Anonymous Referee #1

General comments

This manuscript summarizes research to assess the major sources of uncertainty in projections of future streamflow conditions in the au Saumon River in southern Quebec, Canada. The authors try to determine the uncertainty associated with model structure relative to that associated with variability in climate change model forcing data. It is an interesting question, one that has not necessarily been explicitly answered for many watersheds, particularly in Canada. The authors conclude that much of the uncertainty could be attributed to selection of some aspects of hydrological model structure, and not variability in climate model output. This is a notable result that would be a useful contribution to the literature. However, I found the manuscript lacking in several aspects that need to be addressed. These specifically include how the authors define, describe and discuss the categories of uncertainty. Furthermore, the manuscript has contradictory explanations of how the uncertainty associated with climate change was assessed, so the reader is left without a clear answer of the relative uncertainty from different sources. The introduction, in particular, does not include explanations of the sources of uncertainty as strong as those in Section 3.2.1, much to the detriment of the manuscript.

We thank Anonymous Referee #1 for his constructive comments on our manuscript and work.

We provide in the following detailed answers to his comments, taking into account their added value to the manuscript.

Efforts were made to better define the categories of uncertainties and how we evaluate them in current and climate change contexts. Modifications mostly concern the introduction, uncertainty assessment, as well as discussion and conclusion.

Specific comments

Page 14191 Line 20: The choice of words throughout the manuscript meant I remained unsure of what the authors meant by “natural variability” and how its impact on uncertainty was assessed. Did the authors consider natural variability to be the variability among the output from the several GCM members under different runs with different initial conditions? I don’t consider that “natural variability”, I consider that bias or inaccuracy associated with boundary conditions placed upon the model. I suppose that means I disagree with Kay et al (2006) in how they address natural variability and assess change. Either way, the manuscript would benefit greatly from clearer definitions and more in-depth discussion of the levels and types of uncertainty.

The ‘natural climate variability’ referred to “unforced variability internal to the simulated climate system”, as for example in Deser et al., 2012. We changed several elements of the manuscript to better define and exploit this concept.

Main changes page 5 lines 13 to 21:

> "In this work, PET formulations, snow modules, and lumped hydrological structures are compared under climate change, along with the natural variability of the simulated climate system. This later concept is illustrated here with a climatic ensemble based on five members with slightly different initial conditions, such as in Deser et al. (2012), where the natural climate variability refers to the "unforced variability internal to the real or simulated climate system" as evaluated with 40 members. Climate simulation ensembles allow the analysis of their internal variability (which is mainly a demonstration of natural variability) and can be seen as the irreducible fraction of climate simulations uncertainty (Kay et al., 2009, Velázquez et al., 2013), a part of the "unknowable" knowledge stated above."

In several parts of the manuscript, "natural variability" has been modified to "natural internal variability of simulated climate system" to specify the analysis and refer to its definition.

Added reference:

> Deser, C., Knutti, R., Solomon, S. and Phillips, A. S.: Communication of the role of natural variability in future North American climate, Nat. Clim. Chang., 2(October), 775–780, doi:10.1038/NCLIMATE1562, 2012.

Page 14192 Line 18: Is "global" uncertainty meant to mean overall/total, or global vs.local?

In this manuscript, global uncertainty always refers to "overall/total uncertainty". Changes have been made accordingly.

Page 14193 Line 8: It is unclear what is meant by "under climate change". This, along with the phrase "natural variability" makes it difficult to assess exactly what sources of uncertainty are being evaluated. Maybe be very explicit with the definitions of the uncertainty categories.

We clarified this expression all over the manuscript.

Changes page 5 lines 13 to 14:

> "In this work, PET formulations, snow modules, and lumped hydrological structures are compared, along with the natural variability of the simulated climate system."

I've never felt that summary paragraphs like that at the end of the introduction are necessary, but that is just me.

Removed paragraph:

> "Section 2 outlines the methodology, the *au Saumon* catchment, the data, as well as the modeling tools. Section 3 presents and details the results, followed by conclusions and discussion in the section 4."

Page 14195 Line 18: Should read "This procedure assumes that these corrections..."

“hypothesizes” changed to “assumes”.

Section 2.5: The content here needs to be elaborated upon as this seems to describe how the relative degrees of uncertainty were evaluated among all the different sources. The manuscript should include much more detail of this key methodological information. For instance, it is confusing that the difference in the REF and FUT time series is used to highlight the uncertainty associated with climate change, but this is different than evaluating the effects of initial conditions on GCM output, which is how descriptions of the evaluation of the uncertainty associated with climate change are explained earlier in the manuscript.

We have modified the manuscript according to this comment.

Page 11 lines 23 to 24 and page 12 lines 1 to 25:

> “After the appraisal of the calibration performance on the Nash-Sutcliffe efficiency, to illustrate the effects of modeling tools selection on the calibration process, an uncertainty assessment is performed mainly based on these simulated and projected hydrographs and resulting hydrological indicators (overall mean flow, OMF).
>
> Cumulative streamflow uncertainty is evaluated first, representing the total uncertainty including hydrological models, PET formulations, snow modules, and climatic members. This step is performed on the CAL period where the measured discharges are available and then on REF and FUT periods to illustrate if this uncertainty varies with the simulated or projected period with climatic inputs.
>
> More, on the CAL period, it may be helpful to explore the reliability of the quantiles’ envelopes, empirically drawn from the 3360 simulations, to comment if the latter can be directly interpreted as confidence intervals. The concept of a confidence interval reliability diagram consists in verifying if the observed relative frequency correspond to the simulated one – perfect reliability would result in a 1:1 slope on the diagram (Wilks, 1995). Several confidence intervals are thus plotted (from 0.1 to 0.9) with, for example, 0.5 corresponding to the quartiles spread (25 % to 75 %) and 0.9 corresponding to the spread of the 5 % to 95 % quantiles. Thus, for each of the 3360 simulations and each confidence interval, statement if observed discharge is included or not is verified, resulting in a reliability graph (Boucher et al., 2009; Velázquez et al., 2010).
>
> Streamflow uncertainty is then evaluated for each modeling process (i.e. hydrological, PET, snow, natural climatic variability) based on hydrological indicators, namely the overall mean flow (OMF), corresponding to averaged daily flow for the entire simulation period. A process-based streamflow uncertainty is then available, allowing comments about its extent on the observation period and about its change from REF to FUT periods.

All these steps highlight the influences of climate change on water resources, but mostly evaluate the uncertainty in our diagnosis, related to hydrological modeling and natural internal variability of simulated climate system."

Section 3.2.1 Paragraph 3: Some of this should be in the methods section. The manuscript would benefit from an explanation of how the authors used the confidence intervals to definitively determine if there has been a change in streamflow.

We have changed manuscript to include this comment.

Page 12 lines 8 to 17:

"More, on the CAL period, it may be helpful to explore the reliability of the quantiles' envelopes, empirically drawn from the 3360 simulations, to comment if the latter can be directly interpreted as confidence intervals. The concept of a confidence interval reliability diagram consists in verifying if the observed relative frequency correspond to the simulated one – perfect reliability would result in a 1:1 slope on the diagram (Wilks, 1995). Several confidence intervals are thus plotted (from 0.1 to 0.9) with, for example, 0.5 corresponding to the quartiles spread (25 % to 75 %) and 0.9 corresponding to the spread of the 5 % to 95 % quantiles. Thus, for each of the 3360 simulations and each confidence interval, statement if observed discharge is included or not is verified, resulting in a reliability graph (Boucher et al., 2009; Velázquez et al., 2010)."

Page 14 lines 8 to 13:

"As mentioned in the material and methods section, exploration of the reliability of the quantiles' envelopes, empirically drawn from the 3360 simulations, aims at commenting if the latter can be directly interpreted as confidence intervals. For this purpose, a confidence interval reliability diagram is computed for the au Saumon catchment. Results in Figure 5 reveal a slight under-dispersion, confirming a possible link between the envelopes drawn in Figure 4 and confidence intervals."

Figures 7 and 8: Only a suggestion, would overlapping these hydrographs within one figure better illustrate the changes?

Figure 8 (now figure 7) draws the REF simulation in the background. However, we opt keeping Figure 7 (now Figure 6) as it is, for REF.

Page 14203 Line 15: What is meant by overall mean flow? Is this mean annual flow or the average flow for the entire simulation period.

Overall mean flow (OMF), corresponds to the averaged daily flow for the entire simulation period.

Page 12 lines 18 to 21:

"Streamflow uncertainty is then evaluated for each modeling process (i.e. hydrological, PET, snow, natural climatic variability) based on hydrological indicators, namely the overall mean flow (OMF), corresponding to averaged daily flow for the entire simulation period."

Page 14205 Line 28: How could the methods as described definitively determine how various hydrological processes are responsible for the observed uncertainty? The authors have not provided any data or information to support this statement.

We think that the slightly modified section 3.3.2. and modifications all along the manuscript, about categories of uncertainties and how they are evaluated, clearly support this statement, as well as Fig.10 (now Fig.9) and Table 4 (now Table 5).

Technical corrections

Page 14190 Line 10: I do not understand what the authors mean by "Uncertainties are commented on the observation period and on simulated and projected climates." Maybe say "Uncertainty in simulated streamflow under current and projected climates is assessed."?

We have rephrased the sentence.

Page 1 lines 21 to 22:

"Uncertainty in simulated streamflow under current and projected climates is assessed."

The English grammar and language often seems out of sorts. Another example from the abstract is the second last sentence. It ends with "... propagating this uncertainty on reference and future projection(s), while climatic members add over it." Perhaps the authors could say the "with wide variability in projected future climates further increasing uncertainty". This is an example of a pervasive problem throughout the manuscript that could be addressed with a thorough proof read.

We have rephrased the sentence.

Page 1 lines 26 to 27 and page 2 lines 1 to 2:

"The analysis also illustrates that the streamflow simulation over the current climate period is already conditioned by tools' selection. This uncertainty is propagated to reference simulations and future projections, amplified by climatic members."

We have also modified other elements of the manuscript to address this comment further.

Page 14191 Line 3: Should read "Quantifying the uncertainties associated with the modelling..."

We have rephrased the sentence.

Page 3 lines 9 to 11:

> "Quantifying the uncertainties associated with the modeling of climate change impacts asks for a consistent and documented approach, reflecting the state of the scientific knowledge (Kiparsky and Gleick, 2004; Dettinger, 2005; Maurer, 2007)."

Page 14192 Line 3: Should read "...offer a simple means for unravelling..."

We have rephrased the sentence.

Page 4 lines 7 to 9:

> "Intercomparison studies offer a simple way of unravelling uncertainties associated to the many hydrological structures and concepts."

Page 14192 Line 18: Should read "However, scant research addresses..." Similarly, at the beginning of Section 2.3.1.

We have rephrased the sentence.

Page 4 lines 24 to 25:

> "However, scant research addresses this question even if the diversity of PET formulations and concepts is compatible for intercomparison."

Page 14193 Line 4: Could read "... but the literature targeting snow melt estimates in climate change model projections..."

Here we pointed out that no references are available for uncertainties assessment associated to lumped snow modules applied for future hydrological projections. We only know about few papers targeting lumped snow melt modeling on current period with hydrological modeling purpose. Because these works show large uncertainties on hydrological simulation, we expect that the variability remains at least identical for future projections.

Page 5 lines 8 to 12:

> "The authors are aware of no work addressing the hydrological projections uncertainty emanating from lumped snow modules, but the literature targeting snow melt modeling (e.g. WMO, 1986; Valéry, 2010, Franz et al., 2010) reported large uncertainties on the simulated discharge. It is thus expected that this variability remains at least as important under changing climate."

Page 14196 Line 19: Watch the verb tenses. "were tested"

We have rephrased the sentence.

Page 8 line 19:

> "Twenty conceptual lumped hydrological models (M01 to M20) were tested (see Table 1)."

Page 14202 Line 27: Do the authors mean to say the spring flood is arriving fifteen days earlier?

We have rephrased the sentence.

Page 15 lines 5 to 8:

> "Evolution from REF to FUT reveals a spring flood arriving fifteen days earlier, with a slight decrease in the spring high flows."

Page 14203 Line 20: Much of this detail belongs in the figure caption and not the text of the paper.

Captions for Figures 9 and 10 (now Figures 8 and 9) are changed.

Page 15 lines 24 to 27:

> "Figure 8 illustrates, by type of tools, the OMF uncertainty for simulations on the observation (calibration) period – 168 values per boxplot for the lumped conceptual hydrological models, 140 values per boxplot for the PET formulations, and 480 values per boxplot for the snow modules – while the OMF total uncertainty shows 3360 values."

Section 3.3.2: Much of the content in this section is constructed as a series of short paragraphs, but should be amalgamated into one or two larger paragraphs. A paragraph is meant to contain several thoughts that convey an idea. This section is constructed like a newspaper article.

We have changed this part based on reviewer's advices.

Page 17 lines 6 to 30 and page 18 lines 1 to 2:

> "The total OMF relative change fluctuates from -11 % to + 129 %, but its interquartile range is restrained from +4.2 % to +16.2 %, with a median value of +9.3 %. This total uncertainty is distributed between conceptual hydrological modeling tools (namely PET, hydrological models, and snow modules) and climatic members.
>
> The median OMF relative change per lumped conceptual model fluctuates from +6.3 % (M02) to +16.8 % (M08), confirming the sensitivity to the lumped conceptual model selection. The interquartile range is more uniform from one model to the other than in Figure 8, but M08 differs (18.1 %) in that regard – M08 was already identified with poor transposability on the same catchment by Seiller et al. (2012). The lowest inner sensitivity is achieved by M11 (10.9 %). PET OMF relative change is in general slightly higher than for the lumped conceptual models, from +4.1 % (E13) to +17.1 % (E21), stressing also the sensitivity to the selection of a PET formulation. The highest interquartile range is obtained by E21 (14.5 %), and the lowest by E02 (10.6 %). Again, the behaviour of the snow modules is more uniform than for the lumped conceptual models and for the PET formulations. The median OMF relative change of the snow modules are limited from +9.1 % (N2) to +9.9 % (N3), while their interquartile ranges vary from 12.5 % (N3) to 11.9% (N2).

On the other hand, the behaviour of the climatic members is quite distinct. First, the interquartile ranges of their OMF relative change are much reduced when compared to the others: from 4.8 % (C1) to 3.6% (C4), expressing lower inner sensitivity. Second, their median OMF relative changes vary considerably: between +2.7 % (C4) and +19.1 % (C3). This latter characteristic exemplifies the importance of the climatic natural variability. Changes differ greatly from one climatic member to the other. It is thus evident that a single 30-year realisation of the climate is insufficient to depict all the possible variability. Furthermore, it is also striking that an important part of the uncertainty spread revealed by the various hydrological processes actually originates from the climatic natural variability."

Page 14206 Line 3: Could be rephrased from "The importance..." to: "The example of this application to the au Saumon demonstrates the limit of our ability..."

We have rephrased the sentence.

Page 18 lines 3 to 6:

"The example of this application to the *au Saumon* catchment demonstrates the limit of our ability to provide a clear diagnosis of climate change impacts on water resources, especially when looking at the total OMF relative change, combining 16800 simulations and projections."

Page 14207 Line 4: Perhaps the authors should define the acronym behind the QBIC3 project.

This was added.

Page 19 lines 28 to 30:

"The authors acknowledge NSERC, Ouranos, and Hydro-Québec for support, as well as partners in the QBIC3 (Quebec-Bavaria International Collaboration on Climate Change) project."

Table 1: I am not sure "inspiration" or "inspired by" is the appropriate term. I would suggest "reference".

We use instead "Derived from" because some models are modified from their initial version to be adapted to lumped mode.

Figure 4: Again, no need for the word inspired. The terms PG and P2 need to be defined.

We use "Modified from" because this figure is not the initial one.

P_G is now defined.

Climate change impacts on the hydrologic regime of a Canadian river: Comparing uncertainties arising from climate natural variability and lumped hydrological model structures

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Abstract

Diagnosing the impacts of climate change on water resources is a difficult task pertaining to the uncertainties arising from the different modeling steps. Lumped hydrological model structures contribute to this uncertainty as well as the natural climate variability, illustrated by several members from the same Global Circulation Model. In this paper, the hydroclimatic modeling chain consist of twenty-four potential evapotranspiration formulations, twenty lumped conceptual hydrological models, and seven snowmelt modules. These structures are applied on a natural Canadian sub-catchment to address related uncertainties and compare them to the natural internal variability of simulated climate system as depicted by five climatic members. ~~Uncertainties are commented on the observation period and on simulated and projected climates~~Uncertainty in simulated streamflow under current and projected climates is assessed. They rely on interannual hydrographs and hydrological indicators analysis. Results show that the natural climate variability is the major source of uncertainty, followed by the potential evapotranspiration formulations and hydrological models. The selected snowmelt modules, however, do not contribute much to the uncertainty. The analysis also illustrates that the streamflow

simulation over the current climate period is already conditioned by tools' selection. This uncertainty is propagated to reference simulations and future projections, propagating this uncertainty on reference and future projection, while climatic members add over itamplified by climatic members. These findings demonstrate the importance of opting for several climatic members to encompass the important uncertainty related to the climate natural variability, but also of selecting multiple modeling tools to provide a trustworthy diagnosis of the impacts of climate change on water resources.

Keywords

Hydrological modeling, climate change, uncertainty, intercomparison, natural variability

1 Introduction

The modeling of climate change impacts on water resources remains a major challenge encompassing numerous uncertainties, from the definition of a greenhouse gas scenario to the calculation of the hydrological projection. Every modeling tool involved in this process can potentially affect our ability to render a precise diagnosis of the future.

Quantifying the uncertainties associated ~~to~~ with the modeling of climate change impacts asks for a consistent and documented approach, reflecting the state of the scientific knowledge (Kiparsky and Gleick, 2004; Dettinger, 2005; Maurer, 2007). These uncertainties may be separated into two components: "incomplete" knowledge, reflected by model conceptualization, and "unknowable" knowledge, related to human and climate system behaviors (Carter *et al*., 1999). Among the four levels of climate change impacts modeling uncertainties (Boé *et al.*, 2009), three are associated to future climate calculations (gas emissions scenarios, global climate modeling, and downscaling) and one, to hydrological modeling. Several studies addressed all of them (e.g. ~~Kay *et al.*, 2006;~~ Vicuna *et al.*, 2007; Minville *et al.*, 2008; Kay *et al.*, 2009; Boyer *et al.*, 2010; Görgen *et al.*, 2010; Teng *et al.*, 2012; Jung *et al.*, 2012) while others focused on specific ones (e.g. Ludwig *et al.*, 2009; Gardner, 2009; Poulin *et al.*, 2011; Bae *et al.*, 2011; Teng *et al.*, 2012; Velázquez *et al.*, 2013). However, all these works are based on ensemble intercomparison and advocate the necessity of assessing uncertainties before, for example, comparing river discharges over reference (REF) and future (FUT) periods.

For instance, Minville *et al.* (2008) found that GCMs initiate an important part of the uncertainty but so does, to a lesser extent, climate downscaling and hydrological modeling. Kay *et al.* (~~2006~~2009) arrived to similar conclusions. They compared six different sources of uncertainty: gas emissions scenarization, global climate modeling (GCM), climate downscaling, natural variability (which is disclosed calculating GCM runs from slightly modified initial conditions), and hydrological model structures and parameters. They found that all contribute to the ~~global~~ total uncertainty and that ~~the~~ GCMs are the most uncertain. ~~Minville *et al.* (2008) arrived to similar conclusions: GCM initiate an important part of the uncertainty but so does, to a lesser extent, climate downscaling and hydrological modeling.~~ For their part, Teng *et al.* (2012) exploited fifteen GCM and operated five hydrological model structures to show that the uncertainty deriving from the hydrological modeling should not be disregarded. Conclusions shared by Prudhomme *et al.* (2003), Vicuna *et al.* (2007), Boé *et al.* (2009), Quintana Seguí *et al.* (2010), and others.

Hydrologists continue improving their models, yet the role of the model structures in climate change impacts studies is still little known. Intercomparison studies offer a simple ~~mean~~ way ~~for~~ of unravelling uncertainties associated to the many hydrological structures and concepts. As an example, Ludwig *et al.* (2009) focused on uncertainties emanating from hydrological modeling, comparing structures of different complexity. They confirmed the importance of the climatic projection uncertainty (i.e. scenarios, GCM, downscaling) but also stressed that hydrological modeling tools must be carefully evaluated and that a coherent protocol must be developed. Poulin *et al.* (2011) identified equifinal parameter sets for two hydrological structures implemented on a Canadian catchment. They concluded that model structures and parameter identification are important sources of uncertainty under a changing climate. Velázquez *et al.* (2013) confirmed that the selection of a hydrological model affects climate change impacts conclusions, especially for low flows on two dissimilar catchments, in Germany and Canada.

Many hydrological models resort to a simplistic approach to simulate the actual evapotranspiration, namely to an agronomic concept called potential evapotranspiration (PET), representative of constant crop and soil conditions. PET formulations are largely influenced by a changing climate (changes in the evaporative demand) and are thus a supplemental source of uncertainty. However, scant research~~es~~ addresses this question even if the diversity of PET formulations and concepts is compatible for intercomparison. As an example, Kay and Davies (2008) found that Penman equation compared to a simple temperature-based formulation (Oudin *et al.*, 2005) in a climate change context with A2 scenario, both offer very different results for climate change impacts modeling on water resources for the 2071-2100 period. They advised that the choice of a PET formulation affects hydrological projections. Bae *et al.* (2011) evaluated uncertainties from hydrological models and PET formulations on a Korean catchment. They ~~confronted~~ compared three hydrological models, three PET formulations, and thirty-nine climate scenarios for the 2020 and 2080 horizons. Their results showed that hydrological modeling affects ~~global~~ total uncertainty, revealing the importance of the PET formulation and demonstrating the need to account for them in climate change impacts assessment projects. More, Bormann (2011) compared eighteen PET computations over six German meteorological stations and found a large sensitivity to climate.

The authors are aware of no work addressing the hydrological projections uncertainty emanating from lumped snow modules, but the literature targeting snow melt modeling (e.g. WMO, 1986; Valéry, 2010, Franz *et al.*, 2010) reported large uncertainties on the simulated discharge. It is thus expected that this variability remains at least as important under changing climate.

In this work, PET formulations, snow modules, and lumped hydrological structures are compared ~~under climate change~~, along with the natural variability of the simulated climate system. This later concept is illustrated here with a climatic ensemble based on five members with slightly different initial conditions, such as in Deser *et al.* (2012), where the natural climate variability refers to the “unforced variability internal to the real or simulated climate system” as evaluated with 40 members. Climate simulation ensembles allow the analysis of their ~~natural~~ internal variability (which is mainly a demonstration of natural variability) and can be seen as the irreducible fraction of climate simulations uncertainty (Kay *et al.*, 2009, Velázquez *et al.*, 2013), a part of the “unknowable” knowledge stated above. Climatic reference simulations (REF) and future projections (FUT) may then vary substantially from one member of the ensemble to the other. Indeed, the chaotic nature of the climate produces dissimilar time series when a GCM is initiated with slightly modified ~~initial~~ conditions, here in 1850. The natural climate uncertainty, described by equally valid climatic members (C1 to C5), will thus serve as benchmark for the other explored sources of uncertainty.

More specifically, this project ~~confronts~~ compares uncertainties related to the natural climate variability and to lumped hydrological model structures, in the context of climate change impacts on the hydrologic regime of a Canadian river. It will ~~confer~~ illustrate what is~~on~~ our ability to ~~render~~ produce a diagnosis of climate change impacts on the water resources of the *au Saumon* catchment.

~~Section 2 outlines the methodology, the *au Saumon* catchment, the data, as well as the modeling tools. Section 3 presents and details the results, followed by conclusions and discussion in the section 4.~~

2 Material and methods

2.1 The *au Saumon* catchment

The *Haut-Saint-François* catchment drains a 2940 km^2 territory located 120 km south of Quebec City and 200 km east of Montreal. It fosters three dams for flood control, environmental needs, recreational activities, and water consumption – the lower one is mostly dedicated to hydroelectric production. The natural *au Saumon* (SAU) sub-catchment, upstream the *Haut-Saint-François* River, receives waters from a 738 km^2 area along a south/south-east to north/north-west path. Figure 1 details this location and its geographic characteristics. The hydrographic network is dense and uniformly distributed, altitudes range from 277 m and 1092 m, land use is dominated by mixed coniferous/deciduous forests and agricultural lands, while the geology is dominated by limestone, sandstone, and shale. The hydrologic regime is characterized by an important spring freshet (from March to May) and high autumnal flows.

2.2 Hydrological, meteorological and climatic data

Hydrological and meteorological data are provided by the *Centre d'expertise hydrique du Québec*. Hydrometrical data correspond to daily discharges from the *au Saumon* gauging station (1975 to 2003). The annual mean discharge reaches 771 mm (approximately 18 m^3/s on an average day).

Meteorological observations consist in daily mean, minimum and maximum air temperatures (°C), daily total precipitation (mm), incoming solar radiation (W/m^2), relative humidity (%), and wind speed at 2 m (m/s). Radiation, humidity and wind speed measurements originate from the nearby Sherbrooke station, outside of the watershed. All data are spatially lumped over the catchment and extend from 1975 to 2003. Mean temperature attains 4.5 °C but only -11 °C in January. Precipitation is quite uniform over the year and averages 1284 mm, with 355 mm as solid precipitation. Maximal incoming solar radiation occurs in June (246 W/m^2) while the relative daily humidity fluctuates between 73% (April) and 85% (September). Average wind oscillates from 2 m/s (August) to 3.5 m/s (March).

Climatic data originated from the Canadian Global Climate Model (CGCM version 3 with a 3.75° resolution, Scinocca *et al.*, 2008), fed with SRES A2 scenario (Nakicenovic *et al.*, 2000). Data were dynamically downscaled by the Canadian Regional Climate Model (CRCM version 4.2.3, de Elía and Côté, 2010). The CRCM domain consisted of 111 x 87 grid points with a 45 km resolution (true at 60°N) centered on the Province of Quebec.

Downscaled climatic data were provided by Consortium Ouranos: reference simulations (REF) cover 1971 to 2000 while future projections (FUT), 2041 to 2070 (2050s horizon). The climate natural variability is depicted by five climatic members (C1 to C5) that were bias-corrected to reduce deviation between REF and observations on precipitation and temperature. Monthly correction factors were computed for each climatic member on the 30-years monthly average minimum and maximum temperatures and were applied on each member to preserve their respective variance. Precipitation was corrected using the LOCal Intensity (LOCI) scaling method (Schmidli *et al.*, 2006), adjusting mean monthly precipitation in terms of frequencies and intensity over 30 years. This procedure ~~hypothesizes~~ assumes that these corrections are maintained in future climate. Monthly average FUT temperature time series increase between 2 and 3 °C, without much variability between climatic members. Precipitation highlights a larger variability than temperature, from one climatic member to the other. Projected precipitation changes are substantial, increasing mostly from October to May and decreasing in summer. Incoming solar radiation slightly increases on FUT from June to August and relative humidity is mostly unchanged, with a small increase in March. Wind speed slightly increases in FUT (maximum + 0.8 m/s).

2.3 Hydroclimatic modeling chain

The main objective of this intercomparison consists in evaluating multiple representations of hydrological modeling behaviors, beyond the pre-supposed most appropriate model, because models are conceptualisations of real systems. It would then be possible to evaluate and quantify structural uncertainties in a climate change context. The issue is to select relevant hydrological modeling tools in terms of number, diversity and pertinence, since they must be hypothetically appropriate for simulating catchment flows and must be known for their performance.

2.3.1 Twenty lumped conceptual hydrological models

Researches led by Perrin *et al.* (2001, 2003) and by Mathevet (2005) provide a hefty source of information on lumped conceptual hydrological models. It concerns a large number of rainfall-runoff structures, tested on numerous watersheds, exploiting diverse rainfall-runoff transformation concepts and soil moisture accounting processes (e.g. linear, non-linear, multilayer, etc.). They are also designed to take into account many contributions to the total flow, based on storages (also called buckets) and interconnections, as well as flow routing delay (e.g. unit hydrogram, time laps, etc.). In some cases, when the sensitivity was considered small, their designers have fixed some of their parameters in order to favour the parsimony of the models, reducing computation time and equifinality issues. These models, or part of, were exploited by Velázquez *et al.* (2010) for exploring multimodel ensemble forecasting and by Seiller *et al.* (2012) for assessing the robustness of the ensemble under contrasted climate.

Twenty conceptual lumped hydrological models (M01 to M20) ~~are~~ were tested (see Table 1). They rely on four to ten free parameters and on two to seven storages – the number of storages correspond to the ones structuring the model and consequently they do not all participate directly to the routing. In the same way, it was recognised that interception function can be assimilated as a “surface storage”. Figure 2 illustrates the structural diversity of the selected models. It informs on their inputs and output, as well as on the different types of storages: surface, soil, root zone, groundwater, main routing, delayed routing, etc. All models were applied in exactly the same conditions and run at a daily time step.

2.3.2 Twenty-four potential evapotranspiration formulations

Oudin *et al.* (2005) and Xu and Singh (1997, 1998, 2000, 2001, 2002) provided a great source of inspiration for PET formulation selection. For instance, Oudin *et al.* (2005) implemented 27 PET formulations and four hydrological models on 308 catchments of diverse hydroclimatic conditions.

Twenty-four PET formulations (E01 to E24), adapted to our hydroclimatic context, were selected for this study. They are of three types: combinational (six), temperature-based (eight), and radiation-based (ten). ~~Figure 3~~Table 2 lists the formulas and related input data. Classification into families depends on the development philosophy more than their input data. For example, Priestley-Taylor formula (E04) is combinational even if wind speed is not explicitly used as an input, because it is a simplification of Penman formula (E01). On the opposite, Doorenbos-Pruitt formula (E20) is an adaptation of radiation-based formula E22 (Makkink), even if wind speed is used as an input data. All of them originate from various regional contexts and development objectives, but our selection aims to cover a large spectrum of concepts in order to favour diversity.

Empirical coefficients have been set for the *au Saumon* catchment, based on recent developments and applications. Shared parameters or variables have been computed based on EWRI-ASCE report recommendations (Allen *et al.*, 2005).

2.3.3 Seven snow modules

Valéry (2010) studied existing snow modules from a hydrological (streamflow) point of view, before proposing a novel one: CemaNeige. The latter originates from a comprehensive database composed of 380 watersheds exposed to diverse Nordic meteorological and geographical conditions in Sweden, France, Canada, and Switzerland.

Parsimony, performance and robustness were the main objectives of the CemaNeige development.

The degree-day based CemaNeige (Valéry, 2010; Nicolle *et al.*, 2011) relies on two free-parameters: K_f, the melting rate (mm/°C) and C_{Tg}, the snowpack thermal state coefficient (no unit), and on two state variables: G, the snowpack in mm and eTg, the snowpack thermal state in °C. CemaNeige exploits five altitudinal layers of equal area. Its precipitation partition, between solid and liquid, ~~alternates~~ can be computed by~~between~~ two different formulations, depending on the layer altitude. Liquid precipitation is directly by-passed to the hydrological model, whereas solid precipitation is cumulated in the snowpack G. The thermal state of the snowpack is calculated with air temperature and C_{Tg} coefficient. Melt depends on degree-day and is only activated when temperature is above the melt temperature (fixed at 0 °C) and depending on the K_f parameter. Effective melt (mm/day) is inputted to the hydrological model.

Valéry's thesis details the many concepts and structures considered during the development process of CemaNeige (N1). Inspired by a parsimonious bottom-up point of view, a concept or structure was only retained in CemaNeige if it substantially improved the hydrological performance over most of the 380 tested watersheds. It is thus opted in the present study to explore some of these rejected concepts, functions, and parameters in order to develop six alternative snow modules (N2 to N7) of various structural levels of complexity. Individual concepts (i.e. air temperature, melt temperature, precipitation separation, melting rate, melt weighting, altitudinal layering, thermal state, melt routing, precipitation correction, liquid water retention, and heat due to rain) were ~~confronted~~ compared in order to compile the six new versions (see Figure ~~4~~ 3 and Table ~~2~~3). Selection is a compromise between performance (close or above CemaNeige' ones for the *au Saumon* catchment) and internal diversity (snowpack, solid precipitations, thermal state, and effective melt).

2.4 Model calibration

Hydrological models calibration is achieved over the entire observed dataset (i.e. from 1975 to 2003) – differential split sample tests were performed in Seiller *et al.* (2012). It relies on the Shuffled Complex Evolution (SCE) algorithm (Duan and Gupta, 1992; Duan *et al*. 1994), a robust heuristic automatic optimisation tool (error minimisation) that is common in hydrological sciences and is known for its performance (e.g. Wang *et al.*, 2009). The SCE proceeds in five steps over the entire parametric space by generating an initial parameter population, ranking results, partitioning into complexes, evolving complexes, and recombining them until the convergence criteria is reached. Here, the objective function is the Nash-Sutcliffe efficiency (Nash and Sutcliffe, 1970) computed on root-squared discharges ($\mathrm{NSE}_{\mathrm{sqrt}}$):

$$\mathrm{NSE}_{\mathrm{sqrt}} = 1 - \frac{\sum_{i=1}^{N}\left(\sqrt{Q_{sim,i}} - \sqrt{Q_{obs,i}}\right)^2}{\sum_{i=1}^{N}\left(\sqrt{Q_{obs,i}} - \overline{\sqrt{Q_{obs}}}\right)^2} \quad (1)$$

with $Q_{obs,i}$ and $Q_{sim,i}$ respectively the observed and simulated discharges at time step i and N the total number of observations. Criteria on root-squared discharges are considered as multi-purpose, evaluating global deviation between observed and simulated discharges with a lesser emphasis on high flow discharges than the standard NSE on non-transformed discharges (Chiew and McMahon, 1994; Oudin *et al.*, 2006).

3360 calibrated parameter sets (i.e. one for each hydrological model/PET/snow module combination) are then available for reference simulations (REF, 1970-2000) and future projections (FUT, 2041-2070). Such methodology assumes that the parameter sets are compatible for current and future climatic conditions, addressing the issue of transposability. Transposability in time, on contrasted climatic conditions, is discussed for the same catchment and models in Seiller *et al.* (2012).

2.5 Uncertainty assessment of ~~Hydroclimatic~~ hydroclimatic simulations and projections

Current simulations (or calibration, CAL), reference simulations (REF) and future projections (FUT) consist in a large number of time series. They exploit the 3360 parameter sets, which lead to:

- 3360 simulations (20M x 24E x 7N) for the observed period

- 16800 simulations (20M x 24E x 7N x 5C) for the reference period
- 16800 projections (20M x 24E x 7Nx 5C) for the future period

Together, they form the basis of the present uncertainty assessment. After the appraisal of the calibration performance on the Nash-Sutcliffe efficiency, to illustrate the effects of modeling tools selection on the calibration process, an uncertainty assessment is performed mainly based on these simulated and projected hydrographs and resulting hydrological indicators (overall mean flow, OMF).

Cumulative streamflow uncertainty is evaluated first, representing the total uncertainty including hydrological models, PET formulations, snow modules, and climatic members. This step is performed on the CAL period where the measured discharges are available and then on REF and FUT periods to illustrate if this uncertainty varies with the simulated or projected period with climatic inputs.

More, on the CAL period, it may be helpful to explore the reliability of the quantiles' envelopes, empirically drawn from the 3360 simulations, to comment if the latter can be directly interpreted as confidence intervals. The concept of a confidence interval reliability diagram consists in verifying if the observed relative frequency correspond to the simulated one – perfect reliability would result in a 1:1 slope on the diagram (Wilks, 1995). Several confidence intervals are thus plotted (from 0.1 to 0.9) with, for example, 0.5 corresponding to the quartiles spread (25 % to 75 %) and 0.9 corresponding to the spread of the 5 % to 95 % quantiles. Thus, for each of the 3360 simulations and each confidence interval, statement if observed discharge is included or not is verified, resulting in a reliability graph (Boucher *et al.*, 2009; Velázquez *et al.*, 2010).

Streamflow uncertainty is then evaluated for each modeling process (i.e. hydrological, PET, snow, natural climatic variability) based on hydrological indicators, namely the overall mean flow (OMF), corresponding to averaged daily flow for the entire simulation period. A process-based streamflow uncertainty is then available, allowing comments about its extent on the observation period and about its change from REF to FUT periods.

All these steps Hydrographs and indicators (overall mean flow) on current period simulations (CAL) illustrate the uncertainty of the modeling process, whereas

~~comparison between reference (REF) and future (FUT) time series~~ highlight~~s~~ the influences of climate change on water resources, but mostly evaluate~~s~~ the uncertainty in our diagnosis, related to hydrological modeling and natural internal variability of simulated climate system.

3 Results

3.1 Calibration performance

Table ~~3~~ 4 ~~synthetizes~~ summarises the outcome of the calibration in terms of NSE_{sqrt} for each hydrological tool, providing median values and 5th and 95th percentiles (in brackets). The hydrological model section (M01 to M20) pools 168 values per model, the PET formulation section (E01 to E24) embeds 140 values per formulation, while the snow module section (N1 to N7) groups 480 values per module. The best performance is achieved by M05, with a median NSE_{sqrt} of 0.81, while M02 (0.56) and M13 (0.57) rank last. E12 (0.66) is the less efficient PET formulation while E23 (0.78) is prevalent. It should be highlighted that PET performance is less contrasted than for the hydrological models. Snow modules are quite uniform in terms of performance (0.75), except N7 that is lesser (0.71). The overall performance is quite satisfying and shows a great adequacy between the observed and simulated discharge on the *au Saumon* catchment.

3.2 Cumulative streamflow uncertainty

3.2.1 Observation simulation

Assessment of the observation total cumulative uncertainty illustrates the diversified response of our individual modeling tools on a period for which discharges are available. Initial modeling miscues may thus be identified and characterised, on an interannual average daily basis.

The cumulative uncertainty on the *au Saumon* catchment is illustrated in Figure ~~5~~4: the ~~dark~~ pale and ~~pale~~ dark blue envelopes illustrate the distribution of the streamflow ensemble (5 % to 95% and 25 % to 75 %, respectively), the blue line, the median flow, and the black line, the observed flow. Envelopes are drawn connecting daily discharges, using a moving average to smoother the lines. Observations fall within the 5 % to 95 % envelope except for a part of January (underestimation), a few days in September (overestimation) and from mid-November to the third week of December (underestimation). The highest uncertainty occurs during the most active hydrological period, namely the spring flood, with a maximum spread of 2.74 mm on April 22 (between 7.15 and 4.41 mm). The smallest uncertainty ensues during the winter low flows, with a minimum spread of 0.37 mm on February 10 (between 0.96 and 0.59 mm). These findings confirm that high flows are more complex to encompass than low flows, probably because of their irregular behavior. However, the choice of an objective function based on root-squared transformed discharges may also provide an explanation for this specific behavior. Still, it remains a relevant criterion for climate change impacts.

As mentioned in the material and methods section, ~~In addition, it may be helpful to~~ explor~~e~~ation of the reliability of the quantiles' envelopes, empirically drawn from the 3360 simulations, ~~to~~ aims at comment~~ing~~ing if the latter can be directly interpreted as confidence intervals. For this purpose, a confidence interval reliability diagram is computed for the *au Saumon* catchment~~ (Figure 6)~~. ~~The concept of a confidence interval reliability diagram consists in verifying if the observed relative frequency correspond to the simulated one – perfect reliability would result in a 1:1 slope on the diagram (Wilks, 1995). Several confidence intervals are thus plotted (from 0.1 to 0.9) with, for example, 0.5 corresponding to the quartiles spread (25 % to 75 %) and 0.9 corresponding to the spread of the 5 % to 95 % quantiles. Thus, for each of the 3360 simulations and each confidence interval, statement if observed discharge is included or not is verified, resulting in the reliability graph (Boucher *et al*., 2009; Velázquez *et al*., 2010). R~~Results in Figure ~~6~~ 5 reveal a slight under-dispersion, confirming a possible link between the envelopes drawn in Figure ~~5~~ 4 and confidence intervals.

These results confirm that the ability to simulate the precipitation-runoff transformation is hampered by the choice of lumped conceptual modeling tools. However, it can be questioned if this uncertainty is maintained, reduced or increased with climatic data as inputs and if it persists in future projections, affecting *de facto* our ability to report a diagnosis of the impacts of climate change on water resources.

3.2.2 Climate simulation and projection

Figure ~~7~~ 6 and Figure ~~8~~ 7 ~~propose~~ present a similar hydrograph analysis for reference simulations (REF, green) and future projections (FUT, red), respectively, based on climate data. Streamflow uncertainty originates either from the hydrological modeling process or from the climate natural variability (members), as disclosed by 16800 simulations and projections. For REF (Figure ~~7~~6), as for the observations, the largest uncertainty occurs during spring flood with a maximum spread of 3.19 mm (between 7.53 and 4.34 mm) on April 26, while the smallest uncertainty takes place in winter, December 27, when the spread falls to 0.56 mm (between 1.29 and 0.73 mm). For FUT (Figure ~~8~~7), the largest uncertainty (2.86 mm) is reached on April 19, with discharge oscillating between 6.84 and 3.98 mm, and smallest uncertainty occurs February 1, with a 0.81 mm spread (between 2.42 and 1.61 mm). REF and FUT uncertainties are more important than simulation on the observed period, but the latter do not account for the climate natural variability (members). Envelops are more uniform over the year, when including the climate natural variability.

Evolution from REF to FUT reveals a spring flood ~~anticipated by about 15 days~~arriving fifteen days earlier, with a slight decrease in the spring high flows. More, changes favour an increase of winter low flows and a decrease of summer low flows, demonstrating a substitution in time of the lowest flows.

This streamflow uncertainty analysis, based on interannual hydrographs combining the influence of the hydrological process and of the climate natural variability, reveals some adversity in our ability to produce a clear diagnosis of climate change impacts on water resources for the *au Saumon* catchment. Indeed, cumulative uncertainties envelopes are large, especially on hydrologically sensitive periods such as spring high flows and summer low flows.

3.3 Process-based streamflow uncertainty

Analysis of the cumulative uncertainty from yearly averaged hydrographs highlights the extent of the uncertainty in simulation and projection, but without providing much information about its origin. To assess this question in more details and to identify which modeling step contributed the most to the reported cumulative uncertainty, a water resources manager point of view is taken next, using a simple hydrological indicator: the overall mean flow (OMF). ~~, corresponding to averaged daily flow. A~~This process-based streamflow uncertainty is then ~~available, allowing comments about its extent~~computed on the observation period and on ~~about its~~ changes from REF to FUT periods.

3.3.1 Observation OMF

Figure ~~9~~ 8 illustrates, by type of tools, the OMF uncertainty for simulations on the observation (calibration) period – -168 values per boxplot ~~blue boxplots~~ for the lumped conceptual hydrological models~~ (168 values per boxplot)~~, 140 values per boxplot ~~green boxplots~~ for the PET formulations, ~~(140 values per boxplot),~~ and 480 values per boxplot ~~grey boxplots~~ for the snow modules ~~(480 values per boxplot)~~ – while the OMF total uncertainty ~~black boxplot (3360 values) illustrates~~shows 3360 values~~the OMF total uncertainty~~. In Figure ~~9~~8, colored bars indicate the 25 % and 75 % quartiles of each distribution, while the horizontal white line identifies the median value. The latter can be associated to the uncertainty for each tool, while the interquartile range (e.g. blue bars for the models) can be perceived as depicting sensitivity and robustness. Finally, the observed OMF (2.12 mm) is illustrated by a red cross in the total uncertainty box. The latter is higher than most of the 3360 runs because, as already mentioned in the hydrographs analysis, the observed spring high flow is in general underestimated.

M04 median OMF (2.13 mm) is quite close to the observed one. It is however the highest median OMF out of 20. The lowest one is the M12 median OMF (1.83 mm), disclosing the range of the uncertainty emanating from the lumped conceptual models and the importance of selecting the right model if exploiting only one structure. It can also be pointed out that M05 and M08 generate reduced inner sensitivity (i.e. smaller interquartile ranges), while the opposite is true for M12 and M07.

PET OMFs divulge an even higher uncertainty than for the lumped conceptual models. Indeed, their median OMF range from 2.48 mm (E02) to 1.79 mm (E20), largely encompassing the observed OMF (red cross), but also stressing the necessity of selecting an appropriate PET formulation. The PET inner sensitivity (extent of the green bar) varies also considerably from one another, the largest and smallest ranges originating from E02 and E23, respectively. Note finally that some PET OMF distributions are quite asymmetrical, namely for E01, E02, E03, E04, E06, and E10, combination formulations for most of them.

If the selection of a particular lumped conceptual model and of a particular PET formulation have a huge impact on the OMF uncertainty, it is clearly not the case for the seven selected snow modules, which interquartile ranges and median OMFs, extending from 1.96 mm (N1) to 1.95 mm (N7), are all quite similar.

3.3.2 OMF relative change

A similar analysis is performed on the OMF relative change from REF to FUT [$100\times(OMF_{FUT}-OMF_{REF})/OMF_{REF}$, in %], drawing boxplots (Figure ~~10~~9) for each modeling process and for each climatic member (red), the latter in order to depict the climate natural variability – each member originated from the same GCM initiated with slightly modified initial conditions in 1850, expressing the chaotic nature of the climate. Total OMF uncertainty then combines 16800 relative changes, 840 ones per lumped conceptual model, 700 per PET formulation, 2400 per snow module, and finally 3360 per climatic member. Focus is again mainly given to median values (uncertainty) and interquartile ranges (inner sensitivity).

The total OMF relative change fluctuates from -11 % to + 129 %, but its interquartile range is restrained from +4.2 % ~~mm~~ to +16.2 %, with a median value of +9.3 %. This total uncertainty is distributed between conceptual hydrological modeling tools (namely PET, hydrological models, and snow modules) and climatic members.

The median OMF relative change per lumped conceptual model fluctuates from +6.3 % (M02) ~~+16.8 % (M08)~~ to ~~+6.3 % (M02)~~+16.8 % (M08), confirming the sensitivity to the lumped conceptual model selection. The interquartile range is more uniform from one model to the other than in Figure ~~9~~8, but M08 differs (18.1 %) in that regard – M08 was already identified with poor transposability on the same catchment by Seiller *et al.* (2012). The lowest inner sensitivity is achieved by M11 (10.9 %).

PET OMF relative change is in general slightly higher than for the lumped conceptual models, from +4.1 % (E13)~~+17.1 % (E21)~~ to +17.1 % (E21) ~~+4.1 % (E13)~~, stressing also the sensitivity to the selection of a PET formulation. The highest interquartile range is ~~produced~~ obtained by E21 (14.5 %), and the lowest~~,~~ by E02 (10.6 %).

Again, the behaviour of the snow modules is more uniform than for the lumped conceptual models and for the PET formulations. The median OMF relative change of the snow modules are ~~restrained~~ limited from +9.1 % (N2) ~~+9.9 % (N3)~~ to +9.9 % (N3) ~~+9.1 % (N2)~~, while their interquartile ranges vary from 12.5 % (N3) to 11.9% (N2).

On the other hand, the behaviour of the climatic members is quite distinct. First, the interquartile ranges of their OMF relative change are much reduced when compared to the others: from 4.8 % (C1) to 3.6% (C4), expressing lower inner sensitivity. Second, their median OMF relative changes vary considerably: between +2.7 % (C4) ~~+19.1 % (C3)~~ and +19.1 % (C3) ~~+2.7 % (C4)~~. This latter characteristic exemplifies the importance of the climatic natural variability. Changes differ greatly from one climatic member to the other. It is thus evident that a single 30-year realisation of the climate is insufficient to depict all the possible variability. Furthermore, it is also striking that an important part of the uncertainty spread revealed by the various hydrological processes actually originates from the climatic natural variability.

The example of this application to the *au Saumon* catchment demonstrates the limit of our ability to provide a clear diagnosis of climate change impacts on water resources, especially when looking at~~The importance of~~ the total OMF relative change, combining 16800 simulations and projections~~, stresses the limit of our ability to provide a clear diagnosis of climate change impacts on water resources, namely for the *au Saumon* catchment~~. From these results, climatic natural variability is the first uncertainty driver, followed by PET formulations, lumped conceptual models, and snow modules, as depicted by the standard deviations of the median OMF relative change (Table ~~4~~5), with respective values of 6.9 %, 3.3 %, 2.4 %, and 0.3 %.

Since snow accumulation and melt are important hydrological processes on the *au Saumon* catchment, standard deviations of the median OMF relative change are also provided in Table ~~4~~ 5 distinguishing months with mean interannual air temperature above 0°C (April to October) from months with mean interannual air temperature below 0°C (November to May). This distinction has only a small influence on the respective standard deviation values and none on the ranking of the uncertainty sources.

4 Discussion and conclusion

This paper explored uncertainties related to the hydrological modeling of climate change impacts on water resources. In particular, twenty lumped conceptual hydrological models, twenty-four PET formulations, and seven snow modules were assessed in order to evaluate our skill diagnosing the impacts of climate change on the hydrologic regime of a river. Natural climate variability, ~~by the mean of~~through climatic members, was also studied for comparison with the diverse hydrological structures.

Analysis on uncertainties illustrates that streamflow simulation over the current climate period (calibration) is already largely conditioned by hydrological tools' selection, propagating this uncertainty on reference simulation and future projection. Results indicate that the largest source of uncertainty is associated to the natural climate variability, followed by PET formulations, lumped conceptual models, and snow modules. Calibration process and transposability questions thus appear as major issues for the calculation of future hydrological projections, but natural variability plays an even more substantial role in our ability to provide a diagnosis on the impacts of climate change on the hydrologic regime of a river, especially when exploiting hydrological indicators such as the OMF. Nonetheless, the fact that changes in the hydrologic regime of the *au Saumon* catchment differed greatly from one climatic member to the other; one has to question if a single 30-year realisation of the climate is sufficient to encompass all the possible variability.

This work focussed on only one Canadian catchment and must be confirmed with other watersheds and climate contexts, but the proposed methodology is easily transferable.

Following climate natural variability, PET formulations add to the total uncertainty in a substantial way, but without much distinction between combinational, radiation-based, and temperature-based formulations. It must be acknowledged that PET equations, especially in this climate change context, also rely on empirical coefficients which add another source of uncertainty. Indeed, if different coefficients are selected for different locations under current climate, it is conceivable that different coefficients would also be appropriate for possible future climates in a catchment. This analysis could be extended on future work on this subject, as for example applied in Kay *et al.* (2013). Only lumped conceptual hydrological models were explored, mainly to limit implementation and computation time as well as parameter identification issues, but inclusion of several other model classes would be an important complementary contribution. Finally, uncertainties associated to snow modules turned out small for the current climate period as well as for the projections. It should be mentioned that the selected tools originated from the sane snow module (CemaNeige) re-designed in six other versions and that this approach may have affected the results. Here also, more diverse modules may be considered in further exploration of this issue.

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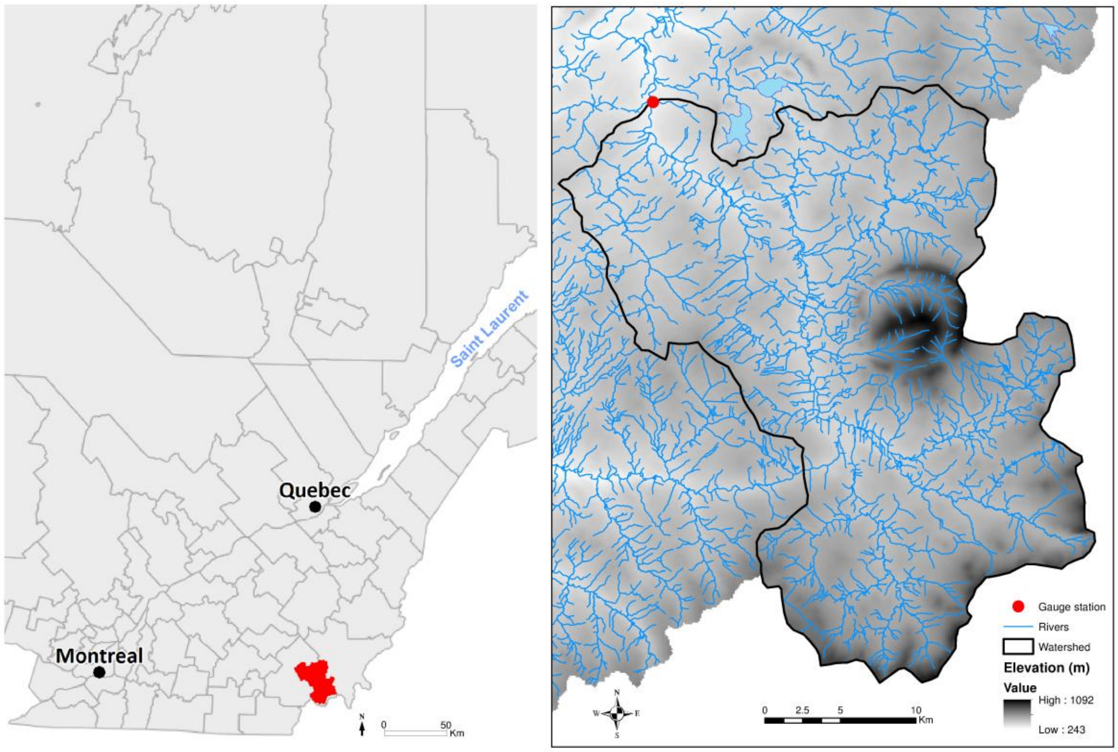

Figure 1: Localisation of the *au Saumon* catchment (738 km²; Canada)

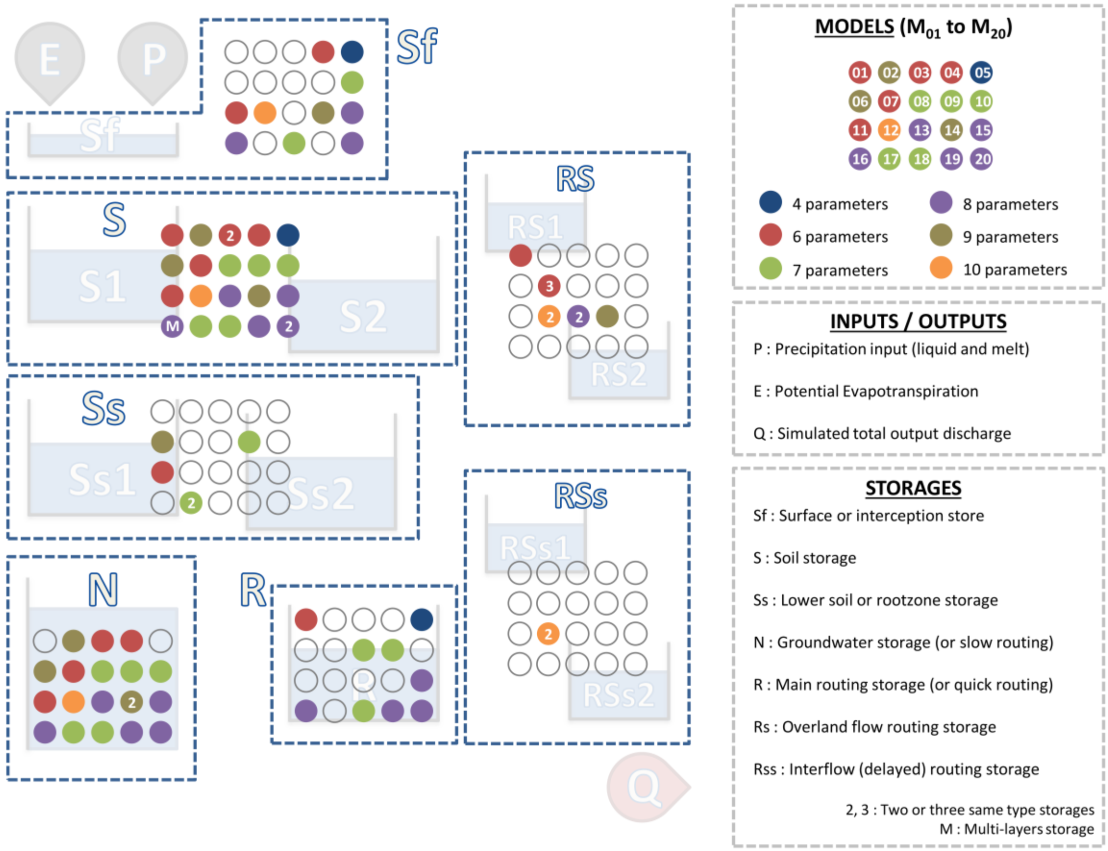

Figure 2: Illustration of the structural diversity of the twenty lumped conceptual models

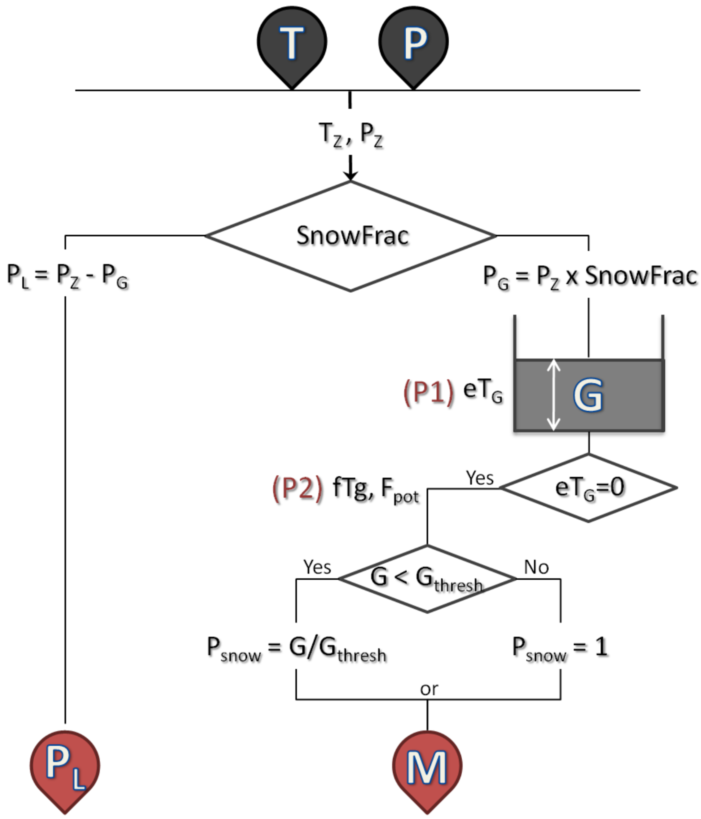

Figure 3~~4~~: Initial version of the CemaNeige snow module (N1). T is temperature, P is total precipitation, P_L is liquid precipitation, P_G is solid precipitation, and M is snowmelt. G corresponds to the snowpack and P1 and P2 are the two free parameters. (~~Inspired~~ Modified from Valéry, 2010)

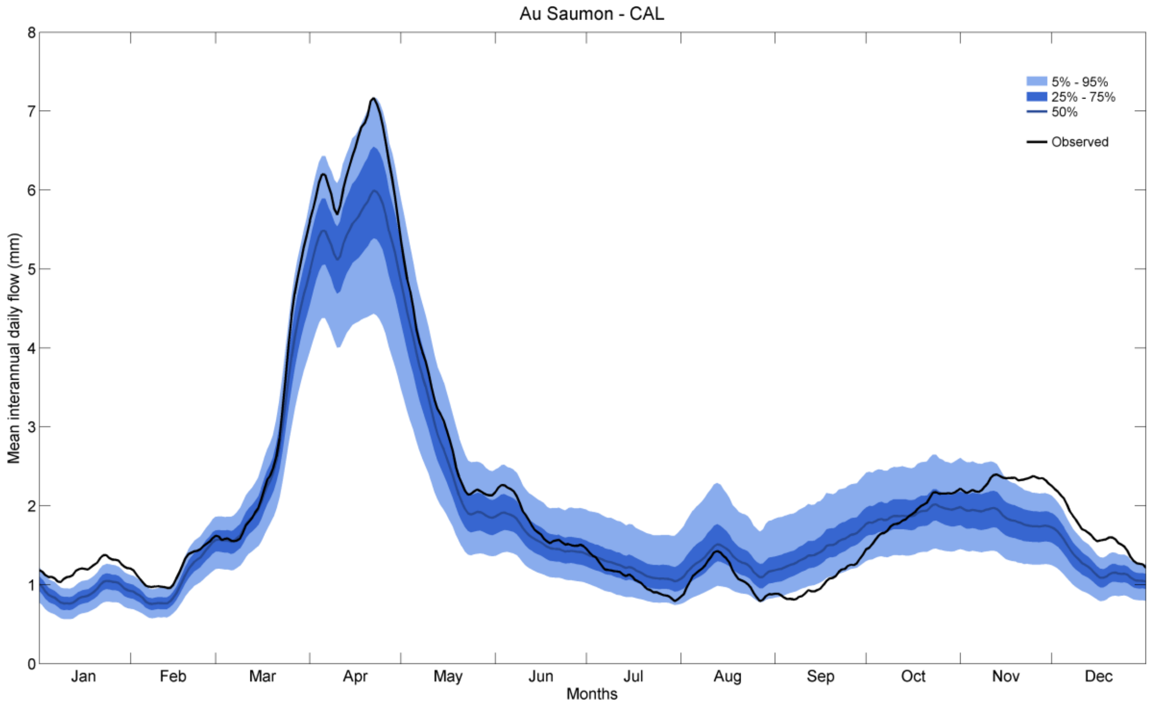

Figure 4~~5~~: Cumulative uncertainties for the observed period simulation. The black line is the observed flow, the blue line depicts the median flow simulation, and the ~~dark~~ pale and ~~pale~~ dark blue envelopes, the distribution of the streamflow ensemble (5 % to 95% and 25 % to 75 %, respectively).

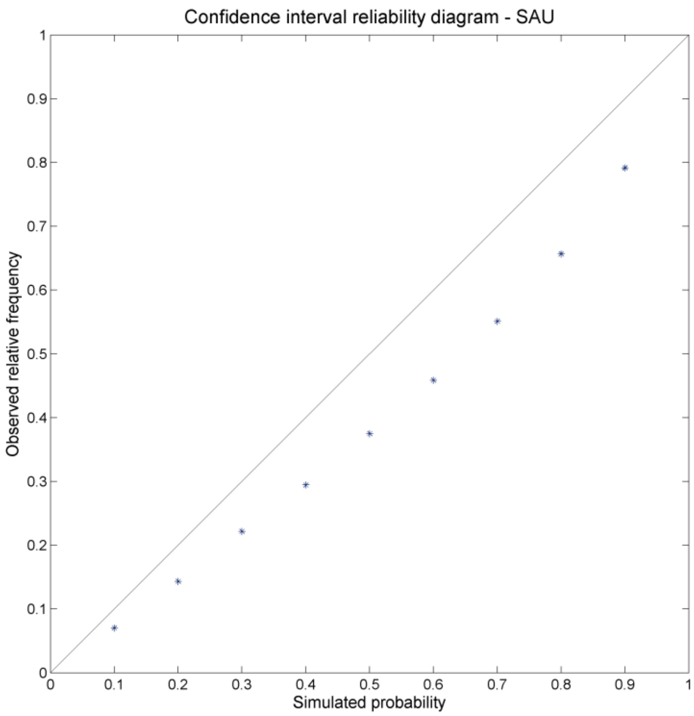

Figure 56: Confidence interval reliability diagram opposing simulated probability (x-axis) and observed relative frequency (y-axis)

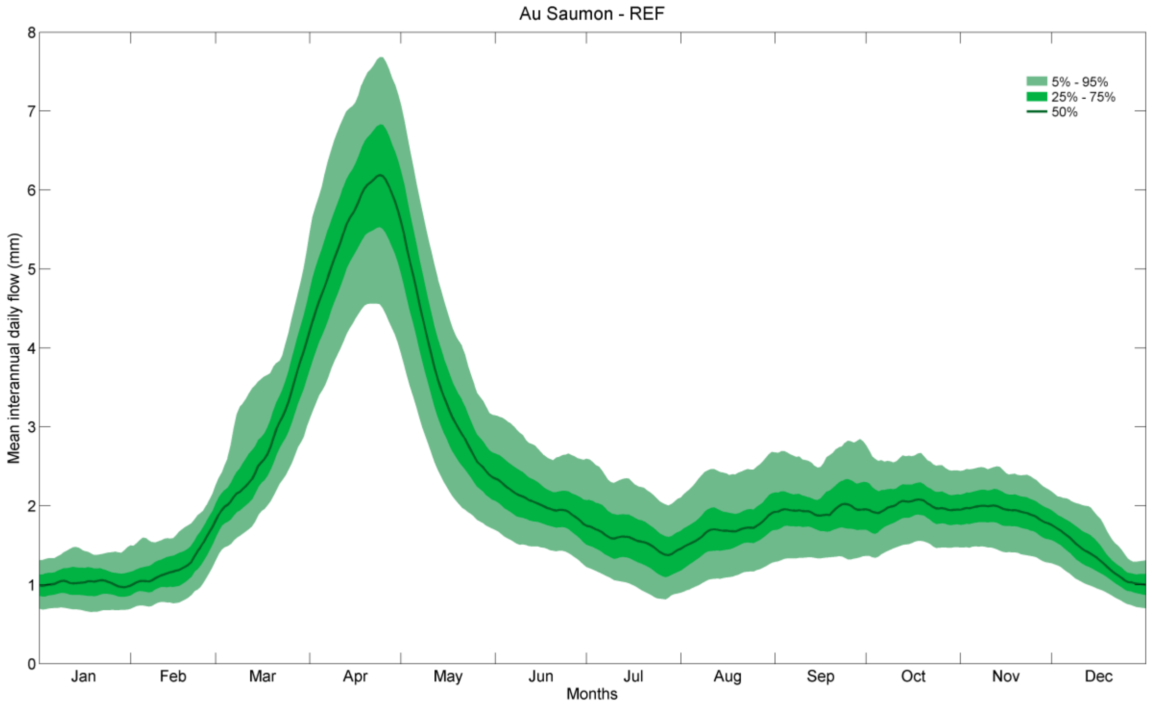

Figure 6~~7~~: Cumulative uncertainties of the reference (REF) simulations. The line depicts the median flow simulation and the ~~dark~~ pale and ~~pale~~ dark green envelopes, the distribution of the streamflow ensemble (5 % to 95% and 25 % to 75 %, respectively).

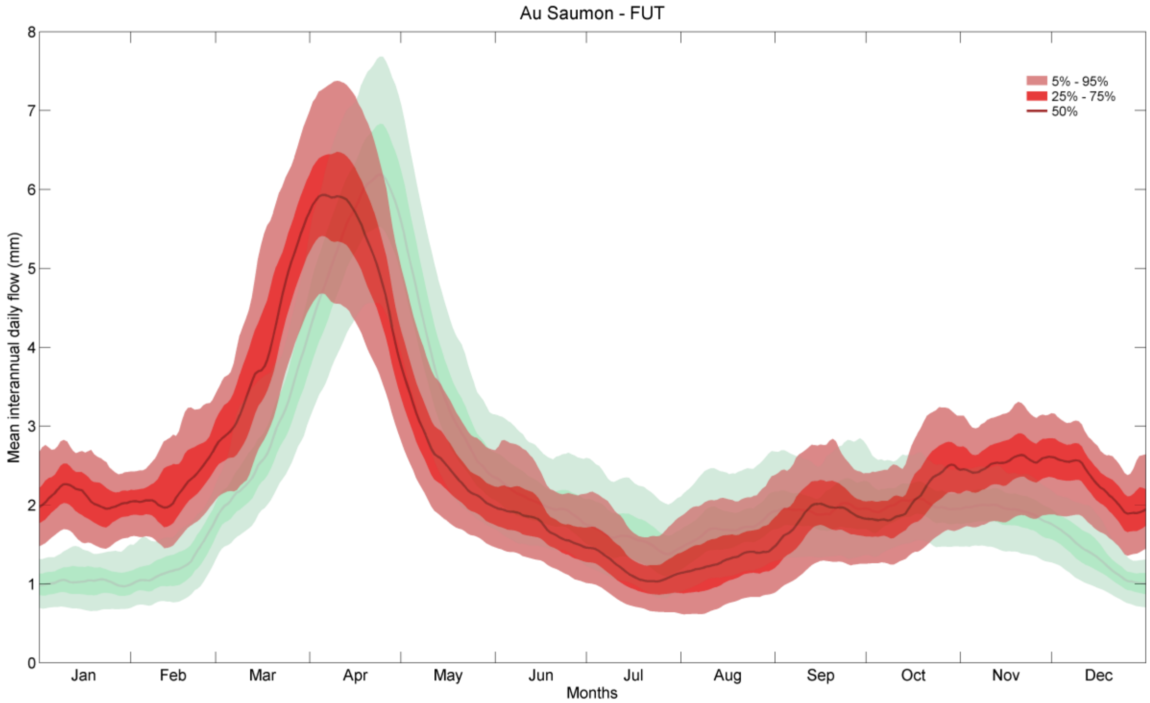

Figure 7~~8~~: Cumulative uncertainties of the future (FUT) projection. The line depicts the median flow projection and the ~~dark~~ pale and ~~pale~~ dark red envelopes, the distribution of the streamflow ensemble (5 % to 95% and 25 % to 75 %, respectively). REF simulation is displayed transparently in green color.

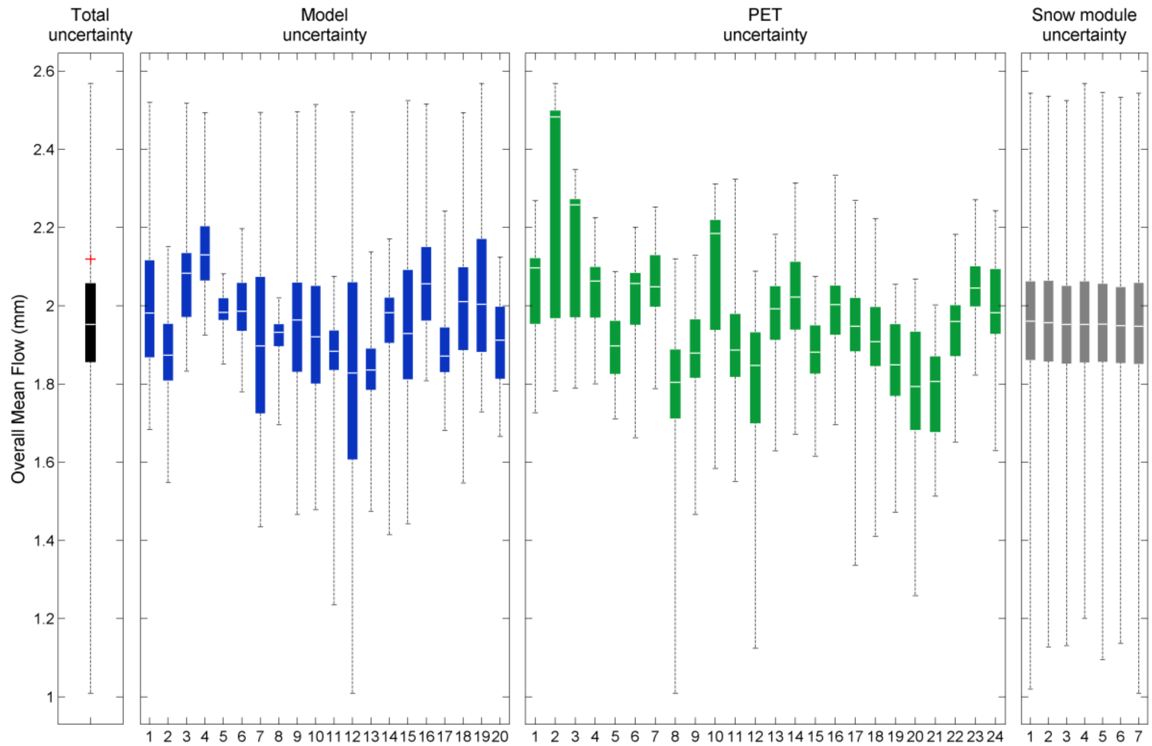

Figure 89: Total (black boxplot) and process-based overall mean flow (OMF, mm) uncertainty, for simulation on the observed period. The observed OMF is illustrated by a red cross in the total uncertainty box. Blue boxplots correspond to the lumped conceptual hydrological models, green boxplots to the PET formulations and grey boxplots to the snow modules.

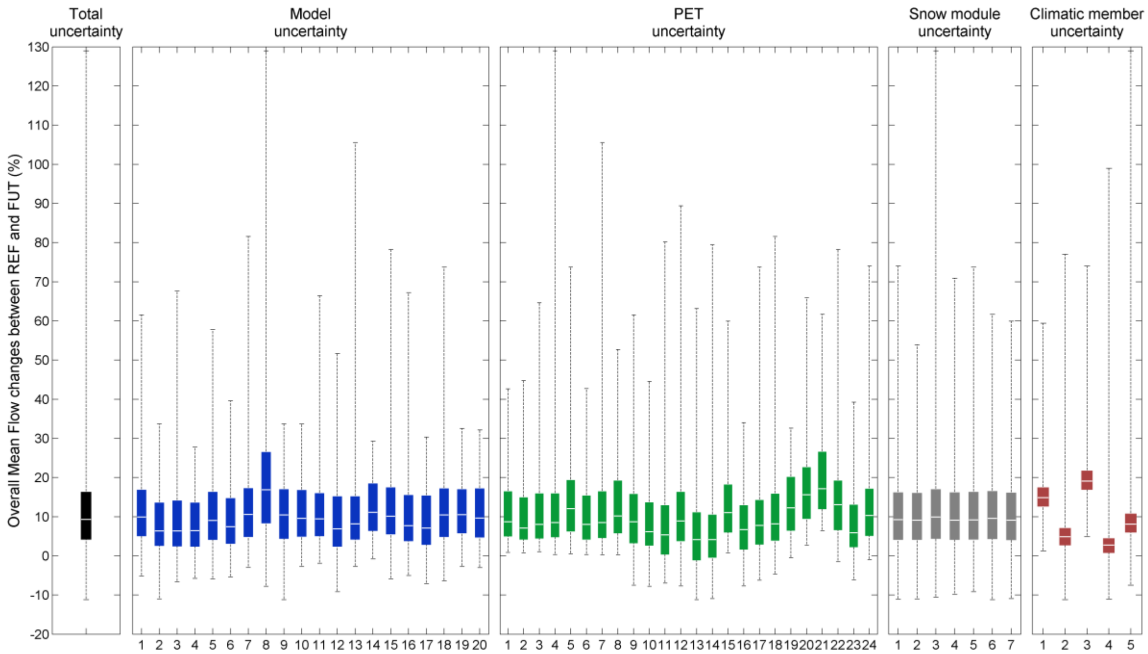

Figure 9~~10~~: Total (black boxplot), process-based, and climate overall mean flow evolution (from REF to FUT, %) uncertainty. Blue boxplots correspond to the lumped conceptual hydrological models, green boxplots to the PET formulations, grey boxplots to the snow modules and red boxplots to the climatic members.

Table 1 – List of the twenty lumped conceptual models and their source of inspiration

Name	Acronym	Free parameters	Storages	~~Inspired by~~Derived from
M01	BUCK	6	3	BUCKET (Thornthwaite et Mather, 1955)
M02	CEQU	9	2	CEQUEAU (Girard et al., 1972)
M03	CRE0	6	3	CREC (Cormary et Guilbot, 1973)
M04	GARD	6	3	GARDENIA (Thiery, 1982)
M05	GR4J	4	3	GR4J (Perrin et al., 2003)
M06	HBV0	9	3	HBV (Bergström et al., 1973)
M07	HYMO	6	5	HYMOD (Wagener et al., 2001)
M08	IHAC	7	3	IHACRES (Jakeman et al., 1990)
M09	MART	7	4	MARTINE (Mazenc et al., 1984)
M10	MOHY	7	3	MOHYSE (Fortin et al., 2007)
M11	MORD	6	4	MORDOR (Garçon, 1999)
M12	NAM0	10	7	NAM (Nielsen et Hansen, 1973)
M13	PDM0	8	4	PDM (Moore et Clarke, 1981)
M14	SACR	9	5	SACRAMENTO (Burnash et al., 1973)
M15	SIMH	8	4	SIMHYD (Chiew et Siriwardena, 2005)
M16	SMAR	8	4	SMARY et SMARG (O'Connell et al., 1970)
M17	TAN0	7	4	TANK (Sugawara, 1979)
M18	TOPM	7	4	TOPMODEL (Beven et Kirkby, 1979)
M19	WAGE	8	3	WAGENINGEN (Warmerdam et al., 1997)
M20	XINA	8	5	XINANJIANG (Zhao et al., 1980)

Table 2 – List of the twenty-four PET formulations per category: combinational, temperature-based, and radiation-based.

PET Class	Short name	Formulation name	Required data
Combinational	E01	Penman	RH, T, U, Rs
	E02	Penman-Monteith	RH, T, U, Rs
	E03	FAO56 P-M (ASCE)	RH, T, U, Rs
	E04	Priestley-Taylor	T, Rs
	E05	Kimberly-Penman	RH, T, U, Rs
	E06	Thom-Oliver	RH, T, U, Rs
Temperature-based	E07	Thornthwaite	T
	E08	Blaney-Criddle	T, Rs
	E09	Hamon	T, Rs
	E10	Romanenko	RH, T
	E11	Linacre	RH, T
	E12	MOHYSE	T
	E13	Hydro-Québec (HSAMI)	T
	E14	Kharrufa	T
Radiation-based	E15	Wendling (WASIM)	T, Rs
	E16	Turc	RH, T, Rs
	E17	Jensen-Haise	T
	E18	McGuinness-Bordne	T
	E19	Hargreaves	T
	E20	Doorenbos-Pruitt	RH, T, U, Rs
	E21	Abtew	RH, T, Rs
	E22	Makkink	T
	E23	Oudin	T
	E24	Baier-Robertson	T

with RH: relative humidity ; T: temperature ; U: wind speed ; Rs: incoming solar radiation

Table 32 – List of the seven snow module versions and free-parameters

Name	Free parameters	Version details
N1	2	Initial CemaNeige version (Valéry, 2010) P1: C_{Tg} ; P2: K_f
N2	4	Modified version (sinusoidal K_f, T_f = -1°C, modified SnowFrac function, eT_G depending on air temp., progressive melt, free TG_{thresh}) P1: C_{Tg} ; P2: min K_f ; P3: max K_f ; P4: TG_{thresh}
N3	5	Modified version (linear SnowFrac with free parameters added, free thermal coeff C_t) P1: CoeffG ; P2: K_f ; P3: C_t ; P4: int ; P5: T_{50}
N4	4	Modified version (modified SnowFrac function, free thermal coeff C_t, free G_{thresh}) P1: C_{Tg} ; P2: K_f ; P3: C_t ; P4: G_{thresh}
N5	5	Modified version (T_f = -1°C, sinusoidal K_f, modified SnowFrac function, free thermal coeff C_t, eT_G depending on air temp., progressive melt, free TG_{thresh}) P1: C_{Tg} ; P2: min K_f ; P3: max K_f ; P4: C_t ; P5: TG_{thresh}
N6	1	Modified version (modified SnowFrac function, eT_G not used) P1: K_f
N7	2	Modified version (50 layers, sinusoidal K_f, modified SnowFrac function) P1: C_{Tg} ; P2: K_f

Table 43 – Characteristics of the calibration performance (NSE_{sqrt}) pooled by hydrological models, PET formulations, and snow modules. Green color corresponds to the best performing options, when red color is the worst option

Hydrological model		PET formulation		Snow module	
Name	Median (5^{th}, 95^{th})	Name	Median (5^{th},95^{th})	Name	Median (5^{th},95^{th})
M01	0.76 (0.67, 0.79)	E01	0.76 (0.56, 0.80)	N1	0.75 (0.53, 0.81)
M02	0.56 (0.48, 0.62)	E02	0.70 (0.50, 0.78)	N2	0.75 (0.53, 0.81)
M03	0.78 (0.70, 0.80)	E03	0.75 (0.55, 0.79)	N3	0.75 (0.55, 0.81)
M04	0.77 (0.68, 0.79)	E04	0.76 (0.58, 0.81)	N4	0.75 (0.55, 0.80)
M05	0.81 (0.72, 0.83)	E05	0.76 (0.55, 0.80)	N5	0.75 (0.52, 0.80)
M06	0.76 (0.69, 0.78)	E06	0.75 (0.56, 0.79)	N6	0.75 (0.56, 0.80)
M07	0.60 (0.49, 0.63)	E07	0.77 (0.60, 0.82)	N7	0.71 (0.52, 0.79)
M08	0.71 (0.64, 0.75)	E08	0.68 (0.47, 0.78)		
M09	0.76 (0.64, 0.80)	E09	0.76 (0.53, 0.81)		
M10	0.73 (0.58, 0.81)	E10	0.67 (0.49, 0.72)		
M11	0.74 (0.63, 0.80)	E11	0.74 (0.54, 0.80)		
M12	0.71 (0.36, 0.78)	E12	0.66 (0.45, 0.79)		
M13	0.57 (0.47, 0.65)	E13	0.77 (0.58, 0.81)		
M14	0.78 (0.68, 0.81)	E14	0.77 (0.61, 0.81)		
M15	0.75 (0.62, 0.79)	E15	0.75 (0.56, 0.79)		
M16	0.78 (0.68, 0.80)	E16	0.76 (0.58, 0.81)		
M17	0.76 (0.68, 0.80)	E17	0.75 (0.56, 0.80)		
M18	0.77 (0.67, 0.80)	E18	0.77 (0.59, 0.80)		
M19	0.76 (0.65, 0.81)	E19	0.75 (0.56, 0.81)		
M20	0.63 (0.56, 0.65)	E20	0.72 (0.54, 0.80)		
		E21	0.69 (0.49, 0.76)		
		E22	0.77 (0.57, 0.81)		
		E23	0.78 (0.59, 0.82)		
		E24	0.77 (0.59, 0.82)		

Table 54 – Characteristics of the median OMF relative change for different processes and periods

	Lowest value	Highest value	Standard deviation
OMF			
Hydrological model	+6.3 % (M02)	+16.8 % (M08)	2.4 %
PET formulation	+4.1 % (E13)	+17.1 % (E21)	3.3 %
Snow module	+9.1 % (N2)	+9.9 % (N3)	0.3 %
Climatic member	+2.7 % (C4)	+19.1 % (C3)	6.9 %
April to October OMF			
Hydrological model	-14.2 % (M06)	-4.1 % (M08)	2.4 %
PET formulation	-15.8 % (E14)	-1.7 % (E21)	3.1 %
Snow module	-11.3 % (N1)	-10.1 % (N6)	0.5 %
Climatic member	-19.5 % (C2)	-2.4 % (C3)	7.6 %
November to May OMF			
Hydrological model	+17.1 % (M17)	+27.5 % (M08)	2.1 %
PET formulation	+14.1 % (E14)	+32.2 % (E21)	4.0 %
Snow module	+20.5 % (N1)	+21.1 % (N6)	0.3 %
Climatic member	+15.7 % (C4)	+26.3 % (C3)	4.7 %