Response to Referee #1

We would like to thank the reviewer for his/her positive and insightful comments on the manuscript. Below is our response to the issues raised in the review (printed in italics).

General comments:

1) *This paper presents an assessment of low flow projections in Austria, putting a strong emphasis on several sources of uncertainty, namely GCM uncertainty, calibration period uncertainty and objective function uncertainty for the hydrological model used. This paper is completely within the scope of HESS and it also responds pretty well to some of the topics of interest of the special issue "HYPER Droughts (HYdrological Precipitation – Evaporation – Runoff Droughts)".*

The topic of this paper also represents an important research field regarding hydrological climate change impact studies. Indeed, still too often authors who write papers presenting an assessment of flows (high or low flows) completely neglect the uncertainty of hydrological models: they use them as a trustful representation of the transformation of P and T into discharge, that will not change over time, meaning that only one hydrological model is used, with only one parameter set (see Alfieri et al., 2015; Thorne, 2011; Milano, 2015). While this kind of studies was justifiable years ago, it is no more defendable in my opinion, now that studies are repeatedly showing the lack of robustness of hydrological models when applied to contrasted climate conditions (Chiew et al., 2015; Coron et al., 2012; Thirel et al., 2015). So the present study is very interesting, but could be improved through several aspects listed below.

Response: We would like to thank the reviewer for this positive evaluation.

2) *The introduction, which serves at locating the paper into the field literature, is rather short. Some "good practice" and some "bad practice" examples of studies are given, but the authors fail to really show what novelty their study brings. I would suggest the authors to work on that.*

Response: In response to this comment, as well as to the comments related to new ANOVA analyses, we have extended the introduction and discussion section. The main idea was to introduce and refer to studies which are related to the uncertainty assessment of hydrologic (low flow) projections.

3) *My second major remark is about the use of a single hydrological model. While this article already presents more than many articles, I would say that the results may be to some extent model-dependent, and that it is worth discussing that somehow in the paper.*

Response: We agree that our results are to some degree model dependent. In response to this comment, we have thus extended the discussion section as follows: "The assessment in Austria enabled us to account for one conceptual hydrologic model and 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), their combinations linked with changes in land use and management at the wider, European scale, as well as to account for hydrologic models of different complexity, wider range of climate scenarios and different downscaling techniques. "

4) Some plots and analysis compare the relative uncertainty between 3 calibration periods and 11 objective functions. I wonder how the difference of the sample size (3 against 11) impacts the range of uncertainty and thus the comparison. I wonder if an ANOVA-type analysis could not be a useful tool for palliating this potential issue (see Vidal et al., 2015, this issue for example).

Response: Thank you for this suggestion. We agree that a variance decomposition as can be extracted from a statistical ANOVA framework may be useful to assess (quantify) the uncertainty contributions from different model/scenario components. In response to this comment we have thus extended the manuscript by introducing the ANOVA-type approach (in the Introduction and methodology sections) and estimating the relative contribution of three components (climate scenario, calibration decade and calibration objective function) to the overall uncertainty of low flow projections in Austria (in the Results and Discussion sections).

Minor remarks:

1) Throughout the whole document, please pay attention to the use of "low flow" -> when it is use as an adjective to a noun, it should be written "low-flow".

Response: Corrected.

2) Abstract: I am not sure that this article "allows disentangling the effect of modelling uncertainty and temporal stability of model parameters". While the second element is correct, I think that the first one is actually about the objective function-related uncertainty and nothing more. Modelling uncertainty would have considered using different modelling approaches.

Response: We agree with the reviewer and in response to this comment we have modified the sentence as follows: "… which allows disentangling the effect of the objective function-related uncertainty and temporal stability of model parameters."

3) p. 12396, l. 24-25: something is missing in this sentence.

Response: Corrected.

p. 12398, l. 18-20: I think that the authors are a bit too optimistic: the Austria climate is very humid, so I doubt that for example the results could be easily generalized for Australia:

Response: We agree with the reviewer and have revised the sentence as follows: "The assessment of uncertainties for winter and summer regimes allows to make generalisation for a similar spectrum of physiographic conditions around the world."

p. 12398, beginning of section 2.1: I am surprised that the authors state that low flow projections are typically performed by a delta change approach. Indeed, other downscaling approaches than the delta change can be used to provide future (or past) climate forcing to hydrological models. What is *truer is that usually the (low) flow projections are analysed by comparing future (low) flows to past (low) flows, as this article presents, and maybe the authors mean that.*

Response: We agree with the reviewer and in response to this comment (and comment of reviewer #2) we have changed the sentence as follows: "In this study, low-flow projections of future climate scenarios are analysed by comparing future to past flows by using a delta change approach."

p. 12400, l. 2: please remove "(3)". L. 17: "rainfall-runoff"

Response: In response to this comment we have corrected the numbering of Equations, as well as the term "rainfall-runoff".

l. 12401, equations 7 and 8: the epsilon term is missing see Pushpalatha et al. (2012).

Response: In our study, no zero flows were observed/simulated, so it was not necessary to set the epsilon term to a small value. We would therefore prefer to leave the equations as they are.

p. 12402, l. 17: is it really 1987-2008? or 1976-2008? (see p. 12404, l. 20) If 1987-2008, please comment the impact of comparing 30-year indices to 20-year indices.

Response: Corrected. In this study, we have compared 30-years periods.

p. 12407, l. 18: basinS

Response: Corrected.

p. 12408, l. 2: "SI variability has A large variability..". l. 8: "weightS"

Response: We have rephrased the sentence as suggested by the reviewer #2. ("The comparison of SI and Q95 uncertainties indicates that large SI variability does not systematically mean large variability in terms of Q95.")

p. 12409, l. 8: "a Q95". L.9-10: please refer to figure 10 here.

Response: Corrected and added a reference to Fig.10.

p. 12409, l. 21-22 and p. 12410, l. 13-14: the verb is misplaced

Response: Corrected.

p. 12416, l. 18: November is misspelled

Response: Corrected.

Table 1: A1B instead of A1B2 (see also Fig. 8). Also, for positive values, sometimes a plus is used, sometimes not. I would suggest homogenising the table.

Response: Corrected.

Figure 1 (and all other maps): what is this point outside of Austria south of Tyrol? In the caption: “Colour and symbol size (: : :) represent: : :” and “The SI and its strength ARE estimated”.

Response: Corrected.

Figure 4: rather than the difference, this graph represents the relative difference between sim and obs.

Response: It shows the relative difference for low-flow quantiles, but difference in days for seasonality index. We thus prefer to retain the caption as it is.

Figure 5: am I right if I say that the Q95 value is different for both curves? That should be specified.

Response: The difference is somewhat less than 8%. We have added this information to the figure caption, as requested by the reviewer.

Figure 7: please use the same panel titles as in Fig. 6.

Response: Corrected.

Figure 8: “Line represents” and “scatter (: : :) showS”.

Response: Corrected.

More generally, although I am not a native English speaker, I feel that regularly articles are missing in the text before nouns. I would suggest checking that.

Response: The English will be checked.

References:

Alfieri, L., Burek, P., Feyen, L., and Forzieri, G.: Global warming increases the frequency of river floods in Europe, Hydrol. Earth Syst. Sci., 19, 2247-2260, doi:10.5194/hess-19-2247-2015, 2015
Chiew, F. H. S., Zheng, H., and Vaze, J.: Implication of calibration period on modelling climate change impact on future runoff, Proc. IAHS, 371, 3-6, doi:10.5194/piahs-371-3-2015, 2015

Coron L., Andréassian V., Perrin C., Lerat J., Vaze J., Bourqui M., Hendrickx F. Crash testing hydrological models in contrasted climate conditions: An experiment on 216 Australian catchments (2012) Water Resources Research, 48 (5)

Milano, M., E. Reynard, N. Bosshard, R. Weingartner, Simulating future trends in hydrological regimes in Western Switzerland, Journal of Hydrology: Regional Studies, Volume 4, Part B, September 2015, Pages 748-761, ISSN 2214-5818, http://dx.doi.org/10.1016/j.ejrh.2015.10.010.

Thirel, G., Andréassian, V., and Perrin, C., 2015. On the need to test hydrological models under changing conditions. Editorial to the Special issue of Hydrological Sciences Journal, 60 (7–8). doi:10.1080/02626667.2015.1050027

Thorne, R.: Uncertainty in the impacts of projected climate change on the hydrology of a subarctic environment: Liard River Basin, Hydrol. Earth Syst. Sci., 15, 1483-1492, doi:10.5194/hess-15-1483-2011, 2011

Vidal, J.-P., Hingray, B., Magand, C., Sauquet, E., and Ducharne, A.: Hierarchy of climate and hydrological uncertainties in transient low flow projections, Hydrol. Earth Syst. Sci. Discuss., 12, 12649-12701, doi:10.5194/hessd-12-12649-2015, 2015.

Reviewer#2

We would like to thank the reviewer for his/her positive and very thorough comments on the manuscript. Below is our response to the issues raised in the review (printed in italics).

General

This paper aims at assessing the contribution of different sources of uncertainties associated with the low-flow projections by 2050 in 262 basins in Austria. The different sources of uncertainties explored are related to the calibration of one hydrological model, TUWmodel, and four future climate scenarios. The impact of the objective function selected on the calibrated parameters as well as their temporal stability are investigated by using 11 objective functions and 3 contrasted periods.

This paper is interesting as it addresses a few aspects that are often missing in studies about impacts of climate change on hydrology: - Low flow projections are of great importance for water management and I agree with the authors that analysis should not only focused on mean flow or hydrological regime as it is often done. - Role of calibration strongly questions the relevance of extrapolating hydrological models in climate change and it is often neglected.

For at least these two reasons, this article is worth to be published. Moreover, the important number of basins considered with contrasted hydrometeorological conditions allows to carry out robust statistical analysis. Eventually, this paper show great technical skills: figures and legends are well designed, and illustrate well the authors' statements.

However, I think that some corrections should be made before publication. I have some concerns about some points of the method, especially concerning the concept of uncertainty, and I think that the readability of the text could be improved.

Response: Thank you for these positive comments.

To my point of view, the main difficulty of this paper is to understand what the authors mean by uncertainty. First of all, a few definitions of uncertainty is used through the text which do not help the reader to follow the authors' statement. It sometimes refers to the range of relative differences between simulated and observed Q95 or SI (e.g. figures 6 or 7), but other times it refers to the range of relative differences (%) between simulated Q95 or SI between the future and reference period (e.g. figures 11 or 12). As the main goal of this article is to assess the uncertainty contribution to low flow projections, I think that uncertainty should only be used for the former definition. In this paper, a little discussion about the concept of uncertainty could also be added a: only a limited part of uncertainty is here explored as only one hydrological model, one method of climate downscaling (especially because other methods of downscaling are now more precise and more widely used than the delta approach, e.g. statistical downscaling methods, Boé et al., 2006 ; Mezghani and Hingray, 2009 ; Chauveau et al., 2013) and four future climate scenarios are used.

Response: The idea of the paper is to compare the ranges of low-flow indices obtained for two cases. One is the model calibration in the reference period, where we tried to assess the variability (range) obtained from different calibration settings (i.e. objective function and decade). The second is the range obtained for future low flow projections, which is affected by different calibration setting as well as by selected climate scenario. But we agree with the reviewer that using "uncertainty " for both cases might be confusing for the readers, so we have tried to revise the formulations and to use the uncertainty only in connection with future low flow projections (i.e. simulations for the future period). In response to this comment we have also made numerous revisions (including the new ANOVA analysis and corresponding extensions in the Introduction, Methods, Results and Discussion sections), which – we believe – improve the readability of the manuscript.

Eventually, I am not comfortable with the method used to assign uncertainty contributions, the ratios method neglects the interactions between the different sources of uncertainty and is not very rigorous. At least, classical ANOVA (von Storch and Zwiers, 1999, chap. 9 ; Yip et al., 2011 ; Sansom et al., 2013) could be used, but to be more rigorous, adapted ANOVA designed especially for this kind of studies are highly recommended (Hingray and Said, 2014 ; Lafaysse et al., 2014 ; Vidal et al, 2015).

Response: In response to this comment, we have extended the manuscript and quantitatively assessed the relative contribution of the three components: climate scenario, calibration decade and calibration objective function to the overall uncertainty of low-flow projections. We have revised/extended the introduction, methods, results and discussion sections accordingly.

The selection of future climate scenarios, although this selection is justified by literature references, is small and unbalanced and this should be added in the conclusion as a limit of this study. In general, I think that conclusions should be moderated or limits of the study should be more explicit. I am not sure the conclusions can all be generalized as it is done presently.

Response: We agree with the reviewer. In order to more clearly moderate the limits of our results, we have revised the discussion section.

The readability of the paper could be improved by deleting some heavy formulations or some redundant parts (parts of the legend are often included in the text). The use of percentage points when differences of percentages are discussed could also really help the reader to get more easily into the results. The use of comparative formulation (less or more) should always be associated with a reference (than sthg).

Response: We have tried to improve the readability of the manuscript. For more details, please see the responses to minor remarks and response to the other reviewer.

Minor remarks

Abstract:

Page 12396, Line 7: "which allows disentangling the effect of model uncertainty and temporal stability of model parameters" I would not say the model uncertainty as different structures of model are not used and thus structural uncertainty is not investigated. However, all aspects of uncertainty related to calibration are explored a: the impact of the criteria selected and the temporal stability of parameters. Therefore, I would suggest something like: "which allows exploring all aspects of uncertainty related to calibration: choice of objective function and temporal stability of model parameters." or "which allows disentangling the impact of simulation scoring and temporal stability of model parameters." Or taking again the sentence page 12402, line 19 : "which allows exploring *the relative contribution of the impact of model calibration (i.e. time stability and objective function selection) and of future climate scenarios."*

Response: In response to this comment and also comment of reviewer #1, we have revised the sentence as follows: “which allows disentangling the effect of the objective function-related uncertainty and temporal stability of model parameters.”

P. 12396, L. 25: I think that "and" has been added by mistake. "In basins with summer low flows and, the total uncertainty is mostly less than 20 %"

Response: Corrected.

P. 12396, L. 25 "While the calibration uncertainty dominates over climate projection uncertainty in terms of low flow magnitudes, the opposite is the case for low flow seasonality." This refers to Fig. 13, I would moderate this statement as the method used is not very robust or I would use one of the method mentioned above.

Response: In response to this comment, we have rephrased the sentence as follows: “While the objective function-related uncertainty dominates over climate projection uncertainty in terms of low-flow magnitudes, the opposite is the case for low-flow seasonality.”

Introduction :

The last paragraph is very well written and clearly defines the objectives and methods of this paper.

Response: Thank you.

Methodology :

2.1 Low flow projections In this paragraph, I would start with the general descriptors of low flow as it is used all along the text, and end with the projections (from the general to the specific).

Response: We agree with the reviewer that there are always different options how to structure the text, however, in this case we like the current structure and prefer to retain the low flow projection part as it is.

P.12398, L.23 Delta change approach: I think that this approach should be criticized in the discussion especially regarding internal variability of climate. I would also delete "typically" as this approach has been criticized and new downscaling technics are now more widely used.

Response: In response to this comment (and comment of reviewer #1), we have rephrased the sentence as follows: “In this study, low-flow projections of future climate scenarios are analysed by comparing future to past flows by using a delta change approach.”

P. 12399, L.5. "The differences between simulations of a hydrological model in the reference and future periods are the used ..."

Response: Corrected.

P. 12399, L.8 could be deleted as it is already said, and the paragraph could directly start from "The future low flow changes...".

Response: Corrected as suggested by the reviewer.

P. 12400, L. 11 : The formulation is a bit heavy, it is obvious that an hydrological model is used, so it could be reduced as follow : "The SI index is estimated for observed and simulated low flows"

Response: Corrected as suggested by the reviewer.

P. 12400, L. 12 : agreement between singular and plural "The differences between model simulations (i.e. Q95 and SI estimates) in the reference and future periods are then used to quantify potential impacts of climate change on low flows."

Response: Corrected.

2.2 Hydrological model

P. 12401, L. 1 : ": : : potential evapotranspiration data: : :"

Response: Corrected.

P.12401 L.3 : I would suggest to add how many parameters are calibrated to have an idea of the degrees of freedom, and especially because some parameters are further mentioned (P.12406 L.3). This very brief description of parameters could be added as a table or a scheme of the TUWmodel, without having to read the reference papers mentioned.

Response: In response to this comment, we have added requested table with brief description of model parameters.

2.3 Uncertainty estimation

P12402, L.3 : comas missing "The uncertainty, defined as the range of low flow projections, is evaluated for two contributions."

Response: Corrected.

P12402, L.7 : "The effect of objective functions ..."

Response: Corrected.

Data

P. 12402, L.24 : conditions that are reflected in different hydrological regimes. "Austria represents diverse climate and physiographic conditions of Central Europe, which are reflected in different hydrological regimes..."

Response: Corrected.

P. 12403, L.14 : As Austria is a land surface, I would rather talk about evapotranspiration than evaporation. ": : : when evapotranspiration exceeds precipitation..."

Response: Corrected.

P. 12403, L. 18 : I am not confortable with the units. I would rather described precipitation in mm/day or kg/m2/s or even mm/yr as it is done in Figure 2.

Response: This unit represents a specific discharge (a typical hydrologic characteristics), which allows to compare basins with different sizes. It is estimated directly from measured discharge (m3/s). We thus preferred not to change the units.

P. 12403, L. 27-29 : The two sentences "The thin lines...winter low flows. The thick lines: : :. selected decades." should be part of the legend and not in the text, and thus should be deleted. When legends are put into the text, it makes the text heavy and the reader confuse. I think that messages are thus not clear enough.

Response: We have removed the two sentences from the text, as suggested by the reviewer.

P. 12403, L. 29 : I would add in brackets, and adverb before verb "The two groups of basins (winter vs. summer low flow regimes) clearly differ..."

Response: We have modified the sentence as suggested by the reviewer.

P. 12404, L. 10-17 : I am not sure it is worthy to describe the different GHG scenarios especially because the results are here examined by 2050, and A2 and A1B do not differ before 2050. Moreover, I am not quite confortable with the justification of the "best performing ones". First, how are the performances assessed ? Second, how do you know that the best performing ones in present would perform the best in future? It can also mean that they are similar so that it reduces the range of possible future climates: : :.? Anyway, I understand that the authors had to make a choice and the justification given in the discussion. P. 12412 from line 7 to line 13 seems to me a better one, and should either be added here or just kept in the conclusion.

Response: We agree with the reviewer that the formulation was not very clear. In response to this comment, we have thus removed the following sentence: “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.” We prefer to retain both parts (a brief description of the scenarios in the Data section, as well as in the Discussion).

Results :

4.1 Low flow simulations in the reference period

This paragraph deals with "uncertainties" related to calibration.

Response: In response to this comment we have extended the title of section(s) 4.1. (and 4.2) to:

4.1 Low-flow simulations and uncertainty in the reference period (4.2 Low-flow projections and uncertainty in the future period).

P. 12405, L.8 : "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 modelling of rainfall-runoff process than in basins with rainfall dominated runoff regime.". An adjective is missing in the last part of the sentence, starting from which, and could you be more explicite, I do not understand why would it be easier? Please rephrase.

Response: The typical snow regime has a relatively simple runoff regime – i.e. minimum runoff during snow accumulation period (which typically lasts from October/November to March) followed by a snowmelt period with large runoff volumes. The runoff generation processes are more linear, the effects of evapotranspiration and soil processes are less important, so easier to model than in rainfall dominated basins. We prefer to retain this part as it is.

P.12405, L.11 : zQ = wQ ME+ (1-wQ) Melog "ZQ increases with decreasing weight wQ, which indicates that the runoff model performance tends to be better for low and high flows (i.e. model has larger runoff efficiency if it is calibrated to logarithmic transformed flows than to non-transformed flows only." I do not agree with this sentence, it seems right but it implies that you can directly compare both efficiencies ME and MElog which is not true. Same values of ME and MElog do not mean the same. You should add a likely somewhere in the sentence because it could only be a mathematical artifact of ZQ.

Response: In response to this comment we have added “likely” to the sentence as suggested by the reviewer: “… runoff model performance likely tends to be better…”.

P. 12405, L.23-25 : To be deleted, part of the legend "The top panels show the Q95 difference estimated from simulated and observed daily flows in the period 1976-2008. This means that t The model calibrated for 11 year period: : :."

Response: We have revised the section as suggested by the reviewer.

P. 12406, L.10 : fit instead of fits "The simulated Q95 in basins with winter low flows fits closer to the observed estimates."

Response: Corrected.

P. 12406, L. 15 : "Overall, the results are similar for large range of wQ." I would delete it, (heavy formulation), with the previous sentence and the following one, the reader understands.

Response: Deleted as suggested by the reviewer.

P. 12406, L. 20 : an article is missing, "this hydrological model tends to..."

Response: Corrected.

P. 12407, L. 1-5 : "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 simulated one 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 runoff generation)." Besides the heavy formulation of this sentence, I don't understand this sentence : the observed low-flow period is interrupted but in brackets, I understand that this is the simulated low-flow period that is interrupted because the soil storage absorbes the precipitation event: : :.?

Response: In response to this comment we have rephrased the sentence as follows: "In some cases there is also a difference in the length of observed and simulated low-flow periods. Some small rainfall-runoff events in the summer or autumn cause an interruption of the observed low-flow periods, but the model simulates a complete absorption of the precipitation event by the soil storage and hence a longer low-flow period."

P.12407, L.8-13 : Part of the legend that should be deleted from the text "Left panels show: : :-1998-2008)."

Response: For clarity we prefer to leave the more detailed description of the figure layout as it is.

P.12407, L.17 : ": : : the differences are larger in basins with the summer low flows..."

Response: Corrected.

P.12407, L.18 : "For particular basins, ..."

Response: Corrected

P. 12407, L.24 : Part of the legend that should be deleted from the text "Figure 7 shows, similarly as Fig. 6, ...calibration variants."

Response: Deleted as suggested by the reviewer.

P. 12407, L.26 : ": : : basins with the winter low-flow regime...than the basins with the summer low-flow regime."

Response: Corrected.

P. 12408, L.1 : The sentence is complicated and, if my understanding is right, I would replace it by : "The comparison of SI and Q95 uncertainties indicate that large SI variability does not systematically mean large variability in terms of Q95."

Response: Thank you. We have rephrased the sentence as suggested by the reviewer.

P. 12408, L.9-11 : Part of the legend that should be deleted from the text. "The line (median) and : : : low-flow regime."

Response: Deleted as suggested by the reviewer.

P. 12408, L. 21 : I am not completely convinced as this is not true for ECHAM5-A1B2 and A2 for wQ=1.

Response: This sentence refer to Fig.8, which shows that selected scenarios for basins with winter low-flow regime (blue colour) project an increase of Q95 (for all weights) and for basins with summer low-flow regime tend to project no change or small decrease in Q95. In response to this comment we have completed the sentence as follows: "The comparison of different scenarios indicates that they are similar in terms of projecting an increase of winter low flows and a tendency for no change or decreasing Q95 ..."

P. 12408, L. 26 : repetition : last part of the sentence is already written in the previous sentence. "The change in low-flow seasonality (Fig. 8, bottom panel) is less pronounced. And i not sensitive to wQ." And the change in low-flow seasonality is less pronounced than what?

Response: Changed as suggested by the reviewer.

P.12409, L. 1 : This point is quite interesting. Do you have notice anything on the parameters ? With the increase of temperature, one process could be not dominant anymore, such as snow processes. The model would thus be less sensitive to the change of one or a few parameters than in the reference period. Do you think it could be a possible explanation?

Response: Yes, we agree with the reviewer that it might be a possible explanation.

P. 12409, L. 6 : "mostly"?

Response: Yes, in some basins the change is larger, but most of the basins have this category (class) of change.

P. 12409, L. 7 : "AIT HADCM3 A1B", AIT has never been mentioned before.

Response: Deleted.

P. 12409, L. 8 : ": : : an increase of Q95..."

Response: Corrected as suggested by the reviewer.

P. 12409, L. 16 : "These Ffigures..."

Response: Corrected.

P. 12409, L.27-29 : Part of the legend.

Response: For the clarity, we would prefer not to remove this description from the text.

P. 12410, L.10 : It sounds in good agreement with P. 12409, L.18, the responses of Q95 to climate scenarios are larger for basin with winter low flows.

Response: Thank you.

Discussion and conclusions

The first paragraph (L. 18-24) of this conclusion is very well written.

Response: Thank you.

P. 12411, L.8-10: "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%." I think that this result is important and I am convinced that uncertainty due to hydrological modeling is very often underestimated but I don't think this conclusion can be generalized in this article considering the selection of future climate scenarios, the use of only one downscaling method and the use of only one hydrological model. For instance, snow processes may be more related to the structure of the model and since only one model is used here, this uncertainty may be under estimated. Using two snow model schemes such as one using a degree-day scheme and another more physically-based would probably change the results. Eventually, I would use "from different climate scenarios" instead of "different emission scenarios", as the results are analyzed by 2050.

Response: Yes, we agree with the reviewer. In response to this comment, we have changed the “emission scenarios “ with “climate scenarios” as suggested by the reviewer.

P. 12412, L. 2: Because the word uncertainty is sometimes not properly used, the following sentence seems to be in contradiction with P. 12411, L.17 "Our results show that 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." ("Our results indicate that the calibration runoff efficiency is larger (than what?), and the uncertainty lower in basins with winter low-flow regime.")

Response: In response to this comment we have rephrased the sentences as follows: “Our results indicate that the calibration runoff efficiency in basins with winter low-flow regime is larger, and varies between basins less than in basins with summer low-flow regime.”…” Our results show that the impact of the objective function is larger for the future projections of low-flow quantiles in basins with winter low-flow regime and for the reference simulations of low-flow seasonality in basins with summer low-flow regime.”

P. 12412, L. 20-23: "The comparison of climate scenario and model calibration uncertainties indicates that the model calibration uncertainty dominates in the estimation of low flow magnitude (in the reference period), and the uncertainty in low-flow seasonality is larger in future climate scenarios...". This formulation is a bit clumsy, I would replace it by : "The comparison of climate scenario and model calibration uncertainties indicates that model calibration uncertainties dominate in the estimation of low flow magnitude, while the future climate scenarios dominates in low-flow seasonality."

Response: Thank you, we have replaced the sentence as suggested by the reviewer.

Table

What are WEGC, ZAMG, AIT, ZAMG? I am sure it is not very important, but as it is written, it should be mentioned. What is the difference between A1B2 and A1B?

Response: We have added the explanation of the abbreviations to the Table 2.

Figures

They are all well designed. I especially appreciate backgrounds of Fig. 6, 7, 9, 10, 11, 12, 13. It is clever and it enables the reader to identify very quickly if there is spatial patterns or not.

Response: Thank you.

Figure 2. I am wondering if summer and winter low flows would not be interesting to show, such as annual minimal runoff or maybe a descriptor of low flow more relevant, because everything is explained in terms of percentage in this article. I am curious about the absolute value of these minima.

Response: We prefer not to extend the figure, as the absolute values of the low flow quantiles are already published in some previous papers (see e.g. Laaha, Bloschl, 2006 or 2007).

Figure 5. Could you enlarge this figure?

Response: We believe that the size of the figure will be changed during the typesetting of the manuscript.

Response to editor:

We would like to thank the editor for his positive and very thorough evaluation of the manuscript. Below is our response to the issues raised in his evaluation (printed in italics).

Dear authors,

Thank you for providing some responses to the referees' comments.

You will find below some comments on the above as well as some additional comments. Both referees found this study quite valuable as I do. However, in general, I find that some interesting referee comments called for either much deeper responses that you provided, or simply actual responses to some parts of the comments. I will highlight them below, and I would really appreciate motivated and extended responses, that would then be transferred into the revised manuscript.

On responses to referee #1

- I would agree with referee #1 that even if I have no doubt about the novelty of this study, it should be clearly demonstrated in the introduction through a thorough comparison of literature review (including the references suggested by the referees).

As we already indicates in the response to comment #2, as well as to the comments related to new ANOVA analyses, we have extended the introduction and discussion section according to this suggestion. In this extension we particularly refer to studies related to quantification of the sources of the overall uncertainty of streamflow projections (e.g. Storch and Zwiers, 1999, Bosshard et al. (2013), Storch and Zwiers, 1999, Coron et al., 2012, Bosshard et al. (2013), Hingray and Said (2014), Chiew et al., 2015, Vidal et al., 2015). For more details please see the revised manuscript. Our idea is to keep the introduction consistent and related to the main objectives of the study (i.e. uncertainty of low flow projections) and prefer not to extend the introduction to topics only generally related to the assessment of climate change impacts (E.g. projected changes in flood hazard as in Alfiere et al., 2015, climate change effects on the Arctic sea-ice cover and subarctic nival regime as in Thorne 2011, assessment of potential hydrologic regime changes in specific small regions as in Milano, 2015, or downscaling of climate projections). The reviewer #1 cites some of such specific studies in the general part of the review, but some of these studies go, in our opinion, beyond the main scope of our paper.

- The comment on the use of single hydrological model would in opinion call for some insights from the authors. Indeed, a calibration is highly dependent on the model structure, and some conclusions even from the reference period may not hold with a different model. This has also been pointed out by referee #2. I would therefore appreciate some more comment on that in the revised manuscript.

As we already indicated, we agree that the results are to some extent model dependent. It is indeed difficult to speculate to what extent The applied hydrologic model represents on one hand a "typical" and widely used conceptual modelling scheme, which is widely applied in Austria (e.g. for climate change assessment, or river flow forecasting) but also worldwide. We thus believe that the results can be transferred also to similar geographical regions. On the other hand, the parametrization and temporal stability of model parameters might be different in different models, however we do not have comparable results for other models, so we prefer not to speculate. In order to highlight this question, we have extended the discussion and call for some future analyses which will evaluate this question.

- The first part of the comment on the uncertainty analysis asks a specific question on the effect of different sample sizes on the robustness of the chosen dispersion indicator, which has not been responded. This question also holds for any anova method, so I would appreciate some comments on that.

In order to complement our previous response we adding following. The ANOVA is a method which can deal with different sample sizes and yields an unbiased estimator of effects given a representative sample. Robustness of individual tests increases with degrees of freedom but it is common to apply ANOVA also to small sample sizes. Here the estimation of the mean effects are clearly more robust than F-tests of effect size. Our focus is on effect sizes, and the variance decomposition as it is used in a statistical ANOVA framework is well suited.

- "delta change approach": I believe there is here some confusion on these terms between the referee and the authors. As mentioned by the referee, the delta change approach refers to a method of obtaining future climate forcings for impact studies, which consists in (1) computing climatological differences between a future time slice and a present-day time slice of a given projection (initially from a GCM run, possibly downscaled), and (2) applying such "deltas" to observed climate time series. This is different from analysing impact changes given such forcings, changes which are commonly examined with reference to values simulated during the present-day period, independently of the method used for obtaining future climate forcings. This confusion is also present in the manuscript: no clear distinction is for example made between the two steps, as noted by referee #2 (comment starting with "2.1 low flow projections"). I would therefore strongly encourage the authors to try and remove any possible confusion, to adopt widely accepted expressions, and possibly restructure the data and methods sections.

Thank you for the comment. It is true that in the first version of the manuscript, we used the term "delta change" also in a more general sense – i.e. also in the context of low flow changes. In the revision, we tried to remove such cases. Please see the:

Section 2.1: "In this study, low-flow projections of future climate scenarios are analysed by comparing future to past flows by using model forcing from a delta change approach".

or

Section 2.3: "The delta change approach is used to derive model forcing for selected future period and simulated future river flows are compared to model simulations in the reference period 1976-2008. The relative changes of .."

Moreover, there are important details missing in the way such "deltas" are applied to observed time series. The main question is: how are monthly precipitation changes applied to observed daily time series? Are all positive values scaled? Is the number of rainy days increased? Any hybrid solution? The delta change method originates from times (a decade ago) when downscaled projections were scarce and transient GCM projections rarely available. As mentioned by both referees, studies have since *shown that this approach is not entirely satisfying, mainly because it does not take account of changes in interannual variability (which has recently been pointed out as the main source of uncertainty in near-term projections for global variables, up to mid-term or even long-term projections for more local hydrological variables), and because choices like the one mentioned before have non-negligible consequences on hydrological impacts. It is especially the case for summer low flows that are quite sensitive to rainfall occurrence. In conclusion, this would require some serious discussion, and more than a rephrasing.*

The idea was to use a classical delta change approach, without a hybrid solution. Such approach was used in the assessment of climate changes in Austria and different national projects, so in order to be consistent and comparable with such results we did not invent and tested any new approach for the corrections of model inputs. We have added relative monthly changes of precipitation and scaled the daily precipitation values accordingly. We did not change the number of rainy days. We agree that such approach is not entirely satisfying. And agree also with the consequences mentioned in the comment. The question of how to solve/account for the differences of GCM or RCM simulations in the reference period and the observations is still a challenge and certainly an interesting topic, but goes beyond the scope of this paper. We have tried to use some bias correction methods in the past, but their validation in the reference period did not bring satisfactory results. The main objective of the paper was indeed to investigate the range/uncertainty of low flow indices for the given methods, not to present the most accurate projections of low flows in the future. We thus prefer not to extensively discuss this topic in the manuscript.

In order to provide more details to the delta change description part, we have added following sentences: "The daily precipitation is scaled by the relative monthly delta changes, with no change in the frequency of rainy days. The daily air temperature is changed by the absolute value of monthly delta changes."

- Referee #1 asked about the nature of a point located outside of Austria in all maps, and this did not prompt any response from your side. Please do comment.

In our response we state it is corrected. The position of the point was wrong due to a type in the coordinates used for the plot (it did not affect the analyses or other results, just their visualisation). We revised the coordinates and replotted all the figures accordingly.

- The comment of referee #1 on the possible difference in Q95 values in Figure 5 makes me wonder how Q95 values are actually computed (I believe independently for each period present/future). This is not clearly stated in the manuscript, please confirm.

Yes, as it is already indicated in the manuscript, we have used lfstat lackage in R and estimated Q95 independently for reference and future periods. We have revised the methods accordingly (please see the end of section 2.1)

On responses to referee #2

- On the definition of uncertainty: I agree with referee #2 that the manuscript is somewhat confusing on this point. Once again (after my initial comments to the authors on the initial version of the manuscript), I urge the authors to use widely accepted expressions.

In response to referee #2 we have indicated numerous revisions made, which include new ANOVA analyses of uncertainty and corresponding extensions in the Introduction, Methods, Results and Discussion sections, the reformulation of term uncertainty only in connection with future low flow projections. We will be happy to make some additional changes if more specifics will be given, but believe that the current revisions already improved the manuscript.

- I appreciate the efforts of the authors to engage in a more formal analysis of variance following the recommendations of referee #2.

We are also very grateful and appreciate this suggestion as it allowed to improve the manuscript.

- On the choice of climate projections: in addition to the referee's comments, I would add that some discussion is required on the unbalanced sample of projections with respect to the emissions scenarios, even if only to state that their effect is nearly equivalent for such close time horizons.

In order to this comment, we have further extended the discussion section as follows:

"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 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. Although this ensemble of four scenario runs seems rather small, the selection accomplished by the reclip:century consortium was not arbitrary, but based quantitative metrics. Prein et al. (2011) investigated the performance of all GCMs in CMIP3 for Central Europe based on a performance index including various parameters. They found that for the given domain the ECHAM5 and the HADCM3 showed highest scores, which justified the selection of these GCMs for driving the RCM. In addition, these two models show different climate sensitivity, where the warming over the course of the 21st century is lower in ECHAM5 and higher in HADCM3. This feature in combination with the utilization of three different scenarios for ECHAM5 provides broad ensemble bounds, although the climate change signal of the different scenarios for the given investigation period (2021-2050) is rather similar, particularly for temperature (cf. Table 1). The projected future decrease of Q95 is most pronounced in the AIT_HADCM3_A1B run, particularly in basins with summer low flow regime in the low 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."

- Delta change approach: again, the response made to this comment is in my opinion unconvincing and too cosmetic (see my discussion above).

Please see our response above (Response to comment "*Moreover, there are important details missing in the way such "deltas" are applied to observed time .."*)

- Discharge unit: the sentence is actually confusing, because it includes "precipitation". Additionally and anecdotally, the lower bound of specific discharge cannot be technically zero if we believe your statement that no zero value was found when computing MlogE.

In order to clarify this sentence we have revised the sentence as follows: "The largest values occur in the Alps, with typical values ranging …". We also corrected the minimum value to 0.02 l/s/km2 to avoid anecdotal interpretations.

- GHG scenarios: you do not happen to have responded to the first part of the comment on the relevance to describe GHG scenarios. See also my comment above.

The rationale to describe and use different scenarios is to make the paper consistent with companion paper in HESS (Laaha et al.) which compares selected scenarios also for time horizon 2080. We believe that the short description of scenarios (with added justification of selection) is not affecting the main message of the paper, so we prefer to retain this part as it is.

- P12405L8: I believe the confusion may arise here for improper uses of comparatives (as noted by referee #2), as in many other places in the manuscript.

In response to this comment we have revised the sentence as follows:

"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 to model rainfall–runoff process easier than in basins with rainfall-dominated runoff regime."

- P12405L11: Here again, this referee comment is in my opinion quite relevant and at least calls for some discussion on a potential artefact when comparing ME and MlogE. Please provide some comments.

In fact we agree with the referee that the formulation was not very precise. We have revised the sentence as suggested by the referee and removed also the problematic part to avoid speculations. This action was not clearly formulated in our response as well. We agree that it would be interesting to look on the possible connection between the two parts of the objective function in the future, but believe it goes beyond the main focus of our manuscript. We thus prefer not to extend the discussion part with respect to this comment.

- P12408L21: Again I feel that some confusion arises from the intermittent use of "low flow" throughout the manuscript to actually mean "Q95". I therefore again encourage the authors to be more rigorous with the terms used throughout the manuscript.

We have tried to be more rigorous throughout the manuscript, and made couple of changes of the terminology (low flow to Q95 or vice versa).

- P12409L1: This is again a quite light response to a yet quite interesting comment. Please provide some more depth to your response.

The key point here is probably the large difference in the reference period. The main reason for this is the difference (day occurrence) between observed and simulated discharges during the periods of low flows. As it is indicated in Figure 5, even if the Q95 quantiles are similar, the days when these discharges occur are different. This makes a large difference in the estimation of the seasonality between observed and simulated discharges in the reference period. The difference obtained by changing model inputs in the future periods (by using delta change approach) is much smaller as it refers only to some changes in model inputs, which are likely often less sensitive as it is already pointed out by the referee.

- P12411L8-10: Again, I can't see in your text any response on the first part of the comment relative to the use of a single hydrological model and the generalization of the results. Please provide some actual comments and relevant changes to the manuscript.

Please see our response to the comment related to the use of single hydrological model (above). It is clear that the results are to some extent related to the selected hydrologic model, climate scenarios, objective function etc. It is indeed difficult to quantify the extent the results can be generalised. So in response to this comment, we have extended the discussion part, where we call for such follow up studies, which can be focused on further evaluations.

- P12412L2: I am afraid I don't understand the proposed revised sentence.

In response to this comment we have tried to simplify and rephrase the sentences as follows: "Our results indicate that the calibration runoff efficiency in basins with winter low-flow regime is larger (more accurate), and varies between basins less than in basins with summer low-flow regime."…" Our results show that the impact of the objective function is larger for SI estimation in basins with summer regime in the reference period and for future projections of Q95 in basins with winter regime."

Additional comments

- Figure 1: As only 2 classes of catchments are considered throughout the manuscript, this figure should rather identify these instead of continuous (and not quite adapted: early January and March have much more similar colours than November and January) seasonality strength.

We have changed the figure according to this suggestion.

As a conclusion, I believe the manuscript has solid scientific contents and brings novelty to the field. I therefore recommend the authors to take account of all referee comments as well as my own ones to revise the manuscript.

Best regards.

Manuscript with marked changes:

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 quantified by different parameterizations of a conceptual semi-distributed hydrologic model (TUWmodel) using 11 objective functions in three different decades (1976-86, 1987-97, 1998-08), which allows disentangling the effect of the objective function-related 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 range of simulated Q_{95} in the reference period 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 of Q_{95} 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 climate change projected for future period 2021-50 relative the reference period 1978-2007. 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. The total uncertainty of Q_{95} projections is the largest in basins with winter low-flow regime and, in some basins it exceeds 60%. In basins with summer low flows, the total uncertainty is mostly less than 20%. The ANOVA assessment of the relative contribution of the three main variance components (i.e. climate scenario, decade used for model calibration and calibration variant representing different objective function) to the low-flow projection uncertainty shows that in basins with summer low-flows the climate scenarios contribute more than 75% to the total projection uncertainty. In basins with winter regime, the median contribution of climate scenario, decade and objective function is 29%, 13% and 13%. While the

objective function-related 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 applications, 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 typically simulated by hydrologic models of various complexity. There is an increasing number of studies evaluating different sources of uncertainty in river flow projections resulting from different GCMs, downscaling methods or hydrologic model parametrization (e.g. Dobler et al., 2012, Finger et al., 2012, Coron et al., 2012, Addor et al., 2014, Chiew et al., 2015). 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 quantification of the relative contribution of different sources to the overall uncertainty of stream flow projections is recently evaluated by using analyses of variance (ANOVA) (Storch and

Zwiers, 1999). Bosshard et al. (2013) synthetized previous studies that investigate hydrological climate-impact projections and their sensitivity to different uncertainty sources. They propose an ANOVA framework to separate the uncertainty from climate models, statistical post-processing (bias correction and delta change approach) and hydrological models. Addor et al. (2014) use the ANOVA framework to quantify the uncertainty of stream flow projections resulting from the combination of emission scenarios, regional climate models, post-processing methods, and hydrological models of different complexity. They report that the main source of uncertainty stems from the climate models and natural climate variability, and the impact of emission scenario increases with increasing future time horizon of climate projections. Hingray and Said (2014) propose a quasi-ergodic two-way ANOVA framework for the partitioning of the total uncertainty of climate projections. This framework is recently tested for the estimation of climate and hydrological uncertainties of transient low flow projections in two basins in the southern French Alps (Vidal et al., 2015). The results show that a large part of the total uncertainty arises from the hydrological modelling and it can be even larger than the contribution from the GCMs.

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 in Austria. Here, the uncertainty and variability of low-flow projections 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 similar spectrum of physiographic conditions around the world.

2 Methodology

2.1 Low-flow projections

In this study, low-flow projections of future climate scenarios are analysed by comparing future to past flows by using model forcing from a delta change approach. This concept allows to remove biases resulted from simulations 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 and used for simulating future hydrologic changes. The daily precipitation is scaled by the relative monthly delta changes, with no change in the frequency of rainy days. The daily air temperature is changed by the absolute value of monthly delta changes. The differences between daily 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.

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 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. *Dj* represents a cyclic variable. Its directional angle, in radians, is given by:

$$\theta_j = \frac{D_j \cdot 2\pi}{365} \tag{1}$$

The arithmetic mean of Cartesian coordinates x_θ and y_θ of a total of *n* single days *j* is defined as:

$$x_\theta = \frac{1}{n}\sum_j \cos(\theta_j) \tag{2}$$

$$y_\theta = \frac{1}{n}\sum_j \sin(\theta_j)$$

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

$$\theta = \arctan\left(\frac{y_\theta}{x_\theta}\right) \qquad \text{1st and 4th quadrant: } x>0 \tag{3}$$

$$\theta = \arctan\left(\frac{y_\theta}{x_\theta}\right) + \pi \qquad \text{2nd and 3rd quadrant: } x<0 \tag{4}$$

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

$$SI = \theta \cdot \frac{365}{2\pi} \tag{5}$$

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):

$$r = \sqrt{\bar{x}^2 + \bar{y}^2} / n \tag{6}$$

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 and simulated low flows. The differences 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 independently for the reference and future periods by the lfstat package in R software (Kofler and Laaha, 2014).

2.2 Hydrologic model

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 evapotranspiration data as an input. The model consists of three modules which allow simulating changes in snow, soil storages and groundwater storages. The calibrated model parameters are presented in Table 1. 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_E^{log}. 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

$$Z_Q = w_Q \cdot M_E + (1 - w_Q) \cdot M_E^{\log} \qquad (7)$$

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

$$M_E = 1 - \frac{\sum_{i=1}^{n} \left(Q_{obs,i} - Q_{sim,i}\right)^2}{\sum_{i=1}^{n} \left(Q_{obs,i} - \overline{Q_{obs}}\right)^2} \qquad (8)$$

$$M_E^{\log} = 1 - \frac{\sum_{i=1}^{n} \left(\log(Q_{obs,i}) - \log(Q_{sim,i})\right)^2}{\sum_{i=1}^{n} \left(\log(Q_{obs,i}) - \overline{\log(Q_{obs}}\right)^2} \qquad (9)$$

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

2.3 Uncertainty estimation

The uncertainty, defined as the range of simulated low-flow indices, 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 functions used for the TUWmodel calibration is evaluated by comparing 11 variants of weights (w_Q) used in Z_Q. Following w_Q 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_{95} and *SI* estimation in the reference and future periods.

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 to derive model forcing for selected future period and simulated future river flows are compared to model simulations in the reference period 1976-2008. The relative 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 of the impact of model calibration (i.e. time stability and objective function selection) and climate scenario is evaluated seasonally at the regional scale.

The uncertainty of low flow projections is then compared to the range of low-flow indices obtained by different calibration variants in the reference period. In addition, the total uncertainty of future low flow projections is decomposed to individual components by means of analysis of variance (ANOVA; e.g. Hingray and Said, 2014; Lafaysse et al., 2014; Vidal et al, 2015; and von Storch and Zwiers, 1999, chap. 9 for a general introduction to ANOVA). The 3-way ANOVA approach is employed to decompose total uncertainty of the projected low-flow changes into three main variance components. These variance components represent uncertainty contributions of 3 main effects: climate scenario (factor A with $I = 4$ levels), decade used for model calibration (factor B with $J = 3$, levels) and calibration variant representing different objective functions (factor C with $K = 11$ levels). The ANOVA model is defined as follows:

$$\Delta Q95_{ijk} = \mu + \alpha_i + \beta_j + \gamma_k + \epsilon_{ijk} \quad (10)$$

In this linear equation (Eq.10), $\Delta Q95_{ijk}$ denotes the ensemble projected changes in Q_{95} for the future horizon at a gauge. It is modelled by a global mean μ and the mean effects (deviations of factor-means from the global mean) of climate scenario ($\alpha_i\ ; i = 1, \dots, I$), decade ($\beta_j\ ; j = 1, \dots, J$), and calibration variant ($\gamma_k\ ;\ k = 1, \dots, K$), and ϵ_{ijk} are the residual errors of the model. In an ANOVA framework, the total variability of $\Delta Q95_{ijk}$ is characterised by the total sum of squares SS_T, and is decomposed into additive variance components of individual effects:

$$S_T = SS_A + SS_B + SS_C + SS_E \quad (11)$$

The variance components of the main effects A, B, C are computed as follows:

$$SS_A = JK \sum_{i=1}^{I} (\bar{y}_{i..} - \bar{y}_{...})^2 \quad (12)$$

$$SS_B = IK \sum_{j=1}^{J} (\bar{y}_{.j.} - \bar{y}_{...})^2 \quad (13)$$

$$SS_C = IJ \sum_{k=1}^{K} (\bar{y}_{..k} - \bar{y}_{...})^2 \quad (14)$$

The variance component of the residuals representing the unexplained variance is:

$$SS_e = \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k=1}^{K} \left(y_{ijk} - \bar{y}_{i..} - \bar{y}_{.j.} - \bar{y}_{..k} + \bar{y}_{...}\right)^2 \quad (15)$$

Based on the SS_e,, an estimate of the variance contributions of each effect A,B,C is computed as:

$$\eta_A^2 = \frac{SS_A}{SS_T}\ ;\ \eta_B^2 = \frac{SS_B}{SS_T}\ ;\ \eta_C^2 = \frac{SS_C}{SS_T}\ ;\ \eta_e^2 = \frac{SS_e}{SS_T} \quad (16)$$

The measure eta-square is also termed the coefficient of determination R^2 (Von Storch and Zwiers, 1999). Eta-square tends to overestimate the variance explained by one factor and is therefore a biased estimate of the effect size. A less biased estimator is given by the measure ω^2:

$$\omega_A^2 = \frac{SS_A - df_A * MS_e}{SS_T + MS_e} \quad (17)$$

where df_A denotes the degrees of freedom of a factor (e.g. for factor A with I levels, $df_A = I - 1$), and $MS_e = SS_E/df_e$ is the residual mean square error. The quantity MS_e denotes the mean residual sum of squares. It is computed by

$$MS_e = SS_e/df_e \qquad (18)$$

The measure omega-square is also termed the adjusted R², in analogy to the adjusted coefficient of determination of multiple regression. Note that the degrees of freedom of the error term df_e depend on the total number of effects in the ANOVA design. For 3-way ANOVA without interactions df_e is obtained by:

$$df_e = df_T - df_A - df_B - df_C = IJK - I - J - K + 2 \qquad (19)$$

Clearly, the adjustment of effect size increases if the residual degrees of freedom are small, what is the case when overall sample size is small. Hence the difference between both measures of effect size will be negligible for designs with large df_e, as it is the case for our study. In our assessment, we will therefore only present ω^2 which is the more general measure of effect size at each catchment. A spatial synthesis of uncertainty contributions for summer and winter dominated basins is finally obtained from the distribution of variance components across basins falling into each low-flow regime group.

3 Data

Study region is Austria (Fig.1). Austria represents diverse climate and physiographic conditions of Central Europe, which are reflected in different hydrologic regimes (Gaál et al., 2012). The topography varies from 115 m a.s.l. in the lowlands to more than 3700 m a.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°C to 10°C. The mean annual precipitation ranges from 550mm/year in the Danube lowlands, to more than 3000mm/year 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. Fig.1 shows two main low-flow regimes in Austria. While orange and red colours indicate 130 stations with dominant summer (June-November) low-flow occurrence, blue colour indicates 132 gauges with winter (December-May) 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 evapotranspiration exceeds precipitation. The different low-flow 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 Alps, with typical values ranging from 6 to 20 l s^{-1} km^{-2}. The lowest values occur in the east ranging from 0.02 to 8 l s^{-1} km^{-2}, although the spatial pattern is much more intricate.

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 calibration and as a reference for future change simulations. Fig. 2 shows basin averages of mean annual air temperature, precipitation and runoff in the period 1976-2008. The two groups of basins (winter vs. summer low flow regimes) clearly differ 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 precipitation 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, 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).

Table 2 summarizes the annual and seasonal differences (delta changes) of mean basin precipitation and air temperature between the future (2021-2050) and reference (1978-2007) periods. Table 2 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 and uncertainty in the reference period

The runoff model efficiency (Z_Q) in the three calibration periods obtained for different variants of the objective function is presented in Fig. 3. The results show that Z_Q is larger and thus runoff simulations are more accurate in basins with winter (blue colour) 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 to model rainfall–runoff process easier than in basins with rainfall-dominated runoff regime.. Z_Q increases with decreasing weight w_Q, which indicates that the runoff model performance likely tends to be better for low than high flows. 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 regime is the largest in the period 1976-1986. While the Z_Q for basins with winter low regime is very similar in all three calibration periods, the Z_Q has an increasing tendency in basins with summer regime. For example, the median of Z_Q for w_Q=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., 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 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 fit 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 calibration variant w_Q=1 that tends to underestimate Q_{95}. 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 this 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 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 observed and simulated low-flow periods. Some small rainfall-runoff events in the summer or autumn cause an interruption of the observed low-flow periods, but the model simulates a complete absorption of the precipitation event by the soil storage and hence a longer low-flow period.

The spatial pattern of the variability of Q_{95} estimation in the reference period 1976-2008 is presented in Fig. 6. Fig. 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 (1976-86, 1987-97, 1998-08). 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 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 summer low flows, particularly for variants calibrated in the period 1976-1986.

For particular basins, 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 variability in terms of low-flow seasonality is presented in Fig. 7. The results clearly indicate that basins with winter low-flow regime (i.e. situated in the Alps) vary significantly less for different calibration settings than the basins with 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} ranges indicates that large *SI* variability does not systematically mean 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 projections and uncertainty in the future period

Low-flow projections for selected climate scenarios and different calibration weights w_Q are presented in Fig. 8. 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 calibration 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%). Fig. 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 they are similar in terms of projecting an increase of winter low flows and a tendency for no change or decreasing low flows 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. 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 significantly 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 - -20%. The most spatially different projection is provided by the HADCM3 A1B climate scenario which simulates the strongest gradient between an increase of Q_{95} 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 (Fig. 10). As already indicated in Fig. 8, the shift in seasonality is larger than one month only in a few basins.

Figure 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 Fig. 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 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. The change is less than 20% in most of the basins. 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 range of low-flow indices simulated 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 basins, however, it is larger than five months. The ratio between the range of projections to the range of calibration differences (bottom panels in Fig. 13 and Fig. 14) indicates that only in 15% of the cases the climate projection uncertainty of Q_{95} is larger than the range obtained in the calibration period. Most of these basins are situated in the mountains (mean basin elevation above 1000m a.s.l.) and have winter low-flow regime. The range of calibrated Q_{95} 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. The *SI* projection uncertainty is only in 15% of the basins lower than the *SI* range obtained in the calibration period. The *SI* uncertainty ratio tends to be lower with increasing mean basin elevation and the basin area, but there is no apparent relationship with the aridity of the basins.

The relative contribution of the three main variance components (i.e. climate scenario, decade used for model calibration and calibration variant representing different objective function) to the overall uncertainty of future low-flow projections is evaluated in Fig. 15. Left and right panels show the distribution of ANOVA variance components for basins with winter (left panel) and summer (right panel) low-flow regime, respectively. The results indicate that the variability from climate scenarios has a dominant contribution to the overall projection uncertainty in basins with summer low-flow regime. While in basins with winter low-flows the median contribution of the three variance components is 29% (climate scenario), 13% (calibration decade) and 13% (objective function), in basins with summer low-flow regime is the median contribution from climate scenario larger than 76%.

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 considerably 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 and 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 climate scenarios is larger than 40% in many basins, the range of low-flow indices 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 analyzed 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 in basins with winter low-flow regime is larger (more accurate), and varies between basins less than in basins with summer 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 different 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 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 *SI* estimation in basins with summer regime in the reference period and for future projections of Q_{95} in basins with winter regime. 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 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. Although this ensemble of four scenario runs seems rather small, the selection accomplished by the reclip:century consortium was not arbitrary, but based quantitative metrics. Prein et al. (2011) investigated the performance of all GCMs in CMIP3 for Central Europe based on a performance index including various parameters. They found that for the given domain the ECHAM5 and the HADCM3 showed highest scores, which justified the selection of these GCMs for driving the RCM. In addition, these two models show different climate sensitivity, where the warming over the course of the 21st century is lower in ECHAM5 and higher in HADCM3. This feature in combination with the utilization of three different scenarios for ECHAM5 provides broad ensemble bounds, although the climate change signal of the different scenarios for the given investigation period (2021-2050) is rather similar, particularly for temperature (cf. Table 1). 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 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 the ranges of low-flow indices projected for different climate scenarios and simulated by different calibration settings (i.e. objective function and calibration decade) in the reference period indicates that the variability of low-flow magnitudes is larger for simulations in the reference period, while the range of seasonality is larger for future projections. Even if the variability and uncertainty of GCM and emission scenarios can be large, the results clearly indicate the importance of selecting objective functions in hydrologic model calibration for simulating low-flow projections.

In our study, we use a 3-way ANOVA approach to decompose the contribution of climate scenarios and hydrologic model settings to the total uncertainty of low-flow projections. While previous studies (e.g. Hingray and Said 2014; Lafaysse et al., 2014, Vidal et al, 2015) assessed the variance components of a temporal change from the multi-member ensemble runs in individual basins, in our study, we lumped the temporal change to one time slice (future horizon) and assessed the variance components in a spatial context of 262 basins. The spatial synthesis of the uncertainty contribution is evaluated for two groups of basins, representing to main (summer and winter) low-flow regimes in Austria. We found that the relative contribution of three variance components - climate scenarios, calibration decade and calibration objective function differs for basins with different low-flow regimes. The uncertainty from climate scenarios dominates in basins with summer low flows, however in basins with winter low flows is the relative contribution from hydrological modelling significantly larger. This is consistent with previous studies that show a substantial uncertainty contribution of hydrological models in basins dominated by snow and ice melt (Addor et al.,2014, Vidal et al., 2015).

The assessment in Austria enabled us to account for one conceptual hydrologic model and 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), their combinations linked with changes in land use and management at the wider, European scale, as well as to account for hydrologic models of different complexity, wider range of climate scenarios and different downscaling techniques. 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 (BGBl 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. TUWmodel parameters. Calibration range is given for parameters calibrated by an automatic routine. Parameters with fixed value are not calibrated.

Model parameter	Definition	Model component	Calibration range
SCF	Snow correction factor (dimensionless)	Snow	1.0-1.5
DDF	Degree-day factor (mm/°C day)	Snow	0.0-5.0
T_R	Threshold temperature for rain (°C)	Snow	2.0
T_S	Threshold temperature for snow (°C)	Snow	0.0
T_M	Melt temperature (°C)	Snow	-1.0-3.0
LP/FC	Ratio of limit for potential evapotranspiration and FC (dimensionless)	Soil	0.0-1.0
FC	Maximum soil moisture storage (mm)	Soil	0.0-600.0
BETA	Nonlinearity parameter of runoff generation (dimensionless)	Soil	0.0-20.0
K_0	Storage coefficient of additional outlet (days)	Runoff	0.0-2.0
K_1	Fast storage coefficient (days)	Runoff	2.0-30.0
K_2	Slow storage coefficient (days)	Runoff	30.0-250.
C_P	Percolation rate (mm/d)	Runoff	0.0-8.0
C_R	Free routing coefficient (days^2/mm)	Runoff	25.0
LS_{UZ}	Storage capacity threshold (mm)	Runoff	1.0-100.0
Bmax	Routing parameter (days)	Runoff	10.0

Table 2. 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 brackets are the median and range (min/max) of differences between the future (2021-2050) and reference (1978-2007) periods in 262 basins. Winter and summer seasons are defined as December-May and June-November, respectively.

Delta change	WEGC* ECHAM5 A1B	ZAMG** ECHAM5 A2	AIT*** HADCM3 A1B	ZAMG ECHAM5 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)

*WEGC= Wegener Center for Climate and Global Change

**ZAMG= Zentralanstalt für Meteorologie und Geodynamik

***AIT= Austrian Institute of Technology

Figure captions:

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

Figure 2. Mean annual air temperature (MAT, top), precipitation (MAP, middle) and runoff (MAR, bottom) for basins with summer (yellow/red) and winter (blue) low-flow minima (Fig.1). Thin lines represent the median of mean annual values of MAT, MAP and MAR. Thick lines indicate the average for each of the three periods: 1976-86, 1987-97 and 1998-08. Scatter (i.e. 75% and 25%- percentiles) indicates the variability between the basins.

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 4. Difference between simulated and observed low-flow characteristics (top panels low-flow quantile Q_{95}, bottom panels seasonality index *SI*) for different calibration variants (w_Q) and calibration periods. Lines represent the median, scatter (i.e. 75%-25% percentiles) show the variability over basins with dominant winter (blue) and summer (orange) low flow regime. The differences are estimated between model simulations and observations in the entire reference period 1976-2008.

Figure 5. Comparison of observed (blue) and simulated (red) flow for Hoheneich/Braunaubach, 291.5 km^2). 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. The relative difference between Q_{95} estimated from simulated and observed flows is 8%.

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 represents the medians, scatter (i.e. 75%-25% percentiles) shows 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 indicate future changes 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. 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. 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 and reference 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 and reference 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 and reference 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.

Figure 15. Relative contribution of the three variance components (i.e. climate scenario, calibration decade and objective function) to the overall uncertainty of future low flow projection in basins with winter (left panel) and summer (right panel) low-flow regime. The boxes and whiskers show 25%- and 75%- percentiles and 5%- and 95%- percentiles of the uncertainty contributions in 130 (summer low-flow regime) and 132 (winter low-flow regime) basins, respectively.