Uncertainty of hydrological modelling in climate change impact studies in a Canadian, snow-dominated river basin

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ARTICLE INFO

Article history:
Received 8 March 2011
Accepted 27 August 2011
Available online 3 September 2011
This manuscript was handled by
Konstantine P. Georgakakos, Editor-in-Chief, with the assistance of Günter Blöschl, Associate Editor

Keywords:
Climate change
Water resources
Hydrological modelling
Uncertainty
Model calibration
Model structure

SUMMARY

This paper investigates the effects of model structure and parameter equifinality on the uncertainty related to hydrological modelling in climate change impact studies. The study is conducted on a snow-dominated watershed located in the southern part of the province of Quebec (Canada). Hydrological model structure uncertainty is examined through the use of two very different simulation tools, a lumped conceptual model and one spatially-distributed physically-based model. Parameter equifinality is examined by performing multiple automatic calibrations with both hydrological models. The analysis is first carried out under recent past climate and then under modified climate conditions following two contrasted projections that are analysed separately. The delta change approach is used to build the two climate projections. Overall, this study reveals that the impact of hydrological model structure uncertainty is more significant than the effect of parameter uncertainty, under recent past climate as well as future climate conditions. Ultimately, the use of hydrological models with different levels of complexity should be considered as part of the global uncertainty related to hydrological model structure.

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1. Introduction and background on hydrological impact assessment uncertainty

It is now widely acknowledged that climate change will have impacts on water resources availability and management throughout the world, in the near and longer terms. Some of the sectors under concern include urban water supply, irrigated agriculture and hydropower production (IPCC, 2007a). In eastern North America where winter precipitation is currently dominated by snow, it is expected that global warming leads to changes in the seasonality of river flows with earlier spring peak flows, increased winter flows and decreased summer flows (Barnett et al., 2005; Dibike and Coulibaly, 2005).

Hydropower production is a dominant industry in the province of Quebec (Canada). More than 60 major reservoirs and run-of-river power stations are currently operated over the province’s territory, in 14 different hydrological systems. Recent studies conducted on one of these water resource systems have shown that hydropower facilities will need to be adapted to a changed climate, to ensure proper operation and safety and hence reduce the negative impacts on water resources management (Minville et al., 2008, 2009). Such impact studies are predominantly based on climate and hydrological modelling.

In the last two decades, with outputs from climate models made available, several impact studies under a changed climate have been carried out over numerous rivers basins located in different countries (e.g. Christensen et al., 2004; Minville et al., 2006; Fowler and Kilsby, 2007; Akhtar et al., 2008; Elshamy et al., 2009). Recently, hydrological impact studies have started to systematically consider the uncertainty related to climate/hydrological modelling. Various sources of uncertainty have now been clearly identified and these should be taken into account and better quantified. According to Wilby (2008), the uncertainties can be classified as follows: (1) greenhouse gas emission scenario (which is related to the future society); (2) global climate model (GCM) structure; (3) downscaling method; and (4) impact (or catchment) model. Natural climate variability could also be added to this list, as a fifth item. So far, only a few recent studies have attempted to address the entire cascade of uncertainties resulting from items 1 to 5. Prudhomme and Davies (2009a,b) conducted a study on four British catchments, under baseline and future climate (2080 horizon). They considered two greenhouse gas emissions scenarios (Special report on emissions scenario – SRES A2 and B2; IPCC, 2000), and used three different GCMs, two...
downscaling techniques (one statistical method and one regional climate model – RCM) and two different versions of the same conceptual hydrological model (a complete 5-parameter version and a simpler 3-parameter version). Hydrologic parameter uncertainty was also taken into account, through the use of near-optimal parameter sets obtained by a semi-automatic calibration procedure. Block resampling was used to assess climate variability for baseline and future time horizons. Although they show that hydrological model uncertainty cannot be ignored, they conclude that the largest source of uncertainty comes from the choice of the GCM, with the downscaling technique also being an important factor of uncertainty. Kay et al. (2009) have investigated the uncertainty of climate change impact on flood frequency for two river basins in England. In this study, four emissions scenarios were considered, over the 2080 horizon: SRES A1F1, B2, B1 and A2 (IPCC, 2000). Five different GCMs were used along with the delta change approach to assess GCM uncertainty. A single GCM was used with both the delta change approach and a RCM, to investigate downscaling method uncertainty. RCM structure uncertainty was also examined through the use of 9 RCMs nested within a single GCM. Two different conceptual hydrological models were used, a spatially distributed one and a lumped one. Multiple calibrated parameter sets were generated for one of the hydrological models by a jack-knife method to assess parameter uncertainty. Finally, internal climate variability was investigated in two different ways: (1) resampling of rainfall series and (2) taking into account 3 members of the same GCM. Similarly to Prudhomme and Davies (2009a,b), Kay et al. (2009) conclude that most of the uncertainty is related to climate modelling, i.e. GCM structure and RCM structure.

Other studies have also examined different combinations of the aforementioned sources of uncertainty, the work by Wilby and Harris (2006) being an important contribution. A small number of these studies have more specifically looked at hydrological modelling uncertainty. Minville (2008) applied two very different hydrological models (one lumped conceptual and one distributed physically-based) to a Canadian river basin, under two climate projections for the 2080 horizon. Output from one GCM under the A2 emissions scenario was downscaled using the delta method as well as a RCM. Results show that hydrological model structure can generate more uncertainty on summer flows than the climate signal. Jiang et al. (2007) have used six conceptual rainfall–runoff models to investigate hydrological model structure uncertainty under fifteen hypothetical climate change scenarios (from the combinations of three temperature increases and five precipitation changes). Their study was carried out on a Chinese watershed. They come to the conclusion that models with similar behaviours under historical climate can perform differently under future climate conditions. Wilby (2005) explored three aspects of conceptual hydrological models uncertainty: parameter stability, model structure and parameter non-uniqueness. Two versions of the same rainfall–runoff model were used, with different structure complexities. Output from a single GCM under emissions scenarios A2 and B2 was statistically downscaled to generate the climate projections for time horizons 2020, 2050 and 2080. The major conclusions of this study are as follows: (1) parameter transferability between wet and dry periods is sensitive to the choice of the training conditions (wetter vs. dryer); (2) model structure and parameter non-uniqueness uncertainties on projected river flows can be comparable to the uncertainty due to the choice of the emissions scenario, in the former case when the simpler model structure is used and in the latter case when summer flows are considered. Hydrological model uncertainty should therefore be acknowledged and routinely investigated as part of climate change impact studies. It can have significant implications on the identification of adaptation or response strategies to climate change. Finally, Ludwig et al. (2009) have undertaken the comparison of two physically-based models and one conceptual model in a climate change context. They conclude that the differences in model structure complexities can play a significant role in the evaluation of model results. However, Ludwig et al. (2009)’s analysis highlights the need for deeper investigation of hydrological model uncertainty in climate change impact studies.

The present paper further extends the investigation about hydrological model uncertainty in climate change impact studies, using a lumped conceptual model (HSAMI; Fortin, 2000; Bisson and Roberge, 1983) and a distributed physically-based model (HYDROTEL; Fortin et al., 2001a,b). The contributions of model internal structure and calibration parameters to uncertainty are examined under recent past and modified climate conditions. The main goals of this study are: (1) to assess whether the uncertainty (defined by the spread of hydrological predictions resulting from both models and multiple calibrations) is modified from recent past to modified climate, and (2) to assess which source of uncertainty (calibration parameters or model structure) is the most significant under both sets of climate conditions. For a given model, it is well known that many equivalent local optima may exist within a realistic parameter space. Several different parameter sets may then be associated with the same “optimal” measure of efficiency. This refers to the concept of equifinality (or parameter non-uniqueness; Beven and Freer, 2001; Beven, 2006). Parameter uncertainty is considered from this perspective in the present study. Model structure uncertainty is illustrated through the use of the two very different models, in terms of internal computation of hydrological processes and in terms of spatial simulation scale (more details about the models structures are given in Section 3.1). The rest of this paper is organised as follows: the experimental river basin and methods are described in the next two sections; then the results are presented and analysed, followed by a discussion. All through the reading of this paper the reader should keep in mind that the results are not meant to compare the performances or the levels of uncertainty of the hydrology models against one another (indeed, comparing the models is tempting but this is not among the objectives of the present paper).

2. Study area and data

The present study is carried out on the Ceizur river basin, which is located in south-western Quebec (Canada). It is the northernmost sub-basin of the Gatineau watershed (Fig. 1). The Ceizur basin’s total area is 6954 km² and it is mainly forested (90% of area), with deciduous trees being predominant (65% of forested area). According to available meteorological data (1970–2005), the mean annual temperature is 1.6 °C, while the yearly mean total precipitation is 985 mm, of which approximately 420 mm fall as snow. The freezing period generally extends over the months of November to April. The Ceizur watershed’s hydrological regime is dominated by the spring snowmelt, with another, less pronounced, flood period in the fall. For the 1975–2003 observation period, the mean spring peak flow at the basin’s outlet (see hydrometric station in Fig. 1) is 782 m³/s and the mean annual streamflow is 128 m³/s.

3. Methodology

This section first gives a description of the hydrological models. Then the calibration/validation and multiple parameter sets generation methods are presented. Finally, the methods used to produce the climate projections and generate model results under a changed climate are described.

3.1. Hydrological models description

The two models used in this study are fundamentally different in their simulation of hydrological processes and spatial
The HYDROTEL simulation tool was developed by a research team from the Institut National de la Recherche Scientifique in Quebec City, Canada (Fortin et al., 2001a,b). It has been applied to several watersheds located in the province of Quebec and in other countries (e.g., southern France, Fortin et al., 1995; and Vietnam, Fortin et al., 2007). HYDROTEL is currently used operationally by the Centre d’expertise hydrique du Québec for flow forecasting.

The HYDROTEL model is spatially distributed and is predominantly (although not fully) physically-based (Fortin et al., 2001a). To run HYDROTEL, a given watershed must first be divided into several simulation units (or elementary subwatersheds) called relatively homogeneous hydrological units (RHHUs). The number of RHHU subdivisions on a given river basin depends on the hydrological network's discretisation specified by the user (see Fortin et al., 2001a for further details). Each RHHU comprises a river reach, may include various land occupations and is assumed to be characterised by a single soil type. The Ceizur river basin (study area, see Section 2) comprises 219 RHHUs.

The simulation of hydrological processes is based on five sub-models (Table 1). Options are available for the potential evapotranspiration (PET) and flow in river reaches sub-models. The options that were selected in the present study are shown in Table 1 (note that PET is simulated according to an empirical equation developed at Hydro-Quebec, which has proven to be well-adapted to PET simulation and only requires temperature data as input, Fortin and Royer (2004); the same equation is also used within the HSAMI model, see Table 1). The number of parameters of each sub-model is also indicated in Table 1 (26 total parameters; in the present study, all 219 RHHUs have the same 26 parameter values). Simulations can be executed at a daily or sub-daily time step. In this study, simulations were run on a daily basis (Table 1). The required meteorological inputs are daily minimum and maximum temperatures and daily precipitation. The data were provided to the model as a grid obtained by kriging at a 10 km resolution following Tapsoba et al. (2005)’s procedure. The grid for the entire Gatineau watershed is represented by the cross symbols in Fig. 1.

The HSAMI model (Fortin, 2000; Bisson and Roberge, 1983) has been used by Hydro-Québec for more than 20 years to forecast flows on numerous watersheds over the province of Quebec. It is a lumped, reservoir-based, conceptual model that simulates the main processes described in Table 1. HSAMI can be run on a daily or sub-daily time step (again, a daily time step was considered, see Table 1). The meteorological grid described in the previous section (Fig. 1) was used to generate the minimum temperature, maximum temperature and precipitation input data. Since HSAMI treats a river basin as a single simulation unit, daily areal averages were computed from the grid points covering the Ceizur river basin. The number of model parameters related to the simulated processes is also indicated in Table 1 (23 total parameters).

### 3.2. Calibration/validation and multiple parameter sets generation

To analyse the parameter uncertainty, multiple automatic calibrations were performed with both hydrological models using the shuffled complex evolutionary algorithm (SCE-UA, Duan et al., 1994). As is the case in most hydrological applications, calibration was accomplished based on observed streamflow data (i.e., available calibration data). In each single calibration, the SCE-UA method searches an optimal parameter set within a bounded parameter space, based on maximisation of the Nash–Sutcliffe efficiency criterion. An initial parameter set may be specified by the user, or not (in the former case, the specified parameter set is introduced into the initial population of parameter arrays randomly generated by the SCE-UA algorithm, while in the latter case, only random initial arrays are used). Sixty-eight (68) calibrated parameter sets were generated with each hydrology model (each individual calibration was started from a different seed number and involved several thousands of model runs; the maximum number of SCE-UA iterations was set to 10,000; based on a stopping criteria that is related to the improvement of the objective function value over consecutive iterations of the SCE-UA, the maximum number of iterations was never reached – see Duan et al., 1994). Then each model was run over a validation period, with the corresponding calibrated parameter sets.

The selected calibration period extends from October 1, 1988 to September 31, 1992. The following criteria lead to the choice of this 4-year period: (1) the length had to be kept reasonable due to computing time considerations with HYDROTEL; (2) the years had to be consecutive for ease of simulation execution with HYDROTEL; and (3) the mean annual streamflow of each hydrological year had to be representative of (or close to) the overall mean of the entire observation period (1975–2003). Because of the rather short length of the calibration period, a longer validation period was selected, going from October 1, 1993 to September 31, 2003.

Two types of calibration experiments were carried out with the HYDROTEL model. In the first one, 12 out of 26 parameters were calibrated: 5 from the snow sub-model, 1 from the PET sub-model, 4 from the vertical water budget sub-model and 2 from the flow on sub-watersheds sub-model (see Table 1). Working with a smaller array of parameters contributes to reducing the calibration computation time, and these are among the model's most sensitive parameters (personal communication from Alain Rousseau and Brou Konan, developers of the HYDROTEL model, Institut de la recherche scientifique 2008; Turcotte et al., 2003). Still, each 12-parameter calibration took up to 2 weeks. The remaining parameters were set to fixed values according to results from a regionalization study (Turcotte et al., 2007) and previous manual calibration experience gained on the Ceizur river basin. Thirty-three (33) calibrations of this first type were performed. Nineteen

Table 1
Simulation of hydrological processes within the HYDROTEL and HSAMI hydrology models.

<table>
<thead>
<tr>
<th>Model</th>
<th>Snow accumulation and melt</th>
<th>Potential evapotranspiration (PET)</th>
<th>Moisture in the soil column/runoff generation</th>
<th>Horizontal flow/flow routing</th>
<th>Spatial/temporal discretisations</th>
</tr>
</thead>
<tbody>
<tr>
<td>HYDROTEL</td>
<td>Snow sub-model: Mixed degree days – energy budget approach (Turcotte et al., 2007)</td>
<td>PET sub-model: Hydro-Quebec (4 other options available, see Fortin et al., 2001a)</td>
<td>Vertical water budget sub-model (based on soil characteristics): 3 soil layers from which surface runoff, interflow and base flow are generated; vertical fluxes described by continuity equations</td>
<td>Flow on subwatersheds sub-model: kinematic wave equation</td>
<td>Simulation time step: 24 h</td>
</tr>
<tr>
<td></td>
<td>10 parameters</td>
<td>1 parameter</td>
<td>11 parameters</td>
<td>Surface and delayed unit hydrographs (no routing since the model is lumped conceptual)</td>
<td>Spatial simulation units: 219 RHHUs (see the Section 3.1)</td>
</tr>
<tr>
<td>HSAMI</td>
<td>Degree-days approach</td>
<td>Hydro-Quebec</td>
<td>3 linear reservoirs for surface, unsaturated and saturated zones</td>
<td></td>
<td>Simulation time step: 24 h</td>
</tr>
<tr>
<td></td>
<td>6 parameters</td>
<td>2 parameters</td>
<td>7 parameters</td>
<td></td>
<td>Spatial simulation unit: entire watershed accounts for a single unit</td>
</tr>
</tbody>
</table>

(19) of these were provided with the same initial parameter array (which consists in the best parameter set obtained by manual calibration), while the other 14 calibrations were run without specifying an initial array.

In the second type of calibration, 10 parameters were taken into account, as two from the first calibration experiment were set to fixed values (again, based on previous calibration experience). These two parameters are related to the kinematic wave computation (flow on sub-watersheds sub-model) which has a significant impact on the overall calibration computational time. Indeed, each 10-parameter calibration took up to a week instead of 2 weeks. Thirty-five (35) calibrations of this second type were performed (20 were provided with the same “best manual” initial parameter set). All 68 HYDROTEL calibrations were run on a multi-processor computer which allowed the execution of as many as 16 simultaneous parallel calibrations (64-bit system with 4 2.94-GHz processors).

To ensure that the calibration results were generated on similar bases with both models, 12 parameters of the HSAMI model (out of 23) were also calibrated. A sensitivity analysis was performed to identify those 12 parameters, while the remaining 11 parameters were set to fixed values according to prior calibration experience on the Ceizur river basin. In each calibration, the same initial parameter set was repeatedly specified. Generation of the 68 calibrated parameter sets took approximately half an hour (on a 32-bit computer with a dual-core 2.0-GHz processor) without using parallel computation. In all the HYDROTEL and HSAMI calibrations, the lower and upper parameter bounds remained within fairly wide but realistic ranges (based on recommendations from experienced users – conceptual processes – and/or the physical meaning of the simulated processes).

3.3. Climate projections and hydrological simulations under a changed climate

In the optics of a first investigation, the delta change approach (Diaz-Nieto and Wilby, 2005; Hay et al., 2000) was used to generate the basin-scale climate projections, keeping in mind that more sophisticated methods could eventually be used to further extend the present study (e.g. using direct output from the Canadian Regional Climate Model; Music and Caya, 2007). Monthly minimum/maximum temperature deltas and precipitation ratios computed from 22 GCM-emissions scenario combinations were available, covering the 2010–2084 time period. Among these sets of deltas, four different scenarios were selected based on the computed values for the time horizon centred on year 2060 (mean values over 2045–2074). By this time horizon the global warming is generally expected to exceed the current natural variability (as indicated by the 2060 delta values used in this study; see also IPCC, 2007b), whereas the expected changes remain within “not too extreme” ranges (relatively to what could be expected further away in the future). The four scenarios were identified in order to: (1) maximise summer runoff (cold – but still warmer than the present climate – and wet conditions in the months of July to September); (2) minimise summer runoff (warm and dry conditions); (3) maximise spring runoff (cold and wet conditions in the months of January to April); and (4) minimise spring runoff (warm and dry conditions). Note that the possible contribution of these scenarios to climate uncertainty is not examined in the present study; the scenarios are meant to be analysed as independent and contrasted sets of climate conditions. The rationale for scenario selection was inspired from Raff et al. (2009). For each summer and winter month of the 2060s data set (hereafter simply termed “year 2060”), all the available temperature deltas from the 22 GCM-emissions scenario combinations (maximum temperature for summer and minimum temperature for winter) were plotted against the corresponding precipitation ratios. The resulting graph was then partitioned into three sections between the minimum and maximum values of both temperature deltas and precipitation ratios, each section of the x-axis and y-axis representing one third of the corresponding range of values. As an example, Fig. 2 shows the grid obtained for the month of September 2060: the available GCM projections are represented by the numbered circles; the upper left and lower right “x” symbols mark the regions of the grid in which the projections that respectively minimise and maximise summer runoff should be located. Each scenario was linked to the GCM projection that was most often located in the appropriate region of the grid, in all four summer or winter months.

The monthly temperature deltas and precipitation ratios from the four scenarios were applied to the corresponding daily climate data of the validation period, according to Eqs. (1) (minimum and maximum temperature) and (2) (precipitation):

\[ T_{\text{lat d-m-y}} = T_{\text{obs d-m-y}} + \Delta T_{\text{m}} \]

\[ P_{\text{lat d-m-y}} = P_{\text{obs d-m-y}} \times \text{Ratio}_{\text{p}} \]
where \( i \) is the scenario index \((i = 1, \ldots, 4)\); \( T_{d,m-y}^i \) is the projected temperature (°C) for scenario \( i \) and day \( d \) of month \( m \) \((m = 1, \ldots, 12)\) in year \( y \) \((y = 1, \ldots, 10)\); \( T_{d,m-y} \) is the observed temperature (°C) for day \( d \) of month \( m \) in year \( y \) under recent past climate; \( \Delta T_{m}^i \) is the temperature delta (°C) for scenario \( i \), computed for month \( m \) of year 2060; \( P_{d,m-y}^i \) is the projected precipitation (mm) for scenario \( i \) and day \( d \) of month \( m \) in year \( y \); \( P_{d,m-y} \) is the observed precipitation (mm) for day \( d \) of month \( m \) in year \( y \) under recent past climate; and \( \text{Ratio}_{m-y}^i \) is the precipitation ratio (%) for scenario \( i \), computed for month \( m \) of year 2060.

The modified climate conditions under each scenario were then used to run both hydrological models over the 10-year “modified” validation period, with the corresponding series of calibrated parameter sets. Sixty-eight (68) simulations were therefore executed with HYDROTEL and HSAMI, for each scenario. Of course, the results from those simulations are subject to the (strong) assumption that land occupation will remain unchanged in the future.

4. Results

The analysis of model uncertainty related to parameters and structure is based on three model outputs: simulated streamflows and two internal variables, namely ground water content (GWC) in unsaturated and saturated zones, and snow water equivalent (SWE). GWC and SWE results are presented to better illustrate the impact of model structure, by looking more closely at internal processes and in the spatial simulation scales between the HSAMI and HYDROTEL models (see Section 1). Structure uncertainty is examined from a global point of view, taking into account these two aspects without any particular distinction.

Each one of the following subsections focuses on a particular model output. In each subsection, results are presented for both hydrological models (HYDROTEL and HSAMI), under recent past climate conditions and under modified climate conditions. In the latter case, results for scenarios 2 and 3 only are presented (minimised summer runoff – MinSm, and maximised spring runoff – MaxSp). The results for scenario 4 (minimised spring runoff) are very similar to those obtained for the MinSm scenario in terms of projected hydrological modifications and models behaviours with respect to uncertainty. The same is observed with scenario 1 (maximised summer runoff) and MaxSp.

4.1. Streamflows

4.1.1. Recent past climate

Results from multi-calibration show that both hydrological models are prone to equifinality: several different sets of parameters result in narrow ranges of Nash–Sutcliffe values. This was somehow expected as a consequence of the rather large (although reduced) number of calibration parameters in both cases. The ranges and distributions of Nash values resulting from the 68 calibrations and validations with both models are shown in Fig. 3. From this figure, it can be seen that 97% of HSAMI calibration Nash values are within [0.865, 0.87] (Fig. 3a) and that 100% of HYDROTEL calibration Nash values are within an equally narrow range of [0.848, 0.853] (Fig. 3c). Both models show inferior, but still satisfactory, performances in the validation period (Fig. 3b and d). This may be explained in part by the shorter length of the calibration period relative to the validation period (the choice of the calibration period is further discussed in Section 5.1).

The parameter uncertainty due to equifinality is also clearly illustrated by the simulated streamflows at the Ceizur basin’s outlet, in Fig. 4 (calibration and validation periods). The hydrographs shown in this figure were computed according to the following steps: (1) for every 68 HYDROTEL and HSAMI simulated streamflow series, mean values were generated for each day of the year, over the simulation periods (4 years in calibration, 10 years in validation); (2) then for each model and simulation period, daily minimum and maximum values were taken from the entire set of mean series and plotted in order to obtain streamflow envelopes. Looking at those results, the following observations can be formulated:

- Both hydrological models generally display higher parameter uncertainties in the spring peak flows and in the summer (HSAMI) to mid-fall (HYDROTEL) period.
- The spread of parameter uncertainty is much lower in the winter period with both models and, for both simulation periods (calibration and validation).

The structure uncertainty is shown by the global envelope that encompasses individual envelopes from the HYDROTEL and HSAMI models throughout the year. Fig. 4 shows that under recent past climate the structure uncertainty is more significant than the parameter uncertainty most of the year (except for the mid-fall period where envelopes overlap, although parameter uncertainties remain important). Furthermore, looking at the spread of the global uncertainty envelope, Fig. 4 reveals that the structure uncertainty is generally more pronounced in the winter season (late fall to end of winter), during the spring peak flows, and at the beginning of the summer period.

4.1.2. Modified climate

Fig. 5 shows the parameter and structure uncertainties resulting from the simulated streamflows under the MinSm and MaxSp climate scenarios. These results were generated in the exact same way as those presented in Fig. 4 (see previous subsection), but using the 10-year streamflow series simulated under the two sets of modified climate conditions. The MinSm scenario is the one that yields the most different results relatively to observed recent past streamflows (similar results were also obtained under the mini-
Fig. 3. Distribution of Nash–Sutcliffe values: (a) HSAMI calibration period; (b) HSAMI validation period; (c) HYDROTEL, calibration period; (d) HYDROTEL, validation period.

Fig. 4. Streamflow uncertainty envelopes under recent past climate: (a) calibration period (4-year mean); (b) validation period (10-year mean).

Fig. 5. Streamflow uncertainty envelopes under modified climate conditions: (a) minimised summer runoff scenario (10-year mean); (b) maximised spring runoff scenario (10-year mean).
mised spring runoff scenario; not shown). This is due to the combined effect of drier and warmer conditions with respect to recent past climate, while in the case of the MaxSp scenario the magnitude of climate modifications relatively to recent past climate is less pronounced (see Section 3.3).

Under the (drier) MinSm scenario the parameter uncertainty from both models seems more important in the summer (HSAMI) to mid-fall (HYDROTEL) period. This was also observed under recent past climate conditions. However, for this same scenario, the parameter uncertainty in the spring flood period is generally smaller than that observed under recent past climate (Fig. 4). Under the (wetter) MaxSp scenario, the parameter uncertainty from the HSAMI model shows more intra-annual variability than under the MinSm scenario. Globally, the two hydrology models display similar behaviours to those observed under recent past climate conditions with the structure uncertainty being more significant than the parameter uncertainty almost all year long, except in the fall period where overlap is marked.

4.2. Snow water equivalent (SWE)

Figs. 6 and 7 show the SWE uncertainty envelopes obtained with both hydrology models, for (1) the calibration and validation periods (recent past climate), and (2) the MinSm and MaxSp modified climate scenarios, respectively. The uncertainty envelopes were generated using the same method as for the streamflows (Section 4.1.1), except that since HYDROTEL is a distributed model, mean areal values over all the RHHUs had to be first computed to produce a single data series for each calibrated parameter set and each simulation period. This additional computation step was necessary to produce results that could be compared on similar bases with both hydrology models. This is a direct consequence of the different spatial computational scales (lumped – HSAMI vs. distributed – HYDROTEL), which contribute to the structure uncertainty.

Figs. 6 and 7 show that under recent past and modified climates, the parameter uncertainty is overall less important at the beginning and at the end of the snow season, where the individual envelopes from each model are narrower. As for the simulated streamflows, these results also clearly indicate that the structure uncertainty is more significant than the parameter uncertainty, for almost the entire snow season for all sets of climate conditions (except at the end of the season under recent past climate where the individual envelopes overlap – see Fig. 6). Looking at Figs. 4 and 6, and then at Figs. 5 and 7, it can be seen that the spring flood structure uncertainty is directly related to the SWE results:

- Models behaviours are consistent under all sets of climate conditions in that higher SWEs generate higher spring flood events (upper uncertainty boundaries – HSAMI), and lower SWEs generate lower spring flood events (lower uncertainty boundaries – HYDROTEL).

![Fig. 6. Snow water equivalent uncertainty envelopes under recent past climate: (a) calibration period (4-year mean); (b) validation period (10-year mean).](image1)

![Fig. 7. Snow water equivalent uncertainty envelopes under modified climate conditions: (a) minimised summer runoff scenario (10-year mean); (b) maximised spring runoff scenario (10-year mean).](image2)
- The spread (or structure uncertainty) of SWE resulting from both models is directly proportional to the spread of simulated streamflows. Smaller SWE spread yields smaller spring flood event spread (see the results for the calibration period in Figs. 4a and 6a), and vice versa.

- Under warmer climate conditions (Fig. 7), the peak of the snow season occurs earlier than under recent past climate (Fig. 6). Consistently, snowmelt and the resulting spring flood also occur earlier (up to 1 month earlier in the case of the MinSm scenario, see Figs. 5a and 7a).
4.3. Ground water content (GWC)

Results for GWC are shown in Figs. 8 and 9, under recent past and modified climate conditions, respectively. The uncertainty envelopes were generated using the averaging method described previously (see preceding section and Section 4.1), but with the following difference. In the case of the lumped conceptual model GWC represents the level of water in the unsaturated and saturated zones reservoirs (which both extend to the entire basin). In the case of the distributed physically-based model, the soil moisture data in the unsaturated and saturated zones in each RHHU have been transformed into average water levels across the river basin, taking into account the soil water content at saturation (which is supplied to the model and depends on the soil type).

Figs. 8 and 9 show that, for all four simulation periods (calibration, validation, MinSm and MaxSp), the individual envelopes (parameter uncertainty) and global spread of uncertainty (structure uncertainty) remain very similar. The main difference between recent past climate results and modified climate results is in the time of occurrence of the peaks of GWCs. As for the SWEs, the peaks of GWCs occur up to 1 month earlier under future climate (Fig. 9), and this is mostly related to the warmer temperatures under these conditions. The most significant effect of structure uncertainty is displayed in Figs. 8 and 9, where the simulated water contents in the unsaturated and saturated zones can differ, on average, by a factor of 3–13. This is a direct consequence of the method used, in each model, to simulate the underground internal processes: conceptual reservoirs extending to the basin’s entire area in HSAMI vs. vertical water budget based on every RHHU’s soil properties in HYDROTEL. Since the saturated zone contributes to baseflow, the structure uncertainty observed in the winter recessions and low flows in Figs. 4 and 5 are related to the global spread of uncertainty observed in Figs. 8c, d and 9c, d.

5. Discussion

5.1. Hydrological model calibration period

In Section 3.2, it is said that the 4-year calibration period (October 1988–September 1992) was chosen according to three criteria including its representativeness, in terms of mean annual streamflow, of the entire observed record at the Ceizur watershed’s outlet (1975–2003). Taken individually, each year is within 10% of the mean observed streamflow for the 1975–2003 period. Looking more closely at each year’s behaviour, the mean summer and winter flows (respectively June–October and November–May) are found to be, on average, within ±4% and ±6% of their respective mean values, computed over the entire observation period (wetter and dryer summers than the mean summer are observed while the winters are always slightly wetter than the mean winter). The same mean annual, summer and winter values computed over the validation period are, on average, within −1%, −4% and −0.5% of their respective counterparts for the complete observation period (which means that the calibration period is slightly wetter). In the validation period, wetter as well as dryer years, summers and winters (relatively to their mean counterparts) are observed. Still, the previous statistics indicate that the differences in the hydrological characteristics of the calibration and validation periods remain relatively modest, and that the choice of the calibration period is fairly acceptable, considering the additional constraints related to the length and continuity of this period (see Section 3.2). In particular, several months were required to produce the 68 sets of calibrated parameters with HYDROTEL. Lengthening the calibration period would have resulted in a proportional increase of the computational time. The differences in the computed Nash values for the calibration and the validation periods are certainly explained by the differences in the lengths and in the above mentioned hydrological characteristics of both simulation periods. But in the end, results from the calibration/validation process remain satisfactory.

5.2. Parameter uncertainty

The present study was conducted on a watershed where the snow-driven hydrological processes are predominant. This particular attribute of the studied watershed combined with the use of the Nash–Sutcliffe criteria as the only measure of calibration efficiency may have influenced the parameter uncertainty results. The importance of the spring snowmelt in the annual water volumes has an impact on the Nash values computation, on the parameter sets generated by automatic calibration and consequently on the resulting parameter uncertainty, which happens to be globally less important than model structure uncertainty. Conversely, Wilby (2005) studied a snowless river basin with a simpler hydrologic regime and found that parameter uncertainty could be highly significant in the summer season under modified climate conditions (see Section 1). The results obtained in the present study under the MinSm scenario could possibly suggest a similar behaviour (see Fig. 5a). That issue is intended to be further investigated in future works through the application of the present methodology to snowless watersheds. The use of other calibration efficiency measures (e.g. root mean square error, bias), will also be further investigated. These could also include metrics related to floods, to better reflect the importance of the spring peak flood in the case of snow-dominated watersheds, for instance.

In the present study, calibration parameter values are assumed to remain stable under modified climate conditions. Parameter values might change as a result of climatic changes and this would be an additional source of parameter uncertainty. Investigation of this additional uncertainty could be performed by the calibrations under different sets of conditions (e.g. wet vs. dry years) of the historic record. This refers to parameter identifiability (under different training conditions) as investigated by Wilby (2005) on snowless river basins. In future works, this additional contribution to parameter uncertainty could be investigated on a snow-dominated watershed such as the one examined in the present study. That said, this paper shows that the uncertainty due to parameter equifinality seems to remain stable under future climate conditions. A key element is that this behaviour is observed for each individual climate projection (i.e. each case of future scenario taken separately) under contrasted modified conditions.

5.3. Hydrological model structure

Overall, the results obtained in this study suggest that the impact of hydrological model structure uncertainty is more significant than the effect of parameter uncertainty. In other words: the structure’s effect is revealed when the individual envelopes from both hydrological models (HYDROTEL and HSAMI) generate a larger band than the largest envelope resulting from a single model. Looking at the streamflow envelopes in Figs. 4 and 5, the structure’s effect is not fully apparent since models’ individual envelopes merge in some periods of the year. However, the structure uncertainty is clearly revealed in Figs. 6–9 where internal hydrological variables (SWE and GWC) are considered. SWE and GWC results were not presented with the intention to draw any conclusions about which model better reproduces these “un-observable” variables. This would involve comparing the models performances which is not among the objectives of the present study (see Section 1). Rather, this paper focuses on a typical application of two different hydrology models with streamflow-based
calibration, where SWE and GWC are used to further illustrate the impact of model internal structure in this type of application.

Ultimately, the use of hydrological models with different levels of complexity remains part of the uncertainty related to hydrological modelling. This point is important as it represents the main novelty of the present paper. No previous study had clearly revealed the predominant impact of using very different hydrological models in terms of internal structure, in climate change impact studies.

5.4. Number of calibration parameters vs. number of calibrations

To clearly bring out the impact of parameter and structure uncertainties, results from both hydrology models have been generated with the same numbers of (1) calibration parameters, and (2) automatic calibrations. As mentioned in Section 3.2, limits on these numbers (respectively 12 and 68) were imposed by the computational time required to automatically calibrate the physically-based HYDROTEL model. But since computational time was not a limiting factor with the conceptual model (HSAMI), two additional calibration experiments were conducted with this single model: (1) all 23 parameters were repeatedly calibrated 1000 times; and (2) the 12 parameters selected in Section 3.2 were repeatedly calibrated 1000 times (following the procedure described in Section 3.2). As expected, the parameter uncertainty increases with increasing numbers of calibration parameters and/or calibrations. However, the impact of the number of parameters on the spread of the uncertainty envelopes is more significant. Whether similar conclusions could be drawn from analogous experiments with the physically-based model still needs to be assessed. However, these results suggest that even if additional calibrations were performed, the general results and conclusions from this study would not be drastically modified.

6. Conclusions

This paper has investigated two different aspects of the uncertainty related to hydrological modelling in the context of climate change impact studies: (1) parameter uncertainty due to equifinality (or multi-calibration uncertainty); and (2) internal structure uncertainty through the use of a lumped conceptual model and a spatially distributed physically-based model. In this context, uncertainty is defined as the spread of hydrological model simulations resulting from multiple calibrated parameter sets and from both hydrological models. The analysis has been applied to a snow-dominated watershed located in the province of Quebec (Canada), under recent past climate and under two distinct climate projections (two contrasted scenarios examined individually: minimised summer runoff and maximised spring runoff).

The main results from this study indicate that:

- Hydrological model structure uncertainty is more significant than parameter uncertainty.
- Parameter uncertainty under future climate conditions remains very similar to that obtained under recent past climate, for both hydrological models, and under the two scenarios of modified climate. Therefore, it can be assumed that (within the context of the present study) anyone of the calibrated parameter sets obtained from the multiple calibrations could be used to generate streamflows under a changed climate with no major contribution to uncertainty (compared to the uncertainty from the type of model).

As a final remark, the use of hydrological models with different levels of complexity should be considered as part of the global uncertainty related to hydrological impact assessment studies. Conceptual models are easier to implement, while more physical models can better represent the real world (e.g. Wilby, 2005; Jones et al., 2006). In a global river flow management perspective, both types of models can yield reliable results. Research works should therefore focus on analysing and better quantifying hydrological model structure and parameter uncertainty. Results presented in this paper will definitely be further validated on additional river basins with different hydrological regimes, and using other conceptual and physically-based hydrological models.

Acknowledgements

The authors wish to thank Mr. Dominique Tapsoba from the Institut de recherche d’Hydro-Québec for providing the Gatineau watershed’s meteorological grid, and Mrs. Diane Chaumont from Ouranos for providing the data that were used to build the climate projections. Financial support for this research was provided by the National Scientific Research Council of Canada, Ouranos, Hydro-Québec, Manitoba Hydro and the Fonds québécois de la recherche sur la nature et les technologies.

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