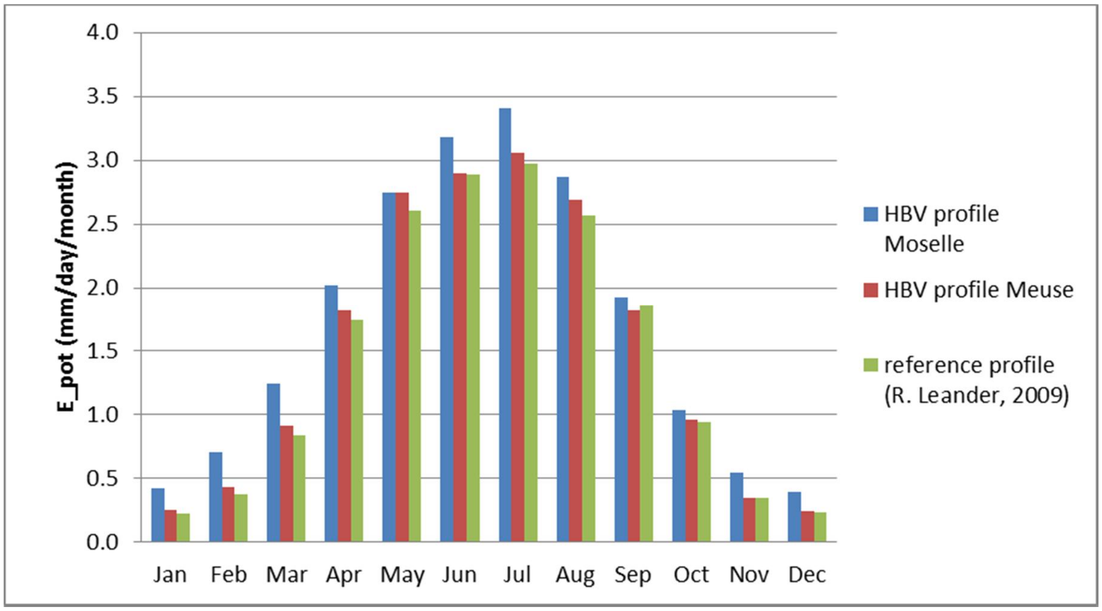

Figure B.5 Comparison of mean daily evaporation per month in the Meuse and the Moselle catchments

As depicted in Figure B.5 the differences in mean daily potential evaporation per month don't exceed 0.5 mm/day in the months with more than 2.5 mm/day potential evaporation on average and less than 0.25 mm/day for the colder months.

B.5 In summary

It was found that mean monthly temperature differences between E-OBS and HBV for the Meuse ranged from -0.6 to +2°C. Mean monthly temperature differences between HYRAS and HBV for a few sub catchments of the Rhine ranged between -1 and +0.4°C. Mean monthly temperature differences between the Moselle and the Meuse approximately never exceeded 1°C.

For the Meuse, mean monthly evaporation differences between the profiles constructed by Leander and the profiles included in HBV ranged from -0.2 to 0.1 mm/day. Differences in evaporation between the Meuse and the Moselle never exceeded 0.5 mm/day.
It could therefore be concluded that there were no large differences between the various temperature and evaporation profiles evaluated for the Rhine and the Meuse, except for Lorraine Sud. This implies that the historical climate is overall well represented in HBV.

From the *etf* analysis, it was found that *etf* values were sensitive to seasonality (Figure A.1in Appendix A), therefore forcing the model with externally calculated evaporation can still be desirable, in spite of the reliability of the profiles included in HBV.