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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

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

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Abstract. The impacts of climate change on the seasonality of low flows were analysed for 134 sub-catchments covering the River Rhine basin upstream of the Dutch-German border. Three seasonality indices for low flows were estimated, namely the 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 were estimated from: (1) observed low flows; (2) simulated low flows by the semi-distributed HBV model using observed climate as input; (3) simulated low flows using simulated inputs from seven combinations of General Circulation Models (GCMs) and Regional Climate Models (RCMs) for the current climate (1964–2007); (4) simulated low flows using simulated inputs from seven combinations of GCMs and RCMs for the future climate (2063–2098) including three different greenhouse gas emission scenarios. These four cases were compared to assess the effects of the hydrological model, forcing by different climate models and different emission scenarios on the three indices.

Significant differences were 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 was found for the SR index, whereas large differences were found for the WMOD and WP indices for the current climate. Finally, comparing the results of cases 3 and 4, we found that SR decreases substantially by 2063–2098 in all seven sub-basins 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 sub-basins. The WMODs of low flows tend to be earlier than for the current climate in all sub-basins except for the Middle Rhine and Lower Rhine sub-basins. 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. From comparison of the error sources evaluated in this study, it is obvious that different RCMs/GCMs have a larger influence on the timing of low flows than different emission scenarios. Finally, this study complements recent analyses of an international project (Rhineblick) by analysing the seasonality aspects of low flows and extends the scope further to understand the effects of hydrological model errors and climate change on three important low flow seasonality properties: regime, timing and persistence.

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, hydrological droughts, causing low flows, develop slowly and affect a much larger area than floods (Van Lanen et al., 2013). 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 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., 2013) and reduced summer runoff contribution from Alpine glaciers (Huss, 2011). 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., 2013). 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 (Graham et al., 2007). 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 in the UK (Wilby and Harris, 2006; Diaz-Nieto and Wilby, 2005) and the River Rhine (Bosshard et al., 2013; 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. Shabalova et al. (2003) showed a decrease of summer low flows and an increase of winter high flows in the River Rhine leading to an increased 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. The recent Rhineblick project (Görgen et al., 2010) focused on climate change impacts on the magnitude of different discharge regimes, high flows in particular.

Several studies documented potential effects of climate change on low flows in the River Rhine (Huang et al., 2013; 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. (2013) 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 the Rhine sub-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., 2013). 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, 2013). The uncertainty due to the hydrological model used generally 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., 2010, 2009) 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 the 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 annual mean and annual maximum flows for 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 monthly dam inflow series and the 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 from 101 sub-catchments and simulated low flow series from 134 sub-catchments are available and used to assess the effects of climate change on the three indices. This study complements the recent analyses of the Rhineblick project (Görgen et al., 2010) by analysing the effects of climate change on three important low flow seasonality properties (regime, timing and persistence of timing) and extending the scope further to understand the effects of hydrological model errors and climate change on these seasonality properties: regime, timing and persistence.

The outline of the paper is as follows. The study area is introduced in Sect. 2. The seasonality indices, the hydrological model and the data used in this study are described 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.

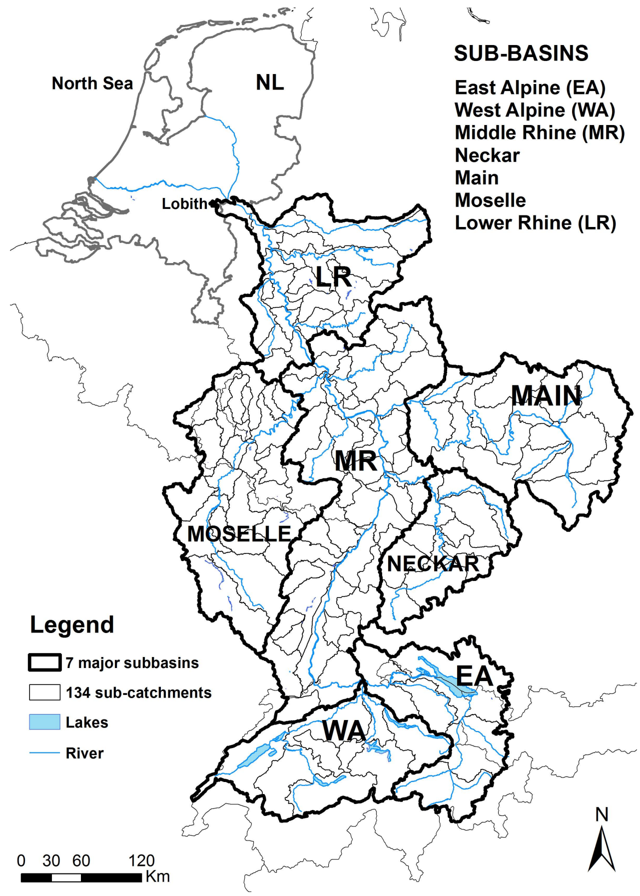

Fig. 1. Schematisation of the 134 sub-catchments (spatial scale of HBV model) and seven major sub-basins of the River Rhine upstream of Lobith.

2 Study area

The River Rhine basin is a major and densely populated river basin in Western Europe accommodating nearly 60 million inhabitants. 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 evapotranspiration 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 sub-basins. 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 sub-basins by Demirel et al. (2013).

The spatial scales of 134 sub-catchments and seven sub-basins 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 second spatial scale 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

Table 1. Overview of the seasonality calculations.

Case number	Number of calculations	Description of calculations
1	1	The three indices are based on observed discharge series with varying lengths
2	1	The three indices are based on simulated discharge using observed climate for 1964–2007 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

#6435060 at Lobith) are used in the seasonality assessment. Although the MR and LR sub-basins have mixed discharge regimes originating from snow- and rainfall-dominated sub-catchments, they are also included in this study.

3 Methods and data

In this study, a simulation approach was 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 were 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) were then used to estimate three seasonality indices as discussed below.

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

3.1 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 were estimated to describe different aspects of the discharge regime of a river. We used three seasonality indices described below as they focus on the differences in discharge regime, timing and variability in timing of the recurrent event (persistence).

3.1.1 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 were then divided into winter and summer low flow series. We used the 75 % exceedence probability (Q_{75}), as in Demirel et al. (2013), 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).

$$\text{Seasonality Ratio}: \frac{Q_{75\mathrm{s}}}{Q_{75\mathrm{w}}} \tag{1}$$

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.

3.1.2 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 sub-catchment, the days on 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 occurrence day 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 number of low flow days i is defined as

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

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

The directional angle (θ) is then estimated by

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

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

The values of θ can vary from 0 to 2π, where a zero value indicates 1 January, $\pi/2$ represents 1 April, π represents 1 July and $3\pi/2$ represents 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:

$$\text{Weighted Mean Occurrence Day}: \theta\frac{365}{2\pi} \tag{6}$$

3.1.3 Weighted Persistence (WP)

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

$$\text{Weighted Persistence}: \sqrt{x_\theta^2 + y_\theta^2} \tag{7}$$

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).

3.2 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 1970s (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 northwestern 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 to 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 the HBV-96 model running at a daily time step and covering the area upstream of the Lobith gauging station comprising 134 sub-catchments. The HBV model was first calibrated by Eberle (2005) on the basis of expert knowledge at the BfG in Koblenz. The HBV model upstream of Maxau has been recalibrated again by Berglöv et al. (2009) at SMHI using a hybrid objective function (NS_{HBV} in Eq. 7) 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.

$$NS_{HBV} = 0.5 \times R^2 + 0.5 \times R^2_{\log} + 0.1 \times \text{ relaccdiff} \tag{8}$$

Where R^2 is the efficiency criterion based on Nash and Sutcliffe (Nash and Sutcliffe, 1970), $R^2_{\log}$ is similar to R^2 but using the logarithmic discharge values giving more weight to low flows, and *relaccdiff* is the relative accumulated difference between the simulated and observed discharge (see Eq. 9 is relaccdiff., Berglöv et al., 2009).

$$\text{relaccdiff}: \frac{\sum_i (Q_{\text{sim},i} - Q_{\text{obs},i})}{\sum_i Q_{\text{obs},i}} \tag{9}$$

The HBV 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 started on the 1st of January 1961 and 2060 respectively. The first three years were used as a “warm-up” period and model simulation results for these periods were not used in the estimation of the seasonality indices.

3.3 Observed data

Daily observed 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, T and PET data were obtained from Deltares (the Netherlands) and the German Federal Institute of Hydrology (BfG) in Koblenz. PET has been estimated with the Penman-Wendling equation (ATV-DVWK, 2002). All three climate variables were spatially averaged over each of the 134 sub-catchments.

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

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

All seven regional climate model (RCM) outputs (Jacob, 2006) that were used in this study were 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

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

ID	SRES	GCM	RCM	Bias correction	Common Period
CS 1	A1B	ECHAM5r3	RACMO	Eqs. (9) and (10) (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		

for biases by Görgen et al. (2010) for the Rhineblick2050 project. The daily time series of areally-averaged PET estimated following the approach of Penman-Wendling (ATV-DVWK, 2002). This is consistent with the observed PET estimation carried out by the Federal Institute of Hydrology in Koblenz, Germany. The main characteristics of the preprocessed climate dataset, comprising an ensemble of bias-corrected outputs of scenarios based on four regional climate models (RCMs), four driving global climate models (GCMs) and three different emission scenarios (SRES), 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., 2013). The biases from the RCM outputs for precipitation have been corrected by Görgen et al. (2010) using the following equation:

$$P_{\mathrm{cor}} = a\, P_{\mathrm{RCM}}^{b} \tag{10}$$

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 non-linear bias-correction method (Eq. 9), 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 for temperature have been corrected by Görgen et al. (2010) using the following equation:

$$T_{\mathrm{cor}} = \frac{\sigma_{\mathrm{o}}}{\sigma_{\mathrm{m}}}\left(T_{\mathrm{RCM}} - \bar{T}_{\mathrm{m}}\right) + \bar{T}_{\mathrm{o}} \tag{11}$$

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. (10) 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).

4 Results

4.1 Sensitivity of low flow seasonality to hydrological model

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 sub-basins as consistent with the previous low flow studies in the River Rhine (Demirel et al., 2013).

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 sub-basins in the River Rhine for the period 1964–2007.

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

* (Simulated index – Observed index)/Observed index. ** Simulated WMOD - Observed WMOD.

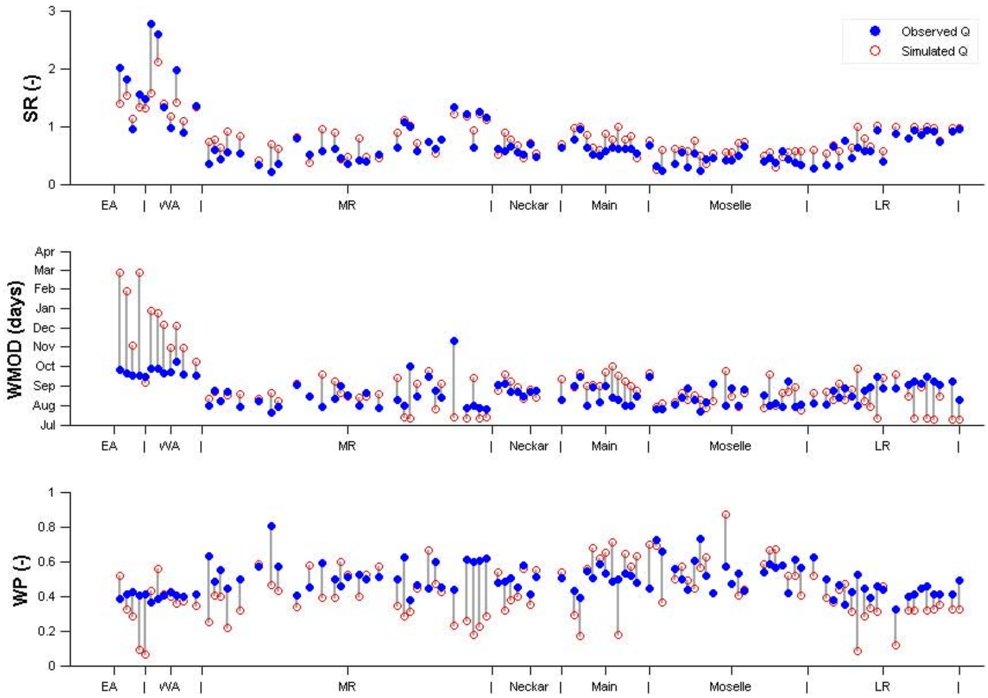

Fig. 2. Three seasonality indices estimated from observed (case 1) and simulated (case 2) low flows in 101 catchments for the period 1964–2007. The grey line is used to connect observed and simulated indices for each catchment.

The results in Fig. 2 reveal that there are significant differences between observed and simulated seasonality indices. The differences in the rain-dominated catchments are smaller than in the snow-dominated catchments. The differences in snow-dominated catchments can be partly explained by the effect of dam operations in the Alpine catchments. Obviously the dam effect is recorded in the observed discharge data, but dams are not incorporated in the hydrological model. Although HBV simulates overall low flows with an error of less than 5 % in the simulation of the mean of minimum annual discharges (Eberle, 2005), dam operations can still affect the seasonality characteristics of the low flows (e.g. WP).

The results in Fig. 2 are presented 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. A significant correlation ($r = \sim 0.7,\ p < 0.05$) between SR and catchment altitude is found in the 101 subcatchments 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 sub-basins. 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 sub-basins 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),

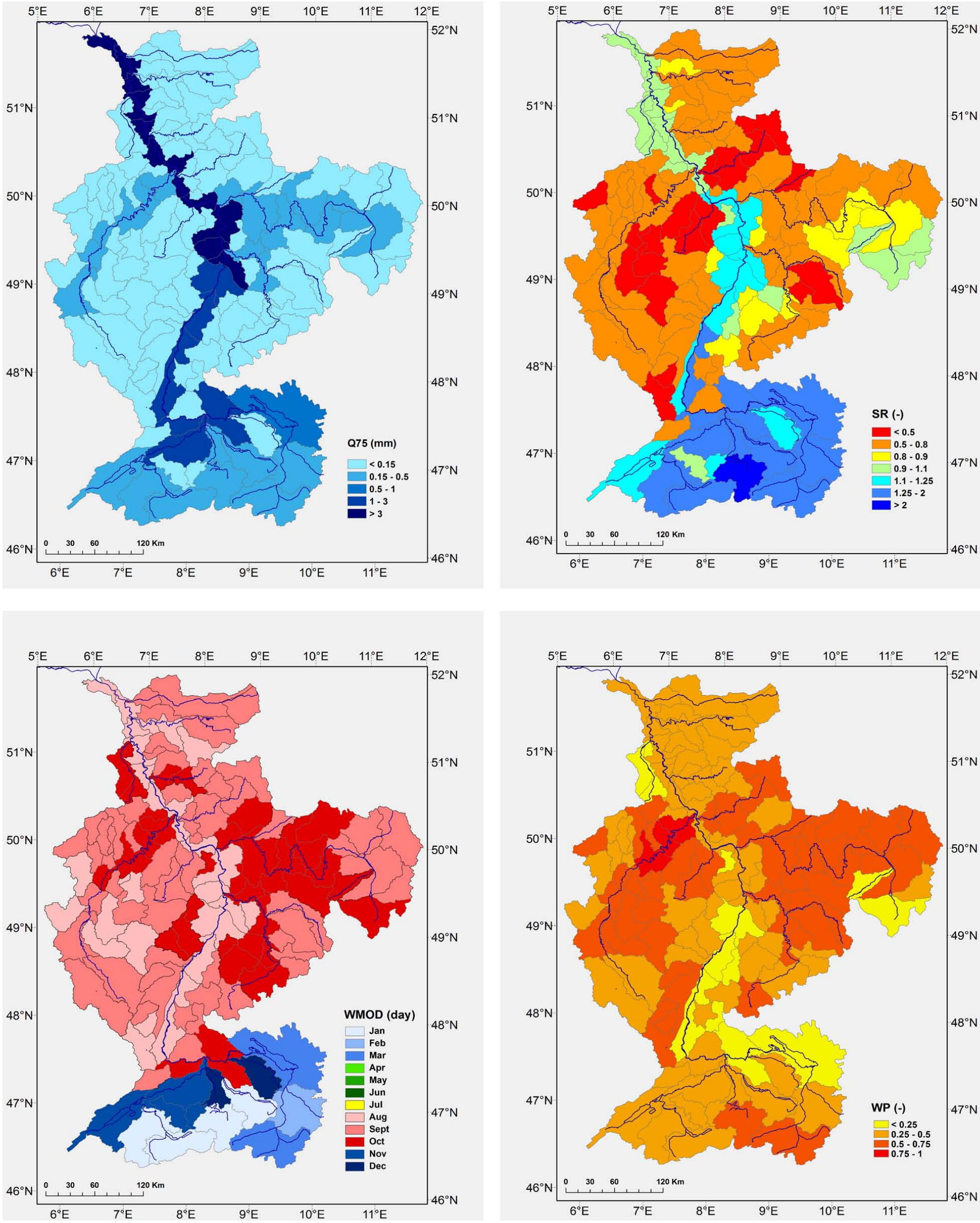

Fig. 3. Low flow threshold (Q_{75} in mm day^{-1} and three seasonality indices (SR, WMOD and WP) estimated from simulated low flows using observed climate as model input in 134 sub-catchments for the period 1964–2007 (case 2).

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 sub-basin is better simulated than in other sub-basins.

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., 2013).

Table 3 compares the differences between the three seasonality indices based on observed and simulated low flows at the outlets of the seven sub-basins. 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 sub-basins.

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

4.2 Sensitivity of low flow seasonality to meteorological forcing

The sensitivity of the three indices to different meteorological forcings is assessed at two spatial scales, i.e. 134 subcatchments and seven major sub-basins. 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 sub-basins except the WA sub-basin for the current climate. The largest difference in SR is found for the Moselle sub-basin. 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 sub-basins).

The differences in the WMODs of low flows in the WA, Neckar and Main sub-basins are mostly less than 30 days, showing that the weighted mean occurrence day of low flows in these sub-basins is simulated well using the outputs of seven climate scenarios for the current climate. The picture is very different for the other sub-basins. For instance, the WMODs based on simulated current climate as input in the HBV model in the EA, MR, Moselle and LR sub-basins are very different from the WMODs simulated using observed climate. The differences vary from 1 day (by climate scenario 5) in the EA sub-basin to 102 days (by climate scenarios 6 and 7) in the MR and LR sub-basins respectively. Very large differences in the WPs in all seven sub-basins, in the EA sub-basin in particular, are simulated using the outputs of climate scenarios. All these differences are positive for the EA sub-basin, showing a substantially smaller variability in timing of low flow events (WPs), whereas all the differences are negative for the Moselle sub-basin, 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 with different emission scenarios are used in these climate scenarios. The significant differences in the climate scenarios 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 sub-basins, whereas large differences in the inter-annual variability of monthly PET in winter months were found only in rain-dominated sub-basins like in the Moselle sub-basin.

4.3 Sensitivity of low flow seasonality to changed climate

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

From the results in Fig. 5, it is apparent that the range of SRs in all seven sub-basins 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 sub-basins, 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., 2013; Huang et al., 2013; Bormann, 2010; Blenkinsop and Fowler, 2007).

Comparing the results for the WMODs, it appears that only the range of WMODs in the WA sub-basin 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 sub-basin. Interesting is that low flows in most of the sub-basins 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 sub-basins.

Large ranges are found for WP for all sub-basins except for the WA sub-basin 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

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).

Index	Climate Scenario	East Alpine	West Alpine	Middle Rhine	Neckar	Main	Moselle	Lower Rhine
SR (%)*	CS 1 (A1B)	6	13	6	5	−9	−5	7
	CS 2 (A1B)	9	19	12	23	6	8	12
	CS 3 (A1B)	−5	0	−13	−25	−19	−33	−12
	CS 4 (A1B)	−9	1	−15	−29	−13	−31	−13
	CS 5 (A1B)	8	20	6	18	14	−1	8
	CS 6 (A2)	10	23	10	21	16	−1	11
	CS 7 (B1)	6	19	4	13	11	−3	6
WMOD (days)**	CS 1 (A1B)	45	12	90	11	−24	−67	75
	CS 2 (A1B)	−11	14	64	−1	−1	−16	56
	CS 3 (A1B)	72	9	56	21	11	−16	55
	CS 4 (A1B)	67	−5	27	−25	−29	−53	14
	CS 5 (A1B)	−1	18	81	7	−17	−30	72
	CS 6 (A2)	45	33	102	1	19	25	94
	CS 7 (B1)	26	24	87	−9	0	102	78
WP (%)*	CS 1 (A1B)	302	4	23	33	−62	−53	−24
	CS 2 (A1B)	57	−34	−3	13	−80	−72	−40
	CS 3 (A1B)	475	49	126	42	12	−4	106
	CS 4 (A1B)	390	14	37	8	−20	−42	64
	CS 5 (A1B)	232	−33	14	10	−63	−55	7
	CS 6 (A2)	325	−4	23	−4	−58	−84	13
	CS 7 (B1)	259	−5	41	20	−59	−75	32

* (Based on simulated input – Based on observed input)/Based on observed input. ** Based on simulated input – Based on observed input.

significant decrease in the variability in timing of low flows (WPs) in the EA sub-basin is found for the future climate. The existence of large lakes in the WA sub-basin 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 sub-basins for the future climate suggesting less variability in the 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 will be amplified, whereas the timing of these extreme events is more predictable by 2063–2098.

Figure 6 shows the changes in the three indices for each climate scenario in the seven sub-basins. Substantial changes in the SR index are found, being more pronounced in the rain-dominated sub-basins than in the two Alpine sub-basins. Moreover, the SRs estimated from inputs by climate scenario 4 show the smallest change in all sub-basins except for the Main sub-basin, 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 sub-basins although these two climate scenarios both use ECHAM5 (versions 1 and 3) as GCM and REMO as RCM. The difference in SR between these 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 sub-basins. Climate scenario 7 shows a very large change in WMOD for the Moselle sub-basin.

The influence of climate scenario 2 on the change in the WP in the Main sub-basin and the influence of climate scenario 6 on the change in the WP in the Moselle sub-basin are both about 400 %, suggesting much less variability in the timing of low flows in these sub-basins. 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 subcatchments. 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

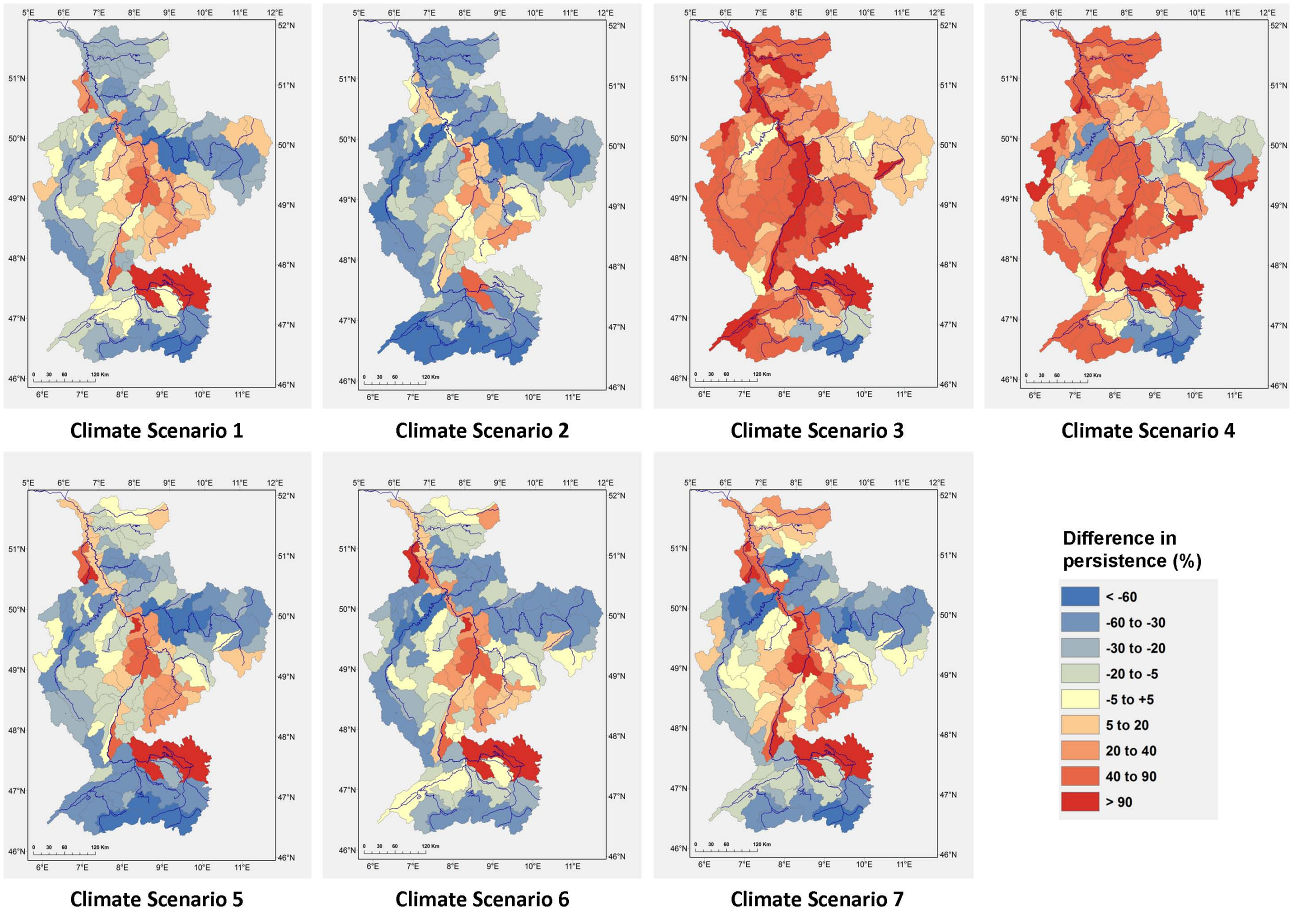

Fig. 4. Relative differences (%)* between low flow persistence estimated from simulated low flows using simulated inputs from seven climate scenarios for the reference period 1964–2007 (case 3) and simulated low flows using observed inputs for the same period (case 2). * (Based on simulated input – Based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

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 sub-basins, whereas large changes are found mostly in summer months in the rain-dominated sub-basins. Further, large changes in the inter-annual variability of monthly PET were found in winter months in all sub-basins. Some of the Alpine catchments show significant increases in the low flow persistence which is consistent with the results of Huang et al. (2013) who reported less variability in the 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 was done to transfer the climate change signal from RCMs to a hydrological model and to evaluate the effects of climate change on the seasonality of low flows. The good low flow simulation performance of the hydrological model, i.e. an error of less than 5 % in the simulation of the mean of minimum annual discharges (Eberle, 2005), was one of the reasons to select HBV for climate impact assessment. The difference between observed and simulated seasonality indices, and the change for the future climate, vary between the sub-basins. Moreover, the differences and changes also depend on the seasonality index considered. The dam operations, large lakes and the contribution of glacier storage are not explicitly incorporated in the HBV model structure (Berglöv et al., 2009). However, all these factors are important for determining the seasonality characteristics of low flows and they can explain the significant differences between observed and simulated seasonality indices in the Rhine catchments and in the Alpine catchments in particular. This result is in line with that of Tallaksen and Van Lanen (2004), who found that the release from other large storages controlled by gravity, such as large lakes, snow storage and glaciers, can be important in sustaining low flows.

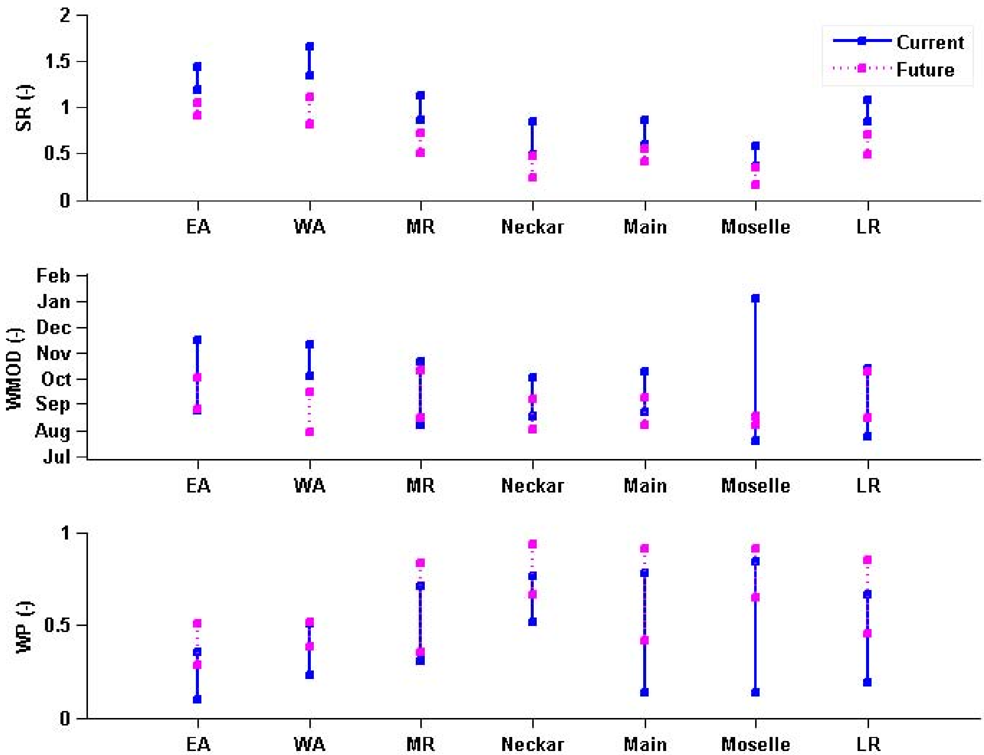

Fig. 5. Range (shown as bar) of three seasonality indices in the seven sub-basins for the current climate (calculations for case 3) and future climate (calculations for case 4).

It appears from the results that the difference between observed and simulated indices is significantly larger compared to the change in the three indices between the current and future climate. This result is in line with that of Booij (2005) who found that the change with respect to the current climate conditions is like a systematic trend and much smaller than the uncertainty in modelling the extreme flow conditions.

The correlation coefficients between the three indices estimated from 134 catchments show that the seasonality ratio and weighted persistence indices are significantly negatively correlated. However, Fig. 3 shows that the sub-catchments with lower seasonality ratio values (rainfed sub-catchments) show higher persistence. Similarly, the sub-catchments with higher seasonality ratio values (alpine sub-catchments) experience low flow events in early winter months in the year compared to the downstream sub-catchments facing low flows in late summer. Therefore, the correlations are negative. It should be noted that the correlation coefficient between seasonality ratio and weighted persistence (i.e. -0.6) is higher than the correlation between seasonality ratio and weighted mean occurrence day (i.e. -0.4) and no significant correlation is found between weighted persistence and weighted mean occurrence day (i.e. 0.1). Regarding interrelations between RCM outputs, as expected for time series resulting from stochastic processes in RCMs, no significant correlations were found (not shown). Moreover, in the IPCC special report on emission scenarios by Nakićenović and Swart (2000), it has been clearly stated that all A and B emission scenarios are equally valid with no assigned probabilities of occurrence.

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 of climate change uncertainty, it appears from Fig. 6 that the GCM/RCM uncertainty has the largest influence on weighted persistence. 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 the three indices using simulated inputs from seven climate scenarios, shown in Fig. 6, it appears that the influence of GCM/RCM uncertainty on seasonality ratio is slightly larger than the influence of emission scenario uncertainty on seasonality ratio, whereas the influence of GCM/RCM uncertainty on weighted mean occurrence day is similar to the influence of emission scenario on weighted mean occurrence day.

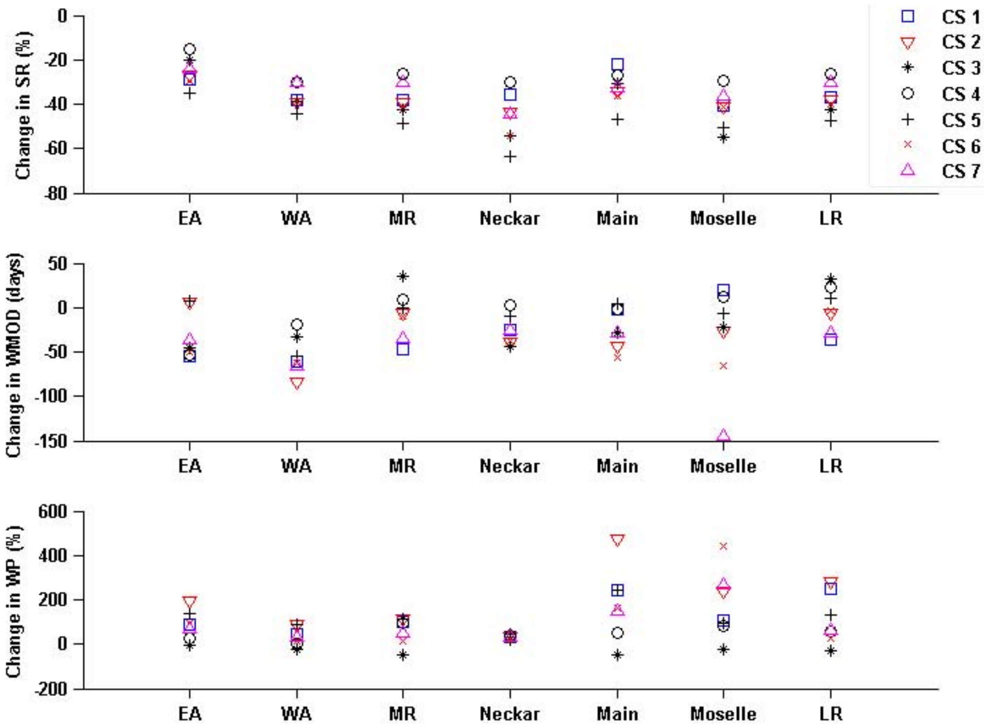

Fig. 6. The relative changes (*) in SR and WP and the changes in WMOD (**) at the outlet of the seven sub-basins estimated from simulated low flows using simulated inputs for the future period 2063–2098 (case 4) compared to simulated low flows using simulated inputs for the reference period 1964–2007 (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.

In this study, the errors induced by the hydrological model and observed inputs were not explicitly assessed as they are reported as less important than the uncertainty due to the climate predictions (Muerth et al., 2013; Blenkinsop and Fowler, 2007). Further, the measurement errors in the observed discharges and the effect of different data lengths for the observed discharge series were implicitly addressed in this study. Nevertheless, it would be interesting to use a multi-model approach to assess model structural uncertainties and employing additional bias-correction techniques like quantile mapping (Teutschbein and Seibert, 2012; Gudmundsson et al., 2012) to the outputs from different RCMs.

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 the 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 model runs 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 sub-basins showed larger differences compared to the rain-dominated sub-basins.
- The comparison of the three seasonality indices based on observed inputs and simulated inputs reveals small differences in SR for all sub-basins except for the

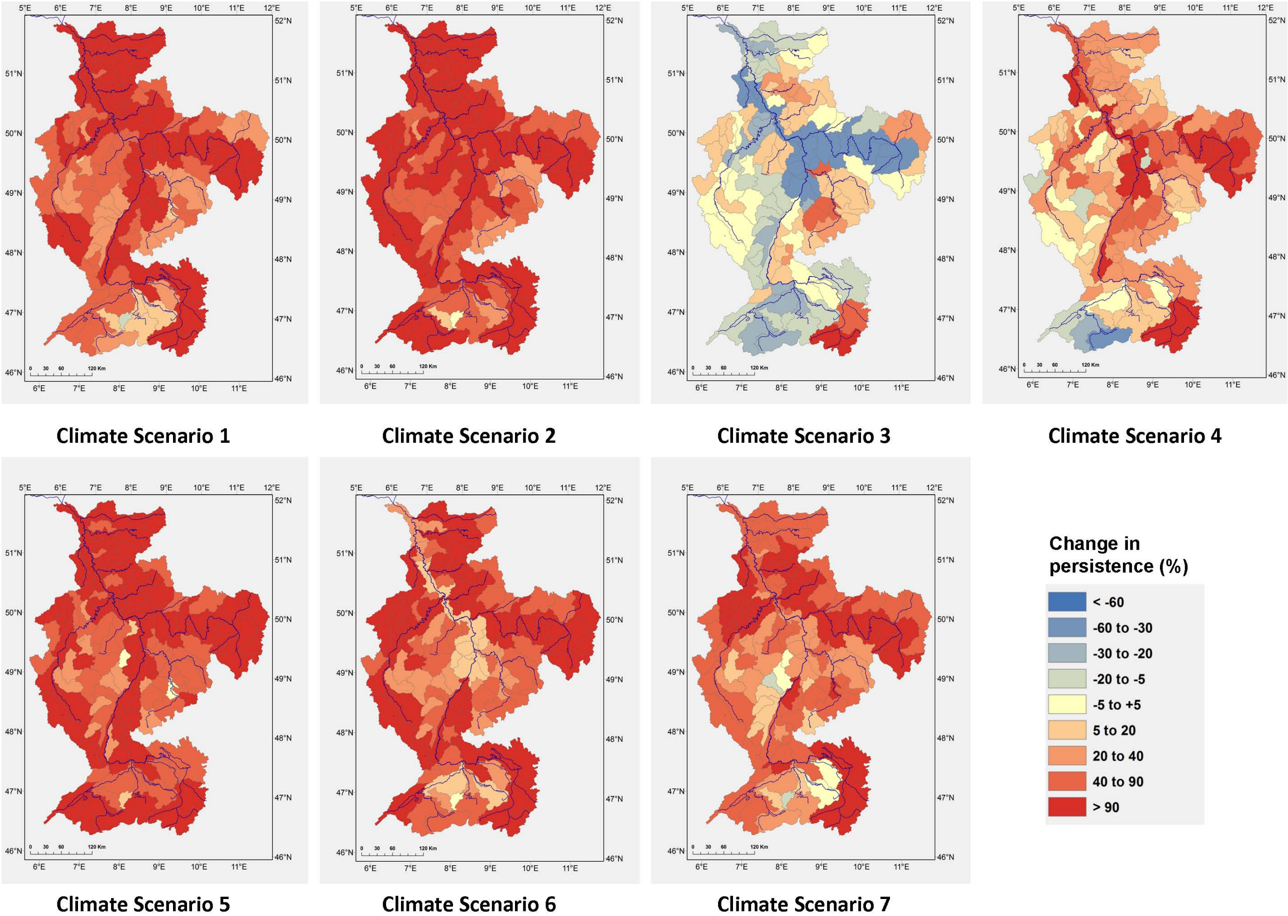

Fig. 7. Relative change (%)* in low flow persistence in 134 sub-catchments based on simulated low flows using simulated inputs from seven climate scenarios for the future period 2063–2098 (case 4) compared to simulated low flows using simulated inputs for the reference period 1964–2007 (case 3). * (Future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

Moselle sub-basin. 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 the current climate and simulated inputs for the 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 sub-basins, showing that a substantial change in the low flow regime in all sub-basins 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 sub-basins. Further, the WMODs of low flows tend to be earlier than for the current climate in all sub-basins except for the Middle Rhine and Lower Rhine sub-basins. 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 found that different RCMs/GCMs have a larger influence on the timing of low flows than different emission scenarios. The influence of different GCMs/RCMs on SR is slightly larger than the influence of different emission scenarios on SR, whereas the influence of different GCMs/RCMs on WMOD is similar to the influence of different emission scenarios on WMOD.

This study has evaluated the impacts of climate change on the seasonality of low flows in the River Rhine basin. A 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. Furthermore, a detailed analysis of the climate change impacts on the return periods of extreme low flows is recommended.

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