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**EQUIFINALITY AND AUTOMATIC CALIBRATION, WHAT IS THE IMPACT OF
HYPOTHESIZING AN OPTIMAL PARAMETER SET ON MODELLED HYDROLOGICAL
PROCESSES?**

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Keywords :calibration, equifinality, hydrological model, HYDROTEL, objective function,
parameter uncertainty

1 Abstract

2 Accepting the concept of equifinality may result in larger uncertainty associated with model
3 predictions than that of the optimal parameter set paradigm. ~~Depite~~Despite the existence of
4 uncertainty ~~earacterisation~~characterization methods, the semi-distributed hydrological model
5 HYDROTEL has been used within the latter paradigm. What is the impact of
6 ~~hypothetizing~~hypothesizing an optimal parameter set? This paper focuses on the assesment of
7 the impact of equifinality of calibration parameters with respect to modelled hydrological
8 variables and indices, namely: (i) daily flows; (ii) seasonal seven- and thirty-day low flows;
9 and maximum flow; (iii) snow water equivalent (SWE); (iv) shallow ground water
10 variations; and (v) actual evapotranspiration. This assessment is presented for ten southern
11 Québec watersheds of the St. Lawrence River. The watershed models ~~are~~were calibrated and
12 validated for 1982-1991 and 1991-2002, respectively. Automatic calibration ~~is~~was performed
13 using the Dynamically Dimensioned Search (DDS) algorithm based on the maximization of
14 two objective functions (OFs): (i) the Kling-Gupta efficiency; and (ii) the Nash-log. DDS was
15 executed to calibrate 12 hydrological parameters for one optimization trial for each watershed
16 and each OF with a budget of 5000 model runs. To analyse ~~the~~-parameter uncertainty and
17 resulting equifinality, 250 sets of parameters were extracted from each trial run. Calibration
18 performances for both OFs were between 0.75 and 0.95, while the selected 250 best sets of
19 parameters had OF values differing by less than 1%. Results ~~show~~showed that the overall OF
20 uncertainty was ~~more important~~larger than the parameter uncertainty for all modelled
21 processes except the SWE. Nevertheless, seasonal results ~~suggests~~suggested ~~that~~-parameter
22 uncertainty ~~can~~could be greater than OF uncertainty for specific seasons or years, although it
23 was not possible to make a general outcome stand out. In particular for impact studies where

24 the variables of interest are not daily flows but rather hydrological indices or variables,
25 parameter uncertainty will need to be accounted for.

26 **Résumé**

27 Accepter l'existence du concept d'équifinalité c'est reconnaître l'incertitude liée à l'existence
28 d'une famille de solutions donnant des résultats de qualité similaire obtenus avec la même
29 fonction objectif. Malgré l'existence de méthodes de caractérisations de cette incertitude, le
30 modèle hydrologique HYDROTEL a été principalement utilisé jusqu'à maintenant selon le
31 paradigme du calage optimal unique sans évaluer *a posteriori* les conséquences de ce choix.
32 Cette étude propose d'évaluer l'impact du choix du jeu de paramètres optimisés sur certaines
33 variables et indicateurs hydrologiques simulés, à savoir: (i) les débits journaliers; (ii) les
34 débits d'étiage à 7 et 30 jours et les débits maximum; (iii) l'équivalent en eau de la neige
35 (EEN), (iv) les variations du contenu en eau du sol peu profond; et (v) l'évapotranspiration
36 réelle. Dans ce contexte, HYDROTEL est mis en place sur dix bassins versant du Québec
37 méridional entre 1982 et 2002. Pour chacune des fonctions objectif (FO) (Kling Gupta
38 efficiency et Nash-log) et chacun des bassins, l'algorithme *Dynamically Dimensioned Search*
39 (DDS) dispose d'un budget de 5000 répétitions pour optimiser les 12 paramètres de calage
40 d'HYDROTEL sur 1981-1991. Ainsi, 250 jeux de paramètres sont conservés pour évaluer
41 l'incertitude paramétrique et l'équifinalité résultante. Les résultats de calage indiquent des
42 fonctions objectif comprises entre 0,75 et 0,95, tandis que pour chaque modèle les 250
43 meilleures répétitions présentent des fonctions objectif égales à 1% près. Globalement, pour
44 tous les processus simulés excepté pour l'EEN, l'incertitude relative aux FO était plus
45 importante que celle relative aux jeux de paramètres. Cependant, les résultats saisonniers
46 suggèrent que l'incertitude paramétrique peut dépasser celle due aux FO dans certaines
47 conditions particulières. Elle devra donc être prise en compte, en particulier pour les études

48 d'impacts et de risque hydrologique dont les variables d'intérêt sont principalement des
49 indicateurs hydrologiques simulés et non pas les débits journaliers.

50

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51 **Introduction**

52 The equifinality concept refers to the existence of many parameter sets (and multiple model
53 structures) associated with the same ‘optimal’ measure of efficiency (Beven 2006a; Beven
54 and Freer 2001). Within a realistic parameter space, for a given mechanistic model of a
55 complex environmental system, many local optima may exist. Despite the computational
56 costs, equifinality has been revealed for many types of models and especially for rainfall-
57 runoff models (Beven 1993; Beven and Binley 1992; Duan *et al.* 1992; Fu *et al.* 2015; Futter
58 *et al.* 2015; Li *et al.* 2012; Linhoss *et al.* 2013; Prada *et al.* 2016; Romanowicz *et al.* 1994;
59 Zeng *et al.* 2016; Zhang *et al.* 2012).

60 The main consequence of accepting the concept of equifinality is that the uncertainty
61 associated with model predictions might be larger than that assessed within the optimal
62 parameter set paradigm. Different types of approaches allow to deal with such an uncertainty
63 (Vrugt *et al.* 2009a). Some approaches have their roots within a formal statistical (Bayesian)
64 framework, but require in-depth understanding of mathematics and statistics as well as
65 experience in implementing (Fisher and Beven 1996; Freer *et al.* 1996) these methods on
66 computers (Vrugt *et al.* 2009b). This probably explains the success of the generalized
67 likelihood uncertainty estimation (GLUE) method of (Beven and Binley 1992). It operates
68 within the context of Monte Carlo analysis coupled with Bayesian or fuzzy estimation and
69 propagation of uncertainty. It is relatively easy to implement and requires no modifications to
70 existing codes of simulation models. More recently, Tolson and Shoemaker (2007) presented
71 how the dynamically dimensioned search (DDS) optimization algorithm could replace random
72 sampling in typical applications of GLUE. They also introduced a more efficient uncertainty
73 analysis methodology called DDS-approximation of uncertainty (DDS-AU) that differs from
74 the automatic calibration and uncertainty assessment using response surfaces (ACUARS)

75 methods (Mugunthan and Shoemaker 2006). The former approach requires many optimisation
76 trials while the latter approach uses only one trial coupled with a declustering technique.

77 The idea of an optimal parameter set remains strong in environmental sciences and even
78 stronger in hydrological modelling. For a physically-based, semi-distributed, model such as
79 HYDROTEL (Bouda *et al.* 2014; Bouda *et al.* 2012; Fortin *et al.* 2001b; Turcotte *et al.*
80 2007a; Turcotte *et al.* 2003), this frame of mind is rooted in two perceptions: (i) multiple
81 feasible descriptions of reality lead to ambiguity and are possibly viewed as a failure of the
82 modelling exercise (Beven 2006a); and (ii) a manual search for an “optimum” is already
83 computationally expensive (Turcotte *et al.* 2003) while an automatic search may provide only
84 a slight increase in model efficiency in comparison with the latter manual calibration (Bouda
85 *et al.* 2014). This is why in the last decade, at the risk of avoiding important issues of model
86 acceptability and uncertainty (Beven 2006a), HYDROTEL has almost always been applied
87 within the optimal parameter set paradigm.

88 For example, in several studies (Aissia *et al.* 2012; Fortin *et al.* 2001a; Fossey and Rousseau
89 2016a, 2016b; Fossey *et al.* 2015; Fossey *et al.* 2016; Khalili *et al.* 2011; Minville *et al.* 2009;
90 Oreiller *et al.*; Quilbé *et al.* 2008; Rousseau *et al.* 2013), HYDROTEL has been manually
91 calibrated following the four-step, trial-and-error, process-oriented, multiple-objective
92 calibration strategy introduced by Turcotte *et al.* (2003). It has also been calibrated using the
93 shuffled complex evolution algorithm (SCE-UA) designed by Duan *et al.* (1993) to find the
94 optimal set of parameters while avoiding local optima (Bouda *et al.* 2014; Gaborit *et al.* 2015;
95 Ludwig *et al.* 2009; Ricard *et al.* 2013; Trudel *et al.* 2016). But two exceptions emerge from
96 the literature, Bouda *et al.* (2012); Poulin *et al.* (2011) both used the SCE-UA algorithm to
97 generate multiple parameter sets and assessed the uncertainty of hydrological modelling under
98 the equifinality assumption. Poulin *et al.* (2011), based on one snow-dominated watershed,
99 concluded that model uncertainty (conceptual models *versus* more physical-based models for

100 example) can be more significant than parameter uncertainty. Meanwhile, Bouda *et al.*
101 (2012), from their work on two watersheds, stressed the need for further research that may
102 lead to the implementation of a systematic uncertainty analysis in an operational hydrological
103 forecasting system. Nevertheless, they both highlighted the need for additional validation of
104 their results on additional watersheds.

105 It is important to mention that the technico-philosophical debate started in 2006 (Beven 2006b,
106 2008) about the methods that should or should not be used to estimate the uncertainties
107 associated with hydrological forecasting is beyond the scope of this paper. Indeed, the debate
108 is still ongoing about the relative performances of formal (DREAM) and informal (GLUE)
109 Bayesian approaches in estimating the consequences of equifinality (Beven 2009; Vrugt *et al.*
110 2009b, 2009c) and about the multiple sources of uncertainty and non-stationarity in the
111 analysis and modelling of hydrological systems (Beven 2016; Nearing *et al.* 2016). In this
112 paper, equifinality is simply explored through the implementation of the automatic calibration
113 algorithm DDS (~~Dynamically Dimensioned Search~~) (Tolson and Shoemaker 2007), which has
114 been reported as being superior to SCE-UA (Arsenault *et al.* 2014; Yen *et al.* 2016). Our
115 contribution builds on the work carried out on hydrological uncertainty to show in practical
116 terms why equifinality does need to be taken into account by answering one simple question
117 taken out of the technico-philosophical debate: what are the consequences of not accounting
118 for equifinality while calibrating HYDROTEL for an environmental impact study? Here,
119 hydrological uncertainty (defined by the spread resulting from multiple calibrations) is
120 assessed for five modelled hydrological variables and indices: (i) daily flows, (ii) seasonal
121 hydrological indices such as the seven-day low flow (7d-Qmin), 30-day low flow (30d-
122 Qmin), and the maximum flow (Qmax), (iii) snow water equivalent (SWE), (iv) shallow
123 ground water content variations (GWC) and (v) actual evapotranspiration (AET). Innovation
124 resides in three elements. A calibration strategy close to that of manual calibration was used

125 in order to demonstrate the need to account for equifinality in impact assessment studies aside
126 from the technico-philosophical debate started in 2006. Moreover, using 10 watersheds across
127 Québec avoided limiting the significance of the results to a specific region. Last, the relative
128 importance of OF uncertainty and parameter uncertainty were differentiated according to the
129 variable being considered and its temporal scale (yearly or seasonal).

130 The next two sections of this paper introduce the modelled watersheds and the methods; the
131 ~~third section introduces the~~ results and ensuing discussions. Throughout the paper, ~~the readers~~
132 should keep in mind that the results do not aim at assessing the formal statistical uncertainty
133 associated with the hydrological processes, but rather at showing the concrete consequences
134 of equifinality on modelled hydrological processes

135 Study area and data

136 This study was carried out in southern Québec (Canada) on ten watersheds spread out in five
137 hydrographic regions of the St. Lawrence River ([Figure 1](#)~~Figure 1~~). These ten watersheds,
138 namely (i) Batiscan, (ii) Bécancour, (iii) Chamouchouane, (iv) Châteauguay, (v) Chaudière,
139 (vi) Du Loup, (vii) Gatineau, (viii) Mistassini, (ix) Rouge, and (x) Yamaska have modelled
140 drainage areas ranging from 855 up to 15,042 km² and various land cover patterns. Table 1
141 ~~shows indicates that all the~~ watersheds, but Yamaska, have a forested (evergreen + deciduous
142 trees) area ~~that represents covering~~ more than 90% of the modelled land cover. Yamaska is the
143 only watershed with a significant portion of urban area. Batiscan has over 40% of evergreen
144 while Gatineau, Chaudière, Rouge and Du Loup have 17, 21.5, 25.6 and 28.4% of evergreen,
145 respectively, and the remaining five watersheds have an evergreen area representing less than
146 10% of their total land cover. It is also noteworthy that Châteauguay, Bécancour and
147 Chaudière have 17.0, 8.2 and 3.9% of cropland while the remaining seven watersheds have
148 less than 1%.

149 According to available meteorological data (1981-2002, 1995 and 1996 being unavailable)
150 from National Resources Canada, the region surrounding the St. Lawrence River delineated in
151 [Figure 1](#)~~Figure 1~~ (-78 : -70; 45 : 52) is characterized by a mean annual temperature of 1.8°C
152 and mean annual total precipitation of 940 mm. All watersheds are snow-dominated with peak
153 flow occurring in spring. A summary of the hydroclimatic characteristics of the watersheds is
154 provided in [Table 2](#)~~Table 2~~ and [Table 3](#)~~Table 3~~ for two hydrological seasons, that is summer
155 (June; 1st to November; 30th) and winter (December; 1st to May; 31st). While the mean
156 summer rainfall is 545 mm and quite homogenous among the watersheds (standard deviation
157 of 30 mm), mean winter rainfall is more heterogeneous with a mean of 208 mm and a
158 standard deviation of 64 mm. Meanwhile, mean snowfall is 271 mm with a standard deviation
159 of 52 mm. Mean summer (10.8°C) and winter (-4.8°C) temperatures are also quite variable

160 with respective standard deviations of 1.8 and 2.8 °C. This shows that in terms of climate
 161 characteristics, the studied watersheds are quite heterogeneous. In terms of hydrological
 162 characteristics, mean summer and winter daily flows are 1.2 and 1.9 mm, respectively, with
 163 standard deviations of 0.44 and 0.23. Winter flows are higher than summer flows on average
 164 because winter includes the snow melt and thus the spring peak flows. Higher variability in
 165 the summer flows is attributed to summer rainfall and convective storms that are more
 166 variable than snowfalls. The hydrological indices mean values indicate that the watersheds,
 167 despite being somewhat located along the St. Lawrence River, have heterogeneous
 168 characteristics with mean 7d-Qmin ranging from 2 up to 156 m³s⁻¹ and from 4 to 120 m³s⁻¹ for
 169 summer and winter, respectively. Heterogeneity is even higher for mean Qmax; ~~that~~
 170 ~~rangeranging~~ from 29 up to 595 m³s⁻¹ and from 84 to 1350 m³s⁻¹ for summer and winter,
 171 respectively.

172 <[Table 1: Land cover of the ten studied watersheds in southern Québec, Canada](#)~~Table~~
 173 ~~1: Land cover of the ten studied watersheds in southern Québec, Canada~~>

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174 **Figure 1: Location of the study watersheds in Québec, Canada, and around the St.**
 175 **Lawrence River**

176 <[Table 2: Summary \(1982-2002\) of the climate characteristics of the study](#)
 177 ~~watersheds~~[Table 2: Summary \(1982-2002\) of the climate characteristics of the study](#)
 178 ~~watersheds~~>

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179 <[Table 3: Summary \(1982-2002\) of the hydrological characteristics of the study](#)
 180 ~~watersheds~~[Table 3: Summary \(1982-2002\) of the hydrological characteristics of the](#)
 181 ~~study watersheds~~>

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182 **Material and Methods**

183 **Hydrological model**

184 HYDROTEL is a process-based, continuous, semi-distributed hydrological model (Bouda *et al.* 2014; Bouda *et al.* 2012; Fortin *et al.* 2001b; Turcotte *et al.* 2007a; Turcotte *et al.* 2003)
185 *al.* 2014; Bouda *et al.* 2012; Fortin *et al.* 2001b; Turcotte *et al.* 2007a; Turcotte *et al.* 2003)
186 that is currently used for inflow forecasting by Hydro-Quebec, Quebec's major power utility,
187 and the Quebec Hydrological Expertise Centre (CEHQ) which is in charge of the
188 management and safety of publicly owned dams (Turcotte *et al.* 2004). It was designed to use
189 available remote sensing and GIS data and use either a 3-hour or a daily time step. It is based
190 on the spatial segmentation of a watershed into relatively homogeneous hydrological units
191 (RHHUs, elementary subwatersheds or hillslopes as desired) and interconnected river
192 segments (RSs) draining the aforementioned units. A semi-automatic, GIS-based framework
193 called PHYSITEL (Noël *et al.* 2014; Rousseau *et al.* 2011; Turcotte *et al.* 2001) allows easy
194 watershed segmentation and parameterization of the hydrological objects (RHHUs and RSs).
195 The model is composed of seven computational modules, which run in successive steps. Each
196 module simulates a specific ~~hydrological~~ process (meteorological data interpolation,
197 snowpack dynamics, soil temperature and freezing depth, potential evapotranspiration,
198 vertical water budget, overland water routing, channel routing). ~~and the reader~~ Readers is are
199 referred to Fortin *et al.* (2001b) and Turcotte *et al.* (2007a) for more details on these aspects
200 of HYDROTEL.

201 The main parameters of HYDROTEL can be subdivided into three groups ~~presented in (see~~
202 Table 4 ~~Table 4~~). The first group includes the snow parameters and the second group includes
203 the soil parameters. The last three individual parameters are related to the interpolations of
204 temperature and precipitation according to the average of the three nearest meteorological
205 stations weighed in by the square of the inverse distances between the RHHU and the three
206 stations (a.k.a. the Reciprocal-Distance-Squared method).

207 <[Table 4: HYDROTEL key parameters](#)>~~Table 4: HYDROTEL key parameters~~

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208 **Data acquisition**

209 Observed climate data for 1981-2002 were computed on a 0.75° x 0.75° grid by isotropic
210 kriging following the method described in Poirier *et al.* (2012) using the meteorological data
211 provided by National Resources Canada. Each grid-point served as a meteorological station in
212 HYDROTEL. Flow data were extracted from the CEHQ data base; which operates around
213 230 hydrometric stations (CEHQ, 2012). Stations were selected for their data availability and
214 proximity to the outlets of the watersheds. For Batiscan (#050304 [-72.4° long., 46.6° lat]),
215 Bécancour (#024007 [-72.3° long., 46.2° lat.]), Châteauguay (#030905 [-73.8° long., 45.3°
216 lat.]) and Rouge (#040204 [-74.7° long., 45.7° lat.]), stations were located at the outlet of each
217 watershed while for Chamouchouane (#061901 [-72.5° long., 48.7° lat.]), Chaudière
218 (#023402 [-71.2° long., 46.6° lat.]), Du Loup (#052805 [-73.2° long., 46.6° lat.]), Gatineau
219 (#040830 [-75.8° long., 47.1° lat.]), Mistassini (#062102 [-72.3° long., 48.9° lat.]) and
220 Yamaska (#030304 [-72.9° long., 45.5° lat.]), the nearest stations were selected (see [Figure](#)
221 [1](#)).

222 **Calibration/validation and parameter sets generation**

223 ~~The calibration of HYDROTEL for~~ Model calibration on each watershed was carried out using
224 a global optimization algorithm, ~~dynamically dimensioned search (DDS)~~ presented in Tolson
225 and Shoemaker (2007). It allows systematic and impartial calibration of HYDROTEL through
226 all the watersheds using a fixed methodology. The shuffled complex evolution (SCE)
227 algorithm (Duan *et al.* 1992; Duan *et al.* 1994; Duan *et al.* 1993) was also considered; viewed
228 as the dominant optimization algorithm before 2007 with more than 300 different applications
229 referring to the original set of SCE papers. However, it has since been proved that DDS is
230 better suited for distributed watershed models requiring extensive computational time
231 ([Arsenault *et al.* 2014; Tolson and Shoemaker 2007; Yen *et al.* 2016.](#) ~~Indeed,~~ DDS performs

232 a low number of model evaluations before converging to a good calibration solution
 233 (~~Arsenault et al. 2014; Tolson and Shoemaker 2007; Yen et al. 2016~~). According to Yen et al.
 234 (2016), DDS outperforms other optimization techniques in both convergence speed and
 235 searching ability for parameter sets that satisfy statistical guidelines (~~Moriasi et al. 2007~~)
 236 while requiring only one algorithm parameter (perturbation factor, default value 0.2) in the
 237 optimization process. This default value was used in this paper.

238 Automatic calibration was performed based on the maximization of four objective functions
 239 (OFs) computed from observed flow data: (i) Kling-Gupta efficiency (KGE); (ii) Nash-log;
 240 that is the Nash-Sutcliffe efficiency (NSE) calculated on log transformed flows; (iii) NSE_Q
 241 and (iv) NSE_{√Q} computed on root squared flows. DDS was executed for one optimization trial
 242 for each watershed and each OF with a budget of 5000 model runs - the trial was initiated
 243 from the same random set of parameter values for every watershed. To analyse the parameter
 244 uncertainty and resulting equifinality, the 250 sets of parameters resulting in the best OF
 245 values were extracted from each trial run. Then each model was run over a validation period
 246 using the corresponding 250 sets of parameters (10 models times 4 OFs). However, this paper
 247 solely focused on two of the four OFs studied namely KGE and Nash-log because including
 248 the two other ~~OFs-functions~~ would not help distinguishing the dominant type of uncertainty.
 249 Indeed, overall results for NSE are close to KGE results except around peak flows (*Gupta et*
 250 *al.*, 2009) while NSE_{√Q} represents a tradeoff between KGE and Nash-log. ~~Plus, KGE is~~
 251 ~~currently the most used OF in hydrological model calibration and u~~Using the combination of
 252 KGE and Nash-log provides a contrasted calibration procedure that in turn favors high flows
 253 and low flows.

254
$$KGE = 1 - \sqrt{(r - 1)^2 + (\alpha - 1)^2 + (\beta - 1)^2} \quad \text{Eq 1}$$

 255 where r is the linear correlation coefficient between simulated and observed values; α is a
 256 measure of relative variability in the simulated and observed values, that is the ratio between

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257 simulated and observed standard deviations; and β stands for the bias, that is the ratio between
 258 the mean simulated and mean observed flows.

$$259 \text{ **Nash-log} = 2 \cdot \alpha_{\log} \cdot r_{\log} - \alpha_{\log}^2 - \beta_{\log n}^2** \text{ Eq 2}$$

260 where α_{\log} and r_{\log} are the linear correlation coefficient and measure of relative variability
 261 between the log transformed simulated and observed flows, respectively; and $\beta_{\log n}$ stands for
 262 the ratio between the bias of log transformed simulated and observed flows, normalized by
 263 the standard deviation of observed values.

264 The calibration period extended from December 1st, 1982 to November 30th, 1991; that is nine
 265 entire hydrological years. The validation period started on December 1st, 1991 and ended on
 266 November 30th, 2002 (remembering that the 1995-1996 meteorological data series were
 267 unavailable); that is eight complete hydrological years (hydrological years 1994 – December
 268 1st, 1994 to November 30th, 1995, and 1995 –December 1st, 1995 to November 30th, 1996
 269 were unavailable), corresponding to nine summers and eight winters (January to the end of
 270 May 1997 is used as a spin-up to make sure that the model is on the right track). In each case,
 271 a 1-year spin-up period was used to minimize initialization errors. During the 1995-1996
 272 meteorological data gap, the model was fed with data from 1993-1994 to prevent the rivers
 273 from drying out. These simulation periods (calibration and validation) simply resulted from
 274 following the split-sample strategy applied to the available meteorological and hydrological
 275 data. The length of the calibration period was not so long as to increase computational costs
 276 too much, but not so short as to have issues related to the interannual variability of climate
 277 data compared with the validation period. Figure 2 illustrates the appropriateness of this
 278 approach in terms of mean annual and seasonal temperatures and precipitations. As seen
 279 the For the calibration and validation, the simulation periods are were relatively similar:
 280 precipitations and temperatures are within [614; 911 mm] and [-1; +6°C], and [646; 845
 281 mm] and [-0.2; 6.4°C], for the calibration and validation periods, respectively.

282 | Out of the eighteen (18) key calibration parameters ([Table 4](#)~~Table 4~~), twelve (12) were
283 | actually adjusted in this study: six (6) snow parameters; five (5) soil parameters; and one (1)
284 | interpolation coefficient. Sensitivity analyses were not formally carried out for any of the
285 | watersheds beforehand, but these calibrated parameters are amongst the model most sensitive
286 | parameters (Turcotte *et al.* 2003). This selection of parameters was based on: (i) information
287 | provided by previous analyses (Ben Nasr 2014; Bouda *et al.* 2014), (ii) knowledge built
288 | through the operational use of HYDROTEL (Turcotte *et al.* 2004) and (iii) experience gained
289 | during the development of a ~~hydroclimatic~~ Hydroclimatic Atlas conveying the potential
290 | impact of climate change on water resources for the 2050 horizon over Southern Québec
291 | (CEHQ 2013, 2015). The remaining parameters were fixed according to: (i) a regionalization
292 | study (Turcotte *et al.* 2007b), (ii) results from the application of a global calibration strategy
293 | (Ricard *et al.* 2013) used in CEHQ (2013, 2015), and (iii) from previous manual calibration
294 | exercises.

295 | **Figure 2: Relationship between mean annual and seasonal temperatures and**
296 | **precipitations for the calibration and validation periods**

297

298 **Results**

299 As previously mentioned model uncertainty related to parameters used for the calibration of
300 HYDROTEL and to the choice of the OF was assessed through five modelled hydrological
301 variables and indices: (i) modelled streamflows, (ii) hydrological indices computed from the
302 latter, and three internal variables, namely (iii) snow water equivalent (SWE), (iv) actual
303 evapotranspiration (AET) and (v) shallow ground water content variations (GWC). In this
304 paper, parameter equifinality refers to the range that each calibration parameter covers within
305 the predefined physical limits attributed to each parameter. Meanwhile parameter uncertainty
306 refers to the consequences of parameter equifinality with respect to the model outputs.
307 Finally, OF uncertainty refers to the effects of using two different functions on the model
308 outputs. For each subsection, a different watershed is used as a showcase while the other nine
309 and their related figures are referred to as alternate watersheds and available as supplemental
310 information upon request to the corresponding author. This choice was made to focus on the
311 global picture ~~recounted~~ conveyed by this paper instead of focusing on the characteristics of a
312 single watershed.

313 **Parameter equifinality**

314 Figure 3 shows the range covered by the 250 sets of parameters used in setting up the 20
315 models in HYDROTEL. The figure was computed by putting together for each model a radar
316 plot of the calibration parameter values. For every set of parameters, a line ~~is was~~
317 link every individual parameter. The computation of the 250 lines ~~makes made~~
318 picture the range covered by the selected sets of parameters within a predefined physical
319 interval that limits the automatic calibration algorithm. These limits were based on the
320 information provided by previous sensitivity analyses, operational experience, and previous
321 calibration exercises.

322 For most watershed models, the parameter equifinality is limited. Indeed, parameter
323 equifinality for the Batiscan watershed, for the KGE OF, covers a maximum of 9.2% of the
324 physical range for the deciduous melting threshold parameter (C in Figure 3), but about 5%
325 for the rain/snow limit (A in Figure 3) for example. The maximum parameter equifinality is
326 obtained for the evergreen melting threshold on the Yamaska watershed for the KGE OF with
327 an equifinality covering 45.6% of the physical range. Overall, the “most equifinal parameters”
328 are the evergreen melting rate (B in Figure 3) and threshold (E in Figure 3).

329 **Figure 3: Radar plots of the twelve parameters used in the automatic calibration of**
330 **HYDROTEL for each study watershed. Parameter A is part of the interpolation**
331 **coefficients, parameters B through G relate to the snow model, and parameters F**
332 **through L relate to the soil group of parameters. The dark blue diagrams refer to the**
333 **KGE objective function OF while the light blue diagrams refer to the Nash-log OF.**

334 Streamflows

335 A tangible evidence of the equifinality of the 20 models is displayed by the narrow ranges of
336 OF values resulting from the 250 calibrations and validations. This was expected despite the
337 careful consideration given to the number of calibration parameters used to avoid over
338 parametrization and limit the possibility of equifinality. [Figure 4](#) shows the KGE and
339 Nash-log values obtained in calibration and validation for the Chamouchouane watershed.
340 KGE as well as Nash-log calibration values belong to equally narrow ranges [0.9464_± 0.9472]
341 and [0.9064_± 0.9072]. For the validation period, ranges are larger, but still quite narrow with
342 100% and 68% of KGE and Nash-log values fitting in the equally narrow ranges [0.8225_±
343 0.8305] and [0.6340_± 0.6420], respectively. Model performances are not as good in validation
344 as in calibration. But as [Table 6](#) shows, differences in performances overpass a 15%
345 difference only three times out of the 20 models. Moreover, the validation period
346 performances either increase as well or as decrease in comparison with calibration values, and

347 that vouches for the split-sample strategy chosen. Indeed, [Table 6](#) introduces the
348 median loss of performances computed from the individual losses of each of the 250
349 calibrations/validations which are different from what could be computed from [Table 5](#)
350 [5](#).

351 [Table 5](#) shows that results of [Figure 4](#) are also valid for the alternate
352 watersheds included in this paper. Indeed, for the calibration period, both KGE and Nash-log
353 values can be constrained in a 0.01 interval while, for the validation period, ~~values they~~ are
354 within a 0.15 interval. What is notable is that ranges seem larger for the Nash-log than for the
355 KGE OFs. Also, the performances in calibration using the Nash-log OF are lower; whereby
356 the mean of the KGE values is 0.916, the mean of the Nash-log values is 0.840. ~~In For~~
357 validation, this gap widens with a mean KGE of 0.823 and a mean Nash-log of 0.679. This
358 important difference may be attributed to the relative inability of Nash-log to represent high
359 flows. Indeed, high flows are less correctly ~~assessed-reproduced~~ by Nash-log ~~than when~~ low
360 flows are assessed using the KGE OF. This explains the observed difference in performances.

361 The simulated streamflow envelopes shown in [Figure 5](#) clearly illustrate parameter
362 uncertainty with respect to [the](#) Rouge watershed. The hydrographs were computed according
363 to the following steps: (i) for every 250 simulated flow series, mean values were generated for
364 each day of the year, over the calibration (9 hydrological years) and validation periods (8
365 hydrological years); (ii) then for each model and simulation period, daily minimum and
366 maximum values were taken from the entire set of mean series and plotted in order to obtain
367 streamflow envelopes. As depicted in [Figure 5](#) ~~which introducing-introduces~~ the
368 individual streamflow uncertainty envelopes for the alternate watersheds, the impact of
369 parameter uncertainty is:

370 - small (most of the time under 0.1 mm/day) for both simulation periods and OFs,

371 - concentrated around the spring peak flow for the Nash-log OF (reaching a maximum
372 of 1mm/day).

373 The OF uncertainty is shown by the global envelope that encompasses individual bands
374 associated with the KGE and Nash-log series of modelled streamflows. ~~Figure 5~~ and
375 alternate figures show that OF uncertainty is more important than parameter uncertainty most
376 of the year (except during the recession of the spring peak flow where the envelopes overlap).
377 Moreover, the spread of the global envelope for the ten watersheds reveals that OF
378 uncertainty is generally more pronounced in the fall and the spring peak flows.

379 **Figure 4: Distribution of the OF values for the Chamouchouane watershed: (a) KGE**
380 **calibration period; (b) KGE validation period; (c) Nash-log calibration period; (d) Nash-**
381 **log validation period**

382 ~~<Table 5: Summary of the KGE and Nash-log values for the ten watersheds over the~~
383 ~~calibration and validation periods>~~
384 ~~Table 5: Summary of the KGE and Nash-log values~~
385 ~~for the ten watersheds over the calibration and validation periods>~~

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386 ~~<Table 6: Median of the KGE and Nash-log loss of performance (positive values)~~
387 ~~between the calibration and validation periods>~~
388 ~~Table 6: Median of the KGE and Nash-~~
389 ~~log loss of performance (positive values) between the calibration and validation periods>~~

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388 **Figure 5: Streamflow uncertainty envelopes for the Rouge watershed: (a) calibration (9-**
389 **year mean) and (b) validation periods (8-year mean). The black and green envelopes**
390 **respectively stand for simulated flows under the KGE and Nash-log objective**
391 **functions** ~~OFs, respectively~~, while the blue line depicts the observed values.

392

393 Hydrological indices

394 [Figure 6](#) introduces, for the Chamouchouane watershed the boxplots of the seasonal
395 hydrological indices for each OF. The two boxplots per year represent the parameter
396 uncertainty (250 sets of parameter) for the KGE and Nash-log OFs for each hydrological
397 index. The reunion of the two boxplots represent the OF uncertainty. Results do not show the
398 30d-Qmin distributions as they are quite similar to the 7d-Qmin distributions, their median
399 being just slightly greater and their [interquartile](#) range being similar.

400 [Figure 6](#) shows that the impact of parameter uncertainty is rather small during both
401 simulation periods (calibration and validation). Indeed for both OFs and both simulation
402 periods, differences between the 1st and 3rd quartiles remain under 5% of the hydrological
403 indices values. Parameter uncertainty is more important for winter Nash-log hydrological
404 indices than for KGE values, whereas they are comparable for summer indices. The impact of
405 OF uncertainty is for all hydrological indices, for almost every year, and for both simulation
406 periods the impact is more important than that of the parameter uncertainty. It is especially the
407 case for winter 7d-Qmin and 30d-Qmin where [OF-the](#) uncertainty is at least five (5) times
408 larger than [the](#) parameter uncertainty. This also applies to winter Qmax where it is at least
409 twice as much important. The main findings [that stand for characterizing](#) almost all watersheds
410 are the following:

- 411 • Parameter uncertainty is :
 - 412 ○ quite stable across years and simulation periods,
 - 413 ○ smaller in summer than in winter especially for Qmax,
 - 414 ○ [comparable-similar](#) for both OFs, both seasons and all hydrological indices
415 (besides a few exceptions related to the performance of the calibration).
- 416 • OF uncertainty is:
 - 417 ○ rather stable across years for every individual seasonal hydrological index,

- 418 ○ more important than parameter uncertainty across the years, simulation
- 419 periods, and seasons,
- 420 ○ ~~higher~~larger in winter than in summer and more important for 7d-Qmin and
- 421 30d-Qmin.

422 **Figure 6: Boxplots of the seasonal hydrological indices for the Chamouchaoune**
423 **watershed for the calibration (1) and validation (2) periods: (as1) and (as2) display the**
424 **distribution of the maximum summer peakflows; (aw1) and (aw2) the distribution of**
425 **maximum winter peakflows; (bs1) and (bs2) the distribution of summer-7-day minimum**
426 **flows; and (bw1) and (bw2) the distribution of winter-7-day minimum flows. The black**
427 **and green boxplots ~~stand illustrate for the distribution of~~ simulated flows under the**
428 **KGE and Nash-log OFs, respectively, while the blue dots depict the observed values. The**
429 **superscripts *w* and *d* on the x-axis indicate the wettest and driest years of each**
430 **simulation period, respectively.**

431 **Snow water equivalent**

432 Figure 7Figure 7 shows the SWE uncertainty envelopes for the Yamaska watershed for the
433 calibration and validation periods as well as the two OFs. The envelopes were computed
434 using the same method as that used for the streamflows, except that since HYDROTEL is a
435 semi-distributed model, mean areal values over the RHHUs were first computed to produce a
436 single data series for each calibrated parameter set and each simulation period.

437 Figure 7Figure 7 shows that parameter uncertainty relative to SWE is less important at the
438 beginning and the end of the snow season while being at a maximum at the peak where the
439 envelopes are the widest. OF uncertainty for SWE, opposite contrary to that for streamflows,
440 is less important than parameter uncertainty as the individual envelopes overlap almost the
441 entire snow season. Parameter uncertainty is higher more important for the Nash-log OF than
442 for the KGE OF. However, these observations do not hold cannot be generalized when

443 examining in details the results for the alternate watersheds. Nonetheless, the overall results
444 can be separated into six groups:

- 445 | (i) For Yamaska and Chateauguay, parameter uncertainty is ~~higher-larger~~ than the OF
446 | uncertainty for the whole year with individual envelopes being wider at the
447 | beginning of February and at the end of March. SWE is higher for the Nash-log
448 | OF than for the KGE OF.
- 449 | (ii) For Chamouchouane and Mistassini, parameter uncertainty is ~~higher-larger~~ than
450 | the OF uncertainty for the whole year with individual envelopes overlapping the
451 | entire year.
- 452 | (iii) For Gatineau, parameter uncertainty is ~~higher-larger~~ than the OF uncertainty from
453 | November to the end of February. OF uncertainty then becomes ~~higher-larger~~ than
454 | parameter uncertainty with individual envelopes not overlapping anymore.
455 | Individual envelopes are quite narrow throughout the year and KGE simulated
456 | SWE is slightly more important than the Nash-log simulated values.
- 457 | (iv) For Batiscan, results are similar to those of group (iii); differing only with respect
458 | to the fact that individual envelopes become slightly wider indicating a more
459 | important parameter uncertainty
- 460 | (v) For Du Loup and Rouge, results indicate a ~~higher-larger~~ OF uncertainty for the
461 | whole year with narrow individual envelopes not overlapping. KGE simulated
462 | SWE values are more important than Nash-log values with a maximum difference
463 | of 50 mm at peak values.
- 464 | (vi) For Bécancour and Chaudière, results are similar to those of group (v) differing
465 | only with respect to the fact that individual envelopes become wider, indicating
466 | that parameter uncertainty is ~~higherlarger~~.

467 | **Figure 7: ~~Snow-water equivalent~~ (SWE) uncertainty envelopes for the Yamaska**
468 | **watershed: (a) calibration (9-year mean) and (b) validation periods (8-year mean). The**
469 | **black and green envelopes ~~stand illustrate the distribution of~~ simulated flows under**
470 | **the KGE and Nash-log ~~objective functions~~ OFs. The line indicates the period of**
471 | **overlapping between the uncertainty envelopes.**

472

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473 Actual evapotranspiration

474 Figure 8 ~~shows~~ ~~depicts~~ the seasonal AET for the Bécancour watershed obtained for both
475 simulation periods and OFs. They were computed as the sum of AET over each hydrological
476 year and season after applying the same methodology as that for the areal SWE in getting a
477 single data series. Parameter uncertainty can be assessed through the amplitude of each
478 boxplot while OF uncertainty is assessed through the combination of the KGE boxplots
479 (black) and Nash-log boxplots (green).

480 Figure 8 shows that parameter uncertainty for the summer season covers around 5% of the
481 AET values for both simulation periods and OFs; but for winter goes as far as 50%. For
482 summer, OF uncertainty is less significant than parameter uncertainty for many years ~~where~~
483 ~~as illustrated by the overlapping of the~~ individual boxplots ~~overlap~~ (1981, 1983, 1985, 1986,
484 1987, 1988, 1992, 1994, 1998, 2000 and 2002). Nevertheless, OF uncertainty is more
485 important than parameter uncertainty for all years but for winter 1990. Also, it is noteworthy
486 that parameter uncertainty is less variable across years during summer than ~~in~~ winter; indeed
487 boxplots have the same width ~~across~~ ~~years~~. Last, Nash-log parameter uncertainty is
488 comparable or ~~higher~~ ~~larger~~ than summer KGE parameter uncertainty ~~in summer~~ whereas it is
489 the opposite ~~in~~ for winter. However, these observations ~~do not hold~~ cannot be generalized
490 when examining in details the results ~~for~~ of the other watersheds (alternate watersheds).
491 Nonetheless, the overall results can be separated into six groups:

492 (i) For Batiscan, Châteauguay, Du Loup and Yamaska, both types of uncertainty are
493 stable constant across simulation periods, years and seasons. OF uncertainty remains
494 around 5% and does not go beyond 10% of the simulated AET values and is more
495 important than parameter uncertainty, while parameter uncertainty is comparable
496 similar for both OFs.

497 (ii) For Rouge, results are similar to those of group (i) differing only with respect to OF
498 uncertainty being larger, around 10%, for both seasons of the simulation periods and
499 all years.

500 (iii) For Gatineau and Mistassini, results are similar to those of group (ii) but ~~present~~ have
501 a ~~higher~~ larger parameter uncertainty for Nash-log simulated values than for KGE
502 values. This behavior is more pronounced in summer than in winter, and more so for
503 Mistassini than for Gatineau.

504 (iv) For Chaudière, results are similar to those of group (ii) but ~~present~~ have an OF
505 uncertainty that flirts with 20%.

506 (v) For Chamouchouane, results are similar to those of group (i) because of the stable
507 constant OF and parameter uncertainties. The difference is that OF uncertainty is
508 nonexistent as individual boxplots overlap for all seasons, years and simulation
509 periods. Parameter uncertainty related to the Nash-log OF is more important than that
510 of KGE simulated values

511 (vi) For Bécancour, results were described in the previous paragraph and are different from
512 the other groups as they ~~present~~ display variability across years and seasons that other
513 watersheds do not show.

514 The only result, apart from the relative ~~stability~~ consistency across the years highlighted in
515 group (vi), that stands across all watersheds, but Bécancour in summer and Yamaska is
516 that simulated AET values are higher for all years and all seasons under the Nash-log OF.

517 This is not a surprising result as it pertains to the nature of the OF with respect to the
518 water balance. That is, if a smaller percentage of precipitations gets discharged through
519 rivers (Nash-log vs KGE), another way to balance the equation for HYDROTEL is to
520 increase water output through evapotranspiration.

521 **Figure 8: Seasonal actual evapotranspiration for the Bécancour watershed: (a) summer**
522 **calibration; (b) summer validation; (c) winter calibration and (d) winter validation. The**
523 **black and green boxplots stand for simulated AET distributions under the KGE and**
524 **Nash-log OFs, respectively. The outliers are represented by red crosses. The**
525 **superscripts w and d on the x-axis stand for the wettest and driest years of each**
526 **simulation period, respectively.**

527 **Shallow groundwater variations**

528 Figure 9 shows the envelopes of areal GWC variations for the calibration and validation
529 periods as well as the two OFs for the Du Loup watershed. The envelopes were computed
530 using the same method as that used for the areal SWE.

531 Figure 9 shows that parameter uncertainty is small and ~~stable-constant~~ for both OFs
532 throughout the whole year with a maximum uncertainty under 2 mm. On the contrary, OF
533 uncertainty is substantial for the whole year (20 to 40 mm for the calibration period, 10 to 20
534 mm for the validation period), but between January and March. For this latter period, the
535 shallow ground water reserves are at their lowest point and individual envelopes overlap
536 during the calibration period or are close to overlapping during the validation period.
537 However, these observations do not hold when examining in details the results for the
538 alternate watersheds. Nonetheless, the overall results can be separated into six groups:

539 (i) For Rouge and Mistassini, the GWC variation patterns are similar to those of Du
540 Loup. Maximum reserves are ~~attained-reached~~ in early May after the snow has
541 melted; they continuously decrease until early September where they reach their
542 minimum to increase until the end of the fall season in early December. Finally,
543 they decrease again to a near minimum value around early March ~~when-theat the~~
544 ~~onset of~~ melt season ~~-starts~~. OF and parameter uncertainties were described in the
545 previous paragraph.

- 546 (ii) For Batiscan, results show similar GWC variation patterns to those of group (i).
547 The difference lies in the parameter uncertainty that covers most the OF
548 uncertainty, but still remains under 10 mm. Indeed, for the calibration period, OF
549 uncertainty is less important than parameter uncertainty from November until the
550 end of September. For the validation period, the overlapping is reduced from
551 December until the end of May. Still, even in the remaining months, OF
552 uncertainty is less important than that of group (i); incidentally not getting larger
553 than 20 mm.
- 554 (iii) For Chamouchouane and Gatineau, results show similar GWC variation patterns to
555 those of groups (i) and (ii), but behave almost at the opposite of group (i) with
556 respect to OF and parameter uncertainties. OF uncertainty is non-existent for the
557 whole year, but for a few days around peak value. Parameter uncertainty is small
558 (less than 2 mm) and individual envelopes overlap.
- 559 (iv) For Bécancour, results show similar GWC variation patterns to those of group (i)
560 apart from the decrease during the snow season that is less pronounced. Parameter
561 uncertainty is more important for both OFs as that of group (i); it represents a
562 maximum of 10 mm for both OFs in the calibration period, but around 5 mm and
563 close to 10 mm respectively for Nash-log and KGE simulated GWC. OF
564 uncertainty as a result is still more significant than parameter uncertainty despite a
565 lag between the OFs that make the individual envelopes overlap around peakflow
566 values.
- 567 (v) For Chaudière, results show similar GWC variation patterns to those of Bécancour
568 (group (iv)) but is clearly different from any other watershed with respect to the
569 OF and parameter uncertainties. The Nash-log parameter uncertainty covers
570 almost all KGE values and ~~presents~~has 40 and 20 mm wide intervals.

571 | respectively, for the calibration and validation periods. The KGE parameter
572 | uncertainty is less than 2 mm for the whole year which results in a non-existent OF
573 | uncertainty for the calibration period while still being significant between August
574 | and December for the validation period.

575 | (vi) For Chateauguay and Yamaska, the GWC variation patterns differ from those of
576 | groups (i) to (v). The GWC is at a minimum around the end of August. The
577 | reserves are then replenished from September until the end of November, before
578 | decreasing only slightly, as opposed to groups (i) and (ii), during the snow season
579 | and attaining their maximum values after the snow has melted. Parameter
580 | uncertainty is small, under 2 and 5 mm ~~respectively~~ for KGE and Nash-log
581 | simulated GWC, respectively, and relatively stable-constant across the year. OF
582 | uncertainty is more important (maximum of 20 and 30 mm ~~maximum respectively~~
583 | for calibration and validation, respectively) for the whole year, but just after peak
584 | value (May and June) for the calibration period and around peak value (April) for
585 | the validation period

586 | It is noteworthy that the two variation patterns relative to GWC, highlighted in the above
587 | groups, reflect the geographical location of the watersheds. Indeed, Bécancour,
588 | Châteauguay, Chaudière and Yamaska are located on the south shore of the St. Lawrence
589 | River, while Batiscan, Chamouchouane, Du Loup, Gatineau, Mistassini and Rouge are
590 | located on the north shore.

591 | **Figure 9: Shallow groundwater content uncertainty envelopes for the Du Loup**
592 | **watershed: (a) calibration (9-year mean) and (b) validation periods (8-year mean). The**
593 | **black and green envelopes ~~stand for~~ illustrate the distribution of simulated flows under**
594 | **the KGE and Nash-log ~~objective functions~~ OFs, respectively.**

595 |

596 Discussion

597 Automatic calibration with DDS

598 In the Material and Methods section-0, it is mentioned that DDS is better suited than SCE-
599 UA (Duan *et al.* 1992; Duan *et al.* 1994; Duan *et al.* 1993) for distributed watershed models
600 ~~that require requiring~~ extensive ~~computing computational~~ time and, thus, ~~impose leading to~~ a
601 low number of model evaluations before converging to a good solution (Arsenault *et al.* 2014;
602 Tolson and Shoemaker 2007; Yen *et al.* 2016). This is mostly due to DDS dynamically
603 adjusting the neighborhood of the best solution by changing the dimension of the search
604 (Tolson and Shoemaker 2007). In other terms, DDS mimics manual calibrations of watershed
605 models as follows: (i) early in the calibration exercise, a number of model parameters are
606 modified to overcome relatively poor solutions, and (ii) later, to avoid losing the current gain
607 in objective function values, parameters are modified one at a time. To avoid introducing a
608 bias in the search algorithm, this paper used a random initial solution, but used the same
609 random solution for every watershed in order to keep the experiments ~~comparable~~ consistent.

610 The stochastic nature of DDS means that multiple optimization trials initialized with different
611 initial solutions can terminate at different final solutions (Tolson and Shoemaker 2008). To be
612 consistent with the framework described in the introduction, that is a majority of the
613 HYDROTEL application studies involved manual calibration, we decided to work with only
614 one optimization trial and a budget of 5000 model runs to answer the research question with
615 respect to equifinality ~~in this constrained context~~ given this framework. Besides, the radar
616 plots of parameter equifinality shown in Figure 3 do not seem to behave in a pattern related to
617 the geographical ~~situation~~ location, the climate, or geological characteristics of each
618 watershed. Indeed, the study watersheds are part of three different geological provinces
619 (Ministère des Ressources naturelles Direction générale de Géologie Québec 2012): (i) the
620 Greenville Province made of allochthonous material north of the St. Lawrence River; (ii) the

621 | St. Lawrence platform around the ~~river~~River; and (iii) the Appalachian province made of
622 | Humber material south of the River. They also belong to three climate classes defined by
623 | Litynski (1988) but mostly to class 14 that stands for moderate temperature, subhumid
624 | precipitations and long growing season. As a consequence, parameter regionalization is not
625 | obvious. This was pointed out as well by Ricard *et al.* (2013) who showed that a global
626 | calibration strategy over southern Québec was preferable although in some cases –the
627 | performances of watershed calibration using HYDROTEL was reduced when compared to
628 | local calibrations.

629 | **OF uncertainty**

630 | Overall, results for all the studied hydrological processes suggest that OF uncertainty is more
631 | important than ~~the~~ parameter uncertainty. In other words, OF uncertainty is seen when the
632 | largest of the individual envelopes or boxplots relative to each objective function (KGE and
633 | Nash-log) is smaller than the reunion of either envelopes or boxplots. ~~The reader~~Readers
634 | should note that results obtained for the NSE_Q and $NSE\sqrt{Q}$ OFs are in complete agreement
635 | with the previous statement. ~~Figure 5~~Figure 5 and alternate figures do not clearly show the
636 | impact of OF uncertainty because individual envelopes often overlap. However, when
637 | considering the seasonal hydrological indices (~~Figure 6~~Figure 6 and alternate figures), the
638 | SWE (~~Figure 7~~Figure 7 and alternate figures), the ~~actual evapotranspiration~~AET (Figure 8
639 | and alternate figures), and the GWC (Figure 9 and alternate figures), OF uncertainty is overall
640 | clearly ~~illustrated~~highlighted.

641 | Some studies highlight the importance of model structure uncertainty over parameter
642 | equifinality (Futter *et al.* 2015; Mockler *et al.* 2016; Poulin *et al.* 2011; Shoaib *et al.* 2016).
643 | Poulin *et al.* (2011) used HYDROTEL and HSAMI to assess the effects of model structure
644 | and parameter equifinality on the uncertainty related to hydrological modelling. Their study
645 | revealed that the impact of hydrological model structure was more significant than the effect

646 of parameter uncertainty (assessed through 68 sets of parameters). Yet, the uncertainty
647 attributed to model structure with respect to streamflows and SWE were of the same order of
648 magnitude than the OF uncertainty assessed in this paper. This would mandate the
649 combination of both studies to clearly assess whether the impact of model structure and OF
650 uncertainty are equivalent or complementary in assessing the consequences of considering the
651 effects of equifinality on modelled hydrological processes.

652 ~~Figure 6~~ and alternate figures showed the boxplots of the seasonal hydrological
653 indices for both OFs (~~section 0~~-Results section). They also indicated observed values as blue
654 dots; less than 50% of the latter are not included within the interval of the simulated values
655 for any of the hydrological indices (Qmax, 7d-Qmin, and 30d-Qmin). This could be seen as a
656 calibration performance issue, but results suggest otherwise. Indeed, all observed values and
657 all, but one, are included within the interval of the simulated values for the summer 7d-Qmin
658 for the Châteauguay and Yamaska, respectively; which have the lowest performances for both
659 OFs (refer to ~~Table 5~~ of ~~section 0~~). This would rather suggest that KGE and Nash-
660 log OFs are not able to force the model to represent the hydrological indices properly. This
661 may be related to the nature of both OFs that are computed over daily data *versus*
662 hydrological indices computed over a period of time (~~seven and 30 days for~~ 7d-Qmin as
663 well as 30d-Qmin, ~~respectively~~). However, for Qmax, this is simply related to the
664 misrepresentation of maximum flows. This result is rather important as hydrological indices
665 are often used in impact assessment studies. This would mandate the use of specific ~~objective~~
666 ~~functions~~ OFs related to low or high flows or even the use of multi-objective functions.

667 **Parameter uncertainty**

668 Despite the fact that the OF uncertainty is overall more important than the consequences of
669 parameter equifinality, parameter uncertainty relative to SWE (~~Results~~ section-0) is generally
670 more important than OF uncertainty. Indeed it is more important for the whole year for

671 Châteauguay, Chamouchouane, Mistassini and Yamaska and, for a few months (November
672 until the end of February), for Gatineau and Batiscan. Seasonal results also suggest that
673 parameter uncertainty can be important or more significant even than OF uncertainty for
674 specific seasons or years (~~Figure 6~~Figure 6, Figure 8 and alternate figures). To get a better
675 understanding of the reasons why parameter uncertainty would prevail only for a few years,
676 driest and wettest years were defined as the hydrological years with the least total amount of
677 precipitation for the simulation periods (indicated on the x-axis of seasonal hydrological
678 indices and AET figures as d and w). The effects of driest and wettest years were assessed in
679 terms of prevalence of any of the two types of uncertainties and magnitudes of uncertainties
680 on both ~~the actual driest and wettest types of~~ years, but also on the following year. Nothing
681 particular stood out that could be construed as a general result that could have given insights
682 about the evolution of the prevalence of the two types of uncertainties in the following years.
683 To get this type of insight, we would probably need to perform calibrations under different
684 sets of contrasting conditions (dry *versus* wet years). This refers to parameter identifiability as
685 researched by Wilby (2005) on snowless watersheds, or to the application of testing schemes
686 such as those performed by Seiller *et al.* (2012) and inspired by Klemeš (1986).

687 **Parameter equifinality**

688 Ben Nasr (2014) as well as Bouda *et al.* (2014) pointed out in sensitivity analyses carried out
689 for two snow-dominated watersheds in southern Québec (Beaurivage and Montmorency
690 modelled using HYDROTEL), that the depth of the lower boundary of ~~the three~~ soil layers
691 (z_1 , z_2 , z_3), the potential evapotranspiration multiplying factor (PETF), and the recession
692 coefficient (RC) were consistently amongst the most sensitive parameters (refer to [Table](#)
693 ~~4~~[Table 4 in section 0](#)). In both ~~case studies~~, sensitivity was assessed from an initial optimal
694 solution and parameter values were modified ($\pm 25\%$), but variations of $\pm 6.25\%$ already gave
695 substantial flow modifications. These results are within the same order of magnitude as the

696 | equifinality measured through the proposed methodology (~~section 0~~) and explain why some
697 | parameters in Figure 2 are more equifinal than others. Typically, parameters that were
698 | identified by Ben Nasr (2014) and Bouda *et al.* (2014) as the most sensitive parameters are
699 | less equifinal than others. This result is not surprising as it pertains to the following statement:
700 | the more sensitive a parameter, the least uncertain it can be around a global optimum for the
701 | OF to remain optimum.

702 | The choice to work with 5000 model runs ensured that the OF values remained within a 0.01
703 | interval (~~section refer to 0~~[Table 5](#)~~Table 5~~) for 250 sets of parameters that captured parameter
704 | equifinality. Neither did working with 500 sets of parameters provide a larger parameter
705 | equifinality, nor did working with 100 sets of parameters provide the complete parameter
706 | equifinality. This is important as Poulin *et al.* (2011) reported that parameter uncertainty
707 | increases with increasing numbers of calibration parameters and/or calibrations. This allows
708 | us to go beyond their research in making sure that our conclusions cannot be disputed with
709 | respect to the impact that parameter equifinality has on global or individual uncertainty
710 | envelopes.

711 | To make sure that working with one optimization trial did not impair the possibility of
712 | capturing the equifinality of the parameters, the smallest watershed model in terms of
713 | modelled area (to minimize computational time) with the smallest parameter equifinality was
714 | calibrated for another 5000-simulation-optimization-trial started at a different initial random
715 | solution. As shown in [Figure 10](#)~~Figure 10~~, this demonstrates that parameter equifinality can
716 | be increased if the calibration methodology is modified. Nonetheless, the covered part of the
717 | physical range does not come close to the maximum equifinality obtained for the Yamaska
718 | watershed in ~~section 0~~[Figure 3](#). Thus, it can be assumed that the results introduced in this
719 | paper would not be drastically modified by a change in the calibration methodology. Plus it
720 | would contradict the choice made not to conduct a formal uncertainty analysis as this

721 methodology of using two or more optimization trials would get closer to the DDS-AU
722 methodology introduced by Tolson and Shoemaker (2008).

723 **Figure 10: Radar plots of the twelve parameters used in the automatic calibration of**
724 **HYDROTEL for each study watershed. Parameter A is part of the interpolation**
725 **coefficients, parameters B through G relate to the snow model, and parameters F**
726 **through L relate to the soil group of parameters. Figure (a) refers to the KGE ~~objective~~**
727 **~~function~~OF; and (b) to the Nash-log ~~objective function~~OF. The dark and light blue data**
728 **refer to the first optimization trial of Figure 3, black data to the second optimization**
729 **trial.**

730 To summarize, it could be said that this paper shows the consequences of the existence of
731 many good sets of parameters (~~parameter equifinality assessed in section 0~~) on modelled
732 hydrological processes around a global optimum rather than properly evaluating their formal
733 statistical uncertainty. If that were the aim, the methodology would have entailed working
734 with one optimization trial per set of parameters which would have resulted in a total of
735 125 000 simulations (250 sets of parameters * 500 simulations) since DDS typically needs
736 500 simulations to find a good global solution (compared to 10,000 for SCE-UA). Note that
737 the computing time for a 10-year calibration period (with a prior 1-year spin-up), one
738 optimization trial of 5000 simulations already took an average 45 hours (on a 64-bit computer
739 with a quad-core 2.53 GHz processor) for each watershed and every OF, resulting in a total
740 calibration time of 900 hours or 37.5 days (45 hours * 10 watersheds * 2 OFs) for the results
741 presented in this paper (excluding the two OFs that were left out of this paper).

742

743 **Conclusion**

744 In the last decade, HYDROTEL has almost always been applied within the optimal parameter
745 set paradigm at the risk of avoiding important issues such as model acceptability and
746 uncertainty (Beven 2006a). This paper builds on the work carried out on hydrological
747 uncertainty by assessing the impact of equifinality and OF related uncertainty on five modelled
748 hydrological variables and indices: (i) daily flows; (ii) seasonal hydrological indices (7d-
749 Qmin, 30d-Qmin, and Qmax); (iii) snow water equivalent (SWE); (iv) shallow ground
750 water content variations (GWC) and (v) actual evapotranspiration (AET). This assessment
751 was carried out for ten watersheds spread out in five hydrographic regions of the St. Lawrence
752 River and spread across southern Québec (Canada).

753 Overall, as introduced in Table 7, the results for all the studied hydrological processes, but the
754 SWE, suggest that OF uncertainty is more important than that arising from parameter
755 equifinality. This would mean that within the context of a study with a limited budget, it
756 would be advisable to prioritize using different objective functions to using many sets of
757 optimal parameters. This result is rather important as it reinforces the choice made in the last
758 decade with HYDROTEL. Nonetheless, parameter uncertainty with respect to SWE is more
759 important than OF uncertainty for eight of the ten studied watersheds for four up to seven
760 months of the year (snow season less than 7-month long). Plus, despite satisfactory
761 performances for both simulation periods, parameter uncertainty with respect to streamflows
762 is rather small during the whole year, except around spring peak flow; while OF uncertainty is
763 generally more pronounced in the fall and during the spring peak flows. Overall, this shows
764 that one type of uncertainty or the other is rather significant during half of the year. Seasonal
765 results with respect to hydrological indices and AET also suggest that parameter uncertainty
766 can be important, or more significant even, than OF uncertainty for specific seasons or years.
767 These results are of the utmost importance for impact assessment studies where the variables

768 of interest are not solely the daily flow data used for calibration, but rather hydrological
769 indices or internal variables. This would mean that parameter uncertainty ~~needs~~does need
770 be taken into account or at least needs to be further researched to better understand the
771 mechanisms ~~driving parameter uncertainty~~behind the phenomena. This study demonstrates,
772 using a substantial set of watersheds; that aside from the technico-philosophical debate started
773 in 2006, equifinality is not so technical to take into account and has tangible significant effect
774 on the uncertainties associated with modeled hydrological processes. As such, we recommend
775 that future work systematically include equifinality by using at least two sets of equifinal
776 parameters without forgetting to assess OF uncertainty.

777 It is noteworthy that the methodology applied in this paper for the HYDROTEL model can be
778 replicated for other hydrological models. Uncertainty associated with OFs and parameter
779 equifinality still needs to be better understood and studied. To improve our understanding of
780 HYDROTEL, and other physically based hydrological models, future work should focus on
781 identifying or using OFs tailored for hydrological indices relevant to impact assessment
782 studies. Finally, for a specific assessment, there is a need to consider as well the question of
783 the uncertainty associated with model structure.

784 <Table 7: Dominant type of uncertainty for each study watershed for the five modelled
785 hydrological variables~~Table 7: Dominant type of uncertainty for each study watershed~~
786 for the five modelled hydrological variables>

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787

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798

799 **References**

- 800 Aissia, M. A. B., F. Chebana, T. B. M. J. Ouarda, L. Roy, G. Desrochers, I. Chartier, and É
801 Robichaud. 2012. Multivariate analysis of flood characteristics in a climate change
802 context of the watershed of the Basketong reservoir, Province of Québec, Canada.
803 *Hydrological Processes* 26 (1):130-142.
- 804 Arsenault, R., A. Poulin, P. Côté, and F. Brissette. 2014. Comparison of stochastic
805 optimization algorithms in hydrological model calibration. *Journal of Hydrologic
806 Engineering* 19 (7):1374-1384.
- 807 Ben Nasr, Imène. 2014. Incertitudes sur les débits simulés par le modèle HYDROTEL
808 attribuables aux incertitudes sur les paramètres. Application au bassin de la rivière
809 Beaurivage, Québec, Canada, Institut National de la recherche scientifique, Centre Eau
810 terre environnement, Québec, QC 94 pp.
- 811 Beven, K. 1993. Prophecy, reality and uncertainty in distributed hydrological modelling.
812 *Advances in Water Resources* 16 (1):41-51.
- 813 Beven, K. 2006a. A manifesto for the equifinality thesis. *Journal of Hydrology* 320 (1-2):18-
814 36.
- 815 Beven, K. 2006b. On undermining the science? *Hydrological Processes* 20 (14):3141-3146.
- 816 Beven, K. 2008. On doing better hydrological science. *Hydrological Processes* 22 (17):3549-
817 3553.
- 818 Beven, K. 2016. Facets of uncertainty: Epistemic uncertainty, non-stationarity, likelihood,
819 hypothesis testing, and communication. *Hydrological Sciences Journal* 61 (9):1652-
820 1665.
- 821 Beven, K., and A. Binley. 1992. The future of distributed models: Model calibration and
822 uncertainty prediction. *Hydrological Processes* 6 (3):279-298.
- 823 Beven, K., and J. Freer. 2001. Equifinality, data assimilation, and uncertainty estimation in
824 mechanistic modelling of complex environmental systems using the GLUE
825 methodology. *Journal of Hydrology* 249 (1-4):11-29.
- 826 Beven, K. J. 2009. Comment on "Equifinality of formal (DREAM) and informal (GLUE)
827 Bayesian approaches in hydrologic modeling?" by Jasper A. Vrugt, Cajo J. F. ter
828 Braak, Hoshin V. Gupta and Bruce A. Robinson. *Stochastic Environmental Research
829 and Risk Assessment* 23 (7):1059-1060.
- 830 Bouda, M., A. N. Rousseau, S. J. Gumiere, P. Gagnon, B. Konan, and R. Moussa. 2014.
831 Implementation of an automatic calibration procedure for HYDROTEL based on prior
832 OAT sensitivity and complementary identifiability analysis. *Hydrological Processes*
833 28 (12):3947-3961.
- 834 Bouda, M., A.N. Rousseau, B. Konan, P. Gagnon, and S.J. Gumiere. 2012. Case study:
835 Bayesian uncertainty analysis of the distributed hydrological model HYDROTEL.
836 *Journal of Hydrologic Engineering* 17 (9):1021-1032.

- 837 | CEHQ. 2012. *Niveau d'eau et débit*. <http://www.cehq.gouv.qc.ca/hydrometrie/index.htm>
838 | (accessed September 2017).
- 839 | CEHQ. 2013. Atlas hydroclimatique du Québec méridional - Impact des changements
840 | climatiques sur les régimes de crue, d'étiage et d'hydraulicité à l'horizon 2050. Québec,
841 | 21 pp.
- 842 | CEHQ. 2015. Hydroclimatic Atlas of Southern Québec. The Impact of Climate Change on
843 | High, Low and Mean Flow Regimes for the 2050 horizon. Québec, 81 pp.
- 844 | Duan, Q., S. Sorooshian, and V. Gupta. 1992. Effective and efficient global optimization for
845 | conceptual rainfall-runoff models. *Water Resources Research* 28 (4):1015-1031.
- 846 | Duan, Q., S. Sorooshian, and V. K. Gupta. 1994. Optimal use of the SCE-UA global
847 | optimization method for calibrating watershed models. *Journal of Hydrology* 158 (3-
848 | 4):265-284.
- 849 | Duan, Q. Y., V. K. Gupta, and S. Sorooshian. 1993. Shuffled complex evolution approach for
850 | effective and efficient global minimization. *Journal of Optimization Theory and*
851 | *Applications* 76 (3):501-521.
- 852 | Fisher, J., and K. J. Beven. 1996. Modelling of stream flow at Slapton Wood using topmodel
853 | within an uncertainty estimation framework. *Field Studies* 8 (4):577-584.
- 854 | Fortin, J.-P., R. Turcotte, S. Massicotte, R. Moussa, and J. Fitzback. 2001a. A distributed
855 | watershed model compatible with remote sensing and GIS data. Part 2: Application to
856 | the Chaudière watershed. *Journal of Hydrologic Engineering* 6 (2):100-108.
- 857 | Fortin, J.-P., R. Turcotte, S. Massicotte, R. Moussa, J. Fitzback, and J.-P. Villeneuve. 2001b.
858 | A distributed watershed model compatible with remote sensing and GIS data. Part I:
859 | Description of the model. *Journal of Hydrologic Engineering* 6 (2):91-99.
- 860 | Fossey, M., and A. N. Rousseau. 2016a. Assessing the long-term hydrological services
861 | provided by wetlands under changing climate conditions: A case study approach of a
862 | Canadian watershed. *Journal of Hydrology* 541, Part B:1287-1302.
- 863 | Fossey, M., and A. N. Rousseau. 2016b. Can isolated and riparian wetlands mitigate the
864 | impact of climate change on watershed hydrology? A case study approach. *Journal of*
865 | *Environmental Management* 184, Part 2:327-339.
- 866 | Fossey, M., A. N. Rousseau, F. Bensalma, S. Savary, and A. Royer. 2015. Integrating isolated
867 | and riparian wetland modules in the PHYSITEL/HYDROTEL modelling platform:
868 | Model performance and diagnosis. *Hydrological Processes* 29 (22):4683-4702.
- 869 | Fossey, M., A. N. Rousseau, and S. Savary. 2016. Assessment of the impact of spatio-
870 | temporal attributes of wetlands on stream flows using a hydrological modelling
871 | framework: A theoretical case study of a watershed under temperate climatic
872 | conditions. *Hydrological Processes* 30 (11):1768-1781.
- 873 | Freer, J., K. Beven, and B. Ambrose. 1996. Bayesian estimation of uncertainty in runoff
874 | prediction and the value of data: An application of the GLUE approach. *Water*
875 | *Resources Research* 32 (7):2161-2173.

- 876 Fu, C., A. L. James, and H. Yao. 2015. Investigations of uncertainty in SWAT hydrologic
877 simulations: A case study of a Canadian Shield catchment. *Hydrological Processes* 29
878 (18):4000-4017.
- 879 Futter, M. N., P. G. Whitehead, S. Sarkar, H. Rodda, and J. Crossman. 2015. Rainfall runoff
880 modelling of the Upper Ganga and Brahmaputra basins using PERSiST.
881 *Environmental Sciences: Processes and Impacts* 17 (6):1070-1081.
- 882 Gaborit, É, S. Ricard, S. Lachance-Cloutier, F. Anctil, and R. Turcotte. 2015. Comparing
883 global and local calibration schemes from a differential split-sample test perspective.
884 *Canadian Journal of Earth Sciences* 52 (11):990-999.
- 885 [Gupta, H. V., H. Kling, K. K. Yilmaz, and G. F. Martinez \(2009\). Decomposition of the mean
886 squared error and NSE performance criteria: Implications for improving hydrological
887 modelling. *Journal of Hydrology*, 377\(1-2\), 80-91. doi: 10.1016/j.jhydrol.2009.08.003.](#)
- 888 Khalili, M., F. Brissette, and R. Leconte. 2011. Effectiveness of Multi-Site Weather Generator
889 for Hydrological Modeling. *Journal of the American Water Resources Association* 47
890 (2):303-314.
- 891 Klemeš, V. 1986. Operational testing of hydrological simulation models. *Hydrological
892 Sciences Journal* 31 (1):13-24.
- 893 Li, C. Z., L. Zhang, H. Wang, Y. Q. Zhang, F. L. Yu, and D. H. Yan. 2012. The
894 transferability of hydrological models under nonstationary climatic conditions.
895 *Hydrology and Earth System Sciences* 16 (4):1239-1254.
- 896 Linhoss, A., R. Muñoz-Carpena, G. Kiker, and D. Hughes. 2013. Hydrologic modeling,
897 uncertainty, and sensitivity in the okavango basin: Insights for scenario assessment.
898 *Journal of Hydrologic Engineering* 18 (12):1767-1778.
- 899 Litynski, J. 1988. Climat du Québec d'après la classification numérique.
- 900 Ludwig, R., I. May, R. Turcotte, L. Vescovi, M. Braun, J. F. Cyr, L. G. Fortin, D. Chaumont,
901 S. Biner, I. Chartier, D. Caya, and W. Mauser. 2009. The role of hydrological model
902 complexity and uncertainty in climate change impact assessment. *Advances in
903 Geosciences* 21:63-71.
- 904 Ministère des Ressources naturelles Direction générale de Géologie Québec. 2012. Map of the
905 main Geological Subdivisions of Québec.
- 906 Minville, M., F. Brissette, S. Krau, and R. Leconte. 2009. Adaptation to climate change in the
907 management of a Canadian water-resources system exploited for hydropower. *Water
908 Resources Management* 23 (14):2965-2986.
- 909 Mockler, E. M., K. P. Chun, G. Sapriza-Azuri, M. Bruen, and H. S. Wheeler. 2016. Assessing
910 the relative importance of parameter and forcing uncertainty and their interactions in
911 conceptual hydrological model simulations. *Advances in Water Resources* 97:299-313.
- 912 Moriasi, D.N., J.G. Arnold, M.W. VanLiew, R.L. Bingner, R.D. Harmel, and T.L. Veith.
913 2007. Model evaluation guidelines for systematic quantification of accuracy in
914 watershed simulations. *Transactions of the ASABE* 50 (3):885-900.

- 915 Mugunthan, P., and C. A. Shoemaker. 2006. Assessing the impacts of parameter uncertainty
916 for computationally expensive groundwater models. *Water Resources Research* 42
917 (10).
- 918 Nearing, G. S., Y. Tian, H. V. Gupta, M. P. Clark, K. W. Harrison, and S. V. Weijs. 2016. A
919 philosophical basis for hydrological uncertainty. *Hydrological Sciences Journal* 61
920 (9):1666-1678.
- 921 Noël, P., A. N. Rousseau, C. Paniconi, and D. F. Nadeau. 2014. An algorithm for delineating
922 and extracting hillslopes and hillslope width functions from gridded elevation data.
923 *Journal of Hydrologic Engineering* 19 (2):366-374.
- 924 Oreiller, M., D. F. Nadeau, M. Minville, and A. N. Rousseau. 2013. Modelling snow water
925 equivalent and spring runoff in a boreal watershed, James Bay, Canada. *Hydrological
926 Processes*.
- 927 [Poirier, C., T. C. Fortier Filion, R. Turcotte, and P. Lacombe \(2012\). Apports verticaux
928 journaliers estimés de 1900 à 2010, Rep., Centre d'expertise hydrique du Québec \(CEHQ\),
929 Direction de l'expertise hydrique, Québec.](#)
- 930 Poulin, A., F. Brissette, R. Leconte, R. Arsenault, and J. S. Malo. 2011. Uncertainty of
931 hydrological modelling in climate change impact studies in a Canadian, snow-
932 dominated river basin. *Journal of Hydrology* 409 (3-4):626-636.
- 933 Prada, A. F., M. L. Chu, and J. A. Guzman. 2016. Probabilistic approach to modeling under
934 changing scenarios. Paper read at 2016 American Society of Agricultural and
935 Biological Engineers Annual International Meeting, ASABE 2016. pp.
- 936 Quilbé, R., A.N. Rousseau, J.S. Moquet, N.B. Trinh, Y. Dikibi, P. Gachon, and D. Chaumont.
937 2008. Assessing the effect of climate change on river flow using general circulation
938 models and hydrological modeling - Application to the Chaudière River (Québec,
939 Canada). *Canadian Water Resources Journal* 33 (1):73-94.
- 940 Ricard, S., R. Bourdillon, D. Roussel, and R. Turcotte. 2013. Global calibration of distributed
941 hydrological models for large-scale applications. *Journal of Hydrologic Engineering*
942 18 (6):719-721.
- 943 Romanowicz, R. J., K. Beven, and J. A. Tawn. 1994. Evaluation of predictive uncertainty in
944 nonlinear hydrological models using a Bayesian Approach. In *Statistics for the
945 Environment, Water Related Issues (Volume 2)*, ed. V. Barnett and F. Turkman, 297-
946 318. John Wiley & Sons.
- 947 Rousseau, A. N., S. Savary, D. W. Hallema, S. J. Gumière, and E. Foulon. 2013. Modeling
948 the effects of agricultural BMPs on sediments, nutrients and water quality of the
949 Beauvillage River watershed (Quebec, Canada). *Canadian Water Resources Journal* 38
950 (2):99-120.
- 951 Rousseau, A.N., J.P. Fortin, R. Turcotte, A. Royer, S. Savary, F. Quévry, P. Noël, and C.
952 Paniconi. 2011. PHYSITEL, a specialized GIS for supporting the implementation of
953 distributed hydrological models. *Water News, Official Magazine of CWRA – Canadian
954 Water Resources Association* 31 (1):18-20.

- 955 Seiller, G., F. Anctil, and C. Perrin. 2012. Multimodel evaluation of twenty lumped
956 hydrological models under contrasted climate conditions. *Hydrology and Earth System
957 Sciences* 16 (4):1171-1189.
- 958 Shoaib, S. A., L. Marshall, and A. Sharma. 2016. A metric for attributing variability in
959 modelled streamflows. *Journal of Hydrology* 541:1475-1487.
- 960 Tolson, B. A., and C. A. Shoemaker. 2007. Dynamically dimensioned search algorithm for
961 computationally efficient watershed model calibration. *Water Resources Research* 43
962 (1).
- 963 Tolson, B. A., and C. A. Shoemaker. 2008. Efficient prediction uncertainty approximation in
964 the calibration of environmental simulation models. *Water Resources Research* 44 (4).
- 965 Trudel, M., P. L. Doucet-Généreux, R. Leconte, and B. Côté. 2016. Vulnerability of water
966 demand and aquatic habitat in the context of climate change and analysis of a no-
967 regrets adaptation strategy: Study of the Yamaska River Basin, Canada. *Journal of
968 Hydrologic Engineering* 21 (2).
- 969 Turcotte, R., J.P. Fortin, A.N. Rousseau, S. Massicotte, and J.P. Villeneuve. 2001.
970 Determination of the drainage structure of a watershed using a digital elevation model
971 and a digital river and lake network. *Journal of Hydrology* 240 (3-4):225-242.
- 972 Turcotte, R., L. G. Fortin, V. Fortin, J. P. Fortin, and J. P. Villeneuve. 2007a. Operational
973 analysis of the spatial distribution and the temporal evolution of the snowpack water
974 equivalent in southern Québec, Canada. *Nordic Hydrology* 38 (3):211-234.
- 975 Turcotte, R., P. Lacombe, C. Dimnik, and J.P. Villeneuve. 2004. Distributed hydrological
976 prediction for the management of Quebec's public dams. *Canadian J. of Civil
977 Engineering* 31 (2):308-320.
- 978 Turcotte, R., A.N. Rousseau, J.-P. Fortin, and J.-P. Villeneuve. 2003. Development of a
979 process-oriented, multiple-objective, hydrological calibration strategy accounting for
980 model structure. In *Advances in Calibration of Watershed Models*, Water Science &
981 Application, no. 6, ed. Q. Duan, S. Sorooshian, H. Gupta, A. N. Rousseau and R.
982 Turcotte, 153-163. Washington, USA: American Geophysical Union (AGU).
- 983 Turcotte, R., A.N. Rousseau, J.P. Fortin, V. Fortin, and J.P. Villeneuve. 2007b. Operational
984 analysis of the spatial distribution and the temporal evolution of the snowpack water
985 equivalent in southern Quebec, Canada. *Nordic Hydrology* 38 (3):211-234.
- 986 Vrugt, J. A., C. J. F. Ter Braak, C. G. H. Diks, B. A. Robinson, J. M. Hyman, and D. Higdon.
987 2009a. Accelerating Markov chain Monte Carlo simulation by differential evolution
988 with self-adaptive randomized subspace sampling. *International Journal of Nonlinear
989 Sciences and Numerical Simulation* 10 (3):273-290.
- 990 Vrugt, J. A., C. J. F. ter Braak, H. V. Gupta, and B. A. Robinson. 2009b. Equifinality of
991 formal (DREAM) and informal (GLUE) Bayesian approaches in hydrologic modeling?
992 *Stochastic Environmental Research and Risk Assessment* 23 (7):1011-1026.
- 993 Vrugt, J. A., C. J. F. ter Braak, H. V. Gupta, and B. A. Robinson. 2009c. Response to
994 comment by Keith Beven on "Equifinality of formal (DREAM) and informal (GLUE)

- 995 Bayesian approaches in hydrologic modeling?". *Stochastic Environmental Research*
996 *and Risk Assessment* 23 (7):1061-1062.
- 997 Wilby, R. L. 2005. Uncertainty in water resource model parameters used for climate change
998 impact assessment. *Hydrological Processes* 19 (16):3201-3219.
- 999 Yen, H., J. Jeong, and D. R. Smith. 2016. Evaluation of Dynamically Dimensioned Search
1000 Algorithm for Optimizing SWAT by Altering Sampling Distributions and Searching
1001 Range. *Journal of the American Water Resources Association* 52 (2):443-455.
- 1002 Zeng, Q., H. Chen, C. Y. Xu, M. X. Jie, and Y. K. Hou. 2016. Feasibility and uncertainty of
1003 using conceptual rainfallrunoff models in design flood estimation. *Hydrology Research*
1004 47 (4):701-717.
- 1005 Zhang, X., G. Hörmann, N. Fohrer, and J. Gao. 2012. Parameter calibration and uncertainty
1006 estimation of a simple rainfall-runoff model in two case studies. *Journal of*
1007 *Hydroinformatics* 14 (4):1061-1074.
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1011 **Tables**1012 **Table 1: Land cover of the ten studied watersheds in southern Québec, Canada**

	Evergreen		Deciduous trees		Water		Urban		Farms		Total
	km ²	%	km ²	%	km ²	%	km ²	%	km ²	%	
<i>Batiscan</i>	1816	41.9	2264	52.3	187	4.3	0	0	67	1.6	4334
<i>Bécancour</i>	255	9.7	2144	81.6	16	0.6	0	0	214	8.2	2629
<i>Chamouchouane</i>	817	5.4	13156	87.5	1040	6.9	0	0	29	0.2	15042
<i>Châteauguay</i>	112	5.0	1722	77.4	13	0.6	0	0	379	17.0	2227
<i>Chaudière</i>	1229	21.5	4206	73.4	71	1.2	0	0	223	3.9	5728
<i>Du Loup</i>	243	28.4	557	65.1	55	6.4	0	0	1	0.1	855
<i>Gatineau</i>	1159	17.0	5298	77.8	353	5.2	0	0	0	0	6810
<i>Mistassini</i>	569	6.1	8341	89.7	384	4.1	0	0	1	0	9295
<i>Rouge</i>	1401	25.6	3791	69.2	285	5.2	0	0	2	0	5480
<i>Yamaska</i>	23	1.7	2050	76.7	2	0.2	5	0.4	289	21.1	1389

1013 **Table 2: Summary (1982-2002) of the climate characteristics of the study watersheds**

	Rain (mm)						Snow (mm)			F mo y Mean Temp. (°C)					
	Summer			Winter			Annual			Summer			Winter		
	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
<i>Batiscan</i>	337	558	645	97	180	403	286	356	416	8 _± 4	10 _± 3	11 _± 5	-7 _± 7	-5 _± 4	-3 _± 1
<i>Bécancour</i>	392	585	809	129	260	490	169	260	372	10 _± 3	11 _± 9	13 _± 3	-5 _± 0	-2 _± 9	-1 _± 0
<i>Chamouchouane</i>	293	518	690	85	131	248	219	290	383	6 _± 4	8 _± 6	10 _± 0	-11 _± 4	-8 _± 7	-5 _± 6
<i>Chateauguay</i>	402	512	620	174	269	429	137	193	252	12 _± 4	13 _± 8	15 _± 2	-3 _± 8	-1 _± 1	0 _± 9
<i>Chaudière</i>	421	590	794	179	253	392	216	266	316	9 _± 5	11 _± 2	12 _± 5	-5 _± 4	-3 _± 3	-1 _± 5
<i>Du Loup</i>	423	547	643	154	233	480	178	224	247	8 _± 5	10 _± 2	11 _± 5	-7 _± 5	-5 _± 3	-3 _± 0
<i>Gatineau</i>	324	519	671	86	145	242	224	290	350	7 _± 9	9 _± 7	11 _± 4	-8 _± 8	-6 _± 4	-3 _± 6
<i>Mistassini</i>	278	515	729	81	126	236	224	300	384	5 _± 9	8 _± 2	9 _± 7	-12 _± 0	-9 _± 2	-6 _± 1
<i>Rouge</i>	372	529	613	100	175	333	248	327	368	9 _± 2	10 _± 8	11 _± 9	-6 _± 9	-4 _± 4	-2 _± 0
<i>Yamaska</i>	476	577	743	180	305	526	122	204	294	11 _± 6	13 _± 1	14 _± 5	-3 _± 9	-1 _± 5	0 _± 6

1014

Review Only

1015 **Table 3: Summary (1982-2002) of the hydrological characteristics of the study watersheds**

	Q (mm/day)						Qmax (m3/s)						7d-Qmin (m3/s)						30d-Qmin (m3/s)					
	Summer			Winter			Summer			Winter			Summer			Winter			Summer			Winter		
	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
Batiscan	0.9	1.6	2.4	1.4	2.1	3.1	140	265	528	349	558	837	17	31	57	18	24	35	22	37	72	19	26	43
Bécancour	0.6	1.1	1.9	1.5	2.1	2.9	69	203	402	296	494	848	2	7	21	7	120	402	3	10	32	8	13	21
Chamouchouane	1.1	1.8	2.6	1.2	1.5	1.9	404	781	1370	610	1350	2159	112	156	199	60	78	102	128	184	245	61	81	116
Chateauguay	0.3	0.6	1.3	1.1	1.8	2.6	27	168	623	193	460	1091	2	4	10	6	10	18	2	6	17	7	12	32
Chaudière	0.5	1.1	2.1	1.6	2.2	3.0	236	646	1318	847	1339	2140	4	10	26	12	19	32	5	17	45	14	23	47
Du Loup	0.3	0.8	1.3	1.0	1.6	2.3	12	29	79	55	84	130	1	2	6	3	4	5	1	3	7	3	4	6
Gatineau	1.0	1.5	2.4	1.1	1.7	2.5	202	425	1200	413	731	1500	19	38	56	20	32	46	21	50	92	22	34	48
Mistassini	1.2	1.9	2.7	1.3	1.7	2.3	314	595	959	604	1257	2050	58	92	129	27	39	67	70	119	159	28	41	76
Rouge	0.8	1.2	1.7	1.3	2.0	2.9	118	243	376	381	588	914	11	27	45	24	36	50	6	32	61	25	39	59
Yamaska	0.4	0.8	1.7	1.2	2.0	2.7	44	142	239	182	320	559	1	1	3	2	4	7	1	2	6	2	6	13

1016 **Table 4: HYDROTEL key parameters**

Type	Parameters	Units
<i>Snow parameters</i>	MFEF - Melt factor for evergreen forests*	mm/d.°C
	MFDF - Melt factor for deciduous forests*	mm/d.°C
	MFOA - Melt factor for open areas*	mm/d.°C
	TEF - Threshold air temperature for melt in evergreen forests*	°C
	TDF - Threshold air temperature for melt in deciduous forests*	°C
	TOA - Threshold air temperature for melt in open areas*	°C
	Melt rate at the snow-soil interface	mm/d

<i>Soil parameters</i>	Compaction coefficient	-
	PETF - Potential evapotranspiration multiplication factor*	-
	z1- Depth of the lower boundary of soil layer #1*	m
	z2- Depth of the lower boundary of soil layer #2*	m
	z3- Depth of the lower boundary of soil layer #3*	m
	RC - Recession coefficient*	m/h
	Extinction coefficient	-

<i>Interpolation coefficients</i>	Maximum variation of soil moisture content	-
	TSL - Threshold air temperature for partitioning solid and liquid precipitation*	°C
	Precipitation vertical gradient	mm/100m
	Temperature vertical gradient	°C/100m

1017 *Parameter calibrated in this paper

1018 ^a For a complete description of snow parameters, the reader is referred to Turcotte et al. (2007a)1019 ^b For a complete description of soil parameters, the reader is referred to Fortin et al. (2001b)

1020

1021 **Table 5: Summary of the KGE and Nash-log values for the ten watersheds over the**
 1022 **calibration and validation periods**

	Calibration						Validation					
	KGE			Nash-log			KGE			Nash-log		
	1st decile	Median	9th decile	1st decile	Median	9th decile	1st decile	Median	9th decile	1st decile	Median	9th decile
<i>Batiscan</i>	0.946	0.946	0.947	0.894	0.896	0.897	0.799	0.805	0.810	0.670	0.674	0.694
<i>Bécancour</i>	0.872	0.874	0.875	0.795	0.799	0.801	0.797	0.807	0.814	0.701	0.706	0.717
<i>Chamouchouane</i>	0.947	0.947	0.947	0.907	0.907	0.907	0.823	0.826	0.829	0.632	0.637	0.641
<i>Chateauguay</i>	0.859	0.860	0.860	0.767	0.768	0.768	0.763	0.767	0.775	0.692	0.695	0.699
<i>Chaudière</i>	0.916	0.916	0.916	0.805	0.810	0.815	0.869	0.871	0.875	0.695	0.709	0.721
<i>Du Loup</i>	0.944	0.945	0.945	0.842	0.842	0.842	0.792	0.796	0.802	0.700	0.703	0.704
<i>Gatineau</i>	0.907	0.907	0.907	0.827	0.828	0.828	0.766	0.768	0.771	0.684	0.686	0.691
<i>Mistassini</i>	0.955	0.955	0.956	0.904	0.905	0.905	0.873	0.875	0.876	0.646	0.652	0.660
<i>Rouge</i>	0.947	0.947	0.947	0.887	0.887	0.887	0.876	0.878	0.880	0.700	0.702	0.704
<i>Yamaska</i>	0.828	0.832	0.835	0.761	0.762	0.764	0.833	0.839	0.845	0.609	0.626	0.637

1023

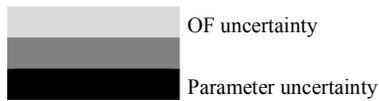
1024 **Table 6: Median of the KGE and Nash-log loss of performance (positive values) between**
1025 **the calibration and validation periods**

	KGE	Nash-log
<i>Batiscan</i>	15%	14%
<i>Bécancour</i>	8%	-8%
<i>Chamouchouane</i>	13%	20%
<i>Chateauguay</i>	11%	-14%
<i>Chaudière</i>	5%	-6%
<i>Du Loup</i>	16%	1%
<i>Gatineau</i>	15%	0%
<i>Mistassini</i>	8%	18%
<i>Rouge</i>	7%	9%
<i>Yamaska</i>	-1%	-6%

1026

1027 **Table 7: Dominant type of uncertainty for each study watershed for the five modelled**
 1028 **hydrological variables**

	Daily Streamflows	7d-and 30d-Qmin	Qmax	SWE	AET	GWC
<i>Batiscan</i>	OF uncertainty	OF uncertainty	OF uncertainty	Parameter uncertainty	OF uncertainty	Parameter uncertainty
<i>Bécancour</i>	OF uncertainty	OF uncertainty	OF uncertainty	OF uncertainty	Parameter uncertainty	OF uncertainty
<i>Chamouchouane</i>	OF uncertainty	OF uncertainty	OF uncertainty	Parameter uncertainty	Parameter uncertainty	Parameter uncertainty
<i>Châteauguay</i>	OF uncertainty	OF uncertainty	OF uncertainty	Parameter uncertainty	OF uncertainty	OF uncertainty
<i>Chaudière</i>	OF uncertainty	OF uncertainty	OF uncertainty	OF uncertainty	OF uncertainty	Parameter uncertainty
<i>Du Loup</i>	OF uncertainty	OF uncertainty	OF uncertainty	OF uncertainty	OF uncertainty	OF uncertainty
<i>Gatineau</i>	OF uncertainty	OF uncertainty	OF uncertainty	Parameter uncertainty	OF uncertainty	Parameter uncertainty
<i>Mistassini</i>	OF uncertainty	OF uncertainty	OF uncertainty	Parameter uncertainty	OF uncertainty	OF uncertainty
<i>Rouge</i>	OF uncertainty	OF uncertainty	OF uncertainty	OF uncertainty	OF uncertainty	OF uncertainty
<i>Yamaska</i>	OF uncertainty	OF uncertainty	OF uncertainty	Parameter uncertainty	OF uncertainty	OF uncertainty



1032 **Figures Captions**

1033 [Figure 1: Location of the study watersheds in Québec, Canada, and around the St. Lawrence](#)
1034 [River](#)~~Figure 1: Location of the study watersheds in Québec, Canada, and around the St.~~
1035 [Lawrence River](#)

1036 Figure 2: Relationship between mean annual and seasonal temperatures and precipitations for
1037 the calibration and validation periods

1038 [Figure 3: Radar plots of the twelve parameters used in the automatic calibration of](#)
1039 [HYDROTEL for each study watershed. Parameter A is part of the interpolation coefficients,](#)
1040 [parameters B through G relate to the snow model, and parameters F through L relate to the](#)
1041 [soil group of parameters. The dark blue diagrams refer to the KGE OF while the light blue](#)
1042 [diagrams refer to the Nash-log OF.](#)~~Figure 3: Radar plots of the twelve parameters used in the~~
1043 ~~automatic calibration of HYDROTEL for each study watershed. Parameter A is part of the~~
1044 ~~interpolation coefficients, parameters B through G relate to the snow model, and parameters F~~
1045 ~~through L relate to the soil group of parameters. The dark blue diagrams refer to the KGE~~
1046 ~~objective function OF while the light blue diagrams refer to the Nash-log OF.~~

1047 [Figure 4: Distribution of the OF values for the Chamouchouane watershed: \(a\) KGE](#)
1048 [calibration period; \(b\) KGE validation period; \(c\) Nash-log calibration period; \(d\) Nash-log](#)
1049 [validation period](#)~~Figure 4: Distribution of the OF values for the Chamouchouane watershed:~~
1050 ~~(a) KGE calibration period; (b) KGE validation period; (c) Nash-log calibration period; (d)~~
1051 ~~Nash-log validation period~~

1052 [Figure 5: Streamflow uncertainty envelopes for the Rouge watershed: \(a\) calibration \(9-year](#)
1053 [mean\) and \(b\) validation periods \(8-year mean\). The black and green envelopes stand for](#)
1054 [simulated flows under the KGE and Nash-log OFs, respectively, while the blue line depicts](#)
1055 [the observed values.](#)~~Figure 5: Streamflow uncertainty envelopes for the Rouge watershed: (a)~~

1056 ~~calibration (9 year mean) and (b) validation periods (8 year mean). The black and green~~
1057 ~~envelopes respectively stand for simulated flows under the KGE and Nash-log objective~~
1058 ~~functions OFs, respectively, while the blue line depicts the observed values.~~

1059 Figure 6: Boxplots of the seasonal hydrological indices for the Chamouchaoune watershed for
1060 the calibration (1) and validation (2) periods: (as1) and (as2) display the distribution of the
1061 maximum summer peakflows; (aw1) and (aw2) the distribution of maximum winter
1062 peakflows; (bs1) and (bs2) the distribution of summer-7-day minimum flows; and (bw1) and
1063 (bw2) the distribution of winter-7-day minimum flows. The black and green boxplots
1064 illustrate the distribution of simulated flows under the KGE and Nash-log OFs, respectively,
1065 while the blue dots depict the observed values. The superscripts *w* and *d* on the x-axis indicate
1066 the wettest and driest years of each simulation period, respectively. ~~Figure 6: Boxplots of the~~
1067 ~~seasonal hydrological indices for the Chamouchaoune watershed for the calibration (1) and~~
1068 ~~validation (2) periods: (as1) and (as2) display the distribution of the maximum summer~~
1069 ~~peakflows; (aw1) and (aw2) the distribution of maximum winter peakflows; (bs1) and (bs2)~~
1070 ~~the distribution of summer 7 day minimum flows; and (bw1) and (bw2) the distribution of~~
1071 ~~winter 7 day minimum flows. The black and green boxplots stand for illustrate the~~
1072 ~~distribution of simulated flows under the KGE and Nash-log OFs, while the blue dots depict~~
1073 ~~the observed values. The superscripts *w* and *d* on the x axis indicate the wettest and driest~~
1074 ~~years of each simulation period, respectively.~~

1075 Figure 7: SWE uncertainty envelopes for the Yamaska watershed: (a) calibration (9-year
1076 mean) and (b) validation periods (8-year mean). The black and green envelopes illustrate the
1077 distribution of simulated flows under the KGE and Nash-log OFs. ~~Figure 7: Snow water~~
1078 ~~equivalent (SWE) uncertainty envelopes for the Yamaska watershed: (a) calibration (9 year~~
1079 ~~mean) and (b) validation periods (8 year mean). The black and green envelopes stand~~

1080 ~~for illustrate the distribution of simulated flows under the KGE and Nash-log objective~~
1081 ~~functions OFs. The line indicates the period of overlapping between the uncertainty envelopes.~~

1082 Figure 8: Seasonal actual evapotranspiration for the Bécancour watershed: (a) summer
1083 calibration; (b) summer validation; (c) winter calibration and (d) winter validation. The black
1084 and green boxplots stand for simulated AET distributions under the KGE and Nash-log OFs,
1085 respectively. The outliers are represented by red crosses. The superscripts w and d on the x -
1086 axis stand for the wettest and driest years of each simulation period, respectively.Figure 8:

1087 ~~Seasonal actual evapotranspiration for the Bécancour watershed: (a) summer calibration; (b)~~
1088 ~~summer validation; (c) winter calibration and (d) winter validation. The black and green~~
1089 ~~boxplots stand for simulated AET distributions under the KGE and Nash-log OFs,~~
1090 ~~respectively. The outliers are represented by red crosses. The superscripts w and d on the x -~~
1091 ~~axis stand for the wettest and driest years of each simulation period, respectively.~~

1092 Figure 9: Shallow groundwater content uncertainty envelopes for the Du Loup watershed: (a)
1093 calibration (9-year mean) and (b) validation periods (8-year mean). The black and green
1094 envelopes illustrate the distribution of simulated flows under the KGE and Nash-log OFs,
1095 respectively.Figure 9: Shallow groundwater content uncertainty envelopes for the Du Loup
1096 ~~watershed: (a) calibration (9 year mean) and (b) validation periods (8 year mean). The black~~
1097 ~~and green envelopes stand for illustrate the distribution of simulated flows under the KGE and~~
1098 ~~Nash-log objective functions OFs, respectively.~~

1099 Figure 10: Radar plots of the twelve parameters used in the automatic calibration of
1100 HYDROTEL for each study watershed. Parameter A is part of the interpolation coefficients,
1101 parameters B through G relate to the snow model, and parameters F through L relate to the
1102 soil group of parameters. Figure (a) refers to the KGE OF; and (b) to the Nash-log OF. The
1103 dark and light blue data refer to the first optimization trial of Figure 3, black data to the
1104 second optimization trial.Figure 10: Radar plots of the twelve parameters used in the

1105 automatic calibration of HYDROTEL for each study watershed. Parameter A is part of the
1106 interpolation coefficients, parameters B through G relate to the snow model, and parameters F
1107 through L relate to the soil group of parameters. Figure (a) refers to the KGE objective
1108 function OF ; and (b) to the Nash log objective function OF . The dark and light blue data refer
1109 to the first optimization trial of Figure 3, black data to the second optimization trial.

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**EQUIFINALITY AND AUTOMATIC CALIBRATION, WHAT IS THE IMPACT OF
HYPOTHESIZING AN OPTIMAL PARAMETER SET ON MODELLED HYDROLOGICAL
PROCESSES?**

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Keywords :calibration, equifinality, hydrological model, HYDROTEL, objective function,
parameter uncertainty

1 **Abstract**

2 Accepting the concept of equifinality may result in larger uncertainty associated with model
3 predictions than that of the optimal parameter set paradigm. Despite the existence of
4 uncertainty characterization methods, the semi-distributed hydrological model HYDROTEL
5 has been used within the latter paradigm. What is the impact of hypothesizing an optimal
6 parameter set? This paper focuses on the assessment of the impact of equifinality of calibration
7 parameters with respect to modelled hydrological variables and indices, namely: (i) daily
8 flows; (ii) seasonal seven- and thirty-day low flows; and maximum flow; (iii) snow water
9 equivalent (SWE); (iv) shallow ground water variations; and (v) actual evapotranspiration.
10 This assessment is presented for ten southern Québec watersheds of the St. Lawrence River.
11 The watershed models were calibrated and validated for 1982-1991 and 1991-2002,
12 respectively. Automatic calibration was performed using the Dynamically Dimensioned
13 Search (DDS) algorithm based on the maximization of two objective functions (OFs): (i) the
14 Kling-Gupta efficiency and (ii) the Nash-log. DDS was executed to calibrate 12 hydrological
15 parameters for one optimization trial for each watershed and each OF with a budget of 5000
16 model runs. To analyse parameter uncertainty and resulting equifinality, 250 sets of
17 parameters were extracted from each trial run. Calibration performances for both OFs were
18 between 0.75 and 0.95, while the selected 250 best sets of parameters had OF values differing
19 by less than 1%. Results showed that the overall OF uncertainty was larger than the parameter
20 uncertainty for all modelled processes except the SWE. Nevertheless, seasonal results
21 suggested parameter uncertainty could be greater than OF uncertainty for specific seasons or
22 years, although it was not possible to make a general outcome stand out. In particular for
23 impact studies where the variables of interest are not daily flows but rather hydrological
24 indices or variables, parameter uncertainty will need to be accounted for.

25 **Résumé**

26 Accepter l'existence du concept d'équifinalité c'est reconnaître l'incertitude liée à l'existence
27 d'une famille de solutions donnant des résultats de qualité similaire obtenus avec la même
28 fonction objectif. Malgré l'existence de méthodes de caractérisations de cette incertitude, le
29 modèle hydrologique HYDROTEL a été principalement utilisé jusqu'à maintenant selon le
30 paradigme du calage optimal unique sans évaluer *a posteriori* les conséquences de ce choix.
31 Cette étude propose d'évaluer l'impact du choix du jeu de paramètres optimisés sur certaines
32 variables et indicateurs hydrologiques simulés, à savoir: (i) les débits journaliers; (ii) les
33 débits d'étiage à 7 et 30 jours et les débits maximum; (iii) l'équivalent en eau de la neige
34 (EEN), (iv) les variations du contenu en eau du sol peu profond et (v) l'évapotranspiration
35 réelle. Dans ce contexte, HYDROTEL est mis en place sur dix bassins versant du Québec
36 méridional entre 1982 et 2002. Pour chacune des fonctions objectif (FO) (Kling Gupta
37 efficiency et Nash-log) et chacun des bassins, l'algorithme *Dynamically Dimensioned Search*
38 (DDS) dispose d'un budget de 5000 répétitions pour optimiser les 12 paramètres de calage
39 d'HYDROTEL sur 1981-1991. Ainsi, 250 jeux de paramètres sont conservés pour évaluer
40 l'incertitude paramétrique et l'équifinalité résultante. Les résultats de calage indiquent des
41 fonctions objectif comprises entre 0,75 et 0,95, tandis que pour chaque modèle les 250
42 meilleures répétitions présentent des fonctions objectif égales à 1% près. Globalement, pour
43 tous les processus simulés excepté pour l'EEN, l'incertitude relative aux FO était plus
44 importante que celle relative aux jeux de paramètres. Cependant, les résultats saisonniers
45 suggèrent que l'incertitude paramétrique peut dépasser celle due aux FO dans certaines
46 conditions particulières. Elle devra donc être prise en compte, en particulier pour les études
47 d'impacts et de risque hydrologique dont les variables d'intérêt sont principalement des
48 indicateurs hydrologiques simulés et non pas les débits journaliers.

49

50 **Introduction**

51 The equifinality concept refers to the existence of many parameter sets (and multiple model
52 structures) associated with the same ‘optimal’ measure of efficiency (Beven 2006a; Beven
53 and Freer 2001). Within a realistic parameter space, for a given mechanistic model of a
54 complex environmental system, many local optima may exist. Despite the computational
55 costs, equifinality has been revealed for many types of models and especially for rainfall-
56 runoff models (Beven 1993; Beven and Binley 1992; Duan *et al.* 1992; Fu *et al.* 2015; Futter
57 *et al.* 2015; Li *et al.* 2012; Linhoss *et al.* 2013; Prada *et al.* 2016; Romanowicz *et al.* 1994;
58 Zeng *et al.* 2016; Zhang *et al.* 2012).

59 The main consequence of accepting the concept of equifinality is that the uncertainty
60 associated with model predictions might be larger than that assessed within the optimal
61 parameter set paradigm. Different types of approaches allow to deal with such an uncertainty
62 (Vrugt *et al.* 2009a). Some approaches have their roots within a formal statistical (Bayesian)
63 framework, but require in-depth understanding of mathematics and statistics as well as
64 experience in implementing (Fisher and Beven 1996; Freer *et al.* 1996) these methods on
65 computers (Vrugt *et al.* 2009b). This probably explains the success of the generalized
66 likelihood uncertainty estimation (GLUE) method of (Beven and Binley 1992). It operates
67 within the context of Monte Carlo analysis coupled with Bayesian or fuzzy estimation and
68 propagation of uncertainty. It is relatively easy to implement and requires no modifications to
69 existing codes of simulation models. More recently, Tolson and Shoemaker (2007) presented
70 how the dynamically dimensioned search (DDS) optimization algorithm could replace random
71 sampling in typical applications of GLUE. They also introduced a more efficient uncertainty
72 analysis methodology called DDS-approximation of uncertainty (DDS-AU) that differs from
73 the automatic calibration and uncertainty assessment using response surfaces (ACUARS)

74 methods (Mugunthan and Shoemaker 2006). The former approach requires many optimisation
75 trials while the latter approach uses only one trial coupled with a declustering technique.

76 The idea of an optimal parameter set remains strong in environmental sciences and even
77 stronger in hydrological modelling. For a physically-based, semi-distributed, model such as
78 HYDROTEL (Bouda *et al.* 2014; Bouda *et al.* 2012; Fortin *et al.* 2001b; Turcotte *et al.*
79 2007a; Turcotte *et al.* 2003), this frame of mind is rooted in two perceptions: (i) multiple
80 feasible descriptions of reality lead to ambiguity and are possibly viewed as a failure of the
81 modelling exercise (Beven 2006a); and (ii) a manual search for an “optimum” is already
82 computationally expensive (Turcotte *et al.* 2003) while an automatic search may provide only
83 a slight increase in model efficiency in comparison with the latter manual calibration (Bouda
84 *et al.* 2014). This is why in the last decade, at the risk of avoiding important issues of model
85 acceptability and uncertainty (Beven 2006a), HYDROTEL has almost always been applied
86 within the optimal parameter set paradigm.

87 For example, in several studies (Aissia *et al.* 2012; Fortin *et al.* 2001a; Fossey and Rousseau
88 2016a, 2016b; Fossey *et al.* 2015; Fossey *et al.* 2016; Khalili *et al.* 2011; Minville *et al.* 2009;
89 Oreiller *et al.*; Quilbé *et al.* 2008; Rousseau *et al.* 2013), HYDROTEL has been manually
90 calibrated following the four-step, trial-and-error, process-oriented, multiple-objective
91 calibration strategy introduced by Turcotte *et al.* (2003). It has also been calibrated using the
92 shuffled complex evolution algorithm (SCE-UA) designed by Duan *et al.* (1993) to find the
93 optimal set of parameters while avoiding local optima (Bouda *et al.* 2014; Gaborit *et al.* 2015;
94 Ludwig *et al.* 2009; Ricard *et al.* 2013; Trudel *et al.* 2016). But two exceptions emerge from
95 the literature, Bouda *et al.* (2012); Poulin *et al.* (2011) both used the SCE-UA algorithm to
96 generate multiple parameter sets and assessed the uncertainty of hydrological modelling under
97 the equifinality assumption. Poulin *et al.* (2011), based on one snow-dominated watershed,
98 concluded that model uncertainty (conceptual models *versus* more physically-based models for

99 example) can be more significant than parameter uncertainty. Meanwhile, Bouda *et al.*
100 (2012), from their work on two watersheds, stressed the need for further research that may
101 lead to the implementation of a systematic uncertainty analysis in an operational hydrological
102 forecasting system. Nevertheless, they both highlighted the need for additional validation of
103 their results on additional watersheds.

104 It is important to mention that the technico-philosophical debate started in 2006 (Beven 2006b,
105 2008) about the methods that should or should not be used to estimate the uncertainties
106 associated with hydrological forecasting is beyond the scope of this paper. Indeed, the debate
107 is still ongoing about the relative performances of formal (DREAM) and informal (GLUE)
108 Bayesian approaches in estimating the consequences of equifinality (Beven 2009; Vrugt *et al.*
109 2009b, 2009c) and about the multiple sources of uncertainty and non-stationarity in the
110 analysis and modelling of hydrological systems (Beven 2016; Nearing *et al.* 2016). In this
111 paper, equifinality is simply explored through the implementation of the automatic calibration
112 algorithm DDS (Tolson and Shoemaker 2007), which has been reported as being superior to
113 SCE-UA (Arsenault *et al.* 2014; Yen *et al.* 2016). Our contribution builds on the work carried
114 out on hydrological uncertainty to show in practical terms why equifinality does need to be
115 taken into account by answering one simple question taken out of the technico-philosophical
116 debate: what are the consequences of not accounting for equifinality while calibrating
117 HYDROTEL for an environmental impact study? Here, hydrological uncertainty (defined by
118 the spread resulting from multiple calibrations) is assessed for five modelled hydrological
119 variables and indices: (i) daily flows, (ii) seasonal hydrological indices such as the seven-day
120 low flow (7d-Qmin), 30-day low flow (30d-Qmin), and the maximum flow (Qmax), (iii) snow
121 water equivalent (SWE), (iv) shallow ground water content variations (GWC) and (v) actual
122 evapotranspiration (AET). Innovation resides in three elements. A calibration strategy close to
123 that of manual calibration was used in order to demonstrate the need to account for

124 equifinality in impact assessment studies aside from the technico-philosophical debate started
125 in 2006. Moreover, using 10 watersheds across Québec avoided limiting the significance of
126 the results to a specific region. Last, the relative importance of OF uncertainty and parameter
127 uncertainty were differentiated according to the variable being considered and its temporal
128 scale (yearly or seasonal).

129 The next two sections of this paper introduce the modelled watersheds and the methods, the
130 results and ensuing discussions. Throughout the paper, readers should keep in mind that the
131 results do not aim at assessing the formal statistical uncertainty associated with the
132 hydrological processes, but rather at showing the concrete consequences of equifinality on
133 modelled hydrological processes

134 **Study area and data**

135 This study was carried out in southern Québec (Canada) on ten watersheds spread out in five
136 hydrographic regions of the St. Lawrence River (Figure 1). These ten watersheds, namely (i)
137 Batiscan, (ii) Bécancour, (iii) Chamouchouane, (iv) Châteauguay, (v) Chaudière, (vi) Du
138 Loup, (vii) Gatineau, (viii) Mistassini, (ix) Rouge, and (x) Yamaska have modelled drainage
139 areas ranging from 855 up to 15,042 km² and various land cover patterns. Table 1 indicates all
140 watersheds, but Yamaska, have a forested (evergreen + deciduous trees) area covering more
141 than 90% of the modelled land cover. Yamaska is the only watershed with a significant
142 portion of urban area. Batiscan has over 40% of evergreen while Gatineau, Chaudière, Rouge
143 and Du Loup have 17, 21.5, 25.6 and 28.4% of evergreen, respectively, and the remaining
144 five watersheds have an evergreen area representing less than 10% of their total land cover. It
145 is also noteworthy that Châteauguay, Bécancour and Chaudière have 17.0, 8.2 and 3.9% of
146 cropland while the remaining seven watersheds have less than 1%.

147 According to available meteorological data (1981-2002, 1995 and 1996 being unavailable)
148 from National Resources Canada, the region surrounding the St. Lawrence River delineated in
149 Figure 1 is characterized by a mean annual temperature of 1.8°C and mean annual total
150 precipitation of 940 mm. All watersheds are snow-dominated with peak flow occurring in
151 spring. A summary of the hydroclimatic characteristics of the watersheds is provided in Table
152 2 and Table 3 for two hydrological seasons, that is summer (June 1st to November 30th) and
153 winter (December 1st to May 31st). While the mean summer rainfall is 545 mm and quite
154 homogenous among the watersheds (standard deviation of 30 mm), mean winter rainfall is
155 more heterogeneous with a mean of 208 mm and a standard deviation of 64 mm. Meanwhile,
156 mean snowfall is 271 mm with a standard deviation of 52 mm. Mean summer (10.8°C) and
157 winter (-4.8°C) temperatures are also quite variable with respective standard deviations of 1.8
158 and 2.8 °C. This shows that in terms of climate characteristics, the studied watersheds are

159 quite heterogeneous. In terms of hydrological characteristics, mean summer and winter daily
160 flows are 1.2 and 1.9 mm, respectively, with standard deviations of 0.44 and 0.23. Winter
161 flows are higher than summer flows on average because winter includes the snow melt and
162 thus the spring peak flows. Higher variability in the summer flows is attributed to summer
163 rainfall and convective storms that are more variable than snowfalls. The hydrological indices
164 mean values indicate that the watersheds, despite being somewhat located along the St.
165 Lawrence River, have heterogeneous characteristics with mean 7d-Qmin ranging from 2 up to
166 $156 \text{ m}^3\text{s}^{-1}$ and from 4 to $120 \text{ m}^3\text{s}^{-1}$ for summer and winter, respectively. Heterogeneity is even
167 higher for mean Qmax; ranging from 29 up to $595 \text{ m}^3\text{s}^{-1}$ and from 84 to $1350 \text{ m}^3\text{s}^{-1}$ for
168 summer and winter, respectively.

169 <Table 1: Land cover of the ten studied watersheds in southern Québec, Canada >

170 **Figure 1: Location of the study watersheds in Québec, Canada, and around the St.**

171 **Lawrence River**

172 <Table 2: Summary (1982-2002) of the climate characteristics of the study watersheds>

173 <Table 3: Summary (1982-2002) of the hydrological characteristics of the study
174 watersheds>

175 **Material and Methods**

176 **Hydrological model**

177 HYDROTEL is a process-based, continuous, semi-distributed hydrological model (Bouda *et al.* 2014; Bouda *et al.* 2012; Fortin *et al.* 2001b; Turcotte *et al.* 2007a; Turcotte *et al.* 2003)
178 *al.* 2014; Bouda *et al.* 2012; Fortin *et al.* 2001b; Turcotte *et al.* 2007a; Turcotte *et al.* 2003)
179 that is currently used for inflow forecasting by Hydro-Quebec, Quebec's major power utility,
180 and the Quebec Hydrological Expertise Centre (CEHQ) which is in charge of the
181 management and safety of publicly owned dams (Turcotte *et al.* 2004). It was designed to use
182 available remote sensing and GIS data and use either a 3-hour or a daily time step. It is based
183 on the spatial segmentation of a watershed into relatively homogeneous hydrological units
184 (RHHUs, elementary subwatersheds or hillslopes as desired) and interconnected river
185 segments (RSs) draining the aforementioned units. A semi-automatic, GIS-based framework
186 called PHYSITEL (Noël *et al.* 2014; Rousseau *et al.* 2011; Turcotte *et al.* 2001) allows easy
187 watershed segmentation and parameterization of the hydrological objects (RHHUs and RSs).
188 The model is composed of seven computational modules, which run in successive steps. Each
189 module simulates a specific process (meteorological data interpolation, snowpack dynamics,
190 soil temperature and freezing depth, potential evapotranspiration, vertical water budget,
191 overland water routing, channel routing). Readers are referred to Fortin *et al.* (2001b) and
192 Turcotte *et al.* (2007a) for more details on these aspects of HYDROTEL.

193 The main parameters of HYDROTEL can be subdivided into three groups (see Table 4). The
194 first group includes the snow parameters and the second group includes the soil parameters.
195 The last three individual parameters are related to the interpolations of temperature and
196 precipitation according to the average of the three nearest meteorological stations weighed in
197 by the square of the inverse distances between the RHHU and the three stations (a.k.a. the
198 Reciprocal-Distance-Squared method).

199 <Table 4: HYDROTEL key parameters>

200 **Data acquisition**

201 Observed climate data for 1981-2002 were computed on a $0.75^\circ \times 0.75^\circ$ grid by isotropic
202 kriging following the method described in Poirier *et al.* (2012) using the meteorological data
203 provided by National Resources Canada. Each grid-point served as a meteorological station in
204 HYDROTEL. Flow data were extracted from the CEHQ data base; which operates around
205 230 hydrometric stations (CEHQ, 2012). Stations were selected for their data availability and
206 proximity to the outlets of the watersheds. For Batiscan (#050304 [-72.4° long, 46.6° lat]),
207 Bécancour (#024007 [-72.3° long., 46.2° lat.]), Châteauguay (#030905 [-73.8° long., 45.3°
208 lat.]) and Rouge (#040204 [-74.7° long., 45.7° lat.]), stations were located at the outlet of each
209 watershed while for Chamouchouane (#061901 [-72.5° long., 48.7° lat.]), Chaudière
210 (#023402 [-71.2° long., 46.6° lat.]), Du Loup (#052805 [-73.2° long., 46.6° lat.]), Gatineau
211 (#040830 [-75.8° long., 47.1° lat.]), Mistassini (#062102 [-72.3° long., 48.9° lat.]) and
212 Yamaska (#030304 [-72.9° long., 45.5° lat.]), the nearest stations were selected (see Figure 1).

213 **Calibration/validation and parameter sets generation**

214 Model calibration on each watershed was carried out using a global optimization algorithm,
215 DDS presented in Tolson and Shoemaker (2007). It allows systematic and impartial
216 calibration of HYDROTEL through all the watersheds using a fixed methodology. The
217 shuffled complex evolution (SCE) algorithm (Duan *et al.* 1992; Duan *et al.* 1994; Duan *et al.*
218 1993) was also considered; viewed as the dominant optimization algorithm before 2007 with
219 more than 300 different applications referring to the original set of SCE papers. However, it
220 has since been proved that DDS is better suited for distributed watershed models requiring
221 extensive computational time (Arsenault *et al.* 2014; Tolson and Shoemaker 2007; Yen *et al.*
222 2016). DDS performs a low number of model evaluations before converging to a good
223 calibration solution. According to Yen *et al.* (2016), DDS outperforms other optimization

224 techniques in both convergence speed and searching ability for parameter sets that satisfy
 225 statistical guidelines while requiring only one algorithm parameter (perturbation factor,
 226 default value 0.2) in the optimization process. This default value was used in this paper.

227 Automatic calibration was performed based on the maximization of four objective functions
 228 (OFs) computed from observed flow data: (i) Kling-Gupta efficiency (KGE); (ii) Nash-log;
 229 that is the Nash-Sutcliffe efficiency (NSE) calculated on log transformed flows; (iii) NSE_Q
 230 and (iv) $NSE_{\sqrt{Q}}$ computed on root squared flows. DDS was executed for one optimization trial
 231 for each watershed and each OF with a budget of 5000 model runs - the trial was initiated
 232 from the same random set of parameter values for every watershed. To analyse parameter
 233 uncertainty and resulting equifinality, the 250 sets of parameters resulting in the best OF
 234 values were extracted from each trial run. Then each model was run over a validation period
 235 using the corresponding 250 sets of parameters (10 models times 4 OFs). However, this paper
 236 solely focused on two of the four OFs studied namely KGE and Nash-log because including
 237 the two other functions would not help distinguishing the dominant type of uncertainty.
 238 Indeed, overall results for NSE are close to KGE results except around peak flows (*Gupta et*
 239 *al.*, 2009) while $NSE_{\sqrt{Q}}$ represents a tradeoff between KGE and Nash-log. Using the
 240 combination of KGE and Nash-log provides a contrasted calibration procedure that in turn
 241 favors high flows and low flows.

$$242 \quad \mathbf{KGE} = \mathbf{1} - \sqrt{(\mathbf{r} - \mathbf{1})^2 + (\boldsymbol{\alpha} - \mathbf{1})^2 + (\boldsymbol{\beta} - \mathbf{1})^2} \quad \mathbf{Eq 1}$$

243 where r is the linear correlation coefficient between simulated and observed values; α is a
 244 measure of relative variability in the simulated and observed values, that is the ratio between
 245 simulated and observed standard deviations; and β stands for the bias, that is the ratio between
 246 the mean simulated and mean observed flows.

$$247 \quad \mathbf{Nash-log} = 2 \cdot \alpha_{log} \cdot r_{log} - \alpha_{log}^2 - \beta_{log n}^2 \quad \mathbf{Eq 2}$$

248 where α_{log} and r_{log} are the linear correlation coefficient and measure of relative variability
 249 between the log transformed simulated and observed flows, respectively; and $\beta_{log n}$ stands for
 250 the ratio between the bias of log transformed simulated and observed flows, normalized by
 251 the standard deviation of observed values.

252 The calibration period extended from December 1st, 1982 to November 30th, 1991; that is nine
 253 entire hydrological years. The validation period started on December 1st, 1991 and ended on
 254 November 30th, 2002 (remembering that the 1995-1996 meteorological data series were
 255 unavailable); that is eight complete hydrological years (hydrological years 1994 – December
 256 1st, 1994 to November 30th, 1995, and 1995 – December 1st, 1995 to November 30th, 1996
 257 were unavailable), corresponding to nine summers and eight winters (January to the end of
 258 May 1997 is used as a spin-up to make sure that the model is on the right track). In each case,
 259 a 1-year spin-up period was used to minimize initialization errors. During the 1995-1996
 260 meteorological data gap, the model was fed with data from 1993-1994 to prevent the rivers
 261 from drying out. These simulation periods (calibration and validation) followed the split-
 262 sample strategy applied to the available meteorological and hydrological data. The length of
 263 the calibration period was not so long as to increase computational costs too much, but not so
 264 short as to have issues related to the interannual variability of climate data compared with the
 265 validation period. Figure 2 illustrates the appropriateness of this approach in terms of mean
 266 annual and seasonal temperatures and precipitations. For the calibration and validation, the
 267 simulation periods were relatively similar: precipitations and temperatures are within [614,
 268 911 mm] and [-1, +6°C], and [646, 845 mm] and [-0.2, 6.4°C], respectively.

269 Out of the eighteen (18) key calibration parameters (Table 4), twelve (12) were actually
 270 adjusted in this study: six (6) snow parameters; five (5) soil parameters; and one (1)
 271 interpolation coefficient. Sensitivity analyses were not formally carried out for any of the

272 watersheds beforehand, but these calibrated parameters are amongst the model most sensitive
273 parameters (Turcotte *et al.* 2003). This selection of parameters was based on: (i) information
274 provided by previous analyses (Ben Nasr 2014; Bouda *et al.* 2014), (ii) knowledge built
275 through the operational use of HYDROTEL (Turcotte *et al.* 2004) and (iii) experience gained
276 during the development of a Hydroclimatic Atlas conveying the potential impact of climate
277 change on water resources for the 2050 horizon over Southern Québec (CEHQ 2013, 2015).
278 The remaining parameters were fixed according to: (i) a regionalization study (Turcotte *et al.*
279 2007b), (ii) results from the application of a global calibration strategy (Ricard *et al.* 2013)
280 used in CEHQ (2013, 2015), and (iii) from previous manual calibration exercises.

281 **Figure 2: Relationship between mean annual and seasonal temperatures and**
282 **precipitations for the calibration and validation periods**

283

284 **Results**

285 As previously mentioned model uncertainty related to parameters used for the calibration of
286 HYDROTEL and to the choice of the OF was assessed through five modelled hydrological
287 variables and indices: (i) modelled streamflows, (ii) hydrological indices computed from the
288 latter, and three internal variables, namely (iii) snow water equivalent (SWE), (iv) actual
289 evapotranspiration (AET) and (v) shallow ground water content variations (GWC). In this
290 paper, parameter equifinality refers to the range that each calibration parameter covers within
291 the predefined physical limits attributed to each parameter. Meanwhile parameter uncertainty
292 refers to the consequences of parameter equifinality with respect to the model outputs.
293 Finally, OF uncertainty refers to the effects of using two different functions on the model
294 outputs. For each subsection, a different watershed is used as a showcase while the other nine
295 and their related figures are referred to as alternate watersheds and available as supplemental
296 information upon request to the corresponding author. This choice was made to focus on the
297 global picture conveyed by this paper instead of focusing on the characteristics of a single
298 watershed.

299 **Parameter equifinality**

300 Figure 3 shows the range covered by the 250 sets of parameters used in setting up the 20
301 models in HYDROTEL. The figure was computed by putting together for each model a radar
302 plot of the calibration parameter values. For every set of parameters, a line was drawn to link
303 every individual parameter. The computation of the 250 lines made it possible to picture the
304 range covered by the selected sets of parameters within a predefined physical interval that
305 limits the automatic calibration algorithm. These limits were based on the information
306 provided by previous sensitivity analyses, operational experience, and previous calibration
307 exercises.

308 For most watershed models, the parameter equifinality is limited. Indeed, parameter
309 equifinality for the Batiscan watershed, for the KGE OF, covers a maximum of 9.2% of the
310 physical range for the deciduous melting threshold parameter (C in Figure 3), but about 5%
311 for the rain/snow limit (A in Figure 3) for example. The maximum parameter equifinality is
312 obtained for the evergreen melting threshold on the Yamaska watershed for the KGE OF with
313 an equifinality covering 45.6% of the physical range. Overall, the “most equifinal parameters”
314 are the evergreen melting rate (B in Figure 3) and threshold (E in Figure 3).

315 **Figure 3: Radar plots of the twelve parameters used in the automatic calibration of**
316 **HYDROTEL for each study watershed. Parameter A is part of the interpolation**
317 **coefficients, parameters B through G relate to the snow model, and parameters F**
318 **through L relate to the soil group of parameters. The dark blue diagrams refer to the**
319 **KGE OF while the light blue diagrams refer to the Nash-log OF.**

320 **Streamflows**

321 A tangible evidence of the equifinality of the 20 models is displayed by the narrow ranges of
322 OF values resulting from the 250 calibrations and validations. This was expected despite the
323 careful consideration given to the number of calibration parameters used to avoid over
324 parametrization and limit the possibility of equifinality. Figure 4 shows the KGE and Nash-
325 log values obtained in calibration and validation for the Chamouchouane watershed. KGE as
326 well as Nash-log calibration values belong to equally narrow ranges [0.9464, 0.9472] and
327 [0.9064, 0.9072]. For the validation period, ranges are larger, but still quite narrow with 100%
328 and 68% of KGE and Nash-log values fitting in the equally narrow ranges [0.8225, 0.8305]
329 and [0.6340, 0.6420], respectively. Model performances are not as good in validation as in
330 calibration. But as Table 6 shows, differences in performances overpass a 15% difference
331 only three times out of the 20 models. Moreover, the validation period performances either
332 increase or as decrease in comparison with calibration values, and that vouches for the split-

333 sample strategy chosen. Indeed, Table 6 introduces the median loss of performances
334 computed from the individual losses of each of the 250 calibrations/validations which are
335 different from what could be computed from Table 5.

336 Table 5 shows that results of Figure 4 are also valid for the alternate watersheds included in
337 this paper. Indeed, for the calibration period, both KGE and Nash-log values can be
338 constrained in a 0.01 interval while, for the validation period, they are within a 0.15 interval.

339 What is notable is that ranges seem larger for the Nash-log than for the KGE OFs. Also, the
340 performances in calibration using the Nash-log OF are lower; whereby the mean of the KGE
341 values is 0.916, the mean of the Nash-log values is 0.840. For validation, this gap widens with
342 a mean KGE of 0.823 and a mean Nash-log of 0.679. This important difference may be
343 attributed to the relative inability of Nash-log to represent high flows. Indeed, high flows are
344 less correctly reproduced by Nash-log when low flows are assessed using the KGE OF. This
345 explains the observed difference in performances.

346 The simulated streamflow envelopes shown in Figure 5 clearly illustrate parameter
347 uncertainty with respect to the Rouge watershed. The hydrographs were computed according
348 to the following steps: (i) for every 250 simulated flow series, mean values were generated for
349 each day of the year, over the calibration (9 hydrological years) and validation periods (8
350 hydrological years); (ii) then for each model and simulation period, daily minimum and
351 maximum values were taken from the entire set of mean series and plotted in order to obtain
352 streamflow envelopes. As depicted in Figure 5 which introduces the individual streamflow
353 uncertainty envelopes for the alternate watersheds, the impact of parameter uncertainty is:

- 354 - small (most of the time under 0.1 mm/day) for both simulation periods and OFs,
- 355 - concentrated around the spring peak flow for the Nash-log OF (reaching a maximum
356 of 1mm/day).

357 The OF uncertainty is shown by the global envelope that encompasses individual bands
358 associated with the KGE and Nash-log series of modelled streamflows. Figure 5 and alternate
359 figures show that OF uncertainty is more important than parameter uncertainty most of the
360 year (except during the recession of the spring peak flow where the envelopes overlap).
361 Moreover, the spread of the global envelope for the ten watersheds reveals that OF
362 uncertainty is generally more pronounced in the fall and the spring peak flows.

363 **Figure 4: Distribution of the OF values for the Chamouchouane watershed: (a) KGE**
364 **calibration period; (b) KGE validation period; (c) Nash-log calibration period; (d) Nash-**
365 **log validation period**

366 <Table 5: Summary of the KGE and Nash-log values for the ten watersheds over the
367 calibration and validation periods>

368 <Table 6: Median of the KGE and Nash-log loss of performance (positive values)
369 between the calibration and validation periods>

370 **Figure 5: Streamflow uncertainty envelopes for the Rouge watershed: (a) calibration (9-**
371 **year mean) and (b) validation periods (8-year mean). The black and green envelopes**
372 **stand for simulated flows under the KGE and Nash-log OFs, respectively, while the blue**
373 **line depicts the observed values.**

374

375 Hydrological indices

376 Figure 6 introduces, for the Chamouchouane watershed the boxplots of the seasonal
377 hydrological indices for each OF. The two boxplots per year represent the parameter
378 uncertainty (250 sets of parameter) for the KGE and Nash-log OFs for each hydrological
379 index. The reunion of the two boxplots represent the OF uncertainty. Results do not show the
380 30d-Qmin distributions as they are quite similar to the 7d-Qmin distributions, their median
381 being just slightly greater and their interquartile range being similar.

382 Figure 6 shows that the impact of parameter uncertainty is rather small during both simulation
383 periods (calibration and validation). Indeed for both OFs and both simulation periods,
384 differences between the 1st and 3rd quartiles remain under 5% of the hydrological indices
385 values. Parameter uncertainty is more important for winter Nash-log hydrological indices than
386 for KGE values, whereas they are comparable for summer indices. The impact of OF
387 uncertainty is for all hydrological indices, for almost every year, and for both simulation
388 periods the impact is more important than that of the parameter uncertainty. It is especially the
389 case for winter 7d-Qmin and 30d-Qmin where the uncertainty is at least five (5) times larger
390 than the parameter uncertainty. This also applies to winter Qmax where it is at least twice as
391 much important. The main findings characterizing almost all watersheds are the following:

- 392 • Parameter uncertainty is :
 - 393 ○ quite stable across years and simulation periods,
 - 394 ○ smaller in summer than in winter especially for Qmax,
 - 395 ○ similar for both OFs, both seasons and all hydrological indices (besides a few
396 exceptions related to the performance of the calibration).
- 397 • OF uncertainty is:
 - 398 ○ rather stable across years for every individual seasonal hydrological index,

- 399 ○ more important than parameter uncertainty across the years, simulation
- 400 periods, and seasons,
- 401 ○ larger in winter than in summer and more important for 7d-Qmin and 30d-
- 402 Qmin.

403 **Figure 6: Boxplots of the seasonal hydrological indices for the Chamouchaoune**
404 **watershed for the calibration (1) and validation (2) periods: (as1) and (as2) display the**
405 **distribution of the maximum summer peakflows; (aw1) and (aw2) the distribution of**
406 **maximum winter peakflows; (bs1) and (bs2) the distribution of summer-7-day minimum**
407 **flows; and (bw1) and (bw2) the distribution of winter-7-day minimum flows. The black**
408 **and green boxplots illustrate the distribution of simulated flows under the KGE and**
409 **Nash-log OFs, respectively, while the blue dots depict the observed values. The**
410 **superscripts w and d on the x-axis indicate the wettest and driest years of each**
411 **simulation period, respectively.**

412 **Snow water equivalent**

413 Figure 7 shows the SWE uncertainty envelopes for the Yamaska watershed for the calibration
414 and validation periods as well as the two OFs. The envelopes were computed using the same
415 method as that used for the streamflows, except that since HYDROTEL is a semi-distributed
416 model, mean areal values over the RHHUs were first computed to produce a single data series
417 for each calibrated parameter set and each simulation period.

418 Figure 7 shows that parameter uncertainty relative to SWE is less important at the beginning
419 and the end of the snow season while being at a maximum at the peak where the envelopes
420 are the widest. OF uncertainty for SWE, contrary to that for streamflows, is less important
421 than parameter uncertainty as the individual envelopes overlap almost the entire snow season.
422 Parameter uncertainty is more important for the Nash-log OF than for the KGE OF. However,

423 these observations cannot be generalized when examining in details the results for the
424 alternate watersheds. Nonetheless, the overall results can be separated into six groups:

425 (i) For Yamaska and Chateauguay, parameter uncertainty is larger than the OF
426 uncertainty for the whole year with individual envelopes being wider at the
427 beginning of February and at the end of March. SWE is higher for the Nash-log
428 OF than for the KGE OF.

429 (ii) For Chamouchouane and Mistassini, parameter uncertainty is larger than the OF
430 uncertainty for the whole year with individual envelopes overlapping the entire
431 year.

432 (iii) For Gatineau, parameter uncertainty is larger than the OF uncertainty from
433 November to the end of February. OF uncertainty then becomes larger than
434 parameter uncertainty with individual envelopes not overlapping anymore.
435 Individual envelopes are quite narrow throughout the year and KGE simulated
436 SWE is slightly more important than the Nash-log simulated values.

437 (iv) For Batiscan, results are similar to those of group (iii); differing only with respect
438 to the fact that individual envelopes become slightly wider indicating a more
439 important parameter uncertainty

440 (v) For Du Loup and Rouge, results indicate a larger OF uncertainty for the whole
441 year with narrow individual envelopes not overlapping. KGE simulated SWE
442 values are more important than Nash-log values with a maximum difference of 50
443 mm at peak values.

444 (vi) For Bécancour and Chaudière, results are similar to those of group (v) differing
445 only with respect to the fact that individual envelopes become wider, indicating
446 that parameter uncertainty is larger.

447 **Figure 7: SWE uncertainty envelopes for the Yamaska watershed: (a) calibration (9-**
448 **year mean) and (b) validation periods (8-year mean). The black and green envelopes**
449 **illustrate the distribution of simulated flows under the KGE and Nash-log OFs. The line**
450 **indicates the period of overlapping between the uncertainty envelopes.**

451

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452 **Actual evapotranspiration**

453 Figure 8 depicts the seasonal AET for the Bécancour watershed obtained for both simulation
454 periods and OFs. They were computed as the sum of AET over each hydrological year and
455 season after applying the same methodology as that for the areal SWE in getting a single data
456 series. Parameter uncertainty can be assessed through the amplitude of each boxplot while OF
457 uncertainty is assessed through the combination of the KGE boxplots (black) and Nash-log
458 boxplots (green).

459 Figure 8 shows that parameter uncertainty for the summer season covers around 5% of the
460 AET values for both simulation periods and OFs; but for winter goes as far as 50%. For
461 summer, OF uncertainty is less significant than parameter uncertainty for many years as
462 illustrated by the overlapping of the individual boxplots (1981, 1983, 1985, 1986, 1987, 1988,
463 1992, 1994, 1998, 2000 and 2002). Nevertheless, OF uncertainty is more important than
464 parameter uncertainty for all years but for winter 1990. Also, it is noteworthy that parameter
465 uncertainty is less variable across years during summer than winter; indeed boxplots have the
466 same width. Last, Nash-log parameter uncertainty is comparable or larger than summer KGE
467 parameter uncertainty whereas it is the opposite for winter. However, these observations
468 cannot be generalized when examining in details the results of the other watersheds (alternate
469 watersheds). Nonetheless, the overall results can be separated into six groups:

- 470 (i) For Batiscan, Châteauguay, Du Loup and Yamaska, both types of uncertainty are
471 constant across simulation periods, years and seasons. OF uncertainty remains around
472 5% and does not go beyond 10% of the simulated AET values and is more important
473 than parameter uncertainty, while parameter uncertainty is similar for both OFs.
- 474 (ii) For Rouge, results are similar to those of group (i) differing only with respect to OF
475 uncertainty being larger, around 10%, for both seasons of the simulation periods and
476 all years.

477 (iii) For Gatineau and Mistassini, results are similar to those of group (ii) but have a larger
478 parameter uncertainty for Nash-log simulated values than for KGE values. This
479 behavior is more pronounced in summer than in winter, and more so for Mistassini
480 than for Gatineau.

481 (iv) For Chaudière, results are similar to those of group (ii) but have an OF uncertainty that
482 flirts with 20%.

483 (v) For Chamouchouane, results are similar to those of group (i) because of the constant
484 OF and parameter uncertainties. The difference is that OF uncertainty is nonexistent as
485 individual boxplots overlap for all seasons, years and simulation periods. Parameter
486 uncertainty related to the Nash-log OF is more important than that of KGE simulated
487 values

488 (vi) For Bécancour, results were described in the previous paragraph and are different from
489 the other groups as they display variability across years and seasons that other
490 watersheds do not show.

491 The only result, apart from the relative consistency across the years highlighted in group
492 (vi), that stands across all watersheds, but Bécancour in summer and Yamaska is that
493 simulated AET values are higher for all years and all seasons under the Nash-log OF. This
494 is not a surprising result as it pertains to the nature of the OF with respect to the water
495 balance. That is, if a smaller percentage of precipitations gets discharged through rivers
496 (Nash-log vs KGE), another way to balance the equation for HYDROTEL is to increase
497 water output through evapotranspiration.

498 **Figure 8: Seasonal actual evapotranspiration for the Bécancour watershed: (a) summer**
499 **calibration; (b) summer validation; (c) winter calibration and (d) winter validation. The**
500 **black and green boxplots stand for simulated AET distributions under the KGE and**
501 **Nash-log OFs, respectively. The outliers are represented by red crosses. The**
502 **superscripts w and d on the x-axis stand for the wettest and driest years of each**
503 **simulation period, respectively.**

504 **Shallow groundwater variations**

505 Figure 9 shows the envelopes of areal GWC variations for the calibration and validation
506 periods as well as the two OFs for the Du Loup watershed. The envelopes were computed
507 using the same method as that used for the areal SWE.

508 Figure 9 shows that parameter uncertainty is small and constant for both OFs throughout the
509 whole year with a maximum uncertainty under 2 mm. On the contrary, OF uncertainty is
510 substantial for the whole year (20 to 40 mm for the calibration period, 10 to 20 mm for the
511 validation period), but between January and March. For this latter period, the shallow ground
512 water reserves are at their lowest point and individual envelopes overlap during the
513 calibration period or are close to overlapping during the validation period. However, these
514 observations do not hold when examining in details the results for the alternate watersheds.
515 Nonetheless, the overall results can be separated into six groups:

516 (i) For Rouge and Mistassini, the GWC variation patterns are similar to those of Du
517 Loup. Maximum reserves are reached in early May after the snow has melted; they
518 continuously decrease until early September where they reach their minimum to
519 increase until the end of the fall season in early December. Finally, they decrease
520 again to a near minimum value around early March at the onset of melt season. OF
521 and parameter uncertainties were described in the previous paragraph.

- 522 (ii) For Batiscan, results show similar GWC variation patterns to those of group (i).
523 The difference lies in the parameter uncertainty that covers most the OF
524 uncertainty, but still remains under 10 mm. Indeed, for the calibration period, OF
525 uncertainty is less important than parameter uncertainty from November until the
526 end of September. For the validation period, the overlapping is reduced from
527 December until the end of May. Still, even in the remaining months, OF
528 uncertainty is less important than that of group (i); incidentally not getting larger
529 than 20 mm.
- 530 (iii) For Chamouchouane and Gatineau, results show similar GWC variation patterns to
531 those of groups (i) and (ii), but behave almost at the opposite of group (i) with
532 respect to OF and parameter uncertainties. OF uncertainty is non-existent for the
533 whole year, but for a few days around peak value. Parameter uncertainty is small
534 (less than 2 mm) and individual envelopes overlap.
- 535 (iv) For Bécancour, results show similar GWC variation patterns to those of group (i)
536 apart from the decrease during the snow season that is less pronounced. Parameter
537 uncertainty is more important for both OFs as that of group (i); it represents a
538 maximum of 10 mm for both OFs in the calibration period, but around 5 mm and
539 close to 10 mm respectively for Nash-log and KGE simulated GWC. OF
540 uncertainty as a result is still more significant than parameter uncertainty despite a
541 lag between the OFs that make the individual envelopes overlap around peakflow
542 values.
- 543 (v) For Chaudière, results show similar GWC variation patterns to those of Bécancour
544 (group (iv)) but is clearly different from any other watershed with respect to the
545 OF and parameter uncertainties. The Nash-log parameter uncertainty covers
546 almost all KGE values and has 40 and 20 mm wide intervals, respectively, for the

547 calibration and validation periods. The KGE parameter uncertainty is less than 2
548 mm for the whole year which results in a non-existent OF uncertainty for the
549 calibration period while still being significant between August and December for
550 the validation period.

551 (vi) For Chateauguay and Yamaska, the GWC variation patterns differ from those of
552 groups (i) to (v). The GWC is at a minimum around the end of August. The
553 reserves are then replenished from September until the end of November, before
554 decreasing only slightly, as opposed to groups (i) and (ii), during the snow season
555 and attaining their maximum values after the snow has melted. Parameter
556 uncertainty is small, under 2 and 5 mm for KGE and Nash-log simulated GWC,
557 respectively, and relatively constant across the year. OF uncertainty is more
558 important (maximum of 20 and 30 mm for calibration and validation, respectively)
559 for the whole year, but just after peak value (May and June) for the calibration
560 period and around peak value (April) for the validation period

561 It is noteworthy that the two variation patterns relative to GWC, highlighted in the above
562 groups, reflect the geographical location of the watersheds. Indeed, Bécancour,
563 Châteauguay, Chaudière and Yamaska are located on the south shore of the St. Lawrence
564 River, while Batiscan, Chamouchouane, Du Loup, Gatineau, Mistassini and Rouge are
565 located on the north shore.

566 **Figure 9: Shallow groundwater content uncertainty envelopes for the Du Loup**
567 **watershed: (a) calibration (9-year mean) and (b) validation periods (8-year mean). The**
568 **black and green envelopes illustrate the distribution of simulated flows under the KGE**
569 **and Nash-log OFs, respectively.**

570

571 **Discussion**

572 **Automatic calibration with DDS**

573 In the Material and Methods section, it is mentioned that DDS is better suited than SCE-UA
574 (Duan *et al.* 1992; Duan *et al.* 1994; Duan *et al.* 1993) for distributed watershed models
575 requiring extensive computational time and, thus, leading to a low number of model
576 evaluations before converging to a good solution (Arsenault *et al.* 2014; Tolson and
577 Shoemaker 2007; Yen *et al.* 2016). This is mostly due to DDS dynamically adjusting the
578 neighborhood of the best solution by changing the dimension of the search (Tolson and
579 Shoemaker 2007). In other terms, DDS mimics manual calibrations of watershed models as
580 follows: (i) early in the calibration exercise, a number of model parameters are modified to
581 overcome relatively poor solutions, and (ii) later, to avoid losing the current gain in objective
582 function values, parameters are modified one at a time. To avoid introducing a bias in the
583 search algorithm, this paper used a random initial solution, but used the same random solution
584 for every watershed in order to keep the experiments consistent.

585 The stochastic nature of DDS means that multiple optimization trials initialized with different
586 initial solutions can terminate at different final solutions (Tolson and Shoemaker 2008). To be
587 consistent with the framework described in the introduction, that is a majority of the
588 HYDROTEL application studies involved manual calibration, we decided to work with only
589 one optimization trial and a budget of 5000 model runs to answer the research question with
590 respect to equifinality given this framework. Besides, the radar plots of parameter equifinality
591 shown in Figure 3 do not seem to behave in a pattern related to the geographical location, the
592 climate, or geological characteristics of each watershed. Indeed, the study watersheds are part
593 of three different geological provinces (Ministère des Ressources naturelles Direction
594 générale de Géologie Québec 2012): (i) the Greenville Province made of allochthonous
595 material north of the St. Lawrence River; (ii) the St. Lawrence platform around the River; and

596 (iii) the Appalachian province made of Humber material south of the River. They also belong
597 to three climate classes defined by Litynski (1988) but mostly to class 14 that stands for
598 moderate temperature, subhumid precipitations and long growing season. As a consequence,
599 parameter regionalization is not obvious. This was pointed out as well by Ricard *et al.* (2013)
600 who showed that a global calibration strategy over southern Québec was preferable although
601 in some cases the performances of watershed calibration using HYDROTEL was reduced
602 when compared to local calibrations.

603 **OF uncertainty**

604 Overall, results for all the studied hydrological processes suggest that OF uncertainty is more
605 important than parameter uncertainty. In other words, OF uncertainty is seen when the largest
606 of the individual envelopes or boxplots relative to each objective function (KGE and Nash-
607 log) is smaller than the reunion of either envelopes or boxplots. Readers should note that
608 results obtained for the NSE_Q and $NSE_{\sqrt{Q}}$ OFs are in complete agreement with the previous
609 statement. Figure 5 and alternate figures do not clearly show the impact of OF uncertainty
610 because individual envelopes often overlap. However, when considering the seasonal
611 hydrological indices (Figure 6 and alternate figures), the SWE (Figure 7 and alternate
612 figures), the AET (Figure 8 and alternate figures), and the GWC (Figure 9 and alternate
613 figures), OF uncertainty is overall clearly highlighted.

614 Some studies highlight the importance of model structure uncertainty over parameter
615 equifinality (Futter *et al.* 2015; Mockler *et al.* 2016; Poulin *et al.* 2011; Shoaib *et al.* 2016).
616 Poulin *et al.* (2011) used HYDROTEL and HSAMI to assess the effects of model structure
617 and parameter equifinality on the uncertainty related to hydrological modelling. Their study
618 revealed that the impact of hydrological model structure was more significant than the effect
619 of parameter uncertainty (assessed through 68 sets of parameters). Yet, the uncertainty
620 attributed to model structure with respect to streamflows and SWE were of the same order of

621 magnitude than the OF uncertainty assessed in this paper. This would mandate the
622 combination of both studies to clearly assess whether the impact of model structure and OF
623 uncertainty are equivalent or complementary in assessing the consequences of considering the
624 effects of equifinality on modelled hydrological processes.

625 Figure 6 and alternate figures showed the boxplots of the seasonal hydrological indices for
626 both OFs (Results section). They also indicated observed values as blue dots; less than 50% of
627 the latter are not included within the interval of the simulated values for any of the
628 hydrological indices (Qmax, 7d-Qmin, and 30d-Qmin). This could be seen as a calibration
629 performance issue, but results suggest otherwise. Indeed, all observed values and all, but one,
630 are included within the interval of the simulated values for the summer 7d-Qmin for the
631 Châteauguay and Yamaska, respectively; which have the lowest performances for both OFs
632 (refer to Table 5). This would rather suggest that KGE and Nash-log OFs are not able to force
633 the model to represent the hydrological indices properly. This may be related to the nature of
634 both OFs that are computed over daily data *versus* hydrological indices computed over a
635 period of time (seven and 30 days for 7d-Qmin as well as 30d-Qmin, respectively). However,
636 for Qmax, this is simply related to the misrepresentation of maximum flows. This result is
637 rather important as hydrological indices are often used in impact assessment studies. This
638 would mandate the use of specific OFs related to low or high flows or even the use of multi-
639 objective functions.

640 **Parameter uncertainty**

641 Despite the fact that the OF uncertainty is overall more important than the consequences of
642 parameter equifinality, parameter uncertainty relative to SWE (Results section) is generally
643 more important than OF uncertainty. Indeed it is more important for the whole year for
644 Châteauguay, Chamouchouane, Mistassini and Yamaska and, for a few months (November
645 until the end of February), for Gatineau and Batiscan. Seasonal results also suggest that

646 parameter uncertainty can be important or more significant even than OF uncertainty for
647 specific seasons or years (Figure 6, Figure 8 and alternate figures). To get a better
648 understanding of the reasons why parameter uncertainty would prevail only for a few years,
649 driest and wettest years were defined as the hydrological years with the least total amount of
650 precipitation for the simulation periods (indicated on the x-axis of seasonal hydrological
651 indices and AET figures as d and w). The effects of driest and wettest years were assessed in
652 terms of prevalence of any of the two types of uncertainties and magnitudes of uncertainties
653 on both types of years, but also on the following year. Nothing particular stood out that could
654 be construed as a general result that could have given insights about the evolution of the
655 prevalence of the two types of uncertainties in the following years. To get this type of insight,
656 we would probably need to perform calibrations under different sets of contrasting conditions
657 (dry *versus* wet years). This refers to parameter identifiability as researched by Wilby (2005)
658 on snowless watersheds, or to the application of testing schemes such as those performed by
659 Seiller *et al.* (2012) and inspired by Klemeš (1986).

660 **Parameter equifinality**

661 Ben Nasr (2014) as well as Bouda *et al.* (2014) pointed out in sensitivity analyses carried out
662 for two snow-dominated watersheds in southern Québec (Beaurivage and Montmorency
663 modelled using HYDROTEL), that the depth of the lower boundary of the three soil layers
664 (z_1 , z_2 , z_3), the potential evapotranspiration multiplying factor (PETF), and the recession
665 coefficient (RC) were consistently amongst the most sensitive parameters (refer to Table 4).
666 In both studies, sensitivity was assessed from an initial optimal solution and parameter values
667 were modified ($\pm 25\%$), but variations of $\pm 6.25\%$ already gave substantial flow modifications.
668 These results are within the same order of magnitude as the equifinality measured through the
669 proposed methodology and explain why some parameters in Figure 2 are more equifinal than
670 others. Typically, parameters that were identified by Ben Nasr (2014) and Bouda *et al.* (2014)

671 as the most sensitive parameters are less equifinal than others. This result is not surprising as
672 it pertains to the following statement: the more sensitive a parameter, the least uncertain it can
673 be around a global optimum for the OF to remain optimum.

674 The choice to work with 5000 model runs ensured that the OF values remained within a 0.01
675 interval (refer to Table 5) for 250 sets of parameters that captured parameter equifinality.
676 Neither did working with 500 sets of parameters provide a larger parameter equifinality, nor
677 did working with 100 sets of parameters provide the complete parameter equifinality. This is
678 important as Poulin *et al.* (2011) reported that parameter uncertainty increases with increasing
679 numbers of calibration parameters and/or calibrations. This allows us to go beyond their
680 research in making sure that our conclusions cannot be disputed with respect to the impact
681 that parameter equifinality has on global or individual uncertainty envelopes.

682 To make sure that working with one optimization trial did not impair the possibility of
683 capturing the equifinality of the parameters, the smallest watershed model in terms of
684 modelled area (to minimize computational time) with the smallest parameter equifinality was
685 calibrated for another 5000-simulation-optimization trial started at a different initial random
686 solution. As shown in Figure 10, this demonstrates that parameter equifinality can be
687 increased if the calibration methodology is modified. Nonetheless, the covered part of the
688 physical range does not come close to the maximum equifinality obtained for the Yamaska
689 watershed in Figure 3. Thus, it can be assumed that the results introduced in this paper would
690 not be drastically modified by a change in the calibration methodology. Plus it would
691 contradict the choice made not to conduct a formal uncertainty analysis as this methodology
692 of using two or more optimization trials would get closer to the DDS-AU methodology
693 introduced by Tolson and Shoemaker (2008).

694 **Figure 10: Radar plots of the twelve parameters used in the automatic calibration of**
695 **HYDROTEL for each study watershed. Parameter A is part of the interpolation**
696 **coefficients, parameters B through G relate to the snow model, and parameters F**
697 **through L relate to the soil group of parameters. Figure (a) refers to the KGE OF; and**
698 **(b) to the Nash-log OF. The dark and light blue data refer to the first optimization trial**
699 **of Figure 3, black data to the second optimization trial.**

700 To summarize, it could be said that this paper shows the consequences of the existence of
701 many good sets of parameters on modelled hydrological processes around a global optimum
702 rather than properly evaluating their formal statistical uncertainty. If that were the aim, the
703 methodology would have entailed working with one optimization trial per set of parameters
704 which would have resulted in a total of 125 000 simulations (250 sets of parameters * 500
705 simulations) since DDS typically needs 500 simulations to find a good global solution
706 (compared to 10,000 for SCE-UA). Note that the computing time for a 10-year calibration
707 period (with a prior 1-year spin-up), one optimization trial of 5000 simulations already took
708 an average 45 hours (on a 64-bit computer with a quad-core 2.53 GHz processor) for each
709 watershed and every OF, resulting in a total calibration time of 900 hours or 37.5 days (45
710 hours * 10 watersheds * 2 OFs) for the results presented in this paper (excluding the two OFs
711 that were left out of this paper).

712

713 **Conclusion**

714 In the last decade, HYDROTEL has almost always been applied within the optimal parameter
715 set paradigm at the risk of avoiding important issues such as model acceptability and
716 uncertainty (Beven 2006a). This paper builds on the work carried out on hydrological
717 uncertainty by assessing the impact of equifinality and OF related uncertainty on five modelled
718 hydrological variables and indices: (i) daily flows; (ii) seasonal hydrological indices (7d-
719 Qmin, 30d-Qmin, and Qmax); (iii) snow water equivalent (SWE); (iv) shallow ground water
720 content variations (GWC); and (v) actual evapotranspiration (AET). This assessment was
721 carried out for ten watersheds spread out in five hydrographic regions of the St. Lawrence
722 River and spread across southern Québec (Canada).

723 Overall, as introduced in Table 7, the results for all the studied hydrological processes, but the
724 SWE, suggest that OF uncertainty is more important than that arising from parameter
725 equifinality. This would mean that within the context of a study with a limited budget, it
726 would be advisable to prioritize using different objective functions to using many sets of
727 optimal parameters. This result is rather important as it reinforces the choice made in the last
728 decade with HYDROTEL. Nonetheless, parameter uncertainty with respect to SWE is more
729 important than OF uncertainty for eight of the ten studied watersheds for four up to seven
730 months of the year (snow season less than 7-month long). Plus, despite satisfactory
731 performances for both simulation periods, parameter uncertainty with respect to streamflows
732 is rather small during the whole year, except around spring peak flow; while OF uncertainty is
733 generally more pronounced in the fall and during the spring peak flows. Overall, this shows
734 that one type of uncertainty or the other is rather significant during half of the year. Seasonal
735 results with respect to hydrological indices and AET also suggest that parameter uncertainty
736 can be important, or more significant even, than OF uncertainty for specific seasons or years.
737 These results are of the utmost importance for impact assessment studies where the variables

738 of interest are not solely the daily flow data used for calibration, but rather hydrological
739 indices or internal variables. This would mean that parameter uncertainty does need to be
740 taken into account or at least needs to be further researched to better understand the
741 mechanisms behind the phenomena. This study demonstrates, using a substantial set of
742 watersheds; that aside from the technico-philosophical debate started in 2006, equifinality is
743 not so technical to take into account and has tangible significant effect on the uncertainties
744 associated with modeled hydrological processes. As such, we recommend that future work
745 systematically include equifinality by using at least two sets of equifinal parameters without
746 forgetting to assess OF uncertainty.

747 It is noteworthy that the methodology applied in this paper for the HYDROTEL model can be
748 replicated for other hydrological models. Uncertainty associated with OFs and parameter
749 equifinality still needs to be better understood and studied. To improve our understanding of
750 HYDROTEL, and other physically based hydrological models, future work should focus on
751 identifying or using OFs tailored for hydrological indices relevant to impact assessment
752 studies. Finally, for a specific assessment, there is a need to consider as well the question of
753 the uncertainty associated with model structure.

754 <**Table 7: Dominant type of uncertainty for each study watershed for the five modelled**
755 **hydrological variables**>

756

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767

768 **References**

- 769 Aissia, M. A. B., F. Chebana, T. B. M. J. Ouarda, L. Roy, G. Desrochers, I. Chartier, and É
770 Robichaud. 2012. Multivariate analysis of flood characteristics in a climate change
771 context of the watershed of the Baskatong reservoir, Province of Québec, Canada.
772 *Hydrological Processes* 26 (1):130-142.
- 773 Arsenault, R., A. Poulin, P. Côté, and F. Brissette. 2014. Comparison of stochastic
774 optimization algorithms in hydrological model calibration. *Journal of Hydrologic
775 Engineering* 19 (7):1374-1384.
- 776 Ben Nasr, Imène. 2014. Incertitudes sur les débits simulés par le modèle HYDROTEL
777 attribuables aux incertitudes sur les paramètres. Application au bassin de la rivière
778 Beauvillage, Québec, Canada, Institut National de la recherche scientifique, Centre Eau
779 terre environnement, Québec, QC 94 pp.
- 780 Beven, K. 1993. Prophecy, reality and uncertainty in distributed hydrological modelling.
781 *Advances in Water Resources* 16 (1):41-51.
- 782 Beven, K. 2006a. A manifesto for the equifinality thesis. *Journal of Hydrology* 320 (1-2):18-
783 36.
- 784 Beven, K. 2006b. On undermining the science? *Hydrological Processes* 20 (14):3141-3146.
- 785 Beven, K. 2008. On doing better hydrological science. *Hydrological Processes* 22 (17):3549-
786 3553.
- 787 Beven, K. 2016. Facets of uncertainty: Epistemic uncertainty, non-stationarity, likelihood,
788 hypothesis testing, and communication. *Hydrological Sciences Journal* 61 (9):1652-
789 1665.
- 790 Beven, K., and A. Binley. 1992. The future of distributed models: Model calibration and
791 uncertainty prediction. *Hydrological Processes* 6 (3):279-298.
- 792 Beven, K., and J. Freer. 2001. Equifinality, data assimilation, and uncertainty estimation in
793 mechanistic modelling of complex environmental systems using the GLUE
794 methodology. *Journal of Hydrology* 249 (1-4):11-29.
- 795 Beven, K. J. 2009. Comment on "Equifinality of formal (DREAM) and informal (GLUE)
796 Bayesian approaches in hydrologic modeling?" by Jasper A. Vrugt, Cajo J. F. ter
797 Braak, Hoshin V. Gupta and Bruce A. Robinson. *Stochastic Environmental Research
798 and Risk Assessment* 23 (7):1059-1060.
- 799 Bouda, M., A. N. Rousseau, S. J. Gumiere, P. Gagnon, B. Konan, and R. Moussa. 2014.
800 Implementation of an automatic calibration procedure for HYDROTEL based on prior
801 OAT sensitivity and complementary identifiability analysis. *Hydrological Processes*
802 28 (12):3947-3961.
- 803 Bouda, M., A.N. Rousseau, B. Konan, P. Gagnon, and S.J. Gumiere. 2012. Case study:
804 Bayesian uncertainty analysis of the distributed hydrological model HYDROTEL.
805 *Journal of Hydrologic Engineering* 17 (9):1021-1032.

- 806 CEHQ. 2012. *Niveau d'eau et débit*. <http://www.cehq.gouv.qc.ca/hydrometrie/index.htm>
807 (accessed September 2017).
- 808 CEHQ. 2013. Atlas hydroclimatique du Québec méridional - Impact des changements
809 climatiques sur les régimes de crue, d'étiage et d'hydraulicité à l'horizon 2050. Québec,
810 21 pp.
- 811 CEHQ. 2015. Hydroclimatic Atlas of Southern Québec. The Impact of Climate Change on
812 High, Low and Mean Flow Regimes for the 2050 horizon. Québec, 81 pp.
- 813 Duan, Q., S. Sorooshian, and V. Gupta. 1992. Effective and efficient global optimization for
814 conceptual rainfall-runoff models. *Water Resources Research* 28 (4):1015-1031.
- 815 Duan, Q., S. Sorooshian, and V. K. Gupta. 1994. Optimal use of the SCE-UA global
816 optimization method for calibrating watershed models. *Journal of Hydrology* 158 (3-
817 4):265-284.
- 818 Duan, Q. Y., V. K. Gupta, and S. Sorooshian. 1993. Shuffled complex evolution approach for
819 effective and efficient global minimization. *Journal of Optimization Theory and*
820 *Applications* 76 (3):501-521.
- 821 Fisher, J., and K. J. Beven. 1996. Modelling of stream flow at Slapton Wood using topmodel
822 within an uncertainty estimation framework. *Field Studies* 8 (4):577-584.
- 823 Fortin, J.-P., R. Turcotte, S. Massicotte, R. Moussa, and J. Fitzback. 2001a. A distributed
824 watershed model compatible with remote sensing and GIS data. Part 2: Application to
825 the Chaudière watershed. *Journal of Hydrologic Engineering* 6 (2):100-108.
- 826 Fortin, J.-P., R. Turcotte, S. Massicotte, R. Moussa, J. Fitzback, and J.-P. Villeneuve. 2001b.
827 A distributed watershed model compatible with remote sensing and GIS data. Part I:
828 Description of the model. *Journal of Hydrologic Engineering* 6 (2):91-99.
- 829 Fossey, M., and A. N. Rousseau. 2016a. Assessing the long-term hydrological services
830 provided by wetlands under changing climate conditions: A case study approach of a
831 Canadian watershed. *Journal of Hydrology* 541, Part B:1287-1302.
- 832 Fossey, M., and A. N. Rousseau. 2016b. Can isolated and riparian wetlands mitigate the
833 impact of climate change on watershed hydrology? A case study approach. *Journal of*
834 *Environmental Management* 184, Part 2:327-339.
- 835 Fossey, M., A. N. Rousseau, F. Bensalma, S. Savary, and A. Royer. 2015. Integrating isolated
836 and riparian wetland modules in the PHYSITEL/HYDROTEL modelling platform:
837 Model performance and diagnosis. *Hydrological Processes* 29 (22):4683-4702.
- 838 Fossey, M., A. N. Rousseau, and S. Savary. 2016. Assessment of the impact of spatio-
839 temporal attributes of wetlands on stream flows using a hydrological modelling
840 framework: A theoretical case study of a watershed under temperate climatic
841 conditions. *Hydrological Processes* 30 (11):1768-1781.
- 842 Freer, J., K. Beven, and B. Ambroise. 1996. Bayesian estimation of uncertainty in runoff
843 prediction and the value of data: An application of the GLUE approach. *Water*
844 *Resources Research* 32 (7):2161-2173.

- 845 Fu, C., A. L. James, and H. Yao. 2015. Investigations of uncertainty in SWAT hydrologic
846 simulations: A case study of a Canadian Shield catchment. *Hydrological Processes* 29
847 (18):4000-4017.
- 848 Futter, M. N., P. G. Whitehead, S. Sarkar, H. Rodda, and J. Crossman. 2015. Rainfall runoff
849 modelling of the Upper Ganga and Brahmaputra basins using PERSiST.
850 *Environmental Sciences: Processes and Impacts* 17 (6):1070-1081.
- 851 Gaborit, É, S. Ricard, S. Lachance-Cloutier, F. Anctil, and R. Turcotte. 2015. Comparing
852 global and local calibration schemes from a differential split-sample test perspective.
853 *Canadian Journal of Earth Sciences* 52 (11):990-999.
- 854 Gupta, H. V., H. Kling, K. K. Yilmaz, and G. F. Martinez (2009), Decomposition of the mean
855 squared error and NSE performance criteria: Implications for improving hydrological
856 modelling, *Journal of Hydrology*, 377(1-2), 80-91. doi: 10.1016/j.jhydrol.2009.08.003.
- 857 Khalili, M., F. Brissette, and R. Leconte. 2011. Effectiveness of Multi-Site Weather Generator
858 for Hydrological Modeling. *Journal of the American Water Resources Association* 47
859 (2):303-314.
- 860 Klemeš, V. 1986. Operational testing of hydrological simulation models. *Hydrological*
861 *Sciences Journal* 31 (1):13-24.
- 862 Li, C. Z., L. Zhang, H. Wang, Y. Q. Zhang, F. L. Yu, and D. H. Yan. 2012. The
863 transferability of hydrological models under nonstationary climatic conditions.
864 *Hydrology and Earth System Sciences* 16 (4):1239-1254.
- 865 Linhoss, A., R. Muñoz-Carpena, G. Kiker, and D. Hughes. 2013. Hydrologic modeling,
866 uncertainty, and sensitivity in the okavango basin: Insights for scenario assessment.
867 *Journal of Hydrologic Engineering* 18 (12):1767-1778.
- 868 Litynski, J. 1988. Climat du Québec d'après la classification numérique.
- 869 Ludwig, R., I. May, R. Turcotte, L. Vescovi, M. Braun, J. F. Cyr, L. G. Fortin, D. Chaumont,
870 S. Biner, I. Chartier, D. Caya, and W. Mauser. 2009. The role of hydrological model
871 complexity and uncertainty in climate change impact assessment. *Advances in*
872 *Geosciences* 21:63-71.
- 873 Ministère des Ressources naturelles Direction générale de Géologie Québec. 2012. Map of the
874 main Geological Subdivisions of Québec.
- 875 Minville, M., F. Brissette, S. Krau, and R. Leconte. 2009. Adaptation to climate change in the
876 management of a Canadian water-resources system exploited for hydropower. *Water*
877 *Resources Management* 23 (14):2965-2986.
- 878 Mockler, E. M., K. P. Chun, G. Sapriza-Azuri, M. Bruen, and H. S. Wheeler. 2016. Assessing
879 the relative importance of parameter and forcing uncertainty and their interactions in
880 conceptual hydrological model simulations. *Advances in Water Resources* 97:299-313.
- 881 Moriasi, D.N., J.G. Arnold, M.W. VanLiew, R.L. Bingner, R.D. Harmel, and T.L. Veith.
882 2007. Model evaluation guidelines for systematic quantification of accuracy in
883 watershed simulations. *Transactions of the ASABE* 50 (3):885-900.

- 884 Mugunthan, P., and C. A. Shoemaker. 2006. Assessing the impacts of parameter uncertainty
885 for computationally expensive groundwater models. *Water Resources Research* 42
886 (10).
- 887 Nearing, G. S., Y. Tian, H. V. Gupta, M. P. Clark, K. W. Harrison, and S. V. Weijs. 2016. A
888 philosophical basis for hydrological uncertainty. *Hydrological Sciences Journal* 61
889 (9):1666-1678.
- 890 Noël, P., A. N. Rousseau, C. Paniconi, and D. F. Nadeau. 2014. An algorithm for delineating
891 and extracting hillslopes and hillslope width functions from gridded elevation data.
892 *Journal of Hydrologic Engineering* 19 (2):366-374.
- 893 Oreiller, M., D. F. Nadeau, M. Minville, and A. N. Rousseau. 2013. Modelling snow water
894 equivalent and spring runoff in a boreal watershed, James Bay, Canada. *Hydrological*
895 *Processes*.
- 896 Poirier, C., T. C. Fortier Filion, R. Turcotte, and P. Lacombe (2012), Apports verticaux
897 journaliers estimés de 1900 à 2010, *Rep.*, Centre d'expertise hydrique du Québec (CEHQ),
898 Direction de l'expertise hydrique, Québec.
- 899 Poulin, A., F. Brissette, R. Leconte, R. Arsenault, and J. S. Malo. 2011. Uncertainty of
900 hydrological modelling in climate change impact studies in a Canadian, snow-
901 dominated river basin. *Journal of Hydrology* 409 (3-4):626-636.
- 902 Prada, A. F., M. L. Chu, and J. A. Guzman. 2016. Probabilistic approach to modeling under
903 changing scenarios. Paper read at 2016 American Society of Agricultural and
904 Biological Engineers Annual International Meeting, ASABE 2016. pp.
- 905 Quilbé, R., A.N. Rousseau, J.S. Moquet, N.B. Trinh, Y. Dikibi, P. Gachon, and D. Chaumont.
906 2008. Assessing the effect of climate change on river flow using general circulation
907 models and hydrological modeling - Application to the Chaudière River (Québec,
908 Canada). *Canadian Water Resources Journal* 33 (1):73-94.
- 909 Ricard, S., R. Bourdillon, D. Roussel, and R. Turcotte. 2013. Global calibration of distributed
910 hydrological models for large-scale applications. *Journal of Hydrologic Engineering*
911 18 (6):719-721.
- 912 Romanowicz, R. J., K. Beven, and J. A. Tawn. 1994. Evaluation of predictive uncertainty in
913 nonlinear hydrological models using a Bayesian Approach. In *Statistics for the*
914 *Environment, Water Related Issues (Volume 2)*, ed. V. Barnett and F. Turkman, 297-
915 318. John Wiley & Sons.
- 916 Rousseau, A. N., S. Savary, D. W. Hallema, S. J. Gumière, and E. Foulon. 2013. Modeling
917 the effects of agricultural BMPs on sediments, nutrients and water quality of the
918 Beauvillage River watershed (Quebec, Canada). *Canadian Water Resources Journal* 38
919 (2):99-120.
- 920 Rousseau, A.N., J.P. Fortin, R. Turcotte, A. Royer, S. Savary, F. Quévry, P. Noël, and C.
921 Paniconi. 2011. PHYSITEL, a specialized GIS for supporting the implementation of
922 distributed hydrological models. *Water News, Official Magazine of CWRA – Canadian*
923 *Water Resources Association* 31 (1):18-20.

- 924 Seiller, G., F. Anctil, and C. Perrin. 2012. Multimodel evaluation of twenty lumped
925 hydrological models under contrasted climate conditions. *Hydrology and Earth System
926 Sciences* 16 (4):1171-1189.
- 927 Shoaib, S. A., L. Marshall, and A. Sharma. 2016. A metric for attributing variability in
928 modelled streamflows. *Journal of Hydrology* 541:1475-1487.
- 929 Tolson, B. A., and C. A. Shoemaker. 2007. Dynamically dimensioned search algorithm for
930 computationally efficient watershed model calibration. *Water Resources Research* 43
931 (1).
- 932 Tolson, B. A., and C. A. Shoemaker. 2008. Efficient prediction uncertainty approximation in
933 the calibration of environmental simulation models. *Water Resources Research* 44 (4).
- 934 Trudel, M., P. L. Doucet-Généreux, R. Leconte, and B. Côté. 2016. Vulnerability of water
935 demand and aquatic habitat in the context of climate change and analysis of a no-
936 regrets adaptation strategy: Study of the Yamaska River Basin, Canada. *Journal of
937 Hydrologic Engineering* 21 (2).
- 938 Turcotte, R., J.P. Fortin, A.N. Rousseau, S. Massicotte, and J.P. Villeneuve. 2001.
939 Determination of the drainage structure of a watershed using a digital elevation model
940 and a digital river and lake network. *Journal of Hydrology* 240 (3-4):225-242.
- 941 Turcotte, R., L. G. Fortin, V. Fortin, J. P. Fortin, and J. P. Villeneuve. 2007a. Operational
942 analysis of the spatial distribution and the temporal evolution of the snowpack water
943 equivalent in southern Québec, Canada. *Nordic Hydrology* 38 (3):211-234.
- 944 Turcotte, R., P. Lacombe, C. Dimnik, and J.P. Villeneuve. 2004. Distributed hydrological
945 prediction for the management of Quebec's public dams. *Canadian J. of Civil
946 Engineering* 31 (2):308-320.
- 947 Turcotte, R., A.N. Rousseau, J.-P. Fortin, and J.-P. Villeneuve. 2003. Development of a
948 process-oriented, multiple-objective, hydrological calibration strategy accounting for
949 model structure. In *Advances in Calibration of Watershed Models*, Water Science &
950 Application, no. 6, ed. Q. Duan, S. Sorooshian, H. Gupta, A. N. Rousseau and R.
951 Turcotte, 153-163. Washington, USA: American Geophysical Union (AGU).
- 952 Turcotte, R., A.N. Rousseau, J.P. Fortin, V. Fortin, and J.P. Villeneuve. 2007b. Operational
953 analysis of the spatial distribution and the temporal evolution of the snowpack water
954 equivalent in southern Quebec, Canada. *Nordic Hydrology* 38 (3):211-234.
- 955 Vrugt, J. A., C. J. F. Ter Braak, C. G. H. Diks, B. A. Robinson, J. M. Hyman, and D. Higdon.
956 2009a. Accelerating Markov chain Monte Carlo simulation by differential evolution
957 with self-adaptive randomized subspace sampling. *International Journal of Nonlinear
958 Sciences and Numerical Simulation* 10 (3):273-290.
- 959 Vrugt, J. A., C. J. F. ter Braak, H. V. Gupta, and B. A. Robinson. 2009b. Equifinality of
960 formal (DREAM) and informal (GLUE) Bayesian approaches in hydrologic modeling?
961 *Stochastic Environmental Research and Risk Assessment* 23 (7):1011-1026.
- 962 Vrugt, J. A., C. J. F. ter Braak, H. V. Gupta, and B. A. Robinson. 2009c. Response to
963 comment by Keith Beven on "Equifinality of formal (DREAM) and informal (GLUE)

- 964 Bayesian approaches in hydrologic modeling?". *Stochastic Environmental Research*
965 *and Risk Assessment* 23 (7):1061-1062.
- 966 Wilby, R. L. 2005. Uncertainty in water resource model parameters used for climate change
967 impact assessment. *Hydrological Processes* 19 (16):3201-3219.
- 968 Yen, H., J. Jeong, and D. R. Smith. 2016. Evaluation of Dynamically Dimensioned Search
969 Algorithm for Optimizing SWAT by Altering Sampling Distributions and Searching
970 Range. *Journal of the American Water Resources Association* 52 (2):443-455.
- 971 Zeng, Q., H. Chen, C. Y. Xu, M. X. Jie, and Y. K. Hou. 2016. Feasibility and uncertainty of
972 using conceptual rainfallrunoff models in design flood estimation. *Hydrology Research*
973 47 (4):701-717.
- 974 Zhang, X., G. Hörmann, N. Fohrer, and J. Gao. 2012. Parameter calibration and uncertainty
975 estimation of a simple rainfall-runoff model in two case studies. *Journal of*
976 *Hydroinformatics* 14 (4):1061-1074.
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- 979

980 **Tables**981 **Table 1: Land cover of the ten studied watersheds in southern Québec, Canada**

	Evergreen		Deciduous trees		Water		Urban		Farms		Total
	km ²	%	km ²	%	km ²	%	km ²	%	km ²	%	
<i>Batiscan</i>	1816	41.9	2264	52.3	187	4.3	0	0	67	1.6	4334
<i>Bécancour</i>	255	9.7	2144	81.6	16	0.6	0	0	214	8.2	2629
<i>Chamouchouane</i>	817	5.4	13156	87.5	1040	6.9	0	0	29	0.2	15042
<i>Châteauguay</i>	112	5.0	1722	77.4	13	0.6	0	0	379	17.0	2227
<i>Chaudière</i>	1229	21.5	4206	73.4	71	1.2	0	0	223	3.9	5728
<i>Du Loup</i>	243	28.4	557	65.1	55	6.4	0	0	1	0.1	855
<i>Gatineau</i>	1159	17.0	5298	77.8	353	5.2	0	0	0	0	6810
<i>Mistassini</i>	569	6.1	8341	89.7	384	4.1	0	0	1	0	9295
<i>Rouge</i>	1401	25.6	3791	69.2	285	5.2	0	0	2	0	5480
<i>Yamaska</i>	23	1.7	2050	76.7	2	0.2	5	0.4	289	21.1	1389

982 **Table 2: Summary (1982-2002) of the climate characteristics of the study watersheds**

	Rain (mm)						Snow (mm)			Mean Temp. (°C)					
	Summer			Winter			Annual			Summer			Winter		
	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
<i>Batiscan</i>	337	558	645	97	180	403	286	356	416	8.4	10.3	11.5	-7.7	-5.4	-3.1
<i>Bécancour</i>	392	585	809	129	260	490	169	260	372	10.3	11.9	13.3	-5.0	-2.9	-1.0
<i>Chamouchouane</i>	293	518	690	85	131	248	219	290	383	6.4	8.6	10.0	-11.4	-8.7	-5.6
<i>Chateauguay</i>	402	512	620	174	269	429	137	193	252	12.4	13.8	15.2	-3.8	-1.1	0.9
<i>Chaudière</i>	421	590	794	179	253	392	216	266	316	9.5	11.2	12.5	-5.4	-3.3	-1.5
<i>Du Loup</i>	423	547	643	154	233	480	178	224	247	8.5	10.2	11.5	-7.5	-5.3	-3.0
<i>Gatineau</i>	324	519	671	86	145	242	224	290	350	7.9	9.7	11.4	-8.8	-6.4	-3.6
<i>Mistassini</i>	278	515	729	81	126	236	224	300	384	5.9	8.2	9.7	-12.0	-9.2	-6.1
<i>Rouge</i>	372	529	613	100	175	333	248	327	368	9.2	10.8	11.9	-6.9	-4.4	-2.0
<i>Yamaska</i>	476	577	743	180	305	526	122	204	294	11.6	13.1	14.5	-3.9	-1.5	0.6

983

984 **Table 3: Summary (1982-2002) of the hydrological characteristics of the study watersheds**

	Q (mm/day)						Qmax (m3/s)						7d-Qmin (m3/s)						30d-Qmin (m3/s)					
	Summer			Winter			Summer			Winter			Summer			Winter			Summer			Winter		
	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
Batiscan	0.9	1.6	2.4	1.4	2.1	3.1	140	265	528	349	558	837	17	31	57	18	24	35	22	37	72	19	26	43
Bécancour	0.6	1.1	1.9	1.5	2.1	2.9	69	203	402	296	494	848	2	7	21	7	120	402	3	10	32	8	13	21
Chamouchouane	1.1	1.8	2.6	1.2	1.5	1.9	404	781	1370	610	1350	2159	112	156	199	60	78	102	128	184	245	61	81	116
Chateauguay	0.3	0.6	1.3	1.1	1.8	2.6	27	168	623	193	460	1091	2	4	10	6	10	18	2	6	17	7	12	32
Chaudière	0.5	1.1	2.1	1.6	2.2	3.0	236	646	1318	847	1339	2140	4	10	26	12	19	32	5	17	45	14	23	47
Du Loup	0.3	0.8	1.3	1.0	1.6	2.3	12	29	79	55	84	130	1	2	6	3	4	5	1	3	7	3	4	6
Gatineau	1.0	1.5	2.4	1.1	1.7	2.5	202	425	1200	413	731	1500	19	38	56	20	32	46	21	50	92	22	34	48
Mistassini	1.2	1.9	2.7	1.3	1.7	2.3	314	595	959	604	1257	2050	58	92	129	27	39	67	70	119	159	28	41	76
Rouge	0.8	1.2	1.7	1.3	2.0	2.9	118	243	376	381	588	914	11	27	45	24	36	50	6	32	61	25	39	59
Yamaska	0.4	0.8	1.7	1.2	2.0	2.7	44	142	239	182	320	559	1	1	3	2	4	7	1	2	6	2	6	13

Review Only

985 **Table 4: HYDROTEL key parameters**

Type	Parameters	Units
<i>Snow parameters</i>	MFEF - Melt factor for evergreen forests*	mm/d.°C
	MFDF - Melt factor for deciduous forests*	mm/d.°C
	MFOA - Melt factor for open areas*	mm/d.°C
	TEF - Threshold air temperature for melt in evergreen forests*	°C
	TDF - Threshold air temperature for melt in deciduous forests*	°C
	TOA - Threshold air temperature for melt in open areas*	°C
	Melt rate at the snow-soil interface	mm/d
	Compaction coefficient	-
<i>Soil parameters</i>	PETF - Potential evapotranspiration multiplication factor*	-
	z1- Depth of the lower boundary of soil layer #1*	m
	z2- Depth of the lower boundary of soil layer #2*	m
	z3- Depth of the lower boundary of soil layer #3*	m
	RC - Recession coefficient*	m/h
	Extinction coefficient	-
	Maximum variation of soil moisture content	-
<i>Interpolation coefficients</i>	TSL - Threshold air temperature for partitioning solid and liquid precipitation*	°C
	Precipitation vertical gradient	mm/100m
	Temperature vertical gradient	°C/100m

986 *Parameter calibrated in this paper

987 ^a For a complete description of snow parameters, the reader is referred to Turcotte et al. (2007a)988 ^b For a complete description of soil parameters, the reader is referred to Fortin et al. (2001b)

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990 **Table 5: Summary of the KGE and Nash-log values for the ten watersheds over the**
 991 **calibration and validation periods**

	Calibration						Validation					
	KGE			Nash-log			KGE			Nash-log		
	1st decile	Median	9th decile	1st decile	Median	9th decile	1st decile	Median	9th decile	1st decile	Median	9th decile
<i>Batiscan</i>	0.946	0.946	0.947	0.894	0.896	0.897	0.799	0.805	0.810	0.670	0.674	0.694
<i>Bécancour</i>	0.872	0.874	0.875	0.795	0.799	0.801	0.797	0.807	0.814	0.701	0.706	0.717
<i>Chamouchouane</i>	0.947	0.947	0.947	0.907	0.907	0.907	0.823	0.826	0.829	0.632	0.637	0.641
<i>Chateauguay</i>	0.859	0.860	0.860	0.767	0.768	0.768	0.763	0.767	0.775	0.692	0.695	0.699
<i>Chaudière</i>	0.916	0.916	0.916	0.805	0.810	0.815	0.869	0.871	0.875	0.695	0.709	0.721
<i>Du Loup</i>	0.944	0.945	0.945	0.842	0.842	0.842	0.792	0.796	0.802	0.700	0.703	0.704
<i>Gatineau</i>	0.907	0.907	0.907	0.827	0.828	0.828	0.766	0.768	0.771	0.684	0.686	0.691
<i>Mistassini</i>	0.955	0.955	0.956	0.904	0.905	0.905	0.873	0.875	0.876	0.646	0.652	0.660
<i>Rouge</i>	0.947	0.947	0.947	0.887	0.887	0.887	0.876	0.878	0.880	0.700	0.702	0.704
<i>Yamaska</i>	0.828	0.832	0.835	0.761	0.762	0.764	0.833	0.839	0.845	0.609	0.626	0.637

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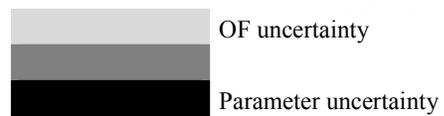
993 **Table 6: Median of the KGE and Nash-log loss of performance (positive values) between**
 994 **the calibration and validation periods**

	KGE	Nash-log
<i>Batiscan</i>	15%	14%
<i>Bécancour</i>	8%	-8%
<i>Chamouchouane</i>	13%	20%
<i>Chateauguay</i>	11%	-14%
<i>Chaudière</i>	5%	-6%
<i>Du Loup</i>	16%	1%
<i>Gatineau</i>	15%	0%
<i>Mistassini</i>	8%	18%
<i>Rouge</i>	7%	9%
<i>Yamaska</i>	-1%	-6%

995

996 **Table 7: Dominant type of uncertainty for each study watershed for the five modelled**
 997 **hydrological variables**

	Daily Streamflows	7d-and 30d-Qmin	Qmax	SWE	AET	GWC
<i>Batiscan</i>						
<i>Bécancour</i>						
<i>Chamouchouane</i>						
<i>Châteauguay</i>						
<i>Chaudière</i>						
<i>Du Loup</i>						
<i>Gatineau</i>						
<i>Mistassini</i>						
<i>Rouge</i>						
<i>Yamaska</i>						



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1001 **Figure Captions**

1002 Figure 1: Location of the study watersheds in Québec, Canada, and around the St. Lawrence
1003 River

1004 Figure 2: Relationship between mean annual and seasonal temperatures and precipitations for
1005 the calibration and validation periods

1006 Figure 3: Radar plots of the twelve parameters used in the automatic calibration of
1007 HYDROTEL for each study watershed. Parameter A is part of the interpolation coefficients,
1008 parameters B through G relate to the snow model, and parameters F through L relate to the
1009 soil group of parameters. The dark blue diagrams refer to the KGE OF while the light blue
1010 diagrams refer to the Nash-log OF.

1011 Figure 4: Distribution of the OF values for the Chamouchouane watershed: (a) KGE
1012 calibration period; (b) KGE validation period; (c) Nash-log calibration period; (d) Nash-log
1013 validation period

1014 Figure 5: Streamflow uncertainty envelopes for the Rouge watershed: (a) calibration (9-year
1015 mean) and (b) validation periods (8-year mean). The black and green envelopes stand for
1016 simulated flows under the KGE and Nash-log OFs, respectively, while the blue line depicts
1017 the observed values.

1018 Figure 6: Boxplots of the seasonal hydrological indices for the Chamouchaoune watershed for
1019 the calibration (1) and validation (2) periods: (as1) and (as2) display the distribution of the
1020 maximum summer peakflows; (aw1) and (aw2) the distribution of maximum winter
1021 peakflows; (bs1) and (bs2) the distribution of summer-7-day minimum flows; and (bw1) and
1022 (bw2) the distribution of winter-7-day minimum flows. The black and green boxplots
1023 illustrate the distribution of simulated flows under the KGE and Nash-log OFs, respectively,

1024 while the blue dots depict the observed values. The superscripts w and d on the x-axis indicate
1025 the wettest and driest years of each simulation period, respectively.

1026 Figure 7: SWE uncertainty envelopes for the Yamaska watershed: (a) calibration (9-year
1027 mean) and (b) validation periods (8-year mean). The black and green envelopes illustrate the
1028 distribution of simulated flows under the KGE and Nash-log OFs.

1029 Figure 8: Seasonal actual evapotranspiration for the Bécancour watershed: (a) summer
1030 calibration; (b) summer validation; (c) winter calibration and (d) winter validation. The black
1031 and green boxplots stand for simulated AET distributions under the KGE and Nash-log OFs,
1032 respectively. The outliers are represented by red crosses. The superscripts w and d on the x-
1033 axis stand for the wettest and driest years of each simulation period, respectively.

1034 Figure 9: Shallow groundwater content uncertainty envelopes for the Du Loup watershed: (a)
1035 calibration (9-year mean) and (b) validation periods (8-year mean). The black and green
1036 envelopes illustrate the distribution of simulated flows under the KGE and Nash-log OFs,
1037 respectively.

1038 Figure 10: Radar plots of the twelve parameters used in the automatic calibration of
1039 HYDROTEL for each study watershed. Parameter A is part of the interpolation coefficients,
1040 parameters B through G relate to the snow model, and parameters F through L relate to the
1041 soil group of parameters. Figure (a) refers to the KGE OF; and (b) to the Nash-log OF. The
1042 dark and light blue data refer to the first optimization trial of Figure 3, black data to the
1043 second optimization trial.

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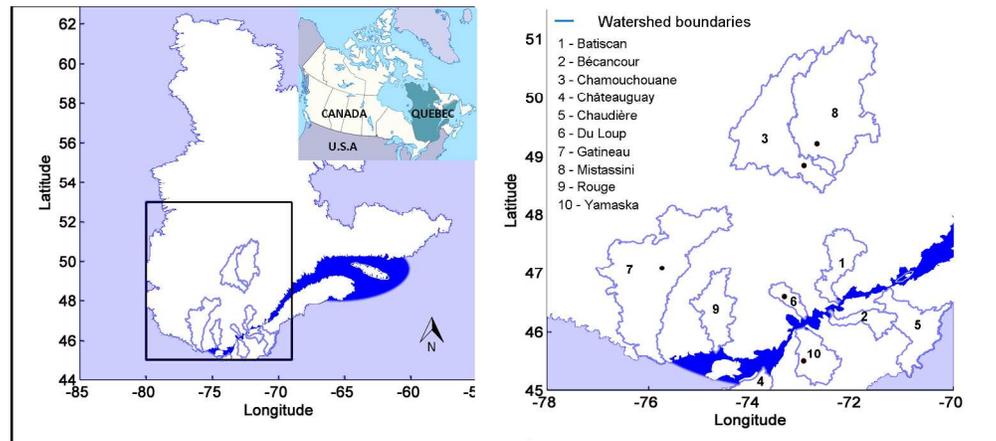


Figure 1: Location of the study watersheds in Québec, Canada, and around the St. Lawrence River

278x122mm (240 x 240 DPI)

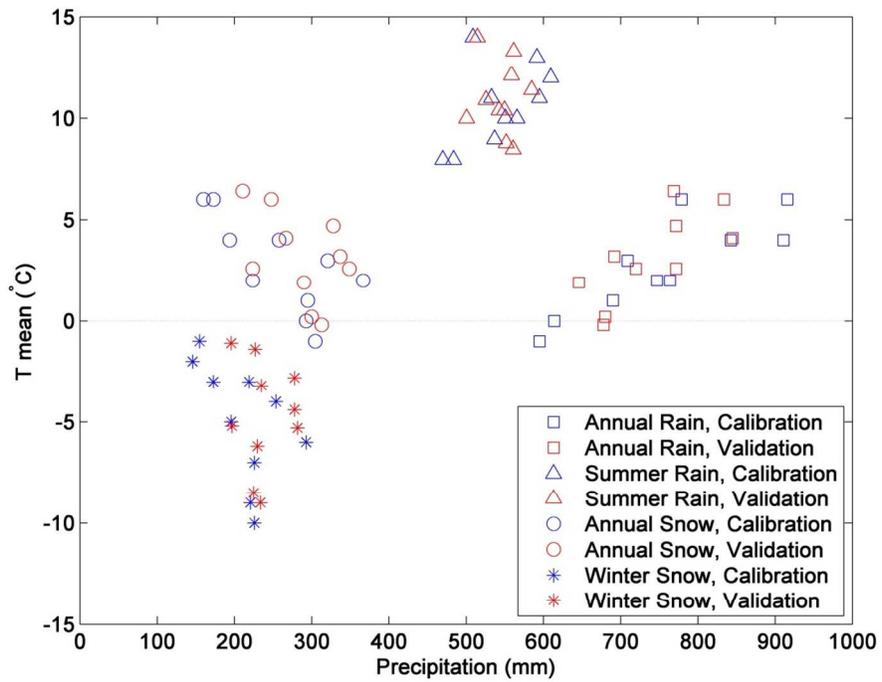


Figure 2: Relationship between mean annual and seasonal temperatures and precipitations for the calibration and validation periods

160x120mm (220 x 220 DPI)

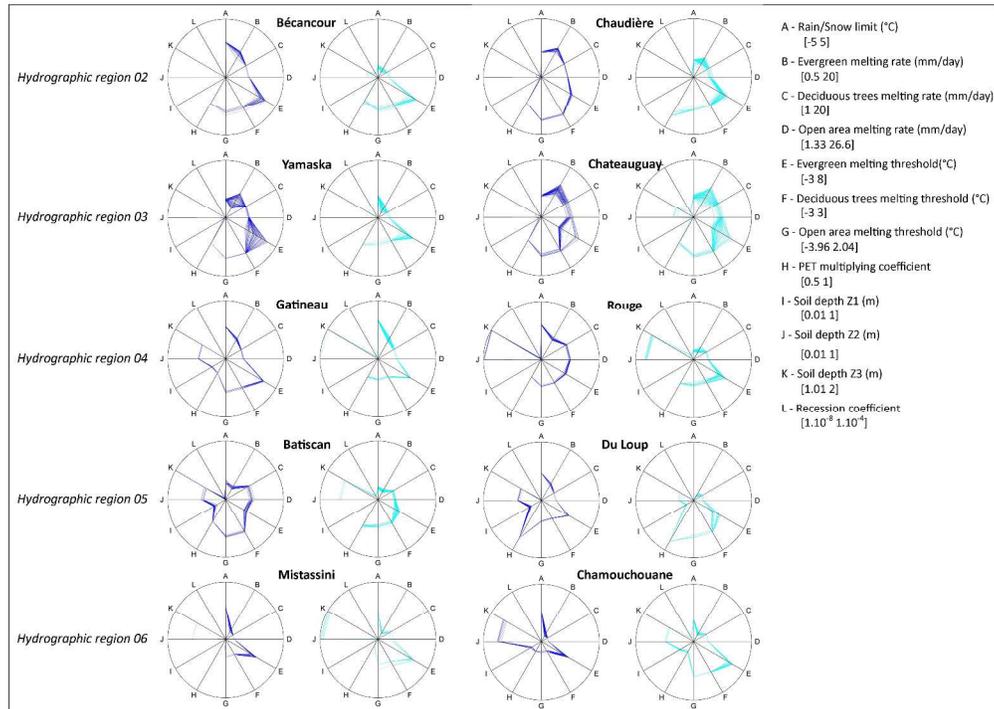


Figure 3: Radar plots of the twelve parameters used in the automatic calibration of HYDROTEL for each study watershed. Parameter A is part of the interpolation coefficients, parameters B through G relate to the snow model, and parameters F through L relate to the soil group of parameters. The dark blue diagrams refer to the KGE OF while the light blue diagrams refer to the Nash-log OF.

512x364mm (240 x 240 DPI)

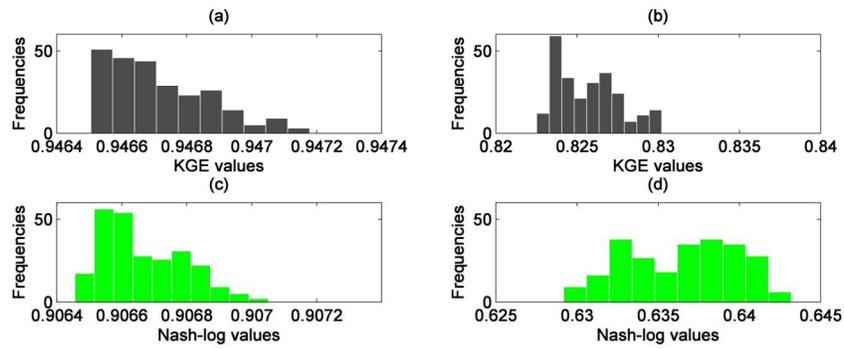


Figure 4: Distribution of the OF values for the Chamouchouane watershed: (a) KGE calibration period; (b) KGE validation period; (c) Nash-log calibration period; (d) Nash-log validation period

188x67mm (220 x 220 DPI)

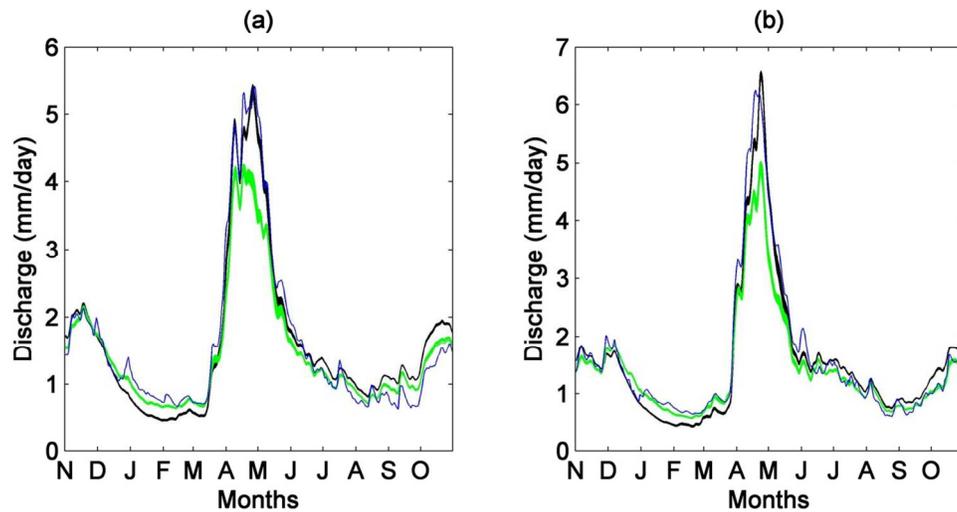


Figure 5: Streamflow uncertainty envelopes for the Rouge watershed: (a) calibration (9-year mean) and (b) validation periods (8-year mean). The black and green envelopes stand for simulated flows under the KGE and Nash-log OFs, respectively while the blue line depicts the observed values.

161x89mm (220 x 220 DPI)

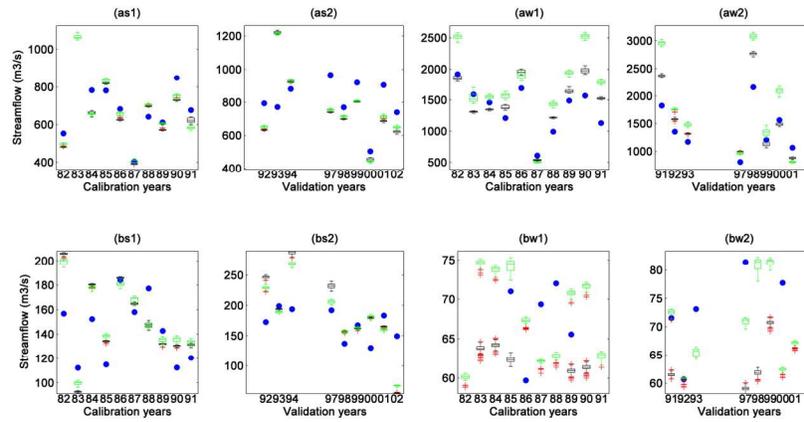
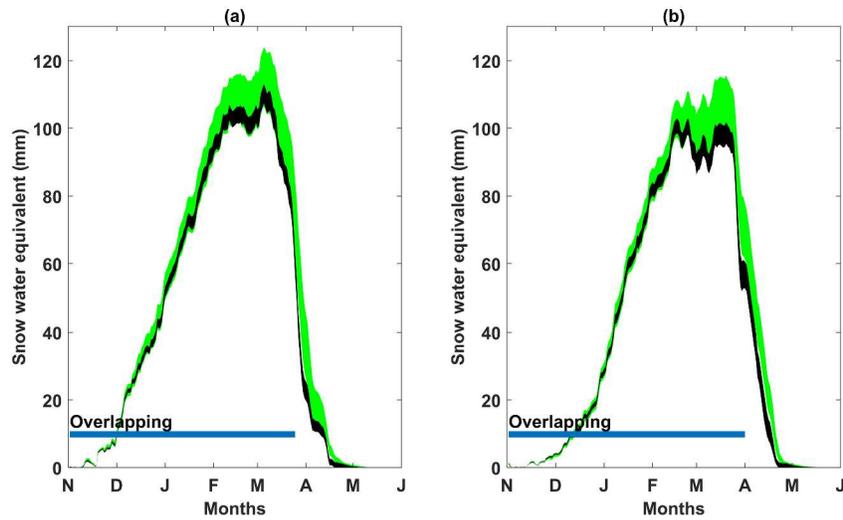


Figure 6: Boxplots of the seasonal hydrological indices for the Chamouchaoune watershed for the calibration (1) and validation (2) periods: (as1) and (as2) display the distribution of the maximum summer peakflows; (aw1) and (aw2) the distribution of maximum winter peakflows; (bs1) and (bs2) the distribution of summer-7-day minimum flows; and (bw1) and (bw2) the distribution of winter-7-day minimum flows. The black and green boxplots illustrate the distribution of simulated flows under the KGE and Nash-log OFs, while the blue dots depict the observed values. The superscripts w and d on the x-axis indicate the wettest and driest years of each simulation period, respectively.

177x82mm (300 x 300 DPI)



SWE uncertainty envelopes for the Yamaska watershed: (a) calibration (9-year mean) and (b) validation periods (8-year mean). The black and green envelopes illustrate the distribution of simulated flows under the KGE and Nash-log OFs. The line indicates the period of overlapping between the uncertainty envelopes.

152x83mm (600 x 600 DPI)

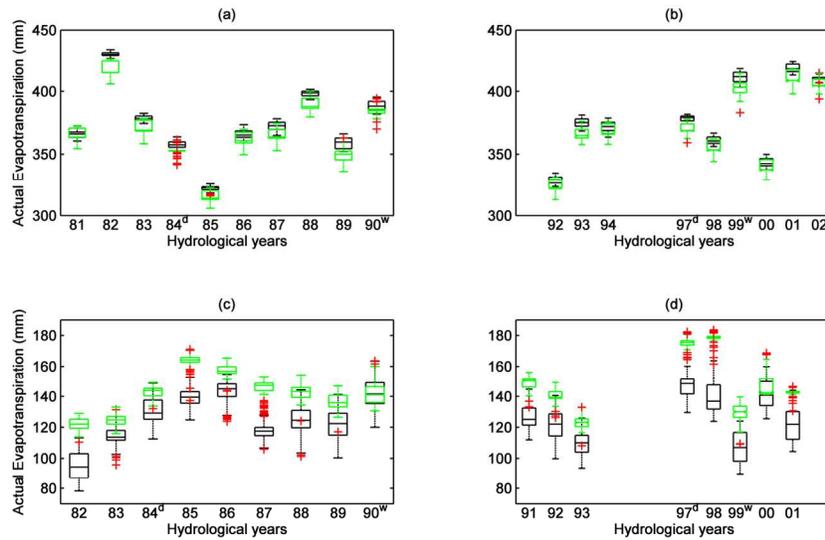


Figure 8: Seasonal actual evapotranspiration for the Bécancour watershed: (a) summer calibration; (b) summer validation; (c) winter calibration and (d) winter validation. The black and green boxplots stand for simulated AET distributions under the KGE and Nash-log OF, respectively. The outliers are represented by red crosses. The superscripts w and d on the x-axis stand for the wettest and driest years of each simulation period, respectively.

152x91mm (300 x 300 DPI)

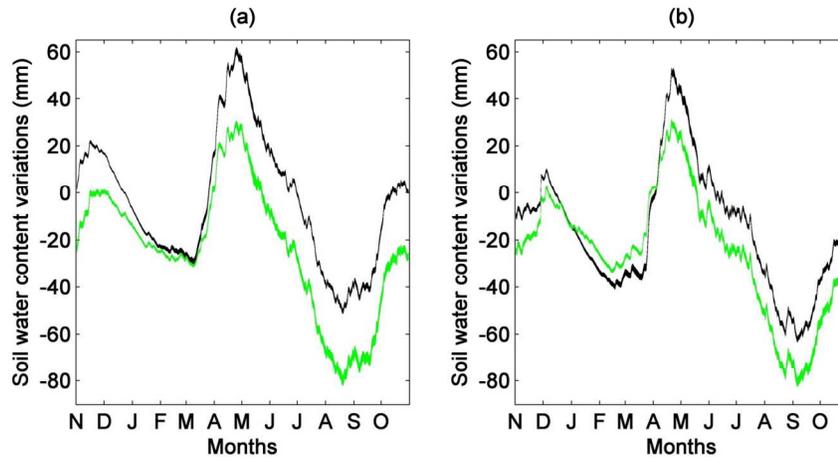


Figure 9: Shallow groundwater content uncertainty envelopes for the Du Loup watershed: (a) calibration (9-year mean) and (b) validation periods (8-year mean). The black and green envelopes illustrate the distribution of simulated flows under the KGE and Nash-log OFs, respectively.

187x85mm (220 x 220 DPI)

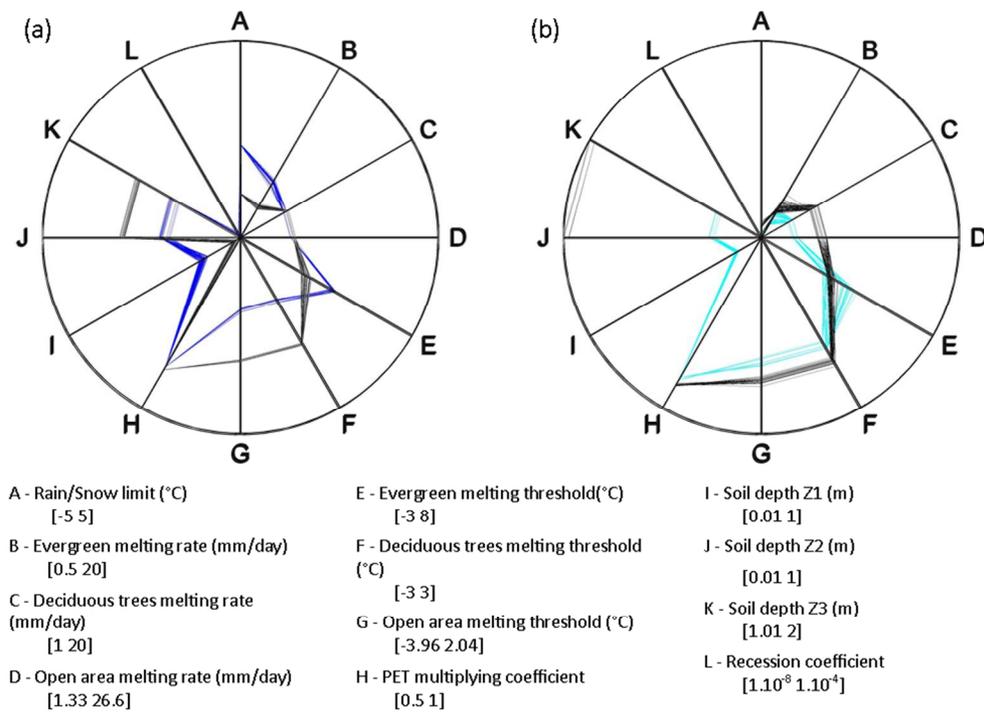


Figure 10: Radar plots of the twelve parameters used in the automatic calibration of HYDROTEL for each study watershed. Parameter A is part of the interpolation coefficients, parameters B through G relate to the snow model, and parameters F through L relate to the soil group of parameters. Figure (a) refers to the KGE OF; and (b) to the Nash-log OF. The dark and light blue data refer to the first optimization trial of Figure 3, black data to the second optimization trial.

261x190mm (96 x 96 DPI)

Only