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# Uncertainty contributions to low flow projections in Austria

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## Abstract

The main objective of the paper is to understand the contributions to the uncertainty in low flow projections resulting from hydrological model uncertainty and climate projection uncertainty. Model uncertainty is guantified by different parameterizations of a

<sup>5</sup> conceptual semi-distributed hydrologic model (TUWmodel) using 11 objective functions in three different decades (1976–1986, 1987–1997, 1998–2008), which allows disentangling the effect of modeling uncertainty and temporal stability of model parameters. Climate projection uncertainty is quantified by four future climate scenarios (ECHAM5-A1B, A2, B1 and HADCM3-A1B) using a delta change approach. The approach is tested for 262 basins in Austria.

The results indicate that the seasonality of the low flow regime is an important factor affecting the performance of model calibration in the reference period and the uncertainty of  $Q_{95}$  low flow projections in the future period. In Austria, the calibration uncertainty in terms of  $Q_{95}$  is larger in basins with summer low flow regime than in basins with winter low flow regime. Using different calibration periods may result in a range of up to 60 % in simulated  $Q_{95}$  low flows.

The low flow projections show an increase of low flows in the Alps, typically in the range of 10-30 % and a decrease in the south-eastern part of Austria mostly in the range -5 to -20 % for the period 2021–2050 relative the reference period 1976–2008.

- <sup>20</sup> The change in seasonality varies between scenarios, but there is a tendency for earlier low flows in the Northern Alps and later low flows in Eastern Austria. In 85% of the basins, the uncertainty in  $Q_{95}$  from model calibration is larger than the uncertainty from different climate scenarios. The total uncertainty of  $Q_{95}$  projections is the largest in basins with winter low flow regime and, in some basins, exceeds 60%. In basins with
- <sup>25</sup> summer low flows and the total uncertainty is mostly less than 20%. While the calibration uncertainty dominates over climate projection uncertainty in terms of low flow magnitudes, the opposite is the case for low flow seasonality. The implications of the uncertainties identified in this paper for water resources management are discussed.



# 1 Introduction

Understanding climate impacts on hydrologic water balance in general and extreme flows in particular is one of the main scientific interests in hydrology. Stream flow estimation during low flow conditions is important also for a wide range of practical appli-

- cations, including estimation of environmental flows, effluent water quality, hydropower operations, water supply or navigation. Projections of low flows in future climate conditions are thus essential for planning and development of adaptation strategies in water resources management. However it is rarely clear how the uncertainties in assumptions used in the projections translate into uncertainty of estimated future low flows.
- There are numerous regional and national studies that have analyzed the effects of climate change on the stream flow regime, including low flows (e.g. Feyen and Dankers, 2009; Prudhomme and Davies, 2009; Chauveau et al., 2013, among others). Most of them apply outputs from different global or regional climate circulation models, which are based on different emission scenarios. The projections of low flows are then typ-
- <sup>15</sup> ically simulated by hydrologic models of various complexity. Only few studies, however, evaluate the uncertainty of low flow projections and the relative contribution of its different sources (i.e. climate projection, hydrologic model structure and/or model parameterizations). Such studies include assessment of the impact of different climate projections on low flows evaluated e.g. in Huang et al. (2013) and Forzieri et al. (2014).
- While Huang et al. (2013) assesses the low flow changes and uncertainty in the five largest river basins in Germany, Forzieri et al. (2014) evaluates the uncertainty of an ensemble of 12 bias corrected climate projections in the whole of Europe. Both studies quantify uncertainty in terms of the number of low flow projections that suggest the same change direction. Their results indicate a consistent pattern of low flow changes
- across different regions in Europe. A common feature of such ensemble climate scenarios is an increase in the agreement between ensemble members with increasing future time horizon of climate projections. The impact of hydrologic model structure and climate projections was evaluated in Dams et al. (2015). They applied four hydrologic



models calibrated with four objective functions to simulate the impact of three climate projections on low flows for a basin in Belgium. They found that besides the uncertainty introduced by climate change scenarios, hydrologic model selection introduces an additional considerable source of uncertainty in low flow projections. The model structure

- uncertainty was particularly important under more extreme climate change scenarios. A similar study was performed by Najafi et al. (2011) who investigated the uncertainty stemming from four hydrologic models calibrated by three objective functions and applied on eight Global Climate Model (GCM) simulations in a basin in Oregon. Their results show that although in general the uncertainties from the hydrologic models are
  smaller than from GCM, in the summer low flow season, is the impact of hydrologic
- model parametrization on overall uncertainty considerably larger than of the GCM.

The objective of this paper is to understand the relative contribution of the impact of hydrologic model calibration and ensemble climate scenarios to the overall uncertainty of low flow projections. Here, the uncertainty and variability of low flow projections

- <sup>15</sup> is assessed for four climate scenarios, 11 variants of objective functions and three decades used for model calibration. Austria is chosen as a case study since it is an ideal test bed for such analysis, as it allows to disentangle the uncertainties separately in regions with summer and winter low flow regimes. The assessment of uncertainties for winter and summer regimes allows to make generalisation for a wide spectrum of physiographic conditions around the world.
  - 2 Methodology

#### 2.1 Low flow projections

Low flow projections of future climate scenarios are typically performed by a delta change approach. This concept allows to remove biases resulted from simulations <sup>25</sup> when regional climate model (RCM) outputs are used as an input in hydrologic modelling. Instead of using RCM simulations of daily air temperature and precipitation for



hydrologic model calibration, the model is first calibrated by using observed climate characteristics in the reference period. In a next step, RCM outputs are used to estimate monthly differences between simulations in the reference (control) and future periods. These differences (delta changes) are then added to the observed model inputs

<sup>5</sup> and used for simulating future hydrologic changes. The difference between simulations of a hydrologic model in the reference and future periods are then used to interpret potential impacts of changing climate on future river flows.

Here we apply the delta change approach to simulate daily flows in the future period. The future low flow changes are quantified by the  $Q_{95}$  low flow quantile and seasonality index SI. The  $Q_{95}$  represents river flow that is exceeded on 95% of the days of the

<sup>10</sup> Index SI. The  $Q_{95}$  represents river flow that is exceeded on 95% of the days of the entire reference or future period. This characteristic is one of the low flow reference characteristic which is widely used in Europe (Laaha and Blöschl, 2006). Seasonality index SI represents the average timing of low flows within a year (Laaha and Blöschl, 2006, 2007). It is estimated from the Julian dates  $D_j$  of all days when river flows are equal or below  $Q_{95}$  in the reference or future periods.  $D_j$  represents a cyclic variable. Its directional angle, in radians, is given by:

$$\theta_j = \frac{D_j \times 2\pi}{365}.$$

The arithmetic mean of Cartesian coordinates  $x_{\theta}$  and  $y_{\theta}$  of a total of *n* single days *j* is defined as:

$$x_{\theta} = \frac{1}{n} \sum_{j} \cos(\theta_{j})$$
$$y_{\theta} = \frac{1}{n} \sum_{j} \sin(\theta_{j})$$

20



(1)

(2)

From this, the directional angle of the mean vector may be calculated by:

$$\theta = \arctan\left(\frac{y_{\theta}}{x_{\theta}}\right)$$
 1st and 4th quadrant:  $x > 0(3)$   
$$\theta = \arctan\left(\frac{y_{\theta}}{x_{\theta}}\right) + \pi$$
 2nd and 3rd quadrant:  $x < 0.$ 

Finally, the mean day of occurrence is obtained from re-transformation to Julian Date:

$$SI = \theta \times \frac{365}{2\pi},\tag{4}$$

<sup>5</sup> and the variability of the date of occurrence about the mean date (i.e. seasonality strength) is characterized by the length parameter r. The parameter r is estimated as (Burn, 1997):

$$r = \sqrt{\overline{x}^2 + \overline{y}^2} / n,$$

and ranges from r = 0 (low strength, uniform distribution around the year) to r = 1 (maximum strength, all extreme events of floods occur on the same day).

The SI index is estimated for observed flows and flows simulated by a hydrologic model. The difference between model simulations (i.e.  $Q_{95}$  and SI estimates) in the reference and future periods are then used to quantify potential impacts of climate change on low flows. Both  $Q_{95}$  and SI measures are estimated by the lfstat package in R software (Koffler and Laaha, 2014).

## 2.2 Hydrologic model

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Low flow projections are estimated by a conceptual semi-distributed rainfall runoff model (TUWmodel, Viglione and Parajka, 2014). The model simulates water balance components on a daily time step by using precipitation, air temperature and potential



(3)

(5)

evaporation data as an input. The model consists of three modules which allow simulating changes in snow, soil storages and groundwater storages. More details about the model structure and examples of application in the past are given e.g. in Parajka et al. (2007, 2008), Viglione et al. (2013) and Ceola et al. (2015).

- In this study, the TUWmodel is calibrated by using the SCE-UA automatic calibration procedure (Duan et al., 1992). The objective function ( $Z_Q$ ) used in calibration is selected on the basis of prior analyses performed in different calibration studies in the study region (see e.g. Parajka and Blöschl, 2008; Merz et al., 2011). It consists of weighted average of two variants of Nash–Sutcliffe model efficiency,  $M_E$  and  $M_F^{\log}$ .
- <sup>10</sup> While the  $M_E$  efficiency emphasize the high flows, the  $M_E^{\log}$  efficiency accentuates more the low flows. The maximized objective function  $Z_Q$  is defined then as

$$Z_Q = w_Q \times M_E + (1 - w_Q) \times M_F^{\log},$$

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where  $w_Q$  represents the weight on high or low flows. If  $w_Q$  equals 1 then the model is calibrated to high flows, if it equals to 0 then to low flows only.  $M_E$  and  $M_E^{\log}$  are estimated as

$$M_E = 1 - \frac{\sum_{i=1}^{n} (Q_{\text{obs},i} - Q_{\text{sim},i})^2}{\sum_{i=1}^{n} (Q_{\text{obs},i} - \overline{Q_{\text{obs}}})^2}$$
$$M_E^{\log} = 1 - \frac{\sum_{i=1}^{n} (\log(Q_{\text{obs},i}) - \log(Q_{\text{sim},i}))^2}{\sum_{i=1}^{n} (\log(Q_{\text{obs},i}) - \overline{\log(Q_{\text{obs}})}^2)^2}$$

where  $Q_{\text{sim},i}$  is the simulated discharge on day *i*,  $Q_{\text{obs},i}$  is the observed discharge,  $\overline{Q_{\text{obs}}}$  is the average of the observed discharge over the calibration (or verification) period of *n* days.



(6)

(7)

(8)

## 2.3 Uncertainty estimation

The uncertainty defined as the range of low flow projections is evaluated for two contributions. The first analyses the uncertainty (i.e. the range of  $Q_{95}$  and SI) estimated for different variants of hydrologic model calibration. Here, two cases are evaluated. In

order to assess the impact of time stability of model parameters (Merz et al., 2011), TUWmodel is calibrated separately for three different decades (1976–1986, 1987–1997, 1998–2008). The effect of objective function used for the TUWmodel calibration is evaluated by comparing 11 variants of weights (*w<sub>Q</sub>*) used in *Z<sub>Q</sub>*. Following *w<sub>Q</sub>* are tested: 0.0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9 and 1.0. The hydrologic model is
 calibrated for all 11 variants in each selected decade. Calibrated models are then used for flow simulations and hence *Q*<sub>95</sub> and SI estimation in the entire reference period 1976–2008.

The second contribution evaluates the uncertainty of  $Q_{95}$  and SI changes simulated for different climate scenarios. The effect of calibration uncertainty (case 1) is compared

- for four selected climate scenarios (more details are given in Data section). The delta change approach is used for simulation of future river flows in the period 2021–2050 relative to the reference period 1987–2008. The delta changes of  $Q_{95}$  and SI values between reference and future periods are estimated for four selected climate scenarios, 11 variants of model calibration and three selected decades. The relative contribution
- <sup>20</sup> of the impact of model calibration (i.e. time stability and objective function selection) and climate scenario is then evaluated seasonally at the regional scale.

#### 3 Data

Study region is Austria (Fig. 1). Austria represents diverse climate and physiographic conditions of Central Europe, which is reflected in different hydrologic regimes (Gaál et al., 2012). The topography varies from 115 ma.s.l. in the lowlands to more than

et al., 2012). The topography varies from 115 ma.s.l. in the lowlands to more than 3700 ma.s.l. in the Alps. Austria is located in a temperate climate zone influenced



by the Atlantic, meridional south circulation and the continental weather systems of Europe. Mean annual air temperature varies between -8 to  $10^{\circ}$ C. The mean annual precipitation ranges from 550 mm year<sup>-1</sup> in the Danube lowlands, to more than  $3000 \text{ mm year}^{-1}$  on the windward slopes of the Alps.

- The analysis is based on daily river flow measurements at 262 gauges (Fig. 1). This dataset represents a subset of data used in Laaha and Blöschl (2006), which consists of gauges for which hydrographs are not seriously affected by abstractions and karst effects during the low flow periods. Figure 1 shows two main low flow regimes in Austria. While orange and red colours indicate 130 stations with dominant summer low
- flow occurrence, blue colour indicates 132 gauges with winter flow minima. These two groups represent basins with distinct low flow seasons, which are controlled by different hydrologic processes. While the winter flow minima in the mountains are controlled by freezing processes and snow storage, summer low flows occur during long-term persistent dry periods when evaporation exceeds precipitation. The different low flow
- <sup>15</sup> generating processes, together with the hydro-climatic variety of the study area, gives rise to an enormous spatial complexity of low flows in Austria. The largest values occur in the high precipitation areas in the Alps, with typical values ranging from 6 to 20 Ls<sup>-1</sup> km<sup>-2</sup>. The lowest values occur in the east ranging from 0 to 8 Ls<sup>-1</sup> km<sup>-2</sup>, although the spatial pattern is much more intricate.
- <sup>20</sup> Climate data used in hydrologic modeling consists of mean daily precipitation and air temperature measurements at 1091 and 212 climate stations in the period 1976– 2008, respectively. Model inputs have been prepared by spatial interpolation and zonal averaging described in detail in previous modeling studies (please see e.g. Merz et al., 2011 or Parajka et al., 2007). These data serve as a basis for hydrologic model cali-
- <sup>25</sup> bration and as a reference for future delta change simulations. Figure 2 shows basin averages of mean annual air temperature, precipitation and runoff in the period 1976– 2008. The thin lines represent the medians of climate characteristic over the averages of basins with summer and winter low flows. The thick lines represent the average over the three selected decades. The two groups of basins differ clearly in the climate



regime. Basins with summer low flows are characterized by higher air temperatures, less precipitation and less runoff. The comparison of three different decades indicates that mean annual air temperatures have increased by 1 °C in the period 1976–2008. This increase is similar for both groups of basins. Interestingly, the mean annual pre-

cipitation has increased over the last three decades, which is likely compensated by increased evapotranspiration, as the mean annual runoff remains rather constant.

The regional climate model (RCM) scenarios used in this study are based on the results of the reclip.century project (Loibl et al., 2011). The ensemble climate projections are represented by COSMO-CLM RCM runs forced by the ECHAM5 and HADCM3 global circulation models for three different IPCC emission scenarios (A1B, B1 and A2,

- <sup>10</sup> global circulation models for three different IPCC emission scenarios (A1B, B1 and A2, Nakicenovic et al., 2000). These represent a large spread of different emission pathways from a "business as usual" scenario with prolonged greenhouse gas emissions (A2), a scenario with moderate decline of emissions after 2050 (A1B) and a scenario indicating considerably reduced emissions from now on (B1). The decision on the two driving GCMs is justified by an analysis of Prein et al. (2008) who investigated the skill
- of the CMIP3 GCM ensemble over Central Europe and show that these two models are among the best performing ones.

Table 1 summarizes the annual and seasonal differences (delta changes) of mean basin precipitation and air temperature between the future (2021–2050) and reference

(1976–2006) periods. Table 1 indicates that the largest warming is obtained by simulations driven by HADCM3. The median of air temperature increase in summer exceeds 2°C. In numerous basins, a small decrease in air temperature in winter is simulated by ECHAM5 A2 and B1 simulations. The changes in mean annual precipitation are within the range ±9% in all selected basins. The increase tends to be larger in winter than in the summer period.



# 4 Results

# 4.1 Low flow simulations in the reference period

The runoff model efficiency ( $Z_{\Omega}$ ) in the three calibration periods obtained for different variants of the objective function is presented in Fig. 3. The results show that  $Z_{0}$  is larger and thus runoff simulations are more accurate in basins with winter (blue colour) 5 than summer low flow minimum (red colour). Most of the basins with winter low flow regime are situated in the alpine western and central part of Austria, where the runoff regime is snow dominated. Such a regime has stronger runoff seasonality (see e.g. Fig. 5 in Laaha et al., this issue) and less difference in rainfall regime, which allows easier modeling of rainfall-runoff process than in basins with rainfall-dominated runoff regime.  $Z_{\Omega}$  increases with decreasing weight  $w_{\Omega}$ , which indicates that the runoff model performance tends to be better for low than high flows (i.e. model has larger runoff efficiency if it is calibrated to logarithmic transformed flows than to non-transformed flows only). The comparison of  $Z_{Q}$  in the three calibration periods indicates that the difference in model performance between basins with winter and summer low flow 15 regime is the largest in the period 1976–1986. While the  $Z_{O}$  for basins with winter low regime is very similar in all three calibration periods, the  $Z_{\Omega}$  has an increasing tendency in basins with summer regime. For example, the median of  $Z_{\Omega}$  for  $w_{\Omega} = 1.0$  increases from 0.64 in the period 1976–1986 to 0.71 in the period 1998–2008. This increase is likely related to increasing number of climate stations and data quality (Merz et al., 20 2009).

How the different calibration variants and periods translate into low flow 95%quantile  $Q_{95}$  and seasonality SI is examined in Fig. 4. The top panels show the  $Q_{95}$ difference estimated from simulated and observed daily flows in the period 1976–2008.

<sup>25</sup> This means that the model calibrated for 11 year period is used to simulate daily flows in the entire reference period 1976–2008. The results show that the model calibrated in the period 1976–1986 significantly overestimates  $Q_{95}$  of the reference period particularly in basins with summer low flow regime. The period 1976–1986 is characterized



by lower air temperatures with less evapotranspiration and relatively higher runoff generation rates which translates into different soil moisture storage (FC model parameter) and runoff generation (BETA) model parameters. Such effects are consistent with findings of Merz et al., (2011). The hydrologic model applied to the entire reference period hence produces larger runoff contribution which tends to overestimate  $Q_{95}$  particularly in the warmer and drier parts of the reference period and drier and warmer parts of Austria. The overestimation is consistent for large range of  $w_Q$  ( $w_Q$  in the range 0.0–0.9) and the median of  $Q_{95}$  difference exceeds 20%. Also the scatter around the median is

- rather large, where 25 % of the basins with the summer low flow regime have  $Q_{95}$  differences larger than 35 %. The simulated  $Q_{95}$  in basins with winter low flows fits closer to the observed estimates. The median is less than 10 % for variants  $w_Q < 1$ . Interestingly, the model simulations based on calibration periods 1987–1997 and 1998–2008 are much closer to the observed values. The results for both groups of basins are very similar and essentially unbiased in terms of 95 % low flow quantile. The exception is the
- <sup>15</sup> calibration variant  $w_Q = 1$  that tends to underestimate  $Q_{95}$ . Overall, the results are similar for large range of  $w_Q$ . There are any significant differences between calibration to low flow only ( $w_Q = 0.0$ ) and other weights, with exception of  $w_Q = 1$ , which represents a typical calibration of using classical Nash–Sutcliffe coefficient.

The results of the seasonality estimation are presented in the bottom panels of Fig. 4.

- It is clear that hydrologic model tends to estimate the low flow period later. This shift is larger in basins with summer low flow regimes. While the median of SI difference in basins with winter regime is around 10–12 days in the period 1976–1986 and increases to 12–19 days in the period 1998–2008, the median of SI difference in basins with summer low flows is in the range of 18–32 days. The scatter is, however, much
- <sup>25</sup> larger for basins with summer regime. Here the model simulates the season of low flow occurrence with more than 2 months shift (earlier or later) in almost 50% of the basins. A typical example of such shift is provided in Fig. 5. The periods with flows below 95% quantile are often very short and the timing of simulated low flows does not fit well with these periods. In some cases there is also a difference in the length of the



low flow period, when the model parameterization does not allow to fit well some small rainfall–runoff events in the summer or autumn, which interrupt the observed low flow period but not the flows simulated by the hydrologic model (i.e. the precipitation event is completely absorbed by the soil storage of the model and does not contribute to the <sup>5</sup> runoff generation).

The spatial pattern of the uncertainty of  $Q_{95}$  estimation in the reference period 1976– 2008 is presented in Fig. 6. Figure 6 shows the range of differences between simulated and observed  $Q_{95}$  for the different calibration variants. Left panels show the range for model calibrations performed by the same objective function (i.e. top left panel –  $w_Q = 0.5$  and bottom left panel –  $w_Q = 0.0$ ) used for calibration in the three different calibration periods (1976–1986, 1987–1997, 1998–2008). Contrary, right panels show the range of differences for one calibration period but between 11 variants of the objective function ( $w_Q$ ) (i.e. top right panel – 1976–1986, bottom right panel – 1998–2008). The results indicate that the  $Q_{95}$  differences vary more between the different objective

- <sup>15</sup> functions (right panels), however in many basins the range exceeds 60% even if the model is calibrated by one objective function but in the different calibration periods. As already indicated in Fig. 4, the differences are larger in basins with the summer low flows, particularly for variants calibrated in the period 1976–1986. For particular basin, the differences are not strongly related to the weight  $w_Q$  used in the calibration, with an
- exception of  $w_Q = 1$ , which tends to have the largest difference to observed  $Q_{95}$ . Some examples of the model performance for individual basins are given in companion paper of Laaha et al. (this issue).

Spatial variability of the model uncertainty in terms of low flow seasonality is presented in Fig. 7. Figure 7 shows, similarly as Fig. 6, the range of differences between the simulated and observed SL for different calibration variants. The results clearly in

the simulated and observed SI for different calibration variants. The results clearly indicate that basins with the winter low flow regime (i.e. situated in the Alps) vary significantly less for different calibration settings than the basins with the summer low flow regime. The range of differences is typically less than 14 days in the mountains, compared to more than 90 days in many basins with the summer regime.



The comparison of SI and  $Q_{95}$  uncertainties indicates that not every basin with large SI variability has the large variability in terms of  $Q_{95}$ . For example, a cluster of basins situated in the south-eastern part of Austria (Styria) has a large SI range of difference (i.e. more than 90 days) for 11 calibration variants in the period 1976–1986, but the variability in  $Q_{95}$  is less than 20% for this case. The same applies for the opposite case of small SI and large  $Q_{95}$  variability in the alpine basins.

# 4.2 Low flow projection in the future period

Low flow projections for selected climate scenarios and different calibration weight  $w_Q$ are presented in Fig. 8. The line (median) and scatter (i.e. 75 and 25% percentiles) show changes in  $Q_{95}$  (top panels) and low flow seasonality (bottom panels) for basins with winter (blue) and summer (orange) low flow regime. Rather than to evaluate in detail the projections in terms of absolute values of low flow changes, the main focus is to assess the range of possible changes caused by different scenarios and objective function used for model calibration. The results show projections based on model cali-

- <sup>15</sup> bration in 1998–2008, but the results are almost identical with results for the other two calibration periods (i.e. the average difference is around 1%). Figure 8 clearly shows the difference in projections for basins with summer and winter low flow regime, particularly for  $Q_{95}$  changes. It is hence important to evaluate the projections and their variability separately for different regimes. The comparison of different scenarios indicates that
- <sup>20</sup> they are similar in terms of projecting an increase of winter low flows and a tendency for decreasing  $Q_{95}$  in the summer period. The increase of winter  $Q_{95}$  slightly varies between climate scenarios and tends to increase for calibration variants with larger  $w_Q$ . The difference in median between  $w_Q < 0.4$  and  $w_Q > 0.8$  is approximately 9%. The projections of  $Q_{95}$  changes in basins with summer low flows have significantly smaller
- variability and do not depend on  $w_Q$ . The change in low flow seasonality (Fig. 8, bottom panels) is less pronounced and is not sensitive to  $w_Q$ . The median of projections is around 5 and 10 days earlier than in the reference period for basins with summer and winter regime, respectively. Interestingly, the variability between basins and  $w_Q$  is sig-



nificantly smaller than obtained for different calibration variants in the reference period (Fig. 4).

Examples of spatial patterns of low flow projections are presented in Fig. 9 and 10. The projections of  $Q_{95}$  changes (Fig. 9) indicate an increase of low flows in the Alps, typically in the range of 10–30%. A decrease is simulated in south-eastern part of Austria (Styria) mostly in the range of -5 to -20%. The most spatially different projection is provided by the AIT HADCM3 A1B climate scenario which simulates the strongest gradient between an  $Q_{95}$  increase in the Alps in winter and a decrease in south-eastern part in summer. The change in the seasonality varies between the scenarios, but there is a tendency for earlier low flows in the Northern Alps and a shift to later occurrence of low flows in the Eastern Austria. As already indicated in Fig. 8, the shift in seasonality is larger than one month only in a few basins.

Figures 9 and 10 show projections of lows flows for four climate scenarios, but only one variant of hydrologic model parameters. The evaluation of the impacts of different calibration variants on the variability of low flow projections is presented in Figs. 11

- <sup>15</sup> calibration variants on the variability of low flow projections is presented in Figs. 11 and 12. These Figures indicate the range of  $Q_{95}$  (Fig. 11) and the seasonality occurrence (Fig. 12) changes obtained by 11 calibration variants and three calibration periods. The range of  $Q_{95}$  changes is interestingly the largest in basins with the winter low flow regime. In the Alps, the increase of  $Q_{95}$  is often in the range of 15% to more
- <sup>20</sup> than 60%. On the other hand, the future  $Q_{95}$  estimates vary only slightly between the calibration variants in basins with the summer low flows. In most of the basins is the change less than 20%. The impact of the selection of objective function is, however, much larger for the estimation of the seasonality changes. Depending on the calibration variant, the change in seasonality can vary within more than 3 months, e.g. in the south-eastern part of Austria.

The total uncertainty of low flow projections of  $Q_{95}$  and SI is presented in Fig. 13. While the top panels show the range of low flow characteristics for all climate scenarios, calibration variants and periods, the bottom panels show the ratio between the uncertainty of future low flow projections to the calibration uncertainty in the reference



period. The results show that the  $Q_{95}$  range is less than 25 % in approximately one third of analyzed basins. On the other hand, 20 % of basins have a range larger than 50 %. These are the basins with the winter low flow regime. The variability in the date of low flow occurrence is less than three months in 40 % of the basins. In almost 20 % of the

- <sup>5</sup> basins, however, it is larger than five months. The ratio between the range of projections to the range of calibration differences (bottom panels in Figs. 13 and 14) indicates that only in 15% of the cases the climate projection uncertainty of  $Q_{95}$  is larger than the calibration uncertainty. Most of these basins are situated in the mountains (mean basin elevation above 1000 m a.s.l.) and have winter low flow regime. The  $Q_{95}$  calibra-
- tion uncertainty is larger in almost all basins with the summer low flow regime, which are characterized by lower mean basin elevation and larger aridity. On the other hand, the climate projection uncertainty dominates for the low flow seasonality and is more than three times larger in 50 % of basins, particularly in the Alps. In only 15 % of the basins is the SI projection uncertainty lower than the SI calibration uncertainty. The SI uncertainty ratio tends to be lower with increasing mean basin elevation and the basin
- <sup>15</sup> uncertainty ratio tends to be lower with increasing mean basin elevation and the bas area, but there is no apparent relationship with the aridity of the basins.

## 5 Discussion and conclusions

The objective of the study is to explore the relative role of hydrologic model calibration and climate scenarios in the uncertainty of low flow projections. While many previous

- studies simulate only the change in hydrologic regime or extreme characteristics due to changes in climate, in this study we focus on the quantification of the range of low flow projections (i.e. uncertainty) due to differences in the objective function used in model calibration, temporal stability of model parameters and an ensemble of climate projections.
- There are a number of studies that compare the uncertainty of projected runoff changes due to different model structure, objective function or GCM and emission scenarios. These studies found that the hydrologic model uncertainty tends to be consid-



erably smaller than that from GCM or emission scenarios (Najafi et al., 2011; Prudhomme and Davies, 2009). Such results, however, refer to the seasonal or monthly runoff and are based on only a limited number of basins. The quantification of the uncertainty in low flows is still rather rare. Some studies (e.g. Huang et al., 2013; Forzieri

et al., 2014) evaluate the low flow uncertainty in terms of the number of projections with the same change direction. They showed that the uncertainty is controlled mainly by the differences in emission scenarios and it decreases with increasing projection horizon. Our results indicate that, although the uncertainty from different emission scenarios is larger than 40% in many basins, the uncertainty from model calibration can
 exceed 60%. This result particularly relates to the assessment of low flow quantile changes.

Some recent low flow studies suggest to more explicitly distinguish between the processes leading to low flow situations (see e.g. Fleig et al., 2006; Laaha et al., 2006; Van Loon et al., 2015; Forzieri et al., 2014). Following this recommendation, we ana-

- <sup>15</sup> lyzed the effects of model calibration and climate scenarios separately for basins with dominant winter and summer low flow regimes. Our results indicate that the calibration runoff efficiency is larger, and the uncertainty lower in basins with winter low flow regime. The calibration uncertainty in basins with summer regime exceeds in many basins 60 % even if the model is calibrated by the same objective function but in differ-
- ent calibration periods. This finding confirms and quantifies the potential impact of time stability of model parameters reported by Merz et al. (2011). The model parameters calibrated in colder periods with relatively larger runoff generation rates tend to overestimate low flows, particularly in basins with summer low flow regime and in warmer and drier parts of the simulation period. The results indicate that the time stability of model parameters to the variable of the simulation period.
- <sup>25</sup> model parameters is not sensitive to the weighting of normal  $(M_E)$  and logarithmic transformed  $(M_E^{\log})$  Nash–Sutcliffe efficiency in the objective function used for calibration. The exception is the case of using only  $M_E$  with no weight on  $M_E^{\log}$ , which does not allow accurate low flow simulations. This finding partly supports the studies that propose logarithmically transformed discharge values for calibrating hydrologic models



with a focus on low flows (please see review in Pushpalatha et al., 2012). Our results show that the impact of the objective function is larger for the estimation of low flow quantiles in basins with winter low flow regime and is particularly large for the estimation of seasonality changes. Depending on the calibration variant, the change in seasonality can vary within more than three months, which clearly indicates a shift in the main hydrologic processes causing the low flows.

The climate change signals captured in selected scenarios are well within the range of the projections of the ENSEMBLES regional climate simulations for Europe (van der Linden and Mitchell, 2009; Heinrich and Gobiet, 2011). Jacob et al. (2015) showed

- <sup>10</sup> that the most recent regional climate simulations over Europe, accomplished by the EURO-CORDEX initiative (RCPs, Moss et al., 2010), are rather similar to the older ENSEMBLES simulations with respect to the climate change signal and the spatial patterns of change. The projected future decrease of  $Q_{95}$  is most pronounced in the AIT\_HADCM3\_A1B run, particularly in basins with summer low flow regime in the low-
- <sup>15</sup> lands. As indicated in Heinrich and Gobiet (2011), the climate sensitivity of HADCM3 is higher than that of ECHAM5, which translates into a higher warming rate of 2.1 °C in summer (c.f. Table 1) compared to 1.2 °C in the ECHAM5 driven run. The higher evaporative demand due to the increased air temperature signal translates into the strongest change of the summer low flow signal.
- The comparison of climate scenario and model calibration uncertainties indicates that the model calibration uncertainty dominates in the estimation of low flow magnitudes in the reference period, and the uncertainty in low flow seasonality is larger for future climate scenarios. Even if the variability and uncertainty of GCM and emission scenarios can be large, the results clearly indicate the importance of selecting objec-
- tive functions in hydrologic model calibration for simulating low flow projections. The assessment in Austria enabled us to account for two different low flow regimes. In the future we plan to extend such comparative assessment to more types of low flows (e.g. as classified in Van Loon and Van Lanen, 2012) and their combinations linked with changes in land use and management at the wider, European scale. This will allow



us to shed more light on the factors controlling the possible scenarios of low flow and water resources changes in the future.

From the practical point of view, the projections of  $Q_{95}$  changes and related uncertainties are an essential input to water quality modelling. The exceedance of environmental quality standards (BGBI II Nr. 99/2010; Zessner, 2008) in case of emissions from point sources (e.g. waste water treatment plants) increases the vulnerability of water resources, particularly during low flow conditions. We therefore also plan to evaluate the impact of climate projection and hydrologic model uncertainties on the assessment of water quality and its changes.

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Table 1. Summary of seasonal and annual changes in the mean basin precipitation and air
temperature as simulated by four selected RCM runs. The first value and values in the brack-
ets are the median and range (min/max) of differences between the future (2021-2050) and
reference (1976-2006) periods in 262 basins. Winter and summer seasons are defined as
December–May and June–November, respectively.

Delta change	WEGC ECHAM5	ZAMG ECHAM5	AIT HADCM3	ZAMG ECHAM5
	A1B2	A2	A1B	B1
Air temperature winter (°C)	+1.5 (0.9/1.7)	+0.7 (-1.1/2.1)	+1.3 (0.8/1.5)	+1.0 (-0.8/2.5)
Air temperature summer (°C)	+1.2 (0.8/1.7)	+0.9 (-0.1/2.2)	+2.1 (1.4/2.4)	+1.3 (0.4/2.5)
Air temperature year (°C)	+1.3 (0.9/1.5)	+0.8 (-0.4/2.2)	+1.7 (1.2/1.9)	+1.2 (0.0/2.5)
Precipitation winter (%)	8.2 (-0.7/16.2)	-1.5 (-5.8/6.4)	1.3 (-9.6/6.8)	0.0 (-8.5/3.3)
Precipitation summer (%)	-6.2 (-9.9/3.7)	0.2 (-8.9/5.7)	-5.0 (-13.5/0.2)	-2.3 (-6.3/2.5)
Precipitation year (%)	0.9 (-4.6/8.7)	-0.9 (-4.1/3.4)	-2.0 (-9.3/1.8)	-1.2 (-5.5/2.8)





**Figure 1.** Topography of Austria and location of 262 river flow gauges. Colour and symbol size of the gauges represents seasonality of low flows SI and its strength (r) in the period 1976–2008, respectively. The SI and its strength is estimated by R lfstat package (Koffler and Laaha, 2014).







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**Figure 3.** Runoff model efficiency ( $Z_Q$ ) for different calibration weights  $w_Q$  in three different calibration periods. Lines represent the medians, scatter (i.e. 75–25% percentiles) shows the  $Z_Q$  variability over basins with dominant winter (blue) and summer (orange) low flow regime.











**Figure 5.** Comparison of observed (blue) and simulated (red) flow for Hoheneich/Braunaubach, 291.5 km<sup>2</sup>). Thick lines show flows below low flow quantile  $Q_{95}$ . Model simulations are based on calibration variant  $w_Q = 0.5$  in the period 1998–2008.





**Figure 6.** Uncertainty of  $Q_{95}$  model simulations estimated from 11 calibration variants calibrated in the same calibration period (right panels, top – calibration period 1976–1986, bottom – calibration period 1998–2008) and from three calibration periods calibrated by the same calibration variant (left panels, top  $w_Q = 0.5$ , bottom  $w_Q = 0.0$ ). The uncertainty is expressed as the range of relative differences (%) between simulated and observed  $Q_{95}$  obtained by particular calibration variants in the period 1976–2008. Colour patterns in the background show the interpolated ranges by using top-kriging method (Skoien et al., 2014).





**Figure 7.** Uncertainty of simulations of low flow seasonality (SI) estimated from 11 calibration variants calibrated in the same calibration period (right panels, top – calibration period 1976–1986, bottom – calibration period 1998–2008) and from three calibration periods calibrated by the same calibration variant (left panels, top  $w_Q = 0.5$ , bottom  $w_Q = 0.0$ ). The uncertainty is expressed as the range of differences (days) between simulated and observed SI in the period 1976–2008. Colour patterns in the background show the interpolated ranges by using top-kriging.





**Figure 8.** Projections of low flows for selected climate scenarios and calibration variants. Line represent the medians, scatter (i.e. 75–25 % percentiles) show the variability over 262 basins. Top and bottom panels show projected changes of low flow quantiles  $Q_{95}$  and seasonality index SI in basins with winter (blue) and summer (orange) low flow regimes, respectively. Projections are estimated by a delta change approach and indicate changes in the period 2021–2050 with respect to the reference period 1976–2008. Calibration variants are calibrated in the period 1998–2008.





**Figure 9.** Projections of low flow quantiles  $Q_{95}$  changes for four climate scenarios in 262 Austrian basins. Projections show changes between future (2021–2050) and reference (1976–2008) periods. Model simulations are based on variant  $w_Q = 0.5$  calibrated in the period 1998–2008. Colour patterns in the background show the interpolated projections by using top-kriging.





**Figure 10.** Projections of changes in low flow seasonality (SI) for four climate scenarios in 262 Austrian basins. Projections show changes between future (2021–2050) and reference (1976–2008) periods. Model simulations are based on variant  $w_Q = 0.5$  calibrated in the period 1998–2008. Colour patterns in the background show the interpolated projections by using top-kriging.





**Figure 11.** Uncertainty of  $Q_{95}$  model projections of low flows for four different climate scenarios. The uncertainty is expressed as the range of relative differences (%) between  $Q_{95}$  simulated in the future (2021–2050) and reference (1976–2008) period obtained for 11 calibration variants calibrated in three calibration periods. Colour patterns in the background show the interpolated ranges by using top-kriging.





**Figure 12.** Uncertainty of model projections of low flow seasonality for four different climate scenarios. The uncertainty is expressed as the range of relative differences (%) between seasonality occurrence (SI) simulated in the future (2021–2050) and reference (1976–2008) period obtained for 11 calibration variants calibrated in three calibration periods. Colour patterns in the background show the interpolated ranges by using top-kriging.





**Figure 13.** Total uncertainty of model projections of low flows for four different climate scenarios, 11 calibration variants and three calibration periods. The uncertainty is expressed as the range of  $Q_{95}$  (left panel) and seasonality (right panel) of differences between model simulations in the future (2021–2050) and reference (1976–2008) periods. Bottom panels show the ratio between the range of climate projections to the range of differences in the reference period. Colour patterns in the background show the interpolated ranges by using top-kriging.





**Figure 14.** Relationship between the uncertainty ratio between calibration and projection uncertainty and basin area (left panels), mean basin elevation (middle panels) and aridity index (right panels). Top and bottom panels show the uncertainty ratio for the low flow quantile (Q95) and seasonality index (SI), respectively. Basins with winter low flow seasonality are plotted in blue, basins with summer low flow seasonality are in yellow.

