Hydrol. Earth Syst. Sci. Discuss., 10, 6807–6845, 2013
www.hydrol-earth-syst-sci-discuss.net/10/6807/2013/
doi:10.5194/hessd-10-6807-2013

Hydrology and Earth System Sciences
Open Access
Discussions

Impacts of climate change on the seasonality of low flows in 134 catchments in the River Rhine basin using an ensemble of bias-corrected regional climate simulations

M. C. Demirel, M. J. Booij, and A. Y. Hoekstra

Water Engineering and Management, Faculty of Engineering Technology,
University of Twente, P.O. Box 217, 7500 AE Enschede, the Netherlands

Received: 7 May 2013 – Accepted: 17 May 2013 – Published: 31 May 2013

Correspondence to: M. C. Demirel (m.c.demirel@rhinelowflows.nl)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

The impacts of climate change on the seasonality of low flows are analysed for 134 sub-catchments covering the River Rhine basin upstream of the Dutch–German border. Three seasonality indices for low flows are estimated, namely seasonality ratio (SR), weighted mean occurrence day (WMOD) and weighted persistence (WP). These indices are related to the discharge regime, timing and variability in timing of low flow events respectively. The three indices are estimated from: (1) observed low flows; (2) simulated low flows by the semi distributed HBV model using observed climate; (3) simulated low flows using simulated inputs from seven climate scenarios for the current climate (1964–2007); (4) simulated low flows using simulated inputs from seven climate scenarios for the future climate (2063–2098) including different emission scenarios. These four cases are compared to assess the effects of the hydrological model, forcing by different climate models and different emission scenarios on the three indices. The seven climate scenarios are based on different combinations of four General Circulation Models (GCMs), four Regional Climate Models (RCMs) and three greenhouse gas emission scenarios.

Significant differences are found between cases 1 and 2. For instance, the HBV model is prone to overestimate SR and to underestimate WP and simulates very late WMODs compared to the estimated WMODs using observed discharges. Comparing the results of cases 2 and 3, the smallest difference is found in the SR index, whereas large differences are found in the WMOD and WP indices for the current climate. Finally, comparing the results of cases 3 and 4, we found that SR has decreased substantially by 2063–2098 in all seven subbasins of the River Rhine. The lower values of SR for the future climate indicate a shift from winter low flows (SR > 1) to summer low flows (SR < 1) in the two Alpine subbasins. The WMODs of low flows tend to be earlier than for the current climate in all subbasins except for the Middle Rhine and Lower Rhine subbasins. The WP values are slightly larger, showing that the predictability of low flow events increases as the variability in timing decreases for the future climate.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀| |▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

From comparison of the uncertainty sources evaluated in this study, it is obvious that the RCM/GCM uncertainty has the largest influence on the variability in timing of low flows for future climate.

1 Introduction

The rivers in Western Europe have a seasonal discharge regime with high flows in winter and low flows in late summer. Many cities are located along these rivers like the River Rhine, as the rivers are used for drinking water supply and industrial use. The rivers are also used for irrigation, power production, freight shipment (Demirel et al., 2010; Jonkeren et al., 2013) and fulfil ecological and recreational functions (De Wit et al., 2007). Floods and low flows in these rivers may cause several problems to society. Since floods are eye-catching, quick and violent events risking human-life, water authorities often focus on flood issues. In contrast, low flows are slowly developing events affecting a much larger area than floods. Low flows in rivers may negatively affect all important river functions. Severe problems, e.g. water scarcity for drinking water supply and power production, hindrance to navigation and deterioration of water quality, have already been seen during low flow events in the River Rhine in dry summers such as in 1969, 1976, 1985 and 2003. Consequently, understanding low flows and its seasonal to inter-annual variation has both societal and scientific value as there is a growing concern that the occurrence of low flows will intensify due to climate change (Grabs et al., 1997; Middelkoop et al., 2001; Huang et al., 2012). We are interested in evaluating the effects of climate change on the seasonality of low flows, and in presenting corresponding uncertainty to provide low flow seasonality information under different climate projections.

Assessing the impacts of climate change and associated uncertainties of the climate change projections is an important field in hydroclimatology (Arnell and Gosling, 2013; Bennett et al., 2012; Chen et al., 2011; Jung et al., 2013; Minville et al., 2008; Prudhomme and Davies, 2009; Taylor et al., 2012). The assessment of the effect of climate change impacts on hydrological catchment response is based on predicted meteorological variables like precipitation and temperature by climate models. Currently available climate change projections are mainly based on the outputs of general circulation models (GCMs) and additionally the outputs of regional climate models (RCMs) with a higher spatial resolution than GCMs. However, it is obvious that regional climate change projections based on these climate model outputs are highly uncertain due to unknown future greenhouse gas emissions and the simplified representation of processes in both RCMs and GCMs (Horton et al., 2006). Therefore, design practices will face new challenges which will require a better quantitative understanding of potential changes in seasonality of low flows complicated by several sources of uncertainty linked to climate change.

Many studies have investigated the impacts of climate change on hydrological regimes of different rivers such as the Nile River (Beyene et al., 2010), the Columbia River in Canada (Schnorbus et al., 2012), the Thames River in the UK (Wilby and Harris, 2006; Diaz-Nieto and Wilby, 2005) and the River Rhine (Bosshard et al., 2012; Shabalova et al., 2003; Lenderink et al., 2007). Most of the River Rhine studies focus on the snow processes in the Swiss Alps (Horton et al., 2006; Bormann, 2010; Jasper et al., 2004; Schaefli et al., 2007). The River Rhine studies show that the projected temperature increase by GCMs strongly determines the temporal evolution of snowmelt and, accordingly, high flows in the catchments studied. For example, Shabalova et al. (2003) showed a decrease of summer low flows and an increase of winter high flows in the River Rhine leading to flood risk in the winter period. Jasper et al. (2004) used 17 combinations of GCMs and emission scenarios to assess the impact of climate change on runoff in two Swiss catchments. They found substantial reductions in snowpack and shortened duration of snow cover, resulting in time-shifted and reduced runoff peaks.

Several studies documented potential effects of climate change on low flows in the River Rhine (Huang et al., 2012; Te Linde et al., 2010) and on low flows in the Thames River (Wilby and Harris, 2006; Diaz-Nieto and Wilby, 2005). Huang et al. (2012) analysed the effects of three climate change projections on the length of the low flow period and on the 50 yr return period of deficit volumes for catchments in Germany. Their study showed that low flow events are likely to occur more frequently by 2061–2100 in Western Germany (Huang et al., 2012). Wilby and Harris (2006) assessed the effects of emission scenarios, GCMs, statistical downscaling methods, hydrological model structure and hydrological model parameters on simulating changes in low flows. Their study showed that GCMs and the downscaling method were the most important sources of uncertainty. Although GCMs are a very important source of uncertainty (Prudhomme and Davies, 2009; Graham et al., 2007), the effects of uncertainty from RCMs should not be neglected (Horton et al., 2006; Yimer and Andreja, 2012). The uncertainty due to the hydrological model used is relatively small compared to the uncertainty from emission scenarios and climate models (Prudhomme and Davies, 2009).

Most of the above mentioned studies focus on the effects of climate change uncertainty on river flow regimes. Earlier work exists for seasonality analysis of observed low flows (Laaha and Blöschl, 2006; Tongal et al., 2013) and floods (Parajka et al., 2009, 2010) to understand the hydrological processes in the studied catchments. However, only few studies analysed the impacts of climate change on the seasonality of floods in Switzerland (Köplin et al., 2013) and seasonality of dam inflows in Korean rivers (Jung et al., 2013). The first study by Köplin et al. (2013) assessed the changes in the seasonality of mean annual and maximum floods of a 22 yr period for 189 catchments in Switzerland using circular statistics and an ensemble of climate scenarios. They assessed both changes in the mean occurrence date of floods as well as changes in the strength of the flood seasonality. The latter study by Jung et al. (2013) has investigated only monthly dam inflow series and standard deviation of these monthly series to reflect the seasonality of dam inflows using 39 climate simulations (13 GCMs with three emission scenarios) and three hydrologic models. They explicitly take into account the hydrological model uncertainty (Jung et al., 2013). To our knowledge, so far no study has assessed the impacts of climate change, driven by state of the art climate scenarios, on the seasonality of low flows.

The objective of this study is to assess the effects of climate change on the seasonality of low flows in the River Rhine basin using different climate change projections. The effects of the hydrological model, the forcing by different combinations of GCMs and RCMs, and different emission scenarios on the seasonality of low flows are evaluated. The seasonality of a hydrological variable is often described in terms of mean value during fixed seasons (e.g. June, July, and August, or JJA) (Baldwin and Lall, 1999; Guo et al., 2008). In this study, following the study of Laaha and Blöschl (2006), seasonality of low flows is described through the analysis of three indices namely the Seasonality Ratio (the ratio of summer low flow and winter low flow), the Weighted Mean Occurrence Day and the Weighted Persistence (measuring the variability in timing) of low flows. Daily observed low flow series available from 101 sub-catchments and simulated low flow series from 134 sub-catchments are used to assess the effects of climate change on the three indices.

The seasonality indices, the hydrological model and the data used in this study are described in Sect. 2. The study area is introduced in Sect. 3. The results are presented in Sect. 4. The findings are discussed in Sect. 5, and the conclusions are drawn in Sect. 6.

2 Methods and data

In this study a simulation approach is used to assess the effects of climate change on the seasonality of low flows in the River Rhine. In this approach, observed inputs and simulated inputs from bias-corrected outputs of seven climate scenarios are used as forcing for the hydrological model. Observed low flows (case 1 in Table 1) and the outputs of the hydrological model (case 2, 3 and 4) are then used to estimate three seasonality indices as will be discussed below.

Cases 1 and 2 are compared to assess the effects of the hydrological model on the three indices. Secondly, we compare the cases 2 and 3 to assess the effects of the meteorological forcing on the three seasonality indices. In the third and final comparison, the cases 3 and 4 are used to assess the effects of different emission scenarios on the seasonality of low flows. We present the differences in the three indices at two spatial scales that are 134 sub-catchments and seven major subbasins.

2.1 Seasonality indices

Laaha and Blöschl (2006) give an overview of seasonality indices and how they can be estimated based on discharge time series. Seasonality indices are estimated to describe different aspects of the discharge regime of a river. We use three seasonality indices described below as they focus on the differences in discharge regime, timing and variability in timing of the recurrent event (persistence).

2.1.1 Seasonality Ratio (SR)

The Seasonality Ratio (SR) index reveals the low flow characteristics in summer and winter periods (Laaha and Blöschl, 2006). The definitions of a low flow threshold and the seasons are crucial for the SR results as the underlying hydrological processes for summer and winter low flows are different (Laaha and Blöschl, 2006; Tongal et al., 2013). Following De Wit et al. (2007), we selected the period from November to April as winter half-year and the period from May to October as summer half-year season. The low flow series are then divided into winter and summer low flow series. We used the 75 % exceedence probability (Q_{75}), as in Demirel et al. (2012), as a threshold for defining summer low flow ($Q_{75\mathrm{s}}$) and winter low flow ($Q_{75\mathrm{w}}$). The SR index is calculated as the ratio of $Q_{75\mathrm{s}}$ and $Q_{75\mathrm{w}}$ (Eq. 1) (Laaha and Blöschl, 2006).

$$\mathrm{SR} = \frac{Q_{75\mathrm{s}}}{Q_{75\mathrm{w}}} \tag{1}$$

A value of SR greater than one indicates the presence of a winter low flow regime and a value smaller than one indicates the presence of a summer low flow regime.

2.1.2 Weighted Mean Occurrence Day (WMOD)

The Weighted Mean Occurrence Day (WMOD) is an index similar to the seasonality index of Laaha and Blöschl (2006). For each subbasin, the days at which the discharge is below the Q_{75} threshold are transformed into Julian dates D_i, i.e. the day of the year ranging from 1 to 365 in regular years and 1 to 366 in leap years. The day number of each low flow event (D_i) is weighted by the inverse low flow value ($1/Q_i$) on the same day to address the severity of a low flow event as well as its occurrence day. The weighted mean day of occurrence is estimated first in radians to represent the annual cycle correctly. Otherwise, a simple averaging of low flow occurrences in winter months, e.g. January and December, can lead to a large error in the results. The weighted mean of Cartesian coordinates x_θ and y_θ of a total of low flow days i is defined as

$$x_\theta = \sum_i \frac{\cos\left(\frac{D_i}{Q_i}\frac{2\pi}{365}\right)}{Q_i^{-1}} \tag{2}$$

$$y_\theta = \sum_i \frac{\sin\left(\frac{D_i}{Q_i}\frac{2\pi}{365}\right)}{Q_i^{-1}} \tag{3}$$

The directional angle (θ) is then estimated by

$$\theta = \arctan\left(\frac{y_\theta}{x_\theta}\right) \qquad \text{1st and 4th quadrants:} \quad x_\theta > 0 \tag{4}$$

$$\theta = \arctan\left(\frac{y_\theta}{x_\theta}\right) + \pi \qquad \text{2nd and 3rd quadrants:} \quad x_\theta < 0 \tag{5}$$

The values of θ can vary from 0 to 2π, where a zero value indicates the 1 January, $\pi/2$ represents the 1 April, π represents the 1 July and $3\pi/2$ represents the 1 October. The main advantage of using circular statistics is that it allows us to correctly average low flow occurrences in the winter half-year period. The WMOD is then obtained by back-transforming the weighted mean angle to a Julian date:

$$\mathrm{WMOD} = \theta \frac{365}{2\pi} \tag{6}$$

2.1.3 Weighted Persistence (WP)

The Weighted Persistence (WP) is calculated using the weighted mean of Cartesian coordinates x_θ and y_θ in Eq. (6).

$$\mathrm{WP} = \sqrt{x_\theta^2 + y_\theta^2} \tag{7}$$

The dimensionless WP indicates the variability in timing of low flows, where a value of 1 indicates that low flow events occurred on exactly the same day of the year (high persistence) and a value of zero indicates that low flow events are uniformly distributed over the year (no persistence) (Laaha and Blöschl, 2006).

2.2 Hydrological model

The HBV-96 model (Hydrologiska Byråns Vattenbalansavdelning) is a semi-distributed conceptual hydrological model which was developed by the Swedish Meteorological and Hydrological Institute (SMHI) in the early 1970's (Lindström et al., 1997; Bergström, 1976). It consists of five subroutines for snow accumulation and melt, soil moisture accounting, fast runoff, groundwater response and river routing. It operates at a daily time step using precipitation (P) and potential evapotranspiration (PET) as inputs. The HBV model has been used in the field of operational forecasting and climate impact modelling in more than 50 countries around the world (Şorman et al., 2009), in North-Western Europe in particular (Görgen et al., 2010; Driessen et al., 2010; Engeland et al., 2010; Te Linde et al., 2008; Wöhling et al., 2006; Booij, 2005). Its good performance with a low number of parameters is the main advantage of the HBV model for large basins (Te Linde et al., 2008). The HBV model has been applied for the River Rhine since 1997 by the Dutch Water authorities, i.e. Rijkwaterstaat Waterdienst (previously RIZA) and Deltares, and the German Federal Institute of Hydrology (BfG) in Koblenz. We use a HBV-96 model running at a daily time step and covering the area upstream of the Lobith gauge station comprising 134 sub-catchments (called HBV-134 hereafter). The HBV model was first calibrated by Eberle (2005) on the basis of expert knowledge in the BfG in Koblenz. The HBV-134 model upstream of Maxau has been recalibrated again by Berglöv et al. (2009) at SMHI using a hybrid objective function ($\mathrm{NS}_{\mathrm{HBV}}$ in Eq. 8) to improve low flow simulations. The calibration was carried out locally for 95 sub-catchments, and validated both locally and for the total river flow. Further, the calibration was mainly done using an automatic routine (Lindström et al., 1997) for the period 1 November 2000–1 November 2007 and the period 1 November 1996–1 November 2000 was used for validation.

$$\mathrm{NS}_{\mathrm{HBV}} = 0.5 \cdot R^2 + 0.5 \cdot R^2_{\mathrm{log}} + 0.1 \cdot \mathrm{relaccdif} \tag{8}$$

Where R^2 is the efficiency criteria based on Nash and Sutcliffe (1970), R^2_{log} is similar to R^2 but using the logarithmic discharge values giving more weights to low flows, and relaccdif is the accumulated difference between simulated and observed discharge (Berglöv et al., 2009).

The HBV-134 model has served as a robust platform for climate impact studies in the River Rhine basin (Görgen et al., 2010; Nilson et al., 2012; Te Linde et al., 2010). The model simulations for the current and future climate were initialized on 1st of January 1961 and 2060. The first three years are considered as a “warm-up” period and model simulation results for these periods are not used in the estimation of the seasonality indices.

2.3 Observed data

Daily discharge (Q_{obs}) data at the outlets of 101 of the 134 sub-catchments were provided by the Global Runoff Data Centre (GRDC) in Koblenz (Germany) and the Bundesamt für Umwelt (BAFU) in Bern (Switzerland). A complete set of daily P and PET were obtained from Deltares (the Netherlands) and the German Federal Institute of Hydrology (BfG) in Koblenz. The PET has been estimated with the Penman–Wendling equation (ATV-DVWK, 2002). Both variables are spatially averaged, i.e. disaggregated over 134 sub-catchments (Photiadou et al., 2011).

The mean altitude of these subcatchments has been provided by the International Commission for the Hydrology of the Rhine basin (CHR). The daily P and PET data series span from 1961 to 2007 whereas the length of the Q_{obs} data series varies from station to station.

2.4 Bias-corrected climate model outputs and transformation to catchment average

All seven regional climate model (RCM) outputs (Jacob, 2006) that are used in this study have been provided by the Royal Netherlands Meteorological Institute (KNMI) and BfG in Koblenz. The grid-based RCM outputs have firstly been transferred into daily catchment averages over 134 sub-catchments of the River Rhine basin and then corrected for biases by Görgen et al. (2010) for the Rhineblick2050 project. The daily time series of areal average PET estimated following the approach of Penman–Wendling (ATV-DVWK, 2002), requiring only forecasted surface solar radiation and temperature at 2 m data. This is consistent with the observed PET estimation carried out by the Federal Institute of Hydrology in Koblenz, Germany. The main characteristics of the pre-processed climate dataset, comprising an ensemble of bias-corrected outputs of scenarios based on four regional climate models (RCMs), three different emission scenarios (SRES) and four driving global climate models (GCMs), are shown in Table 2.

The three scenarios, i.e. A2, A1B and B1, are based on three different greenhouse gas emission scenarios as defined by the Intergovernmental Panel on Climate Change (IPCC) in the Special Report on Emissions Scenarios (Hurkmans et al., 2010; Nakićenović and Swart, 2000). The A2 scenario assumes a world with a continuously increasing population and very regionally oriented economic growth, whereas A1B indicates a globalized, very rapidly growing economy with fast introduction of new technologies that are balanced between fossil fuel intensive and sustainable and clean ones. The global population in the A1B scenario increases rapidly until the middle of 21st the century and decreases thereafter. The third scenario, B1, assumes a globalized, rapidly growing population with changes in economic structure with an environmental emphasis and fast introduction of clean and efficient technologies.

Transferring the indicators of climate change from climate models to hydrological models is not a straightforward process due to the systematic errors in simulated meteorological variables, i.e. precipitation and temperature. For example, many RCMs exhibit a bias in the order of 25 % for the amount of summer precipitation in the Alpine region (Graham et al., 2007). Hydrological simulations using uncorrected inputs would be pointless for assessing impacts of climate change on low flow seasonality as summer precipitation amounts are crucial for low flows (Demirel et al., 2012). The biases from the RCM outputs have been corrected by Görgen et al. (2010) using Eq. (8) for precipitation.

$$P_{\mathrm{cor}} = aP_{\mathrm{RCM}}^{b} \tag{9}$$

Where P_{cor} (mm) is the bias-corrected precipitation, P_{RCM} (mm) is the precipitation from RCMs and, a and b are transformation coefficients which are determined separately for each of the 134 sub-catchments and for each of the 12 calendar months. The frequency distribution of the wet-day precipitation, i.e. location and shape, is not affected by this nonlinear bias-correction method (Eq. 8), whereas the frequency of wet days is corrected as in most RCMs the frequency of wet days is overestimated (Görgen et al., 2010).

The biases from the RCM outputs have been corrected by Görgen et al. (2010) using Eq. (9) for temperature.

$$T_{\mathrm{cor}} = \frac{\sigma_{\mathrm{o}}}{\sigma_{\mathrm{m}}}\left(T_{\mathrm{RCM}} - \bar{T}_{\mathrm{m}}\right) + \bar{T}_{\mathrm{o}} \tag{10}$$

where T_{cor}(°C) is the bias-corrected temperature, σ_{o} (°C) is the standard deviation of the observed daily temperature, σ_{m} (°C) is the standard deviation of the daily RCM temperature,T_{RCM} (°C) is the RCM temperature, $\bar{T}_{\mathrm{m}}$ (°C) is the long term mean of the RCM temperature and, $\bar{T}_{\mathrm{o}}$ (°C) is the long term mean of the observed temperature series for each of the 134 sub-catchments.

By using Eq. (9), the mean and standard deviation of the bias-corrected RCM temperature data are forced to be equal to those of the observed current climate data. The bias-corrections are described in detail in Görgen et al. (2010).

3 Study area

The River Rhine basin is a major and densely populated river basin in Western Europe accommodating nearly 60 million inhabitants (Te Linde et al., 2011). The surface area of the basin is approximately 185 300 km^2 and the river flows along a 1233 km course from the Alps to the North Sea. The topography of the basin is quite diverse varying from high Alpine mountains to flat lands in the downstream part. In addition to its importance as an inland water, the River Rhine serves as a vital freshwater resource for the Netherlands as well as for the other upstream countries such as Luxemburg, Germany and Switzerland (Middelkoop and Van Haselen, 1999). The average discharge downstream of the Alpine mountains is approximately 1000 m^3 s^{-1}. It then increases up to 2300 m^3 s^{-1} at the Lobith gauging station after the German–Dutch border. The minimum observed discharge at this gauging station was 575 m^3 s^{-1} in 1929. The contribution of the Alps to the total discharge can be more than 70 % in summer, whereas it is only about 30 % in winter (Middelkoop and Van Haselen, 1999). In the winter period, the precipitation is stored as snow and ice in the Alps until late spring. Due to the high evaporation and little melt-water input from the Alps, low flows typically occur in late summer or autumn (Nilson et al., 2012).

Figure 1 shows the River Rhine basin at two spatial scales i.e. 134 sub-catchments and seven subbasins. The hydrology of the River Rhine basin has already been modelled at a spatial scale of 134 sub-catchments (Eberle, 2005; Görgen et al., 2010; Renner et al., 2009; Te Linde et al., 2008), whereas the indicators of low flow events have been assessed at an aggregated spatial scale of seven major subbasins by Demirel et al. (2012).

The spatial scales of 134 sub-catchments and seven subbasins are used to present our results. The first spatial scale allows us to compare the differences in the three indices at a very detailed level, whereas the spatial scale of seven subbasins gives insight about the hydrological processes in the major tributaries of the River Rhine. The outlet discharges for the East Alpine (EA) (station #2143 at Rekingen), West Alpine (WA) (station #2016 at Aare-Brugg), Neckar (station #6335600 at Rockenau), Main (station #24088001 at Frankfurt), Moselle (station #6336050 at Cochem), Middle Rhine (MR) (station #6335070 at Andernach) and Lower Rhine (LR) (station #6435060 at Lobith) are used in the seasonality assessment. Although the MR and LR subbasins have mixed discharge regimes originating from snow- and rain-dominated sub-basins, they are also included in this study.

4 Results and discussion

4.1 Effects of hydrological model on the seasonality of low flows

Figure 2 shows the three seasonality indices based on observed and simulated low flows for the common 101 catchments. These catchments are grouped into the seven major subbasins as consistent with the previous low flow studies in the River Rhine (Demirel et al., 2012).

The results in Fig. 2 reveal that there are significant differences between observed and simulated seasonality indices, showing the errors due to the observed meteorological inputs and the hydrological model. The differences in the simulated SRs in the rain-dominated catchments are smaller than in the snow-dominated catchments. Further, we present our results for 101 catchments as a function of the mean catchment altitude. This altitude sorting (high to low altitude from left to right) is done within the seven major sub-basins since the mean catchment altitude is an important catchment characteristic for the discharge regime in the Rhine basin. Significant correlations between SR and catchment altitude are found in the EA, WA and Neckar subbasins as catchments with a higher altitude tend to have winter low flows and higher SR values. Contrary to expectations, no significant correlations are found between SR and catchment altitude in the Main and Moselle subbasins. Further, no significant relation is found between catchment altitude and the two other indices, WMOD and WP.

The weighted mean occurrence days (WMODs) of simulated low flow events are too late for the EA and WA subbasins. The WMODs for observed low flows in these Alpine subbasins are mostly around October, whereas the WMODs for the simulated low flows considerably vary from October to March showing the uncertainty originating from the HBV model and its inputs (Fig. 2). It should be noted that the effect of the varying lengths of observed discharge time series on the estimation of the WMODs can be substantial for different catchments. This finding for the low flow simulation performance is consistent with that of Te Linde et al. (2008), who found variable performance of HBV on the low flow timing and significant errors in the duration of low flows. The weighted persistence (WP) of low flow events in the WA subbasin is better simulated than in other subbasins.

Figure 3 shows the three seasonality indices based on simulated low flows for the 134 catchments. From the SR and WMOD plots in Fig. 3 it is apparent that the Alpine catchments have winter low flows, whereas other catchments have summer low flows. The WMODs for the simulated winter low flows are mostly in January and February, whereas those for the simulated summer low flows are in September and October.

Moreover, the WP in the rain-dominated catchments is generally higher than in the Alpine catchments. The dam operations in the Alpine catchments in winter periods can marginally affect the WP as the dam operations are usually carried out in high flow periods for flood prevention (Middelkoop and Van Haselen, 1999; Bosshard et al., 2012).

Table 3 compares the differences between the three seasonality indices based on observed and simulated low flows at the outlets of the seven subbasins. It should be noted that the relative differences for SR and WP are presented as a percentage, whereas the difference for WMOD is equal to the difference in days at the outlet of the seven subbasins.

No significant differences in SR were found between simulated and observed low flows in the WA, MR, Main and LR subbasins, whereas the largest difference in SR was found in the Moselle subbasin. The negative differences in SR were found only in the EA and WA subbasins showing that the SR estimated from simulated low flows (case 2) is smaller than the SR estimated from observed low flows (case 1) at the outlet of the two Alpine subbasins. It is obvious that the MR and LR subbasins have mixed discharge regimes and, therefore, they are affected by the differences in the upstream subbasins. For instance, the WMOD in the EA subbasin, which is 10 days earlier than the WMOD estimated from observed low flows (case 1), resulted in 83 days earlier WMOD in the MR subbasin. The effect is reduced to 30 days earlier WMOD in the LR subbasin after the inclusion of other tributaries with late WMODs. The large differences in the WPs in all subbasins except for the Neckar subbasin show that the simulation of the distribution of low flow events in a year is a difficult task in hydrological modelling.

4.2 Effects of meteorological forcing on the seasonality of low flows

The effects of the meteorological forcing on the three indices are assessed at two spatial scales, i.e. 134 sub-catchments and seven major subbasins. This is done for the current climate (1964–2007) using observed and simulated inputs for HBV. From the results in Table 4, we can see that the outputs of climate scenarios 3 and 4 result in smaller SRs than those simulated using observed climate as input for all subbasins except the WA subbasin for the current climate. The largest difference in SR is found for the Moselle subbasin. The differences (mostly negative) for climate scenarios 3 and 4, both having boundary conditions from the HADCM3 GCM, are larger than the other five climate scenarios (except for the EA and WA subbasins).

The differences in the WMODs of low flows in the WA, Neckar and Main subbasins are mostly less than 30 days, showing that the weighted mean occurrence day of low flows in these subbasins is simulated well using the outputs of seven climate scenarios for the current climate. The picture is very different for the other subbasins. For instance, the WMODs based on simulated current climate as input in the HBV model in the EA MR, Moselle and LR subbasins are very different from the WMODs simulated using observed climate. The differences vary from 1 day (by climate scenario 5) in the EA subbasin to 102 days (by climate scenarios 6 and 7) in the MR and LR subbasins respectively. Very large differences in the WPs in all seven subbasins, in the EA subbasin in particular, are simulated using the outputs of climate scenarios. All these differences are positive for the EA subbasin, showing a substantially smaller variability in timing of low flow events (WPs), whereas all the differences are negative for the Moselle subbasin, showing a larger variability in WPs. Since large differences are found in the WP index, we also present the detailed effects of seven climate scenarios on the weighted persistence in the 134 sub-catchments in Fig. 4.

There are large differences in the WPs using the outputs of climate scenarios. Climate scenarios 3 and 4 result in a higher WP than those simulated using observed climate as input. However, climate scenario 2 results in a lower WP than that simulated using observed climate as input. It should be noted that the WPs from climate scenarios 5, 6 and 7 are similar as the same version of ECHAM5 and REMO climate models are used in these scenarios. The significant differences in climate scenarios 2, 3 and 4 can be partly explained by the inter-annual variability of monthly P and PET simulated by the climate scenarios over a year. We found large differences between cases 2 and 3 in the inter-annual variability of monthly P in winter months for all subbasins, whereas large differences in the inter-annual variability of monthly PET in winter months were found only in rain-dominated subbasins like in the Moselle subbasin.

4.3 Effects of changed climate on the seasonality of low flows

Figure 5 shows the differences in the three indices for the current and future climate. Here, the effects of the three emission scenarios (A1B, A2 and B1) on the three indices are also evaluated.

From the results of Fig. 5, it is apparent that the range of SRs in all seven subbasins for the future climate is not overlapping with those for the current climate. The uncertainty in SRs is considerably smaller than the uncertainty in the other two indices. Further, the SRs are always lower than for the current climate. The lower values of SR for the EA and WA subbasins, for the latter in particular, indicate a substantial shift from winter low flows ($SR > 1$) to summer low flows ($SR < 1$) which is in line with other climate impact studies (Hurkmans et al., 2010; Bosshard et al., 2012; Huang et al., 2012; Bormann, 2010; Blenkinsop and Fowler, 2007).

Comparing the results for the WMODs, it appears that only the range of WMODs in the WA subbasin for the future climate is not overlapping with that for the current climate. The largest range of WMODs for the current climate is found in the Moselle subbasin. Interesting is that low flows in most of the subbasins tend to occur earlier by 2063–2098 based on the WMOD results in Fig. 5. The uncertainty in the WMODs varies from several weeks to five months in the subbasins.

Large ranges are found for WP for all subbasins except for the WA subbasin using the inputs from seven climate scenarios, indicating that the WP index is highly uncertain. The distribution of precipitation over a year can affect the WP results significantly as the distribution of precipitation determines the variability in simulated discharges. A significant decrease in the variability in timing of low flows (WPs) in the EA subbasin is found for the future climate. The existence of large lakes in the WA subbasin can be a reason for a less sensitive WP. The most striking result from the WP plot in Fig. 5 is that the weighted persistence is increased in all subbasins for the future climate suggesting less variability in timing of low flows. This finding is in line with the scientific consensus that climate change will likely increase the persistence of both high and low flows due to decreasing snowfall and earlier snowmelt, resulting in an earlier occurrence of snowmelt-induced peaks and drier summers (Jung et al., 2013; Horton et al., 2006). This means that the magnitude of extreme high and low flows is amplified, whereas the timing of these extreme events is more predictable by 2063–2098.

Figure 6 shows the effects of each combination of climate scenarios on the three indices in the seven subbasins. Substantial changes in the SR index are found, being more pronounced in the rain-dominated subbasins than in the two Alpine subbasins. Moreover, the SRs estimated from inputs by climate scenario 4 show the smallest change in all subbasins except for the Main subbasin, whereas climate scenario 5 shows the largest change in SR. Interestingly, the SRs estimated from the inputs by climate scenarios 2 and 5 are slightly different in all subbasins although these two climate scenarios both use ECHAM5 (versions 1 and 3) as GCM and REMO as RCM. The difference in SR between two climate scenarios with the same GCM, RCM and emission scenario can be explained by the different initial conditions used in their driving GCM (Görgen et al., 2010).

From the results in Fig. 6, it is apparent that climate change result in a negative change in WMODs for the EA and WA subbasins. Climate scenario 7 shows a very large change in WMOD for the Moselle subbasin.

The influence of climate scenario 2 on the change in the WP in the Main subbasin and the influence of climate scenario 6 on the change in the WP in the Moselle subbasin are both about 400 %, suggesting much less variability in timing of low flows in these subbasins. Since large changes are found in the WP index for the future climate, we present Fig. 7 to compare the effects of seven equally probable climate scenarios on the weighted persistence in the 134 sub-catchments. It is obvious from Fig. 7 that the outputs of climate scenario 2 show the largest change in WPs in the 134 sub-catchments for the future climate, whereas climate scenario 3 shows the smallest change in the WPs.

It should be noted that the WPs from climate scenarios 5, 6 and 7 are significantly different as different emission scenarios are used in these scenarios. The large changes in these climate scenarios for the future climate can be partly explained by the inter-annual variability of monthly P and PET simulated by the climate scenarios. We found large changes in the inter-annual variability of monthly P in all months in the Alpine subbasins, whereas large changes are found mostly in summer months in the rain-dominated subbasins. Further, large changes in the inter-annual variability of monthly PET were found in winter months in all subbasins. Some of the Alpine catchments show significant increases in the low flow persistence which is consistent with the results of Huang et al. (2012) who reported less variability in occurrence of low flows for the Alpine regions for all climate scenarios investigated.

5 Discussion

For the River Rhine basin, a number of hydrological simulations were carried out using observed inputs and the outputs from an ensemble of seven climate scenarios. This is done to transfer the climate change signal from RCMs to a hydrological model and to evaluate the effects climate change on the seasonality of low flows. The uncertainty originating from the RCMs, GCMs and emission scenarios is evaluated using the outputs from an ensemble of seven climate scenarios. If these seven climate scenarios are representative, it appears from Fig. 6 that the GCM/RCM uncertainty has the largest influence on WP. This result is in line with that of Prudhomme and Davies (2009) who found that the effect of emission scenario uncertainty was not larger than the effect of GCM uncertainty on the magnitude of changes in monthly summer flows. Further, the present findings seem to be consistent with other studies, which found that GCMs and RCMs were the most important sources of uncertainty in simulating climate change impacts on low flows (Wilby and Harris, 2006). Moreover, based on the ranges in average change in three indices using simulated inputs from seven climate scenarios, shown in Fig. 6, it appears that the influence of GCM/RCM uncertainty on SR is slightly larger than the influence of emission scenario uncertainty on SR, whereas the influence of GCM/RCM uncertainty on WMOD is similar to the influence of emission scenario on WMOD.

The present study does not evaluate the hydrological model structure uncertainties explicitly as they are reported as less important than the uncertainty due to the climate predictions (Muerth et al., 2013; Blenkinsop and Fowler, 2007). Nevertheless, it would be interesting to use a multi-model approach and employing additional bias-corrected outputs from different RCMs and emission scenarios and several equivalent hydrological models to assess model structural uncertainties.

6 Conclusions

The results of this study about climate change impacts on the seasonality of low flows are based on a simulation approach using the outputs of an ensemble of climate models to drive a hydrological model. Three seasonality indices, namely seasonality ratio (SR), weighted mean occurrence day (WMOD) and weighted persistence (WP) are used to reflect the discharge regime, timing and variability in timing of low flow events respectively. Our analysis focuses on the effects of the hydrological model and its inputs, the use of different GCMs and RCMs and the use of different emission scenarios. Sixteen experiments were considered. They are based on two periods, i.e. 1964–2007 and 2063–2098, four different GCMs, four different RCMs and three emission scenarios (A1B, A2 and B1). The 134 sub-catchments studied cover the entire River Rhine basin upstream of the Lobith gauging station at the Dutch-German border. They are representative of the different hydro-climatic regions and two distinct low flow regimes, winter and summer low flows, due to the Swiss Alps in the upstream part and rain-dominated catchments in the middle and downstream part of the basin. From the results presented in this study we can draw the following conclusions.

- Significant differences have been found between seasonality indices based on observed low flows and simulated low flows with observed climate as input due to the uncertainty arising from hydrological model inputs and structure. The weighted mean occurrence day and the weighted persistence in the two Alpine subbasins showed larger differences compared to the rain-dominated subbasins.
- The comparison of the three seasonality indices based on observed inputs and simulated inputs reveals small differences in SR for all subbasins except for the Moselle subbasin. Large differences are found for the WMOD and WP indices showing that these indices are very sensitive to uncertainties from the climate models.
- Based on the results of the comparison of the three seasonality indices using simulated inputs for current climate and simulated inputs for future climate, the largest range of change is found for WP, whereas the smallest range of change is found for SR. The SRs by 2063–2098 significantly decrease in all subbasins, showing that a substantial change in the low flow regime in all subbasins of the River Rhine is expected, whereas a regime shift from winter low flows to summer low flows is likely to occur in the two Alpine subbasins. Further, the WMODs of low flows tend to be earlier than for the current climate in all subbasins except for the Middle Rhine and Lower Rhine subbasins. The WPs by 2063–2098 slightly increase, showing that the predictability of low flow events increases as the variability in timing decreases.
- From comparison of the uncertainty sources evaluated in this study, it is obvious that the RCM/GCM uncertainty has the largest influence on the uncertainty in the variability of the timing of low flows for the future climate. The influence of GCM/RCM uncertainty on SR is slightly larger than the influence of emission scenario uncertainty on SR, whereas the influence of GCM/RCM uncertainty on WMOD is similar to the influence of emission scenario on WMOD.

This study has evaluated the impacts of climate change on the seasonality of low flows in the River Rhine basin. The next step would be to assess the impacts of land use change on the seasonality of low flows and the relationship between groundwater seasonality and low flow seasonality. Further research is crucial for a detailed analysis of the climate change impacts on the return periods of extreme low flows.

Acknowledgements. We acknowledge the financial support of the Ir. Cornelis Lely Stichting (CLS), Project No. 20957310. The research is part of the programme of the Department of Water Engineering and Management of the University of Twente and it supports the work of the UNESCO-IHP VII FRIEND-Water programme. Discharge data for the River Rhine were provided by the Global Runoff Data Centre (GRDC) in Koblenz (Germany). Catchment averaged precipitation and evapotranspiration data were supplied by the Federal Institute of Hydrology (BfG), Koblenz (Germany) and Deltares (the Netherlands). REGNIE grid data were extracted from the archive of the Deutscher Wetterdienst (DWD: German Weather Service), Offenbach (Germany). Bias-corrected forcing data were provided by Jules Beersma (KNMI) and Enno Nilson (BfG). The GIS base maps with delineated 134 sub-catchments of the River Rhine basin were provided by Eric Sprokkereef, the secretary general of the International Commission for the Hydrology of the Rhine basin (CHR). The stand-alone version of the HBV-134 daily hydrological model environment was provided by Albrecht Weerts from Deltares (the Netherlands).

References

Arnell, N. W. and Gosling, S. N.: The impacts of climate change on river flow regimes at the global scale, J. Hydrol., 486, 351–364, doi:10.1016/j.jhydrol.2013.02.010, 2013.

ATV-DVWK: Verdunstung in Bezug zu Landnutzung, Bewuchs und Boden, Merkblatt ATV-DVWK-M 504, Hennef, 2002.

Baldwin, C. K. and Lall, U.: Seasonality of streamflow: The Upper Mississippi River, Water Resour. Res., 35, 1143–1154, doi:10.1029/1998wr900070, 1999.

Bennett, K. E., Werner, A. T., and Schnorbus, M.: Uncertainties in Hydrologic and Climate Change Impact Analyses in Headwater Basins of British Columbia, J. Climate, 25, 5711–5730, doi:10.1175/jcli-d-11-00417.1, 2012.

Berglöv, G., German, J., Gustavsson, H., Harbman, U., and Johansson, B.: Improvement HBV Model Rhine in FEWS Final Report, SMHI Hydrology, Tech., Norrköping, 2009.

Bergström, S.: Development and application of a conceptual runoff model for scandinavian catchments, Department of water resources engineering, University of Lund, Lund, Sweden, 1976.

Beyene, T., Lettenmaier, D., and Kabat, P.: Hydrologic impacts of climate change on the Nile River Basin: implications of the 2007 IPCC scenarios, Climatic Change, 100, 433–461, 2010.

Blenkinsop, S. and Fowler, H. J.: Changes in drought frequency, severity and duration for the British Isles projected by the PRUDENCE regional climate models, J. Hydrol., 342, 50–71, doi:10.1016/j.jhydrol.2007.05.003, 2007.

Booij, M. J.: Impact of climate change on river flooding assessed with different spatial model resolutions, J. Hydrol., 303, 176–198, 2005.

Bormann, H.: Runoff regime changes in German rivers due to climate change, Erdkunde, 64, 257–279, doi:10.3112/erdkunde.2010.03.04, 2010.

Bosshard, T., Carambia, M., Görgen, K., Kotlarski, S., Krahe, P., Zappa, M., and Schär, C.: Quantifying uncertainty sources in an ensemble of hydrological climate-impact projections, Water Resour. Res., 49, 1523–1536, doi:10.1029/2011WR011533, 2012.

Chen, J., Brissette, F. P., Poulin, A., and Leconte, R.: Overall uncertainty study of the hydrological impacts of climate change for a Canadian watershed, Water Resour. Res., 47, W12509, doi:10.1029/2011wr010602, 2011.

Demirel, E., Ommeren, J. V., and Rietveld, P.: A matching model for the back-haul problem, Transportation Research Part B: Methodological, 44, 549–561, doi:10.1016/j.trb.2009.10.006, 2010.

Demirel, M. C., Booij, M. J., and Hoekstra, A. Y.: Identification of appropriate lags and temporal resolutions for low flow indicators in the River Rhine to forecast low flows with different lead times, Hydrol. Process., doi:10.1002/hyp.9402, in press, 2012.

De Wit, M. J. M., van den Hurk, B., Warmerdam, P. M. M., Torfs, P., Roulin, E., and van Deursen, W. P. A.: Impact of climate change on low-flows in the river Meuse, Climatic Change, 82, 351–372, 2007.

Diaz-Nieto, J. and Wilby, R. L.: A comparison of statistical downscaling and climate change factor methods: impacts on low flows in the River Thames, UK, Climatic Change, 69, 245–268, 2005.

Driessen, T. L. A., Hurkmans, R. T. W. L., Terink, W., Hazenberg, P., Torfs, P. J. J. F., and Uijlenhoet, R.: The hydrological response of the Ourthe catchment to climate change as modelled by the HBV model, Hydrol. Earth Syst. Sci., 14, 651–665, doi:10.5194/hess-14-651-2010, 2010.

Eberle, M.: Hydrological Modelling in the River Rhine Basin Part III – Daily HBV Model for the Rhine Basin BfG-1451, Institute for Inland Water Management and Waste Water Treatment (RIZA) and Federal Institute of Hydrology (BfG) Koblenz, Germany, 2005.

Engeland, K., Renard, B., Steinsland, I., and Kolberg, S.: Evaluation of statistical models for forecast errors from the HBV model, J. Hydrol., 384, 142–155, 2010.

Görgen, K., Beersma, J., Brahmer, G., Buiteveld, H., Carambia, M., de Keizer, O., Krahe, P., Nilson, E., Lammersen, R., Perrin, C., and Volken, D.: Assessment of Climate Change Impacts on Discharge in the Rhine River Basin: Results of the RheinBlick 2050 Project, Lelystad, CHR, ISBN 978–90-70980-35-1, 211 pp., 2010.

Grabs, W., Daamen, K., and de Montmollin, F.: Impact of Climate Change on Hydrological Regimes and Water Resources Management in the Rhine Basin, CHR/KHR, Lelystad, 1997.

Graham, L., Hagemann, S., Jaun, S., and Beniston, M.: On interpreting hydrological change from regional climate models, Climatic Change, 81, 97–122, 2007.

Guo, H., Hu, Q., and Jiang, T.: Annual and seasonal streamflow responses to climate and land-cover changes in the Poyang Lake basin, China, J. Hydrol., 355, 106–122, doi:10.1016/j.jhydrol.2008.03.020, 2008.

Horton, P., Schaefli, B., Mezghani, A., Hingray, B., and Musy, A.: Assessment of climate-change impacts on alpine discharge regimes with climate model uncertainty, Hydrol. Process., 20, 2091–2109, 2006.

Huang, S., Krysanova, V., and Hattermann, F.: Projection of low flow conditions in Germany under climate change by combining three RCMs and a regional hydrological model, Acta Geophys., 61, 1–43, doi:10.2478/s11600-012-0065-1, 2012.

Hurkmans, R., Terink, W., Uijlenhoet, R., Torfs, P., Jacob, D., and Troch, P. A.: Changes in streamflow dynamics in the Rhine basin under three high-resolution regional climate scenarios, J. Climate, 23, 679–699, 2010.

Jasper, K., Calanca, P., Gyalistras, D., and Fuhrer, J.: Differential impacts of climate change on the hydrology of two alpine river basins, Clim. Res., 26, 113–129, 2004.

Jonkeren, O., Rietveld, P., Ommeren, J., and Linde, A.: Climate change and economic consequences for inland waterway transport in Europe, Regio. Environ. Change, 1–13, doi:10.1007/s10113-013-0441-7, 2013.

Jung, I. W., Bae, D. H., and Lee, B. J.: Possible change in Korean streamflow seasonality based on multi-model climate projections, Hydrol. Process., 27, 1033–1045, doi:10.1002/hyp.9215, 2013.

Köplin, N., Schädler, B., Viviroli, D., and Weingartner, R.: Seasonality and magnitude of floods in Switzerland under future climate change, Hydrol. Process., doi:10.1002/hyp.9757, in press, 2013.

Laaha, G. and Blöschl, G.: Seasonality indices for regionalizing low flows, Hydrol. Processes, 20, 3851–3878, doi:10.1002/hyp.6161, 2006.

Lenderink, G., Buishand, A., and van Deursen, W.: Estimates of future discharges of the river Rhine using two scenario methodologies: direct versus delta approach, Hydrol. Earth Syst. Sci., 11, 1145–1159, doi:10.5194/hess-11-1145-2007, 2007.

Lindström, G., Johansson, B., Persson, M., Gardelin, M., and Bergstrom, S.: Development and test of the distributed HBV-96 hydrological model, J. Hydrol., 201, 272–288, 1997.

Middelkoop, H. and Van Haselen, C. O. G.: Twice a river. Rhine and Meuse in the Netherlands, RIZA report 99.003, RIZA, Arnhem, 127, 1999.

Middelkoop, H., Daamen, K., Gellens, D., Grabs, W., Kwadijk, J. C. J., Lang, H., Parmet, B., Schadler, B., Schulla, J., and Wilke, K.: Impact of climate change on hydrological regimes and water resources management in the Rhine Basin, Climatic Change, 49, 105–128, 2001.

Minville, M., Brissette, F., and Leconte, R.: Uncertainty of the impact of climate change on the hydrology of a nordic watershed, J. Hydrol., 358, 70–83, 2008.

Muerth, M. J., Gauvin St-Denis, B., Ricard, S., Velázquez, J. A., Schmid, J., Minville, M., Caya, D., Chaumont, D., Ludwig, R., and Turcotte, R.: On the need for bias correction in regional climate scenarios to assess climate change impacts on river runoff, Hydrol. Earth Syst. Sci., 17, 1189–1204, doi:10.5194/hess-17-1189-2013, 2013.

Nakićenović, N. and Swart, R.: Special Report on Emissions Scenarios, Cambridge University Press, Cambridge, UK, 612 pp., 2000.

Nash, J. E. and Sutcliffe, J. V.: River flow forecasting through conceptual models part I – A discussion of principles, J. Hydrol., 10, 282–290, 1970.

Parajka, J., Kohnová, S., Merz, R., Szolgay, J., Hlavčová, K., and Blöschl, G.: Comparative analysis of the seasonality of hydrological characteristics in Slovakia and Austria, Hydrol. Sci. J., 54, 456–473, 2009.

Parajka, J., Kohnová, S., Bálint, G., Barbuc, M., Borga, M., Claps, P., Cheval, S., Dumitrescu, A., Gaume, E., Hlavcová, K., Merz, R., Pfaundler, M., Stancalie, G., Szolgay, J., and Blöschl, G.: Seasonal characteristics of flood regimes across the Alpine-Carpathian range, J. Hydrol., 394, 78–89, 2010.

Photiadou, C. S., Weerts, A. H., and van den Hurk, B. J. J. M.: Evaluation of two precipitation data sets for the Rhine River using streamflow simulations, Hydrol. Earth Syst. Sci., 15, 3355–3366, doi:10.5194/hess-15-3355-2011, 2011.

Prudhomme, C. and Davies, H.: Assessing uncertainties in climate change impact analyses on the river flow regimes in the U K. Part 2: future climate, Climatic Change, 93, 197–222, 2009.

Renner, M., Werner, M. G. F., Rademacher, S., and Sprokkereef, E.: Verification of ensemble flow forecasts for the River Rhine, J. Hydrol., 376, 463–475, 2009.

Schaefli, B., Hingray, B., and Musy, A.: Climate change and hydropower production in the Swiss Alps: quantification of potential impacts and related modelling uncertainties, Hydrol. Earth Syst. Sci., 11, 1191–1205, doi:10.5194/hess-11-1191-2007, 2007.

Schnorbus, M., Werner, A., and Bennett, K.: Impacts of climate change in three hydrologic regimes in British Columbia, Canada, Hydrol. Process., doi:10.1002/hyp.9661, in press, 2012.

Shabalova, M., van Deursen, W., and Buishand, T.: Assessing future discharge of the river Rhine using regional climate model integrations and a hydrological model, Clim. Res., 23, 233–246, 2003.

Şorman, A. A., Şensoy, A., Tekeli, A. E., Şorman, A. Ü., and Akyürek, Z.: Modelling and forecasting snowmelt runoff process using the HBV model in the eastern part of Turkey, Hydrol. Process., 23, 1031–1040, doi:10.1002/hyp.7204, 2009.

Taylor, I. H., Burke, E., McColl, L., Falloon, P., Harris, G. R., and McNeall, D.: Contributions to uncertainty in projections of future drought under climate change scenarios, Hydrol. Earth Syst. Sci. Discuss., 9, 12613–12653, doi:10.5194/hessd-9-12613-2012, 2012.

Te Linde, A. H., Aerts, J., Hurkmans, R., and Eberle, M.: Comparing model performance of two rainfall-runoff models in the Rhine basin using different atmospheric forcing data sets, Hydrol. Earth Syst. Sci., 12, 943–957, 2008, http://www.hydrol-earth-syst-sci.net/12/943/2008/.

Te Linde, A. H., Aerts, J. C. J. H., Bakker, A. M. R., and Kwadijk, J. C. J.: Simulating low-probability peak discharges for the Rhine basin using resampled climate modeling data, Water Resour. Res., 46, W03512, doi:10.1029/2009wr007707, 2010.

Te Linde, A. H., Bubeck, P., Dekkers, J. E. C., de Moel, H., and Aerts, J. C. J. H.: Future flood risk estimates along the river Rhine, Nat. Hazards Earth Syst. Sci., 11, 459–473, doi:10.5194/nhess-11-459-2011, 2011.

Tongal, H., Demirel, M. C., and Booij, M. J.: Seasonality of low flows and dominant processes in the Rhine River, Stoch. Environ. Res. Risk Assess., 27, 489–503, doi:10.1007/s00477-012-0594-9, 2013.

Wilby, R. L. and Harris, I.: A framework for assessing uncertainties in climate change impacts: Low-flow scenarios for the River Thames, UK, Water Resour. Res., 42, W02419, doi:10.1029/2005wr004065, 2006.

Wöhling, T., Lennartz, F., and Zappa, M.: Technical Note: Updating procedure for flood forecasting with conceptual HBV-type models, Hydrol. Earth Syst. Sci., 10, 783–788, doi:10.5194/hess-10-783-2006, 2006.

Yimer, E. G. and Andreja, J.: Downscaling technique uncertainty in assessing hydrological impact of climate change in the Upper Beles River Basin, Ethiopia, Hydrol. Res., 44, 377–398, doi:10.2166/nh.2012.037, in press, 2012.

Table 1. Overview of the seasonality calculations.

Case number	Number of calculations[a]	Calculation detail
1	1	The three indices are based on observed discharge
2	1	The three indices are based on simulated discharge using observed climate as input
3	7	The three indices are based on simulated discharge using simulated climate for 1964–2007 as input
4	7	The three indices are based on simulated discharge using simulated climate for 2063–2098 including three emission scenarios as input

[a] Calculation of the three seasonality indices.

Table 2. Climate data availability and seven climate scenarios (CSs).

ID	SRES	GCM	RCM	Bias correction	Common period
CS 1	A1B	ECHAM5r3	RACMO	Eqs. (8) and (9) (Görgen et al., 2010)	1961–2007 (current) 2060–2098 (future)
CS 2	A1B	ECHAM5r3	REMO		
CS 3	A1B	HADCM3Q16	HADRM3Q16		
CS 4	A1B	HADCM3Q3	HADRM3Q3		
CS 5	A1B	ECHAM5r1	REMO		
CS 6	A2	ECHAM5r1	REMO		
CS 7	B1	ECHAM5r1	REMO		

Table 3. Differences between the three seasonality indices estimated from observed (case 1) and simulated (case 2) low flows at the outlets of the seven subbasins in the River Rhine for the period 1964–2007.

	East Alpine	West Alpine	Middle Rhine	Neckar	Main	Moselle	Lower Rhine
SR (%)[a]	−11	−2	1	11	9	29	2
WMOD (days)[b]	−10	23	−83	33	5	54	−30
WP (%)[a]	−85	−17	−16	6	56	52	−34

[a] (Simulated index – Observed index)/Observed index.

[b] Simulated WMOD – Observed WMOD.

Table 4. Differences between the three seasonality indices estimated from simulated low flows using observed inputs for the reference period 1964–2007 (case 2) compared to the simulated low flows using simulated inputs from seven climate scenarios (CSs) for the same period (case 3). Differences larger than 30 are in italic.

Index	Subbasin	CS 1	CS 2	CS 3	CS 4	CS 5	CS 6	CS 7
SR (%)[a]	East Alpine	6	9	−5	−9	8	10	6
	West Alpine	13	19	0	1	20	23	19
	Middle Rhine	6	12	−13	−15	6	10	4
	Neckar	5	23	−25	−29	18	21	13
	Main	−9	6	−19	−13	14	16	11
	Moselle	−5	8	*−33*	*−31*	−1	−1	−3
	Lower Rhine	7	12	−12	−13	8	11	6
WMOD (days)[b]	East Alpine	*45*	−11	*72*	*67*	−1	*45*	26
	West Alpine	12	14	9	−5	18	*33*	24
	Middle Rhine	*90*	*64*	*56*	27	*81*	*102*	*87*
	Neckar	11	−1	21	−25	7	1	−9
	Main	−24	−1	11	−29	−17	19	0
	Moselle	*−67*	−16	−16	*−53*	−30	25	*102*
	Lower Rhine	*75*	*56*	*55*	14	*72*	*94*	*78*
WP (%)[a]	East Alpine	*302*	*57*	*475*	*390*	*232*	*325*	*259*
	West Alpine	4	*−34*	*49*	14	*−33*	−4	−5
	Middle Rhine	23	−3	*126*	*37*	14	23	41
	Neckar	*33*	13	*42*	8	10	−4	20
	Main	*−62*	*−80*	12	−20	*−63*	*−58*	*−59*
	Moselle	*−53*	*−72*	−4	*−42*	*−55*	*−84*	*−75*
	Lower Rhine	−24	*−40*	*106*	*64*	7	13	*32*

[a] (Based on simulated input – Based on observed input)/Based on observed input.

[b] Based on simulated input – Based on observed input.

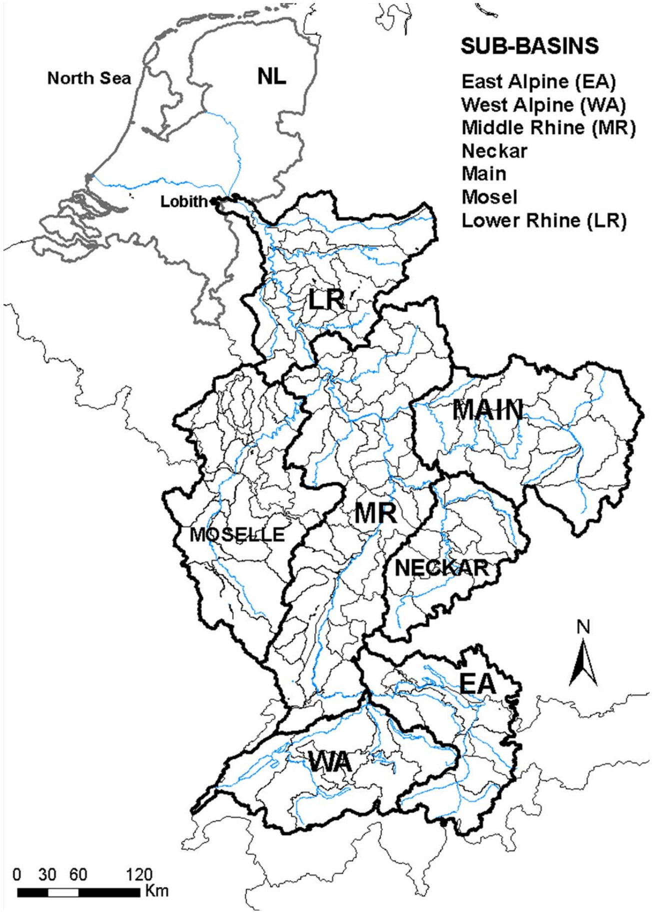

Fig. 1. Schematisation of the 134 sub-catchments and seven major subbasins of the River Rhine upstream of Lobith.

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◄
►
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

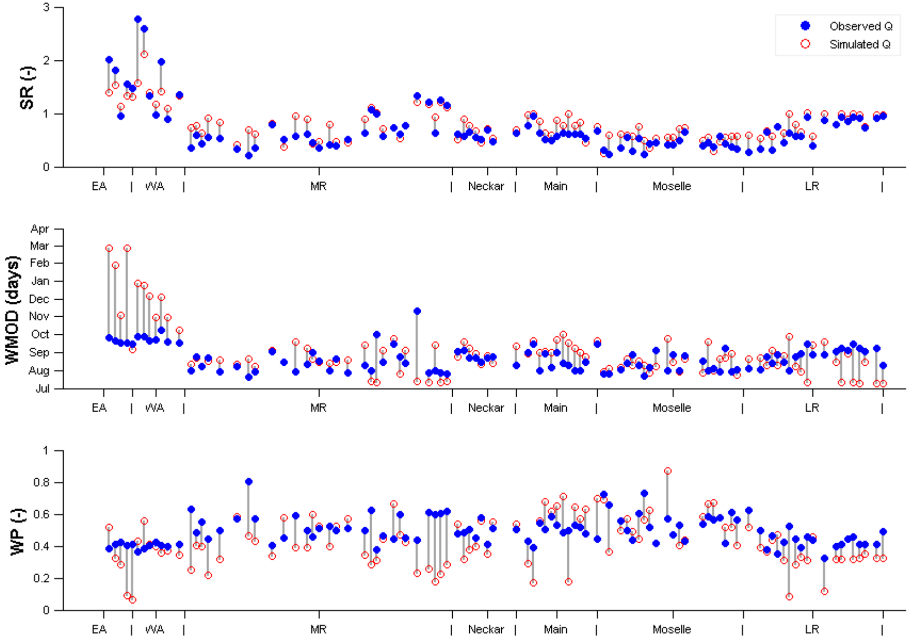

Fig. 2. Three seasonality indices estimated from observed (case 1) and simulated (case 2) low flows in 101 catchments for the period 1964–2007. The grey line is used to connect observed and simulated indices for each catchment.

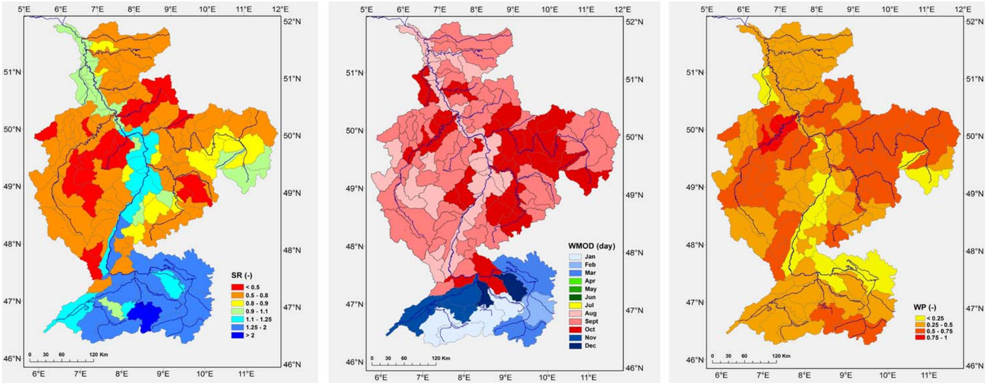

Fig. 3. Three seasonality indices (SR, WMOD and WP) estimated from simulated low flows using observed climate as model input in 134 sub-catchments for the period 1964–2007 (case 2).

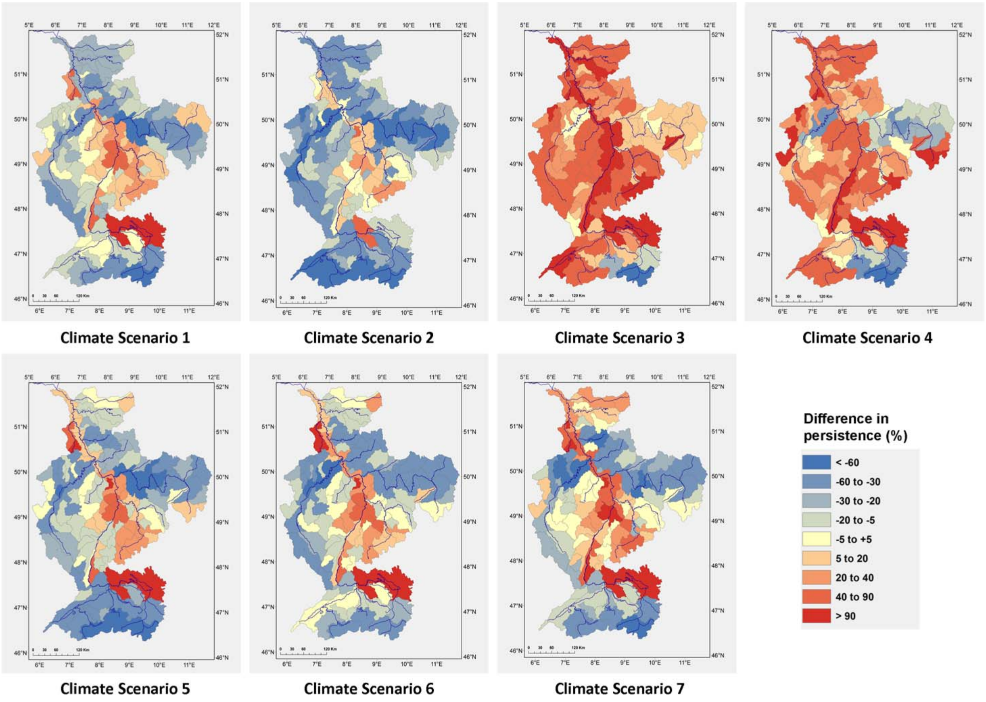

Fig. 4. Relative differences (%)* between low flow persistence estimated from simulated low flows using simulated inputs from seven climate scenarios for the reference period 1964–2007 (case 3) and simulated low flows using observed inputs for the same period (case 2). * (Based on simulated input – Based on observed input)/Based on observed input.

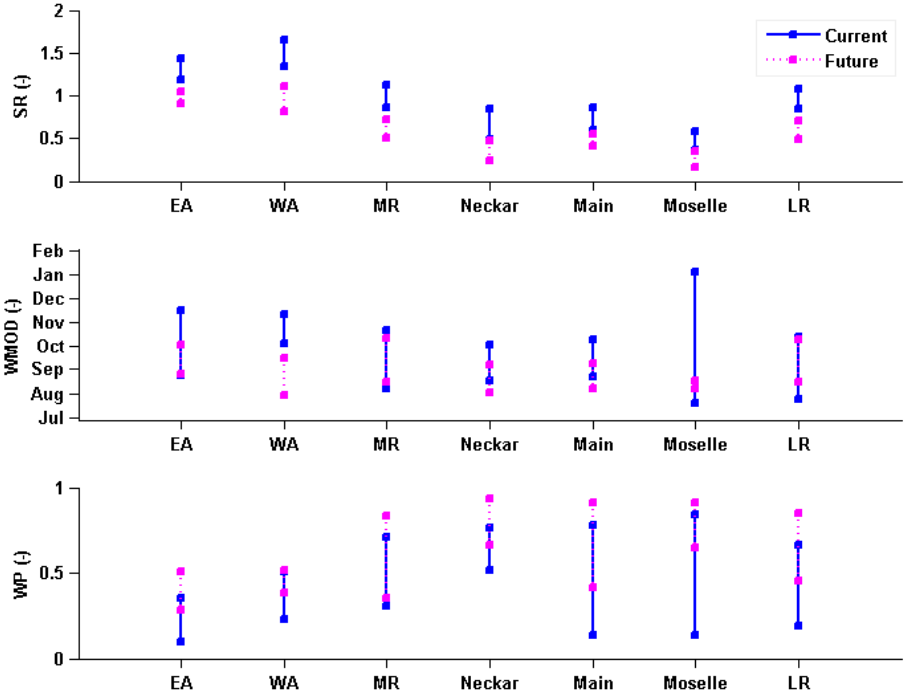

Fig. 5. Range (shown as bar) of three seasonality indices in the seven subbasins for the current climate (calculations for case 3) and future climate (calculations for case 4).

Fig. 6. The relative changes (*) in SR and WP and the changes in WMOD (**) at the outlet of the seven subbasins estimated from simulated low flows using simulated inputs for the future period 2063–2098 (case 4) compared to simulated low flows using simulated inputs for the reference period 1964–2007 (case 3) from seven climate scenarios (CSs). * (Based on simulated input for future climate – based on simulated input for current climate)/Based on simulated input for current climate. ** Based on simulated input for future climate – based on simulated input for current climate.

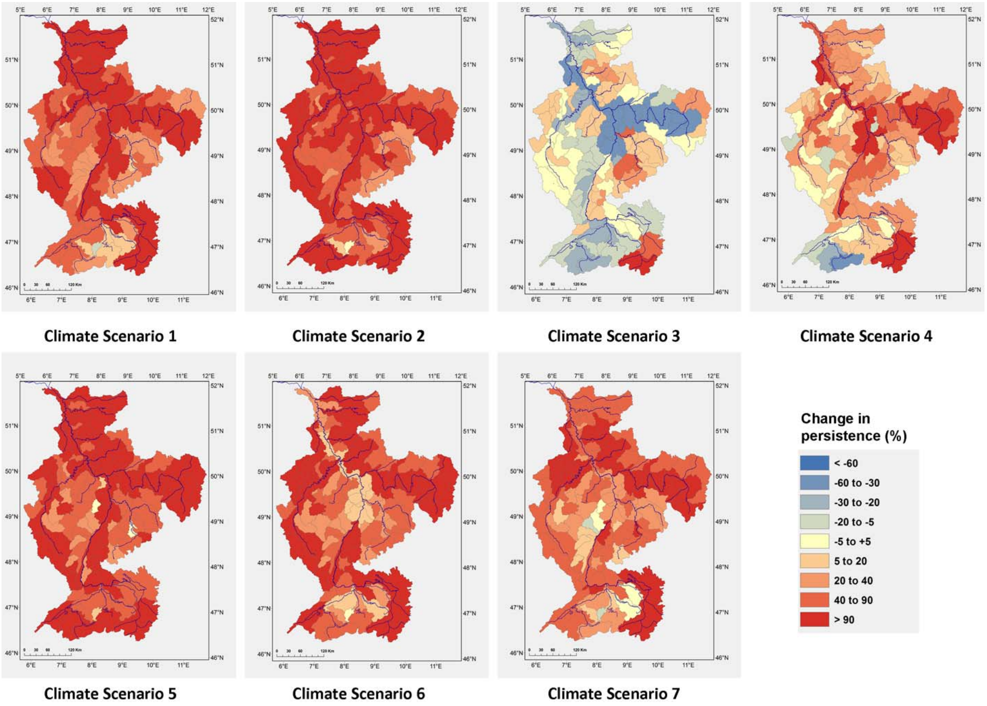

Fig. 7. Relative change (%)* in low flow persistence in 134 sub-catchments based on simulated low flows using simulated inputs from seven climate scenarios for the future period 2063–2098 (case 4) compared to simulated low flows using simulated inputs for the reference period 1964–2007 (case 3). * (Future period – Current period)/Current period.