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1 **PUB in Québec: A robust geomorphology-based deconvolution-**
2 **reconvolution framework for the spatial transposition of**
3 **hydrographs**

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8
9 **Highlights**

- 10 • Successful geomorphology-based discharge prediction on snow influenced catchments.
- 11 • Model efficiency governed by both structural and circumstantial effects.
- 12 • Ghosh distance between catchments characterizes transposition configurations.
- 13 • Performances in pseudo-ungauged catchments open options for ungauged catchments.

14 **Abstract**

15 The flexibility and parsimony of transpositioning hydrographs using geomorphology-based
16 deconvolution-reconvolution frameworks is particularly adapted to prediction in ungauged basins.
17 Although already tested in semi-arid and oceanic-temperate hydro-climates, its predictions must be
18 reproducible in a variety of hydrological contexts. The present study explores the nivo-pluvial
19 hydrological regime using geomorphology-based hydrograph transposition between 21 gauged
20 catchments ranging from 1.1 to 4466.4 km² in Québec, Canada, and constitutes a case study in
21 prediction in ungauged basins. Three metrics were used to assess model performance for each
22 donor-target pair: Nash Sutcliffe Efficiency (NSE), NSE calculated for the square root of discharge
23 (NSE_{sqrt}), and Volumetric Efficiency. The classic transposition of hydrographs using the specific

24 discharge ratio, used as a reference, was almost always outperformed by the geomorphology-based
25 approach. Good but seasonally variable performance values were obtained for several pairs of
26 catchments, revealing simultaneous structural and situational effects. The difference in size, the
27 physical distance between the gauged donor and its target ungauged catchment, and the season
28 influenced the performance of the geomorphology-based transposition.

29

30 **Keywords**

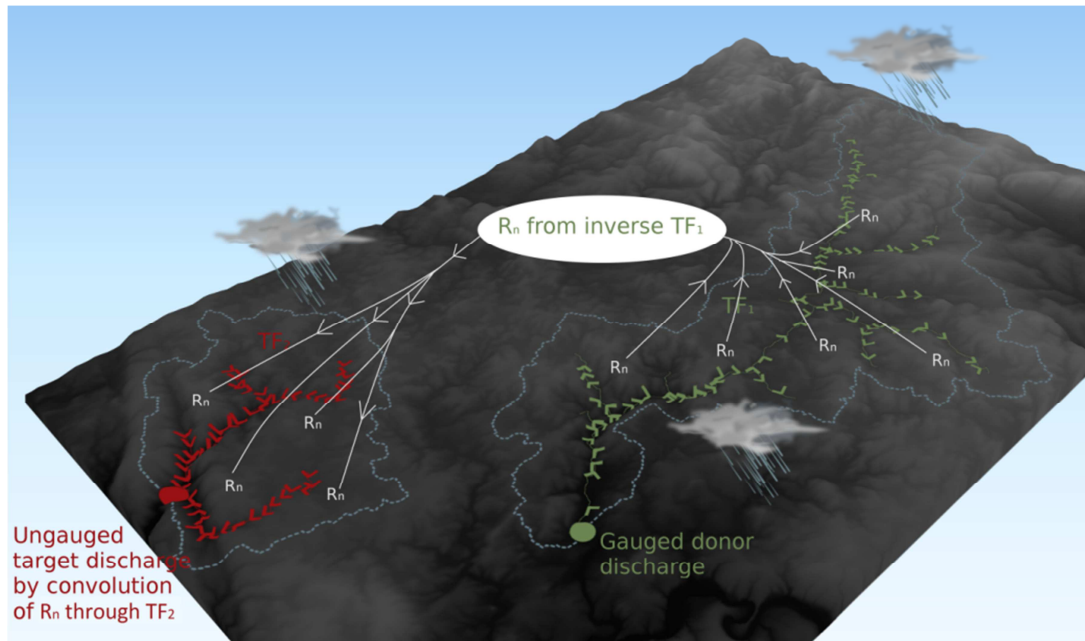
31 Ungauged basin; Geomorphology; Hydrograph transposition; Scaling; Seasonality; Nivo-pluvial
32 regime

33 1. Introduction

34 Prediction in Ungauged Basins (PUB), as an agenda-setting theme (Sivapalan et al., 2003), has
35 triggered important methodological progress (Blöschl et al., 2013; Hrachowitz et al., 2013b) and
36 practical advances (Pomeroy et al., 2013; Spence et al., 2013). Elementary and synthetic
37 developments have been achieved, especially in terms of general understanding; similarity
38 assessment and classification; and flexible hierarchical modelling approaches applied to annual and
39 seasonal runoff, flow duration curves, low flows, and floods. Nevertheless, beyond the end of the
40 International Association of Hydrological Sciences 2003-2012 decade on PUB, some methods remain
41 to be explored, improved, or adapted to other hydrological settings. Key paths of further progress
42 include comparative hydrology; transfer of knowledge from experimental catchments to data-scarce
43 areas; and flexible approaches across contexts and scales, temporal variability, and densities of data
44 availability (Blöschl et al., 2013; Hrachowitz et al., 2013a; Sivakumar, 2007). Runoff hydrographs
45 remain particularly critical as they encompass the full temporal pattern of catchment hydrology and
46 constitute the composite of all signatures and variabilities (McMillan et al., 2017; Parajka et al.,
47 2013). In particular, robust simulation of discharge remains challenging at infra-daily time steps over

48 long periods for different sizes of catchments, due to event-level, seasonal, or interannual
49 hydrometeorological variability.

50 Within the general geomorphology-based unit hydrograph framework (Cudennec et al., 2004;
51 Franchini and O'Connell, 1996; Rigon et al., 2016; Rodríguez-Iturbe and Valdés, 1979), the family of
52 methods, which derives a transfer function from easily observable geomorphometric width and area
53 functions (Cudennec, 2007; Kirkby, 1976; Robinson et al., 1995; Snell and Sivapalan, 1994; Surkan,
54 1969), opens modelling opportunities which exploit an explicit structure, low calibration
55 requirements, and flexibility. For instance, Cudennec (2000) and Boudhraâ et al. (2006, 2009)
56 explored geomorphology-based transfer functions of water through the river network down to the
57 outlet of the catchment. Inversion of a transfer function deconvolutes the outlet discharge series into
58 a space-averaged net rainfall series, defined here as the hillslope response to a rainfall impulse, i.e.
59 the water flowing through the hillslope-river interface (Boudhraâ et al., 2018; Formetta et al., 2011;
60 Gupta and Mesa, 1988; Robinson and Sivapalan, 1996; Wang et al., 1981). The inversion has been
61 operationalized further (Menke, 1989; Tarantola, 1987; Tarantola and Valette, 1982) with verification
62 of the statistical distribution of errors, testing of several *a priori* options for initialization, and
63 sensitivity analysis of parameters (Boudhraâ et al., 2018; de Lavenne et al., 2015). Simulating the
64 discharge series at another outlet thus becomes possible by 1) assuming that the net rainfall series
65 can be spatially transferred or generalized from one or several (here one) gauged donor catchments
66 to an ungauged target catchment, based on nesting, neighbouring, or similarity configurations; 2)
67 estimating the geomorphology-based transfer function of the ungauged catchment, and 3)
68 convoluting these net rainfall series and the transfer function. Applications in the context of PUB
69 require robustness and parsimony of both the deconvolution and convolution steps. These qualities
70 are obtained by assuming linearity of the transfer functions used for the donor and target
71 catchments, which corresponds to an assumption and estimation of average flow velocity through
72 the river network of a given catchment, and the exclusion of hydraulic and geomorphological
73 dispersions. Fig. 1 summarises the two-step process.



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Figure 1. Diagram of geomorphology-based inversion-transposition of a hydrograph. The spatially-averaged net rainfall series (R_n) is estimated from deconvoluted discharge using the inversion of the transfer function (TF) of the gauged catchment (TF_1). It is then transposed to the ungauged catchment and convoluted using the ungauged TF (TF_2). Arrows indicate the direction of deconvolution (from downstream to upstream) and convolution (from upstream to downstream).

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To date, this framework has been applied to two contrasting hydrological settings: semi-arid Tunisia and humid temperate France, relying on dense gauging networks and configurations, in which some gauged catchments were considered as pseudo-ungauged ones to provide blind references. The Horton-type rainfall-runoff dynamics of semi-arid Tunisia allowed for initial development of the framework due to the region's simple hillslope dynamics (Boudhraâ et al., 2018; Bull and Kirkby, 2002; Merheb et al., 2016) and simple characteristic time of events on small catchments up to several tens of km^2 in area (Nasri et al., 2004b). Yet the approach still faces challenges for larger catchments or areas (Chargui et al., 2013; Cudennec et al., (2005, 2016; Feki et al., 2012; Kingumbi et al., 2005), such as rainfall variability in space and time, and effects of infrastructure such as soil and water conservation installations and small dams (Lacombe et al., 2008; Nasri et al., 2004a; Ogilvie et al., 2016, 2018). A more systematic application in humid temperate Brittany, France, allowed further exploration of the articulation of hillslope-river network compartments, and hence the physical significance of the net rainfall signal and the strategy for pairing donor and target catchments or groups of catchments (de Lavenne et al., 2015), such as those of a coastal bay (de Lavenne and

94 Cudennec, 2014). Geomorphology-based transposition was also applied to the Loire River catchment
95 (the largest one in France, ca. 110,000 km² at Mont-Jean-sur-Loire before tidal influence) and its
96 related tributaries (de Lavenne et al., 2016). Using the mean net rainfall series estimated from the
97 five closest catchments, results were generally of high quality according to several metrics. In
98 addition, comparison to the top-kriging approach (Skøien et al., 2006) used as a reference showed
99 that, on average, geomorphology-based transposition had similar and sometimes better results,
100 which is promising given its methodological robustness and flexibility in using available data. These
101 applications showed some adaptability to contrasting hydrological contexts and added values in
102 modelling discharge series in (pseudo-) ungauged catchments, as well as limitations of the
103 application domain.

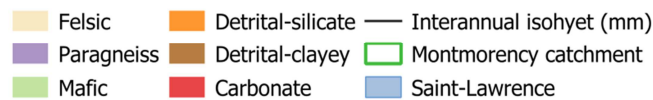
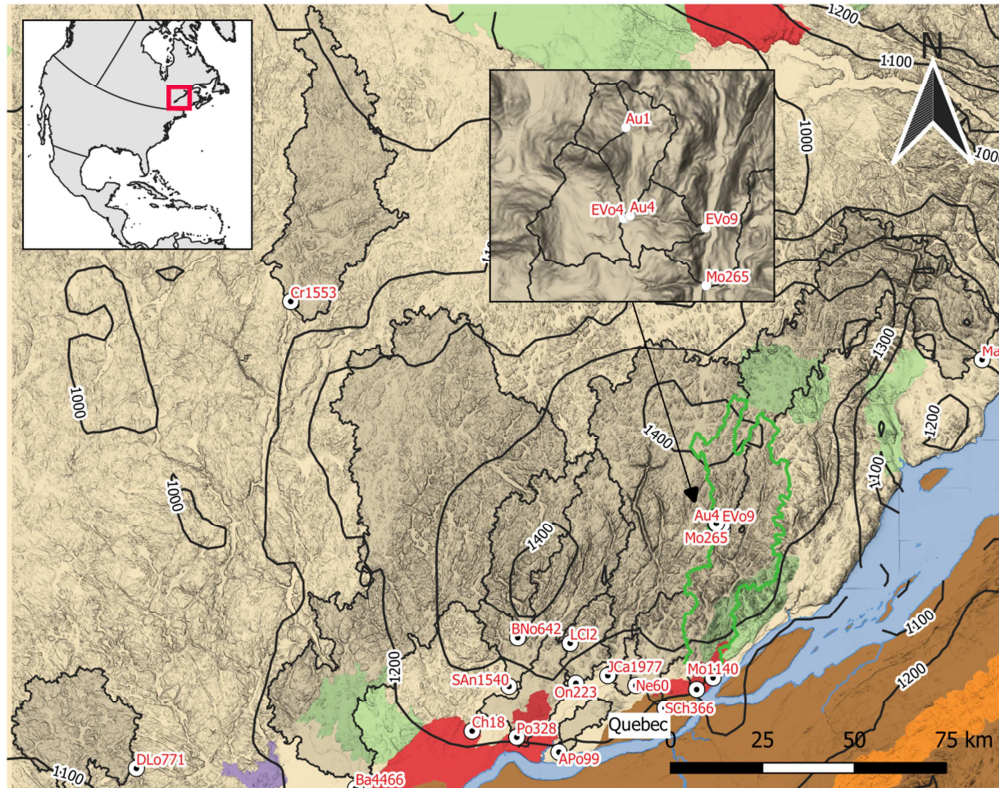
104 The aim of this study was to apply and assess the relevance of geomorphology-based transposition in
105 yet another hydrological context – Québec, Canada – which differs from previous regions in its
106 hydrological regime, snow influence, physical geography, and gauging configurations. Data from
107 national and academic hydrometric facilities allowed a variety of topological and geometric
108 configurations to be explored. The data set was also excellent for exploring hydrographic and
109 synoptic effects with a clear and homogeneous underlying geography. Hourly simulations were
110 assessed using several metrics, and specific discharge was used as reference for comparison.

111 2. Materials and methods

112 2.1. Study area

113 The northern side of the Saint Lawrence River near Québec City has developed into a geologic
114 interface between the Canadian Shield, composed of hard rocks (mafic-felsic-paragneiss), and the
115 sedimentary Saint Lawrence valley, where carbonates and detrital rocks abound (Fig. 2). This
116 geological setting underlies the land cover distribution, dominated by unmanaged forests and
117 mountainous landscapes in the north and anthropogenic activities in the valley. In the study region,
118 the mean interannual precipitation ranges from 1000 mm to the north, east, and west to 1400 mm in

119 the centre. Due to the topographic configuration and the presence of Gulf of Saint Lawrence and the
 120 Atlantic Ocean to the east, the Montmorency forest, north of Québec City, constitutes a ‘hotspot’ of
 121 precipitation, despite being relatively homogeneous (Fig. 2).



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 123 **Figure 2. Geological map (MDDELCC and DEB, 2018) of the interface between the Canadian Shield and Saint Lawrence**
 124 **platform, splitting the region into a hard rock area to the north and a sedimentary area to the south. The 21 catchments**
 125 **used in the study are plotted at their outlets (see Table 1 for catchment names). Numbers in catchment codes represent**
 126 **surface areas (km²).**

127 The region is monitored with a configuration of gauging stations on 21 catchments, offering a long-
 128 term regional synoptic view of tributaries that flow mostly north-south, and including six nested
 129 catchments ranging from 1-1140 km² in the Montmorency River catchment (Tremblay et al., 2008)
 130 (Table 1). Codes are composed of initial letters of the full names and surface areas (km²). Most of the
 131 catchments are dominated by forests, except for Beauport (Be23), Nelson (Ne60), Aux Pommés

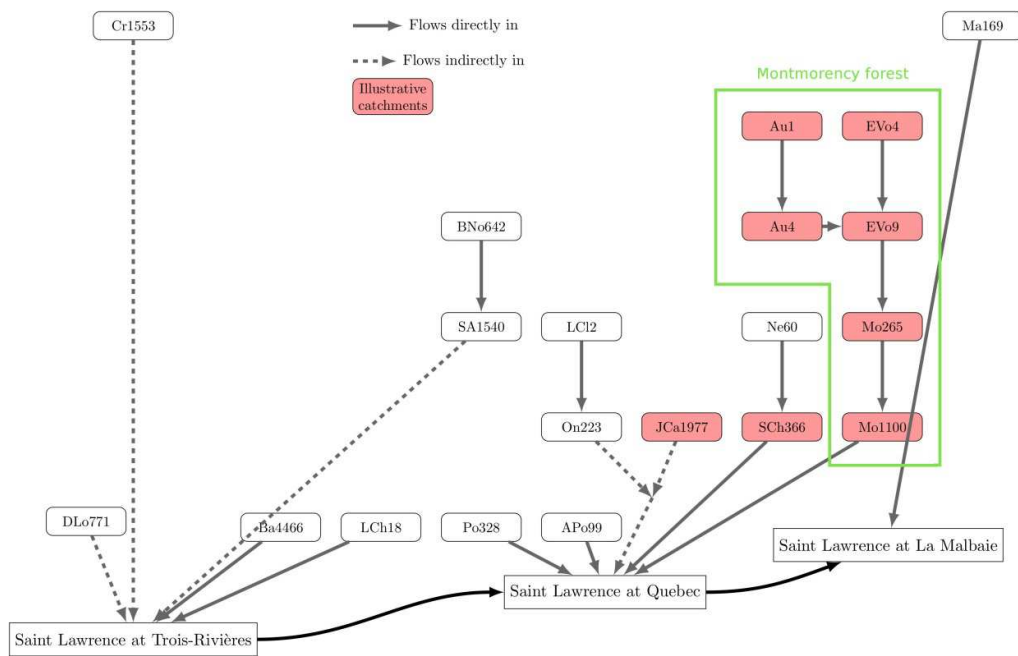
132 (Apo99), and Saint-Charles (SCh366), which are strongly artificial. The Des Aulnaies catchments (Au1
 133 and Au4) also have a larger percentage of forest.

134 **Table 1. Characteristics of studied catchments in order of increasing surface area. Bold codes identify nested catchments**
 135 **in the Montmorency River catchment (Au1, Au4, EVo4, EVo9, Mo265, Mo1140) and the two immediate neighbours**
 136 **(JCa1977, SCh366). Land cover data were provided by the MDDELCC and DEB (2018).**

Name	Code	Area (km ²)	Mean elevation (m)	Agriculture (%)	Unmanaged forest (%)	Managed forest (%)	Wetland (%)	Water (%)	Artificial (%)
Des Aulnaies	Au1	1.1	859.4	0	37.6	62.4	0	0	0
Décharge du lac Clair	LC12	1.9	303.1	0	79.0	0	0	21.0	0
Des Aulnaies	Au4	3.5	818.9	0.3	70.2	24.7	3.6	0	1.3
Des Eaux Volées	EV04	3.7	813.2	0	82.2	15.9	1.7	0	0.2
Des Eaux Volées	EV09	9.0	798.3	0.1	80.5	16.4	2.5	0	0.5
La Chevrotière	Ch18	17.6	119.7	11.8	70.8	5.2	10.2	0.2	1.8
Beauport	Be23	22.6	145.7	5.7	31.6	0.4	0.2	0.3	61.8
Nelson	Ne60	60.1	218.7	7.1	69.7	2.0	4.0	0.6	16.6
Aux Pommes	APo99	98.6	137.3	29.1	51.4	1.1	7.7	0.3	10.5
Ontaritz	On223	223.0	318.0	3.5	80.9	2.4	3.3	7.6	2.4
Montmorency	Mo265	264.8	857.9	0.0	80.5	11.8	4.2	2.2	1.3
Portneuf	Po328	327.6	165.5	22.7	62.7	1.6	2.7	2.7	7.5
Saint-Charles	SCh366	366.4	306.3	2.6	72.3	1.2	2.2	2.8	18.9
Bras du Nord	BNo642	641.8	568.8	0.6	81.2	10.4	2.8	5.0	0.1
Du Loup	DLo771	771.3	426.3	0	83.0	3.3	4.3	9.2	0.1
Montmorency	Mo1140	1139.8	717.3	0.1	82.9	9.4	2.8	2.5	2.4
Saint-Anne	SAn1540	1540.1	553.6	1.7	81.9	8.2	3.0	4.5	0.8
Croche	Cr1553	1553.4	389.6	0.0	79.6	8.5	6.3	5.1	0.4
Malbaie	Ma1693	1692.8	679.5	0.5	79.9	11.1	2.5	4.8	1.0
Jacques-Cartier	JCa1977	1976.5	716.4	0.5	82.2	7.8	3.7	4.6	1.3
Batiscan	Ba4466	4466.4	383.3	4.1	78.8	4.5	3.8	7.5	1.2

137
 138 The organization of the study area splits the data set into three parts, according to the rivers that
 139 flow into the Saint Lawrence River mostly from the west (Saint Lawrence near Trois-Rivières) or the
 140 east (Saint Lawrence at Québec City, Saint Lawrence at La Malbaie) (Fig. 3).

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142
 143 **Figure 3. Topological diagram of the 21 catchments studied, according to their location on the study area and the order**
 144 **they flow into the Saint Lawrence. Catchments that are part of the Montmorency nesting configuration and its two**
 145 **immediate neighbours are highlighted in red. See Table 1 for catchment names. Numbers in catchment codes represent**
 146 **surface areas (km²).**

147 2.2. Data

148 Fifteen-minute streamflow data were obtained from a public web platform maintained by the
 149 Québec government (https://www.cehq.gouv.qc.ca/hydrometrie/historique_donnees/default.asp).
 150 Because of less frequent sampling before 2000, data from 1 April 2000 to 1 December 2016 were
 151 chosen. Quasi-continuous data are available after 2005, whereas some gaps appear before then.
 152 Winter observations are missing as they were influenced by ice. Geomorphological analysis was
 153 based on a 10 m-resolution DEM from the Québec government.

154 The study area has a humid continental climate. Its catchments are subject to a strong spring freshet
 155 and high autumnal flows, typical of a nivo-pluvial hydrological regime. Low flows occur in winter
 156 when snow accumulates on the ground and in summer when a dry spell develops during peak
 157 evapotranspiration. This contrasts with the French temperate context (de Lavenne et al., 2015,

158 2016), which has the same latitude as Québec, and even more with the Tunisian semi-arid context
159 (Boudhraâ et al., 2009, 2018).

160 2.3. Methods

161 2.3.1. Geomorphology-based transposition of discharge

162 Hydro-geomorphological analysis followed the approach of previous studies (Boudhraâ et al., 2009;
163 Boudhraâ et al., 2018; Cudennec, 2000; de Lavenne et al., 2015; de Lavenne et al., 2016). For each
164 catchment, water paths from a regular grid of points were identified through the hillslopes and the
165 river network (based on a threshold of 0.25 km²) down to the outlet, using GIS analysis (Aouissi et al.,
166 2013; Cudennec et al., 2004) based on GRASS 7.4.0 software. Thus the probability density function
167 (*pdf*) of the hydraulic length L (i.e. the length of the path through the river network to the outlet) was
168 assessed at the catchment level. The $pdf(L)$ was then used to establish the transfer function $TF =$
169 $pdf(t)$ through the river network based on average velocity \bar{v} . Use of an average velocity is consistent
170 with the classic simplifying and parsimonious assumption of linear transfer function through the river
171 network (Beven and Wood, 1993; Blöschl and Sivapalan, 1995; Franchini and O'Connell, 1996;
172 Grimaldi et al., 2012; Robinson and Sivapalan, 1996; Woods and Sivapalan, 1999). This assumption
173 remains especially acceptable for relatively small catchments (<500 km²), where hydrodynamic and
174 geomorphologic dispersions (unknown in ungauged catchments) can be ignored.

175 Discharge $Q(t)$ [m³s⁻¹] at the catchment outlet can be simulated by convolution between the spatially-
176 averaged net rainfall series $R_n(t)$ [m] over the catchment and the transfer function TF , rescaled by
177 catchment surface area S [m²]:

$$178 \quad Q(t) = S \int_0^t R_n(t - \tau) \cdot TF(\tau) \cdot d\tau \quad (1)$$

179 This convolution can also be written as:

$$180 \quad \mathbf{Q} = \mathbf{TF} \cdot \mathbf{R}_n \quad (2)$$

181 where \mathbf{Q} is the vector of discharge components (expressed in the same units as rainfall for
 182 convenience), \mathbf{TF} the matrix composed of transfer function components, and \mathbf{R}_n the net rainfall
 183 vector.

184 The net rainfall vector is estimated through inverse modelling (deconvolution) of observed
 185 discharges \mathbf{Q}_m , in accordance with the model defined by Eq. 2. A solution was found by minimizing
 186 the following expression (Boudhraâ et al., 2018; Cudennec, 2000; Menke, 1989):

$$187 \quad \Phi(\mathbf{Q}, \mathbf{R}_n) = (\mathbf{Q} - \mathbf{Q}_m)^t \mathbf{C}_Q^{-1} (\mathbf{Q} - \mathbf{Q}_m) + (\mathbf{R}_n - \mathbf{R}_n^{apriori})^t \mathbf{C}_R^{-1} (\mathbf{R}_n - \mathbf{R}_n^{apriori}) \quad (3)$$

188 where Φ is the likelihood function; \mathbf{C}_Q and \mathbf{C}_R covariance matrices of discharge and net rainfall,
 189 respectively (given by Eq. 5 and 6); $\mathbf{R}_n^{apriori}$ the vector of *a priori* net rainfall components; and t the
 190 symbol of a transposed matrix. Statistical distributions of both $(\mathbf{Q} - \mathbf{Q}_m)$ and $(\mathbf{R}_n - \mathbf{R}_n^{apriori})$ were assumed
 191 to be normal and unbiased. Eq. 2 being a linear model, the solution satisfied:

$$192 \quad \mathbf{R}_n = \mathbf{R}_n^{apriori} + \mathbf{C}_R \mathbf{TF}^t (\mathbf{TF}^t \mathbf{C}_R \mathbf{TF} + \mathbf{C}_Q)^{-1} \mathbf{Q}_m - \mathbf{TF} \mathbf{R}_n^{apriori} \quad (4)$$

193 Menke (1989) described the stability, convergence, and uniqueness of the solution of such nonlinear
 194 problems in generic terms, and the geomorphology-based linear transfer function has been
 195 specifically assessed (Boudhraâ et al., 2009; Boudhraâ et al., 2018; Cudennec, 2000).

196 Eq. 3 and 4 introduce a *priori* information, formed by vector $\mathbf{R}_n^{apriori}$ and its associated covariance
 197 matrix \mathbf{C}_R , along with the level of confidence to be ascribed to this knowledge. According to Boudhraâ
 198 et al. (2018), who tested multiple options, the *a priori* net rainfall $\mathbf{R}_n^{apriori}$ to use is the specific
 199 discharge at the outlet of the catchment translated upstream along the time axis by the mean
 200 catchment lag time. The lag time is approximated from the mean hydraulic length divided by the
 201 characteristic velocity.

202 Observations suffer from measurement error, defined by the following covariance:

203
$$cov[Q_m(i), Q_m(j)] = \sigma_Q(i)\sigma_Q(j)exp\left[-\frac{1}{2}\left|\frac{(i-j)\Delta t}{T_Q}\right|^2\right] \quad (5)$$

204 where the standard deviation (SD) $\sigma_Q(i)$ of discharge measurement error is a linear function of
 205 discharge, according to parameters A_Q and B_Q : $\sigma_Q(i) = A_Q \cdot Q_m(i) + B_Q$. The covariance expression is
 206 consistent with the hypothesis of a normal distribution, and T_Q stands for the decorrelation time of
 207 discharge errors.

208 Uncertainties in net rainfall are also estimated by \mathbf{C}_R , the covariance matrix of errors between *a priori*
 209 net rainfall $\mathbf{R}_n^{apriori}$ and true (unknown) net rainfall. The covariance is assumed to follow an
 210 exponential model:

211
$$cov[R_n(i), R_n(j)] = \sigma_R(i)\sigma_R(j)exp\left[-\frac{1}{2}\left|\frac{(i-j)\Delta t}{T_R}\right|^2\right] \quad (6)$$

212 where the SD $\sigma_R(i)$ of net rainfall error is a linear function of net rainfall, according to parameters A_R
 213 and B_R : $\sigma_R(i) = A_R \cdot R_n(i) + B_R$. The covariance expression is consistent with the hypothesis of a
 214 normal distribution, and T_R stands for the decorrelation time of residuals between the *a priori* and
 215 true net hyetographs.

216 In this study, we used robust and versatile parameter values identified from a systematic sensitivity
 217 analysis(Boudhraâ et al., 2018; de Lavenne et al., 2015; de Lavenne et al., 2016) which equal 0.9,
 218 0.15, 0.001, 0.01, 20 (min), and 1 (min) for A_R , A_Q , B_R , B_Q , T_R , and T_Q , respectively.

219 2.3.2. Velocity

220 The velocity of water flow through the river network was calculated for each rainfall event recorded.
 221 To prepare the data for PUB, velocity was regionalized based on all flood events in the data set (21
 222 catchments from 2000-2016), following de Lavenne (2013), with slight adjustments in
 223 parameterization for consistency with the data set and its hydrological context. An event was
 224 detected if the slope of the rising limb of the hydrograph exceeded $0.25\% \text{ h}^{-1}$ and if the volume of
 225 water displaced during the event exceeded 0.01 mm. For every event detected, the rising time was

226 extracted, which allowed calculation of event mean velocity vs. the mean hydraulic length \bar{L} of the
227 catchment. The distribution of velocities across seasons for the 21 catchments was ultimately
228 analysed to estimate regional velocity.

229 2.3.3. Systematic approach

230 Although the main purpose of geomorphology-based hydrological modelling is to simulate discharge
231 at the outlet of ungauged catchments, the present study explores a pseudo-ungauged approach to
232 allow comparison with observations (Fig. 2). To simulate a target pseudo-ungauged catchment from
233 a donor gauged catchment, a systematic approach was used involving all 21 gauged catchments. For
234 spring, summer, and autumn seasons, and the 2000-2016 period, each of the catchments was used
235 as the donor to, and then as the target of, all other catchments. This approach yielded 420 donor-
236 target combinations. Unlike de Lavenne et al. (2016), who used the five closest donors to estimate a
237 mean net rainfall series, and knowing the lower size and density of the gauging network considered,
238 we chose to follow a one-to-one approach to investigate successful pairs.

239 To assess simulation quality, transposition of specific discharge was used as a reference (Eq. 7):

$$240 \quad Q_t = Q_d \left(\frac{S_t}{S_d} \right) \quad (7)$$

241 where Q_t is the simulated discharge in the target catchment and Q_d the source discharge in the donor
242 catchment. S_t and S_d are areas of the target and donor catchments, respectively.

243 It assumes a linear relationship between discharge and catchment area, and homogeneity of runoff
244 generation in the donor and target catchments (Archfield and Vogel, 2010; Gianfagna et al., 2015;
245 Karlsen et al., 2016). The geostatistical top-kriging approach (Skøien et al., 2006), used as a reference
246 by de Lavenne et al. (2016) in the Loire River catchment (110,000 km², 389 gauging stations), could
247 not be used as a reference in the present study because of the lower gauging density in Québec.

248 Geomorphology-based transposition was first applied to the Montmorency catchment, which
249 contains 6 gauging stations that monitor nested catchments ranging from 1-1140 km². As a thorough
250 test case, 2013 was examined in detail as it had marked discharge fluctuations.

251 2.3.4.Verification metrics

252 Three goodness-of-fit metrics were calculated. To assess goodness-of-fit from geomorphology-based
253 and specific discharge transpositions consistently, metrics were calculated only when observed
254 discharge (Q_{obs}) and simulated discharge (Q_{sim}) were available, although missing values were plotted
255 on hydrographs. Values were missing in early spring and late autumn in particular, when gauging
256 stations were closed, and during some summer low flows.

257 Nash-Sutcliffe Efficiency (NSE) (Nash and Sutcliffe, 1970), a common metric used to assess
258 hydrological model performance, was calculated:

$$259 \quad NSE = 1 - \frac{\sum(Q_{obs,t} - Q_{sim,t})^2}{\sum(Q_{obs,t} - \bar{Q}_{obs})^2} \quad (8)$$

260 NSE ranges from] - ∞; 1], equalling 0 when the model is as accurate as the mean of the observed
261 discharge and 1 when the model provides a perfect fit. The NSE emphasises high flows as it is based
262 on the mean squared error, which makes it sensitive to large errors (Muleta, 2012). A variant of the
263 NSE, calculated for the square root of discharge (NSE_{sqrt}), was also calculated as it provides a
264 compromise between emphasis on high or low flows (Oudin et al., 2006; Seiller et al., 2017):

$$265 \quad NSE_{sqrt} = 1 - \frac{\sum(\sqrt{Q_{obs,i}} - \sqrt{Q_{sim,i}})^2}{\sum(\sqrt{Q_{obs,i}} - \sqrt{\bar{Q}_{obs}})^2} \quad (9)$$

266 Volumetric Efficiency (VE) (Criss and Winston, 2008) was also calculated as it estimates the bias in
267 volume:

$$268 \quad VE = 1 - \frac{\sum|Q_{obs} - Q_{sim}|}{\sum Q_{obs}} \quad (10)$$

269 VE has as same range and interpretation as NSE and NSE_{sqr} .

270 To qualify metrics values, four classes were chosen for each criterion: “very good” when >0.66 ,
271 “good” when $0.33-0.66$, “average” when $0-0.33$ and “poor” when <0 . The terms “functioning pairs”
272 and “failing pairs” are also used to describe pairs of donor-target catchments with “very good” or
273 “poor” values for all metrics, respectively.

274 To compare the overall quality of the geomorphology-based transposition among metrics and
275 catchments, heatmaps (Guttman, 1950; Sneath, 1957) were constructed and reordered according to
276 the Ghosh distance of each catchment from the most south-westerly catchment, Du Loup (DLo771).

277 2.3.5. Ghosh distance-based statistical analysis

278 The Ghosh distance (Ghosh, 1951), which estimates a distance between two spatially gridded
279 polygons, was estimated using the ‘rtop’ package (Skøien et al., 2014) of the R environment (R
280 Development Core Team, 2017) for the 420 donor-target combinations. It was used to quantify the
281 geometry of the 6 nested catchments and their neighbours to further analyse the quality of
282 transpositions. A continuous and integrative method called “integrative function” was developed to
283 assess model performance according to the Ghosh distance. Assuming a vector of metric \mathbf{C} values
284 $\mathbf{C} = (C_1, \dots, C_i, \dots, C_n)$ ordered by increasing Ghosh distance, the following function f was applied to
285 each i^{th} position:

$$286 \quad f_{\text{int}}(i) = f(\mathbf{C}(C_1, C_2, \dots, C_i)) \quad (12)$$

287 where f is the mean or the SD. The purpose of this integrative function is to assess the overall trend
288 of metrics as Ghosh distance increases.

289 Ghosh distance was used to compare seasonal differences in hydrological behaviour.

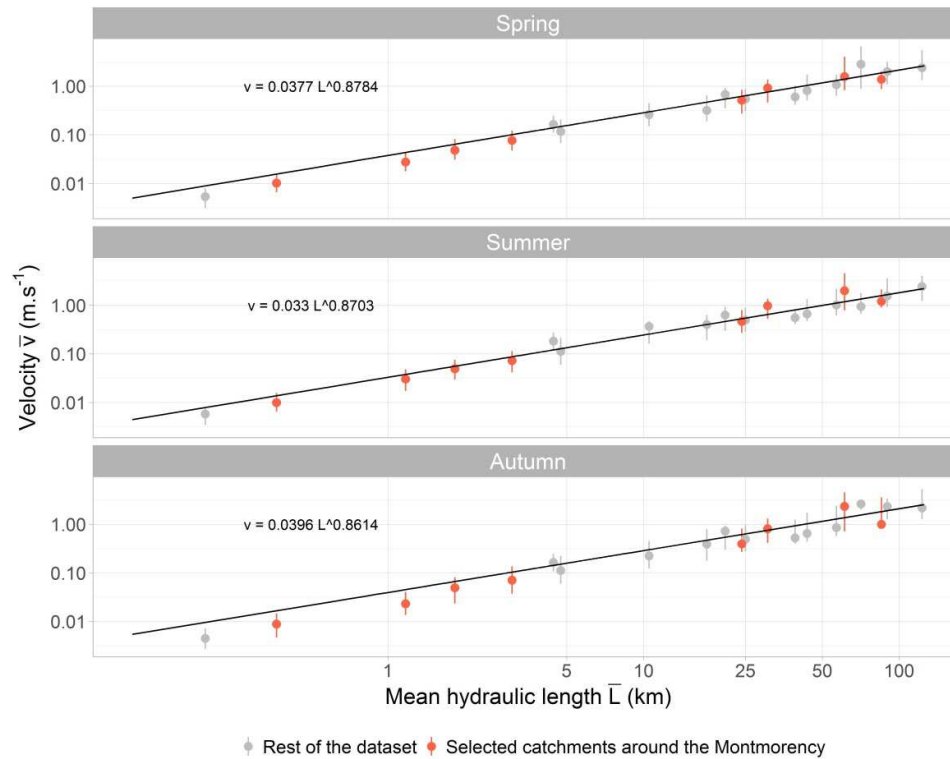
290 3. Results

291 Results are organized into five sections: 1) regionalization of the characteristic velocity, 2) analysis of
292 hydrograph transpositions comparing geomorphology-based transposition and specific discharge, 3)
293 overall comparison of both approaches, 4) identification of heterogeneous behaviours for the entire
294 catchment data set, and 5) seasonal behaviours and physical significance of net rainfall based on the
295 Ghosh distance.

296 3.1. Regionalization of river flow velocity

297 A total of 19,894 rainfall-runoff events were identified from 1 April 2000 to 1 December 2016. A non-
298 linear relationship between characteristic velocity and mean hydraulic length existed which was
299 represented well with power-law regressions with similar coefficients (Fig. 4). Root mean squared
300 errors equalled 0.320, 0.302, and 0.419m.s⁻¹ for spring, summer, and autumn, respectively. Median
301 velocities ranged from 0.005-2.392 m.s⁻¹. At the event scale, stream velocity varied by a factor of 2.2
302 to 5.8 from the 10th to 90th quantiles, respectively, depending on the catchment. Velocity remained
303 remarkably stable for each catchment around the median and across the three seasons (Fig. 4).

304



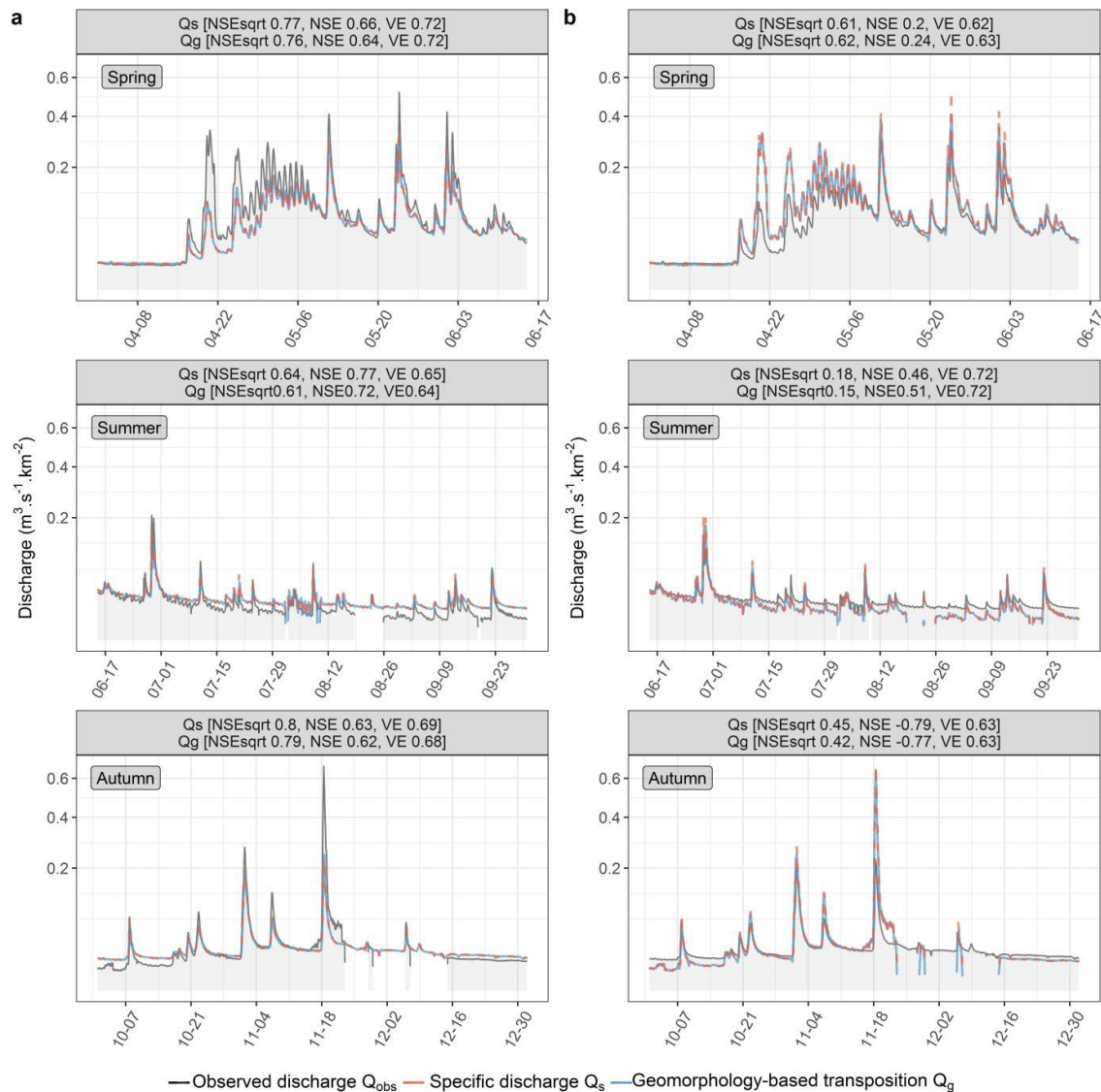
305 \blacklozenge Rest of the dataset \blacklozenge Selected catchments around the Montmorency
 306 **Figure 4. Velocity estimated by extracting the hydraulic length and rising time from 19,894 rainfall-runoff events in**
 307 **spring, summer, and autumn. Point range plots describe inter-event variability for each catchment; error bars represent**
 308 **10th and 90th quantiles, while points are medians. Power law regression is drawn for each season, where \bar{v} is the median**
 309 **velocity ($\text{m}\cdot\text{s}^{-1}$) across the river network of the catchment considered and \bar{L} the mean hydraulic length (km).**

310 3.2. Comparison of hydrographs obtained from geomorphology-based (Q_g) and specific-
 311 discharge (Q_s) transposition

312 3.2.1. Montmorency catchment

313 When examining small neighbouring catchments Des Aulnaies (Au4) and Des Eaux Volées (EVo4),
 314 transposition was worse depending on the season and was sometimes “average” or “poor”, despite
 315 their proximity and similar size (Fig. 5). Geomorphology-based and specific-discharge transposition
 316 yielded similar results. Both approaches resulted in higher NSE and NSE_{sqrt} in the direction
 317 $\text{EVo4} \rightarrow \text{Au4}$ than $\text{Au4} \rightarrow \text{EVo4}$. VE was similar and “very good” in both directions, but the other
 318 metrics, especially NSE, were “average” or “poor” for $\text{Au4} \rightarrow \text{EVo4}$. A seasonal pattern appeared with
 319 an underestimation of discharge in spring and late autumn (snowmelt and wet seasons) in the
 320 direction $\text{EVo4} \rightarrow \text{Au4}$ but overestimation in summer and early autumn (dry season). When switching
 321 donor and target catchments, the inverse occurred. These two 4 km² catchments are nested within
 322 EVo9, Mo265 and Mo1140. The opposite bias observed between EVo4 and Au4 can be combined to

323 yield more accurate predictions.

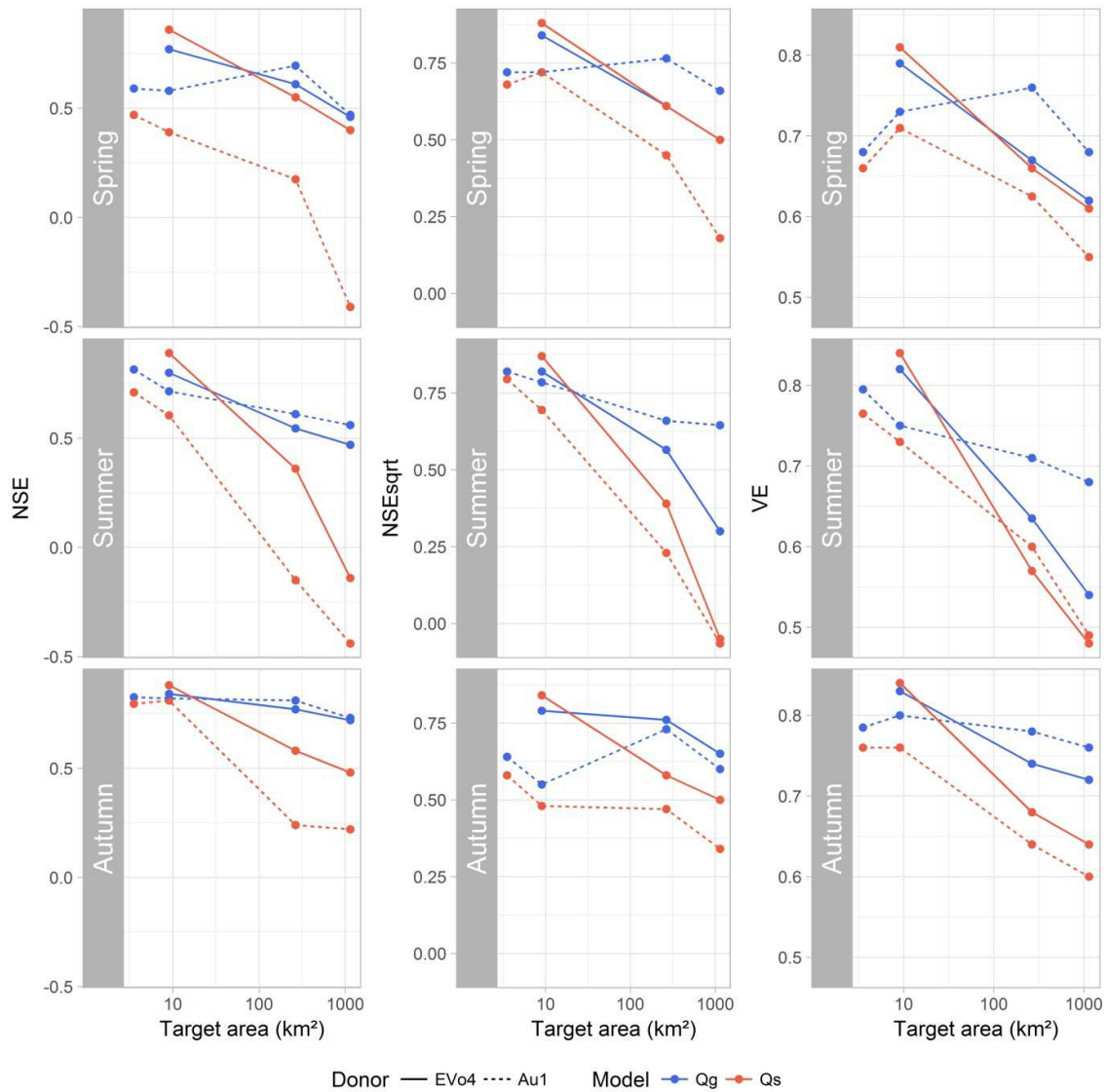


324

325 **Figure 5. Observed discharge vs. discharge simulated by geomorphology-based transposition (Q_g) or specific-discharge**
 326 **transposition (Q_s) of two small neighbours from the Montmorency catchments: (a) EVo4→Au4 and (b) Au4→EVo4 in**
 327 **2013 and their goodness-of-fit metrics – Nash Sutcliffe Efficiency (NSE), NSE calculated for the square root of discharge**
 328 **(NSE_{sqrt}), and Volumetric Efficiency (VE) – in spring, summer, and autumn.**

329 Within the Montmorency catchment, both heterogeneous catchments Au1 and EVo4 were
 330 transposed to downstream nested catchments (summarized in Figure 6). Regardless of season and
 331 the metric, as target size increased, specific-discharge transposition increasingly failed. Conversely,
 332 for geomorphology-based transposition, although the same decrease was visible in summer,
 333 transposition quality remained stable (autumn) or increased at first and then decreased (spring).

334 Transposition quality towards Au4 and EVo9 was similar for both methods, for which
 335 geomorphology-based transposition largely outperformed specific-discharge transposition. In
 336 addition, specific-discharge transposition from Au1 was always worse than that from Evo4. For
 337 geomorphology-based transposition, Au1 was worse than Evo4 for small catchments, but this
 338 behaviour reversed as target catchment size increased.



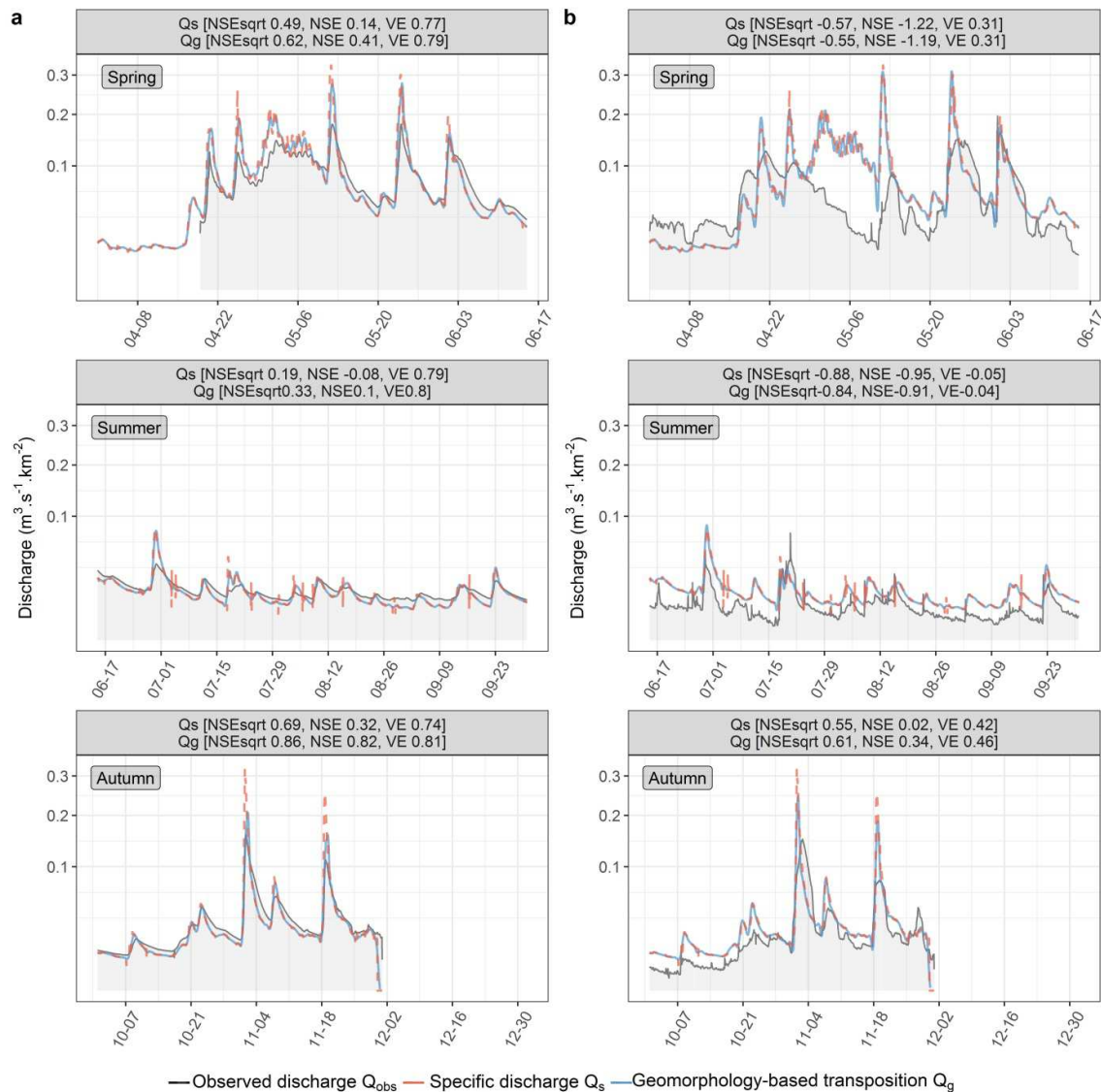
339

340 **Figure 6. Geomorphology-based transposition (Q_g) and specific-discharge transposition (Q_s) metrics – Nash Sutcliffe**
 341 **Efficiency (NSE), NSE calculated for the square root of discharge (NSE_{sqrt}), and Volumetric Efficiency (VE) – from two small**
 342 **neighbouring catchments, Au1 and EVo4, to downstream nested catchments Au4, Evo9, Mo265, and M1140. Each point**
 343 **corresponds to the median of interannual seasonal simulations.**

344 3.2.2. Between neighbouring catchments

345 Analysis then focused on the three largest neighbouring catchments studied (Mo1140, JCa1977, and
346 SCh366). From Mo1140 to JCa1977, geomorphology-based transposition outperformed specific-
347 discharge transposition according to all metrics (Fig. 7a). While the advantage was small according to
348 VE ("very good" for all seasons), it was large for NSE and NSE_{sqrt} (0.41/0.11/0.81 vs. 0.13/-0.08/0.32
349 and 0.62/0.33/0.82 vs. 0.48/0.19/0.66 for spring, summer, and autumn, respectively). Specific-
350 discharge transposition strongly overestimated observed discharge during freshet, while
351 geomorphology-based transposition reproduced peak flow better. In addition, metrics differed
352 greatly by season. Metrics of geomorphology-based transposition were "good" and "very good" in
353 spring and autumn, respectively, but "average" for NSE and NSE_{sqrt} in summer. However, volume was
354 well conserved, with "very good" VE values. The shape of the hydrograph was also reproduced well.
355 From Mo1140 to SCh366, strong differences appeared in the hydrographs, especially seasonal
356 behaviours (Fig. 7b). In 2013, Mo1140 discharged more intensively than SCh366, resulting in "poor"
357 or "average" VE for each season. Despite synchronicity in the shape of their hydrographs, particularly
358 visible for peak flows, volume was not simulated well. In addition, both geomorphology-based and
359 specific-discharge transposition overestimated discharge during the first 20 days of May. In spring,
360 Mo1140 flowed much more than SCh366, which must have been circumstantial (ie: depending on
361 certain circumstances, especially the initial states), and did so for the rest of the year, which must

362 have been a structural difference.



363

364 **Figure 7. Observed discharge vs. discharge simulated by geomorphology-based transposition (Q_g) or specific-discharge**
 365 **transposition (Q_s) of (a) Mo1140 to JCa1977 and (b) Mo1140 to Sch366 in 2013 and their goodness-of-fit metrics – Nash**
 366 **Sutcliffe Efficiency (NSE), NSE calculated for the square root of discharge (NSE_{sqrt}), and Volumetric Efficiency (VE) – in**
 367 **spring, summer, and autumn.**

368 3.3. Overall comparison of geomorphology-based transposed discharge (Q_g) and specific

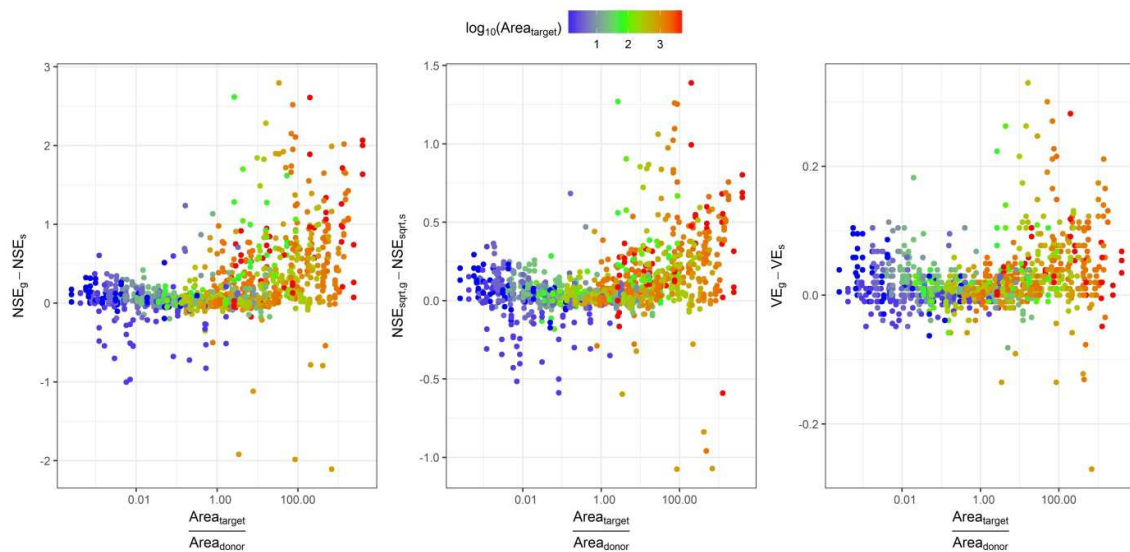
369 discharge (Q_s) hydrographs

370 A comparison of each metric for Q_g and Q_s as a function of the ratio of the surface area of the target

371 catchment to that of the donor catchment shows similar results among metrics, but greater

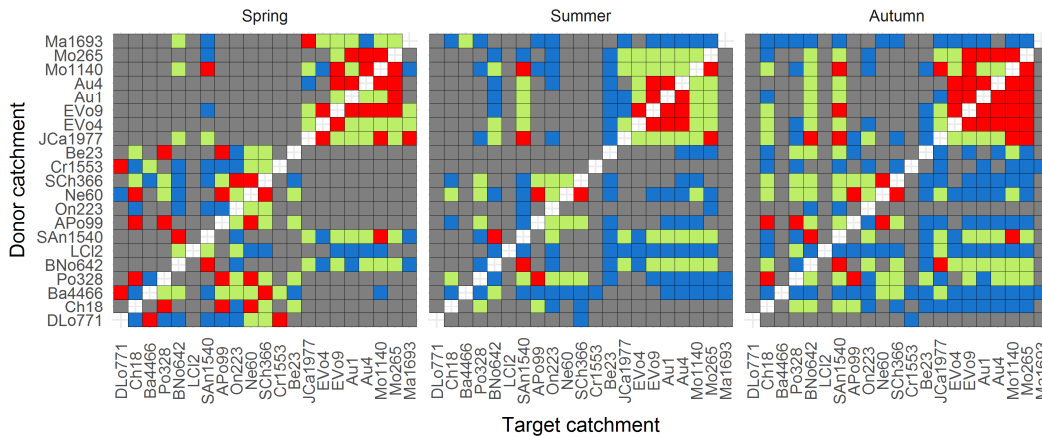
372 differences were observed for NSE (Fig. 8). Geomorphology-based transposition tended to yield

373 higher metric values than specific-discharge transposition, especially in the small→large direction
 374 (i.e. ratio > 1). In the large→small direction, results of the two approaches were more similar,
 375 although geomorphology-based transposition clearly had better results. Specific discharge
 376 transposition had the worst results in the large→small direction, but “poor” and erratic values were
 377 also obtained in the small→large direction. More similar results were observed for similarly sized
 378 donor and target catchments (ratio = 1). For NSE_{sqrt} and VE, a relationship in the form $y=x^2$ was
 379 observed, with a minimum at a surface area ratio close to 1.

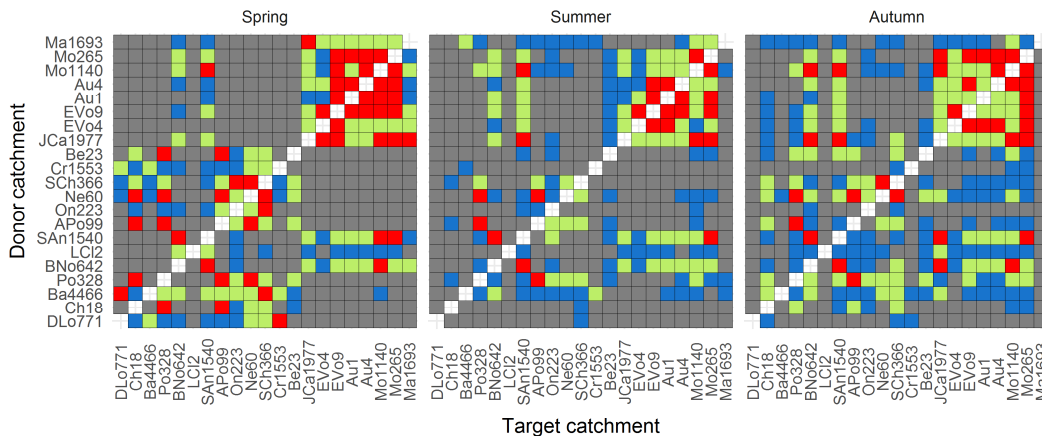


380
 381 **Figure 8. Differences in simulation metrics between geomorphology-based and specific-discharge transposition for all**
 382 **420 configurations as a function of the ratio of the surface area of the target catchment to that of the donor catchment.**
 383 **On the x-axis, ratios greater than 1 identify simulations in the small→large direction . The y-axis is log-modulus**
 384 **transformed to constrain the wide range of positive and negative values (John and Draper, 1980).**

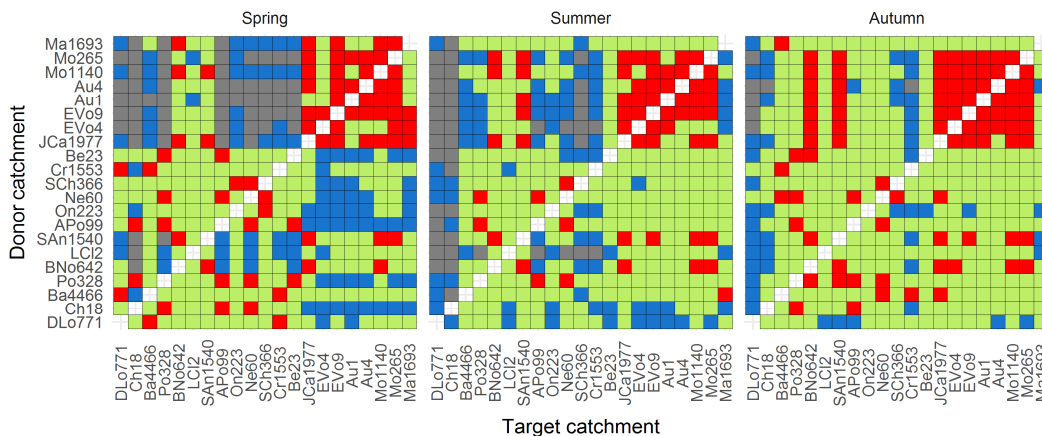
3.4. Overview of geographic quality of geomorphology-based transposition through heatmaps



NSE Poor Average Good Very good



NSE_{sqrt} Poor Average Good Very good



VE Poor Average Good Very good

386
387
388
389

Figure 9. Heatmaps of Nash Sutcliffe Efficiency (NSE), NSE calculated for the square root of discharge (NSE_{sqrt}), and Volumetric Efficiency (VE) metrics for all 420 configurations of catchment transposition for all seasons and criteria. Catchments on each axis are ordered as a function of the Ghosh distance from the most south-westerly catchment,

390 DLo771. Metrics are “poor” when <0, “average” when 0-0.33, “good” when 0.33-0.66, and “very good” when >0.66.
391 Numbers in catchment codes represent surface areas (km²).

392 According to the heatmaps, NSE was a more challenging metric than NSE_{sqrt} and VE (Fig. 9). The
393 volume of water (VE) was relatively homogeneous in the data set, unlike high flows (NSE). Most
394 NSE_{sqrt} quality classes were identical to those of NSE. Overall, most of the catchments conserved a
395 similar volume (VE), while the pattern of functioning/failing pairs remained nearly the same among
396 metrics.

397 The geographic ordering of the heatmaps revealed pairs of properly functioning geomorphology-
398 based transposition patterns that were consistent among metrics. The highest metrics were obtained
399 between Montmorency catchments (EVo4-9, Au1-4, Mo265-1140, and JCa1977) and those to the
400 west-north-west (BNo642, San1540 and LCl2, except Cr1553). Lower metrics were obtained between
401 Montmorency catchments and the most distant ones (Ba4466, DLo771, Ch18, Po328). Other “poor”
402 metrics were obtained between Montmorency catchments and coastal catchments along the Saint
403 Lawrence River (APo99, On223, Ne60, SCh366, and Be23). In any case, metrics were generally higher
404 when nearby catchments were transposed (Fig. 9).

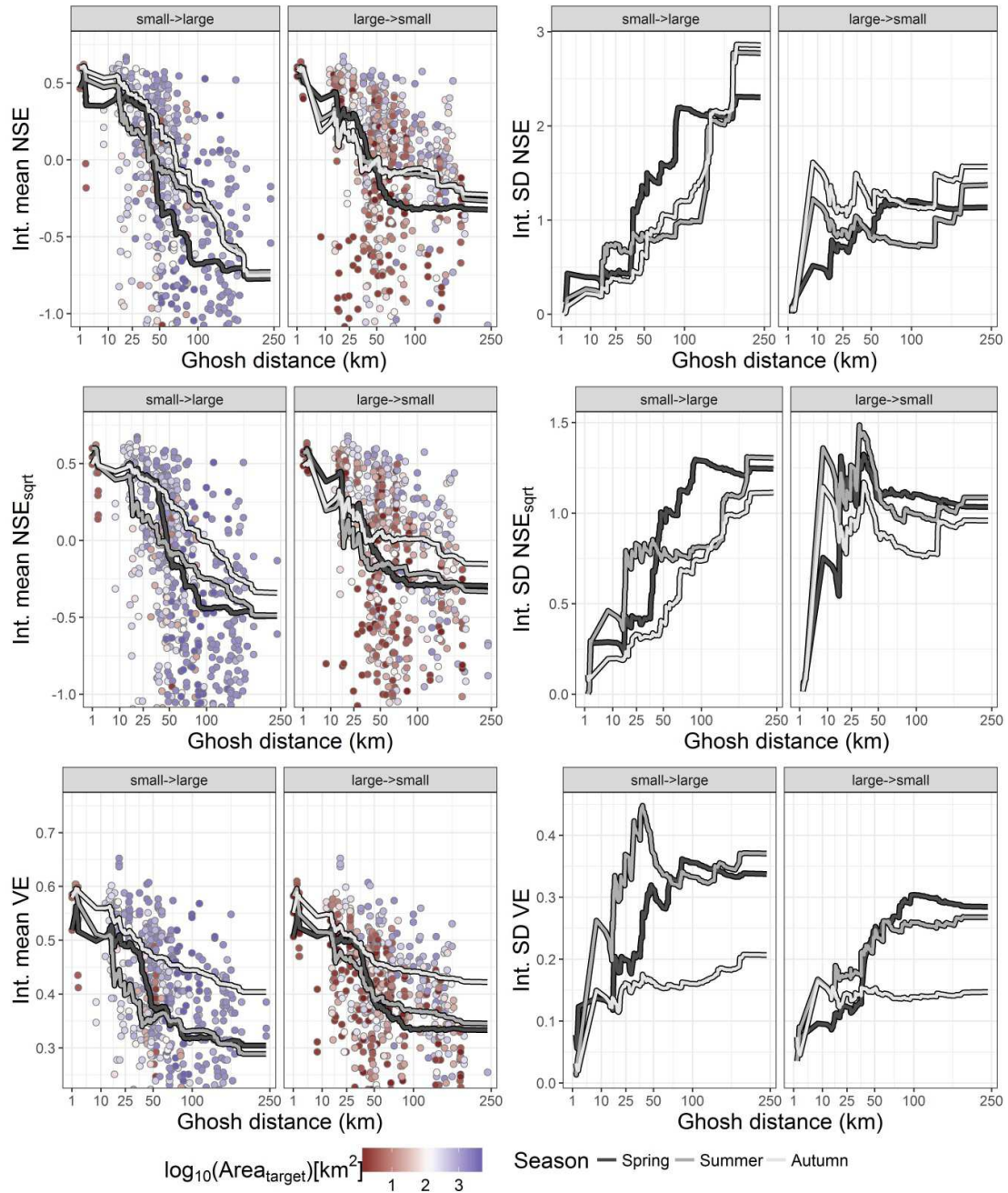
405 Patterns of similarity were observed among seasons. Spring had the most “very good” metrics,
406 followed by autumn and summer. Spring also had the most “poor” metrics, followed by summer and
407 autumn. In autumn, metrics values were generally more homogeneous over the entire catchment.

408 3.5. Ghosh distance analysis

409 A double effect on Ghosh distances appeared for both small→large and large→small transposition
410 directions, as the overall decrease was also affected by seasonality (Fig. 10). For all metrics and both
411 directions, as Ghosh distance increased, the integrative mean decreased. While the rate of decrease
412 was low up to a Ghosh distance of ca. 25 km, it increased substantially afterwards. The effect was
413 greater for the integrative SD. As Ghosh distance increased, the variability/range of the integrative
414 SD increased, but the pattern differed between directions. For large→small transposition, the
415 integrative SD tended to increase at a higher rate at shorter distances (<25 km), while for

416 small→large transposition, the integrative SD increased continuously. More generally, autumn, as
417 well as large→small transposition, had a more linear response.

418 None of the integrative mean metrics was “very good” at longer Ghosh distances; instead, they were
419 restricted to a specific maximum value that decreased with Ghosh distance. Beyond ca. 100 km, the
420 integrative mean of metrics rarely reached “good” or “average” values for small→large transposition.
421 For large→small transposition, this threshold increased to ca. 150 km. Variability (via the integrative
422 SD) also differed, revealing strong seasonal heterogeneities. For instance, in the small→large
423 direction, integrative means were generally higher and decreased more slowly in autumn than in
424 summer or spring. In the opposite direction, the spring integrative mean was higher than that in
425 autumn, except for VE, and this trend reversed itself beyond 50 km. A similar pattern was observed
426 for all metrics: while autumn was almost always better, summer outperformed spring, except from
427 20-50 km. In summer, and less so in autumn, the integrative SD was generally higher at short Ghosh
428 distances (<25 km), then increased substantially. In spring, the integrative SD increased slowly up to
429 40 km before reaching the highest values among all seasons. This was particularly visible in the
430 small→large direction. For both directions, the relationship between the integrative mean and Ghosh
431 distance was similar among metrics, with stability until 20 km, followed by a decrease. For both
432 directions, integrative mean VE was highest in autumn. This was also supported by the smaller
433 increase in the integrative SD of VE. The integrative SD and mean of NSE curves each had similar
434 shape in autumn and summer, especially in the large→small direction. More generally, the
435 integrative SD increased more slowly in the large→small than small→large direction. In addition, the
436 worst values in the large→small direction occurred for the smallest target catchments, especially for
437 NSE and NSE_{sqr} .



438

439 **Figure 10. Assessing geomorphology-based transposition as a function of donor-target distance (Ghosh), according to (a)**
 440 **Nash-Sutcliffe Efficiency (NSE), (b) NSE of the square root of discharge (NSE_{sqrt}), and (c) Volumetric Efficiency (VE) for**
 441 **spring, summer and autumn and by directions of transposition by catchment area. For each metric, the two left graphs**
 442 **represent simulations from smaller to larger catchments (small→large), while the two right graphs represent the inverse**
 443 **(large→small). The integrative mean axis is log-modulus transformed (John and Draper, 1980).**

444

445 4. Discussion

446 4.1. Performance in a new hydrological context

447 Several findings emerge from these results, giving geomorphology-based transposition a net
448 advantage over specific-discharge transposition, used here as a reference method for spatial
449 transposition of hydrographs. Geomorphology-based transposition uses structural information of the
450 stream network to construct a realistic transfer function most likely to distribute net rainfall
451 accurately in time. As a major parameter of this approach, stream characteristic velocities were
452 stable across seasons in each catchment. River flow velocity depends essentially on the morphology
453 and physical properties of the stream network, which are structural. Stability is also consistent with
454 the intrinsic conceptualization of the geomorphology-based framework, including the articulation
455 between hillslopes and the river network. The velocity considered refers to water dynamics across a
456 river network; they are related to non-seasonal river hydraulics and not to water dynamics across the
457 hillslope, which are much more season- and event-dependent.

458 Simulations were evaluated using three metrics: NSE, NSE_{sqrtr} and VE. Overall, for 420 pairs and three
459 seasons, the 1260 simulations ranged from (first to third quartiles) -0.87 to 0.35, -0.89 to 0.34, and
460 0.32 to 0.6 for NSE, NSE_{sqrtr} and VE, respectively. In Tunisia, Boudhraâ et al. (2009) used four
461 neighbouring catchments (3.16-192 km²) in a one-to-one approach. Based on two hydrological
462 events following a convective storm, NSE ranged from 0.82-0.99. The dominance of Hortonian runoff
463 led to excellent performance values. For six catchments in Brittany (4.9-316 km²), also using a one-to-
464 one approach, de Lavenne (2013) obtained NSE of 0.01-0.90 at the annual scale. In another study, de
465 Lavenne et al. (2016) estimated mean net rainfall of the target catchment from the five closest Ghosh
466 donors and then convoluted. Evaluation at the interannual scale (>3 years simulated) yielded first
467 and third quartiles of NSE equal to 0.55 and 0.86, respectively.

468

469 4.2. Structural similarity

470 Hydrographs of Q_g and Q_s showed infra-seasonal heterogeneity depending on the pair of catchments
471 studied. The first example of catchments Mo1140 and Mo265 illustrated classic nesting of two meso-
472 scale catchments with apparent similarity in geography and hydroclimate. This is consistent with the
473 “very good” results obtained for both Q_g and Q_s , despite non-negligible error in 2013 autumnal
474 floods. Mo1140 aggregates many sub-catchments, such as EVo4 and Au4 that function differently
475 despite proximity and similarities in geography and hydroclimate. Discharge inverted in spring and
476 summer, with Au4 flowing strongly when snowmelt began, while EVo4 started flowing later. During
477 summer, however, EVo4 flowed more strongly than Au4, suggesting a difference in hydrological
478 behaviour or delayed snowmelt. This simple desynchronization may be smoothed by ensemble
479 modelling of two spatially closed catchments with equal weights. There was a clear difference in
480 runoff generation between EVo4 and Au4 despite their proximity and apparent similarity.

481 Catchments Au1, Au4, and EVo4 have 38%, 70% and 82% of forested land, respectively, but also 62%,
482 25% and 16% of timberland, respectively (Table 1). Following the general assumption of a
483 Representative Elementary Area of 1-15 km² (Blöschl et al., 1995; Fan and Bras, 1995; Wood et al.,
484 1988), the heterogeneity of hillslope topography, geography, and hydrological conditions may
485 question the representativeness of catchments such as Au1, Au4, and EVo4 even though they belong
486 to an apparently homogeneous region. This observation is transposable to Mo1140: heterogeneous
487 low-level behaviours resulted in different responses of the two nested catchments. Interestingly,
488 there was a difference between specific-discharge and geomorphology-based transposition from Au1
489 and EVo4 to downstream catchments. EVo4 was initially more representative of downstream
490 catchments but became less so as target size increased. This pattern reveals the structural evolution
491 of the catchment and the associated hydrological signature from *a priori* similar hydrological sub-
492 units.

493 Between neighbours, the lack of nested similarity between upstream-downstream hydrological
494 responses rendered transposition more difficult. This was seen in transposed hydrographs for
495 Mo1140 to JCa1977 and Mo1140 to SCh366, both of which had lower metric values and large

496 variations across seasons. However, JCa1977 and SCh366 clearly differed, the former flowing like
497 Mo1140, while the later was not synchronized and showed substantial bias in water volume (via VE).
498 JCa1977 was more similar to Mo1140 in many respects (Table 1). SCh366 lies more to the south and
499 yet remains in the calcareous Saint Lawrence Plateau, unlike Mo1140, which drains the Grenvillien
500 bedrock further to the north. The calcareous bedrock may modify groundwater-river exchange and
501 increase infiltration, unlike the Grenvillien, which increases surface runoff. In addition, the Saint
502 Charles River drains 18.9% of artificial area vs. 2.4% for the Montmorency River, which significantly
503 modifies hydrological processes (Table 1). The large difference observed in spring may result from
504 snowpack, which is deeper in the Montmorency catchment. This is a good example of a spatially
505 close pair of catchments for which hydrograph transposition fails because of differences in the input
506 (snowpack and rainfall quantity, and hence net rainfall) and/or geography.

507 4.3. Circumstantial component

508 Heatmaps were used to identify a structural effect (transposition pairs functioning or failing) and a
509 supplementary circumstantial effect. The former was observed in the relative similarity of
510 functioning and failing pairs among heatmaps; however, differences appeared among seasons. For
511 instance, most transpositions between catchments DLo771, La Chevrotière (Ch18), and Croche
512 (Cr1553) failed regardless of the season and metric because of structural dissimilarities. For instance,
513 metric values were more homogeneous and transposition failed less in autumn. Volume was
514 generally reproduced well (VE) due to spatially homogeneous climatic forcing. Water flow dynamics
515 varied greatly (NSE and NSE_{sqrt}), due more to different dominant flow paths or net rainfall variability
516 at the event scale. Spring is dominated by snowmelt on saturated or frozen soils. Production
517 processes from hillslopes are more homogeneous and mainly physically oriented (no biological
518 activities), despite distances between catchments, increasing conservation of water balance in early
519 spring, but a decorrelation during the transition to summer. This was visible in the large number of
520 both “very good” and “poor” metrics. Summer accentuates heterogeneous behaviours, but

521 transposition remains a valid option between geographically close catchments. Summer is dominated
522 by low flows without many hydrological peaks; performance is thus determined mostly by base flow
523 discharges. During this period, metrics were more homogeneous than in spring, but only a few were
524 “very good”. In autumn, following rewetting of soils and longer hydrological events, metric values
525 were generally higher, implying a tendency to return to spatial homogeneity.

526 4.4. Evidence of structural and circumstantial similarities through Ghosh distance analysis

527 Hydrograph transposition between a pair of catchments functions when both experience a
528 simultaneous net rainfall event. Transposition between north-eastern and south-western catchments
529 failed because the longer distances decreased the physical significance of net rainfall between
530 catchments. Transposition between northern catchments (Mo1140, Mo265, Au1, Au4, EVo4, EVo9,
531 SAn1540, BNo642, and JCa1977) and southern ones flowing into the Saint Lawrence (APo99, On223,
532 Ne60, SCh366, and Be23) also failed, as seen between Mo1140 and SCh366. These results reveal that
533 the distance between the catchments to be transposed should be kept in mind. In this study, this
534 distance effect was assessed using the Ghosh distance. The study area has a climatic gradient from
535 catchments in the north-east (Montmorency) (higher precipitation and elevation, lower
536 temperature) to those in the south-west (lower precipitation and elevation, higher temperature).
537 Hydrograph transposition was influenced by this gradient, which increases with distance. Hydrology
538 is driven by snowmelt and synoptic events in spring, by convective events in summer, and by
539 synoptic events again in autumn. The flow signal resulting from these types of climatic forcing is
540 derived directly from the net rainfall entering the stream network, which is the variable used for
541 geomorphology-based transposition. During snowmelt, net rainfall is produced mainly by overland
542 flow after an increase in net radiation and air temperature (Dunne and Black, 1971; Kane and Stein,
543 1983). Net radiation depends greatly on catchment morphology and orientation, resulting in
544 heterogeneous behaviours at the daily scale. Conversely, air temperature can be the same over a
545 large area, resulting in homogeneous snowmelt at the catchment scale, especially at similar latitudes.

546 Overall, assuming similar snowpack among catchments, net rainfall should follow the assumption of
547 spatial homogeneity more closely in spring, leading to better transposition of hydrographs and
548 volume conservation. However, for longer distances, differing snowpack and snowmelt rates lead to
549 heterogeneity in hydrograph transposition, as illustrated by Mo1140 to SCh366. During the transition
550 between spring and summer, heterogeneous metric values appeared, especially for longer distances,
551 because of different snowpack depths, as illustrated by large heterogeneities in heatmap zones. In
552 summer, hillslopes are disconnected from groundwater, the latter sustaining base flow in the stream.
553 Convective events such as storms are highly heterogeneous in space and time; consequently, soil
554 moisture and water levels in hydrological compartments (i.e. groundwater, hillslope, and riparian
555 areas) may differ greatly between catchments, producing different amounts of net rainfall at the
556 event scale. Because of the assumption of spatially homogeneous net rainfall, hydrograph
557 transposition may be more difficult in summer than in spring (with its freshet). However, this effect
558 has much less influence in Québec than in the Tunisian semi-arid context previously explored.
559 Indeed, Hortonian overflow is the dominant process involved in runoff in Tunisia; hence, net rainfall
560 time series there closely follow the space-time variability in rainfall, which can be high for convective
561 events. Dominant flow paths evolve according to hydrological conditions and rainfall intensity. In a
562 natural catchment and during intense rainfall, net rainfall is dominated more by the rainfall itself and
563 may be more homogeneous over short distances. It may also explain the strong decrease in metric
564 values in summer and the sudden increase in variability in VE beyond 40 km. Autumn is characterized
565 by inversion of the water balance and progressive rewetting and filling of hydrological
566 compartments, as well as synoptic events. As a consequence, the circumstantial effect is limited,
567 failing pairs resulting from a structural difference in the production of net rainfall.

568 Above all, the size effect was larger than these seasonal and physical distance effects. Runoff
569 discharge at the outlet results from integration of upstream variability in hydrological processes and
570 geography, but larger catchments also benefit from a wider spectrum of hydroclimate signals.
571 Consequently, discharge at the outlet represents more the mean of several hydroclimates and may

572 be more robust for transposition (both geomorphology-based and specific-discharge). Theoretically,
573 the larger the donor catchment, the more distant the target catchment can be, as observed from the
574 integrative metrics. Small→large transposition provides better results at short distances but
575 decreases strongly at longer distances. In contrast, large→small transposition provides worse results
576 at short distances, but with a less steep decrease with increasing distance.

577 5. Conclusion

578 This study, conducted in a nivo-pluvial context, identified critical functioning points of
579 geomorphology-based inversion-transposition. Seasonality was identified as a major component of
580 the effectiveness of transposition in Québec, Canada, highlighting variability in dominant flow paths
581 in the resulting transposed net rainfall between pairs of catchments. Several pairs always
582 experienced functioning or failing transposition, regardless of the metric or season, revealing
583 structural differences between catchments. In addition, the Ghosh distance explained decreases in
584 values of all metrics, with heterogeneities according to season, adding a circumstantial component
585 to the previous structural one. Overall, either direction of geomorphology-based transposition
586 (small→large or large→small) yielded better results than specific-discharge transposition, with the
587 best results from small→large catchments. This confirms, like similar studies in two other
588 hydrological regimes, the flexibility and realism of the geomorphology-based transposition approach
589 to PUB.

590 **References**

- 591 Aouissi, J., Pouget, J.-C., Boudhraâ, H., Storer, G., Cudennec, C., 2013. Joint spatial, topological and
 592 scaling analysis framework of river-network geomorphometry. *Géomorphol.*, 19(1): 7-16.
 593 <https://doi.org/10.4000/geomorphologie.10082>
- 594 Archfield, S.A., Vogel, R.M., 2010. Map correlation method: Selection of a reference streamgage to
 595 estimate daily streamflow at ungauged catchments. *Water Resour. Res.*, 46(10).
 596 <https://doi.org/10.1029/2009wr008481>
- 597 Beven, K., Wood, E.F., 1993. Flow routing and the hydrological response of channel networks.
 598 *Channel Netw. Hydrol.*, Chichester, 99-128 p. <https://doi.org/10.1080/02626667909491869>
- 599 Blöschl, G., Grayson, R.B., Sivapalan, M., 1995. On the representative elementary area (REA) concept
 600 and its utility for distributed rainfall-runoff modelling. *Hydrol. Process.*, 9(3-4): 313-330.
 601 <https://doi.org/10.1002/hyp.3360090307>
- 602 Blöschl, G., Sivapalan, M., 1995. Scale issues in hydrological modelling: A review. *Hydrol. Process.*,
 603 9(3-4): 251-290. <https://doi.org/10.1002/hyp.3360090305>
- 604 Blöschl, G., Sivapalan, M., Wagener, T., Viglione, A., Savenije, H., 2013. *Runoff Prediction in*
 605 *Ungauged Basins: Synthesis across Processes, Places and Scales.* Cambridge University Press,
 606 Cambridge, 484 p. <https://doi.org/DOI:10.1017/CBO9781139235761>
- 607 Boudhraâ, H., Cudennec, C., Andrieu, H., Slimani, M., 2018. Net rainfall estimation by the inversion of
 608 a geomorphology-based transfer function and discharge deconvolution. *Hydrol. Sci. J.*, 63(2):
 609 285-301. <https://doi.org/10.1080/02626667.2018.1425801>
- 610 Boudhraâ, H., Cudennec, C., Slimani, M., Andrieu, H., 2006. Inversion of geomorphology-based unit
 611 hydrograph model: Physical interpretation and first implementation. *IAHS Publ.*, 303: 391-
 612 399.
- 613 Boudhraâ, H., Cudennec, C., Slimani, M., Andrieu, H., 2009. Hydrograph transposition between basins
 614 through a geomorphology-based deconvolution-reconvolution approach. *IAHS Publ.*, 333: 76-
 615 83.
- 616 Bull, L.J., Kirkby, M.J., 2002. *Channel heads and channel extension.* Hydrology and Geomorphology of
 617 Semi-Arid Channels, Chichester, 263-287 p. <https://doi.org/10.1007/s11069-010-9598-2>
- 618 Chargui, S., Slimani, M., Cudennec, C., 2013. Statistical distribution of rainy events characteristics and
 619 instantaneous hyetographs generation (Merguellil watershed in central Tunisia). *Arab. J.*
 620 *Geosci.*, 6(5): 1581-1590. <https://doi.org/10.1007/s12517-011-0440-2>
- 621 Criss, R.E., Winston, W.E., 2008. Do Nash values have value? Discussion and alternate proposals.
 622 *Hydrol. Process.*, 22(14): 2723-2725. <https://doi.org/10.1002/hyp.7072>
- 623 Cudennec, C., 2000. Description mathématique de l'organisation du réseau hydrographique et
 624 modélisation hydrologique. Ph.D. thesis, Ecole Nationale Supérieure Agronomique de
 625 Rennes, Rennes, France, 262 p.
- 626 Cudennec, C., 2007. On width function-based unit hydrographs deduced from separately random
 627 self-similar river networks and rainfall variability: Discussion of "Coding random self-similar
 628 river networks and calculating geometric distances: 1. General methodology" and "2.
 629 Application to runoff simulations". *Hydrol. Sci. J.*, 52(1): 230-237.
 630 <https://doi.org/10.1623/hysj.52.1.230>
- 631 Cudennec, C., Fouad, Y., Sumarjo Gatot, I., Duchesne, J., 2004. A geomorphological explanation of the
 632 unit hydrograph concept. *Hydrol. Process.*, 18(4): 603-621. <https://doi.org/10.1002/hyp.1368>
- 633 Cudennec, C., Gelfan, A., Ren, L., Slimani, M., 2016. Hydrometeorology and Hydroclimate. *Adv.*
 634 *Meteorol.*, 2016: 1-4. <https://doi.org/10.1155/2016/1487890>
- 635 Cudennec, C., Slimani, M., Goulven, P., 2005. Accounting for sparsely observed rainfall space—time
 636 variability in a rainfall—runoff model of a semiarid Tunisian basin. *Hydrol. Sci. J.*, 50(4): 617-
 637 630. <https://doi.org/10.1623/hysj.2005.50.4.617>

638 de Lavenne, A., 2013. Modélisation hydrologique à base géomorphologique de bassins versants non
639 jaugés par régionalisation et transposition d'hydrogramme. Ph.D. thesis, Agrocampus Ouest,
640 Rennes, France, 226 p.

641 de Lavenne, A., Boudhraâ, H., Cudennec, C., 2015. Streamflow prediction in ungauged basins through
642 geomorphology-based hydrograph transposition. *Hydrol. Res.*, 46(2): 291.
643 <https://doi.org/10.2166/nh.2013.099>

644 de Lavenne, A., Cudennec, C., 2014. Prediction of streamflow from the set of basins flowing into a
645 coastal bay. *PIAHS*, 365: 55-60. <https://doi.org/10.5194/piahs-365-55-2015>

646 de Lavenne, A., Skøien, J.O., Cudennec, C., Curie, F., Moatar, F., 2016. Transferring measured
647 discharge time series: Large-scale comparison of Top-kriging to geomorphology-based
648 inverse modeling. *Water Resour. Res.*, 52(7): 5555-5576.
649 <https://doi.org/10.1002/2016wr018716>

650 Dunne, T., Black, R.D., 1971. Runoff Processes during Snowmelt. *Water Resour. Res.*, 7(5): 1160-1172.
651 <https://doi.org/10.1029/WR007i005p01160>

652 Fan, Y., Bras, R.L., 1995. On the concept of a representative elementary area in catchment runoff.
653 *Hydrol. Process.*, 9(7): 821-832. <https://doi.org/10.1002/hyp.3360090708>

654 Feki, H., Slimani, M., Cudennec, C., 2012. Incorporating elevation in rainfall interpolation in Tunisia
655 using geostatistical methods. *Hydrol. Sci. J.*, 57(7): 1294-1314.
656 <https://doi.org/10.1080/02626667.2012.710334>

657 Formetta, G., Mantilla, R., Franceschi, S., Antonello, A., Rigon, R., 2011. The JGrass-NewAge system
658 for forecasting and managing the hydrological budgets at the basin scale: models of flow
659 generation and propagation/routing. *Geoscientific Model Dev.*, 4(4): 943-955.
660 <https://doi.org/10.5194/gmd-4-943-2011>

661 Franchini, M., O'Connell, P.E., 1996. An analysis of the dynamic component of the geomorphologic
662 instantaneous unit hydrograph. *J. Hydrol.*, 175(1-4): 407-428. [https://doi.org/10.1016/S0022-1694\(96\)80018-7](https://doi.org/10.1016/S0022-1694(96)80018-7)

663

664 Ghosh, B., 1951. Random distances within a rectangle and between two rectangles. *Calcutta Math.*
665 *Soc.*, 43(1): 17-24.

666 Gianfagna, C.C., Johnson, C.E., Chandler, D.G., Hofmann, C., 2015. Watershed area ratio accurately
667 predicts daily streamflow in nested catchments in the Catskills, New York. *J. Hydrol.: Reg.*
668 *Stud.*, 4: 583-594. <https://doi.org/10.1016/j.ejrh.2015.09.002>

669 Grimaldi, S., Petroselli, A., Nardi, F., 2012. A parsimonious geomorphological unit hydrograph for
670 rainfall-runoff modelling in small ungauged basins. *Hydrol. Sci. J.*, 57(1): 73-83.
671 <https://doi.org/10.1080/02626667.2011.636045>

672 Gupta, V.K., Mesa, O.J., 1988. Runoff generation and hydrologic response via channel network
673 geomorphology—Recent progress and open problems. *J. Hydrol.*, 102(1-4): 3-28.
674 [https://doi.org/10.1016/0022-1694\(88\)90089-3](https://doi.org/10.1016/0022-1694(88)90089-3)

675 Guttman, L.A., 1950. The basis for scalogram analysis. *Measurement and prediction*, 4: 60-90.

676 Hrachowitz, M., Savenije, H., Bogaard, T.A., Tetzlaff, D., Soulsby, C., 2013a. What can flux tracking
677 teach us about water age distribution patterns and their temporal dynamics? *Hydrol. Earth*
678 *Syst. Sci.*, 17(2): 533-564. <https://doi.org/10.5194/hess-17-533-2013>

679 Hrachowitz, M., Savenije, H.H.G., Blöschl, G., McDonnell, J.J., Sivapalan, M., Pomeroy, J.W., Arheimer,
680 B., Blume, T., Clark, M.P., Ehret, U., Fenicia, F., Freer, J.E., Gelfan, A., Gupta, H.V., Hughes,
681 D.A., Hut, R.W., Montanari, A., Pande, S., Tetzlaff, D., Troch, P.A., Uhlenbrook, S., Wagener,
682 T., Winsemius, H.C., Woods, R.A., Zehe, E., Cudennec, C., 2013b. A decade of Predictions in
683 Ungauged Basins (PUB)—a review. *Hydrol. Sci. J.*, 58(6): 1198-1255.
684 <https://doi.org/10.1080/02626667.2013.803183>

685 John, J.A., Draper, N.R., 1980. An Alternative Family of Transformations. *Journal of the Royal*
686 *Statistical Society. Series C (Applied Statistics)*, 29(2): 190-197.
687 <https://doi.org/10.2307/2986305>

688 Kane, D.L., Stein, J., 1983. Water movement into seasonally frozen soils. *Water Resour. Res.*, 19(6):
689 1547-1557. <https://doi.org/10.1029/WR019i006p01547>

690 Karlsen, R.H., Seibert, J., Grabs, T., Laudon, H., Blomkvist, P., Bishop, K., 2016. The assumption of
691 uniform specific discharge: unsafe at any time? *Hydrol. Process.*, 30(21): 3978-3988.
692 <https://doi.org/10.1002/hyp.10877>

693 Kingumbi, A., Bargaoui, Z., Hubert, P., 2005. Investigation of the rainfall variability in central Tunisia.
694 *Hydrol. Sci. J.*, 50(3). <https://doi.org/10.1623/hysj.50.3.493.65027>

695 Kirkby, M., 1976. Tests of the random network model, and its application to basin hydrology. *Earth
696 Surf. Process.*, 1(3): 197-212. <https://doi.org/10.1002/esp.3290010302>

697 Lacombe, G., Cappelaere, B., Leduc, C., 2008. Hydrological impact of water and soil conservation
698 works in the Merguellil catchment of central Tunisia. *J. Hydrol.*, 359(3-4): 210-224.
699 <https://doi.org/10.1016/j.jhydrol.2008.07.001>

700 McMillan, H., Westerberg, I., Branger, F., 2017. Five guidelines for selecting hydrological signatures.
701 *Hydrol. Process.*, 31(26): 4757-4761. <https://doi.org/10.1002/hyp.11300>

702 MDDELCC, DEB, 2018. Cadre écologique de référence du Québec (CERQ) [Données numériques
703 vectorielles]. In: Québec, G.d. (Ed.). Gouvernement du Québec.

704 Menke, W., 1989. Geophysical data analysis: Discrete inverse theory. Academic press, INC. Harcourt
705 Brace Jovanovich Ed., 45. <https://doi.org/10.1016/C2011-0-69765-0>

706 Merheb, M., Moussa, R., Abdallah, C., Colin, F., Perrin, C., Baghdadi, N., 2016. Hydrological response
707 characteristics of Mediterranean catchments at different time scales: a meta-analysis.
708 *Hydrol. Sci. J.*, 61(14): 2520-2539. <https://doi.org/10.1080/02626667.2016.1140174>

709 Muleta, M.K., 2012. A Formal, Bayesian Approach for Uncertainty Analysis of a Watershed Model. In:
710 Engineers, A.S.o.C. (Ed.), *World Environ. Water Resour. Congr. 2012. Proceedings.*
711 <https://doi.org/10.1061/9780784412312.375>

712 Nash, J.E., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models part I — A
713 discussion of principles. *J. Hydrol.*, 10(3): 282-290. [https://doi.org/10.1016/0022-1694\(70\)90255-6](https://doi.org/10.1016/0022-1694(70)90255-6)

714

715 Nasri, S., Albergel, J., Cudennec, C., Berndtsson, R., 2004a. Hydrological processes in macrocatchment
716 water harvesting in the arid region of Tunisia: the traditional system of tabias. *Hydrol. Sci. J.*,
717 49(2). <https://doi.org/10.1623/hysj.49.2.261.34838>

718 Nasri, S., Cudennec, C., Albergel, J., Berndtsson, R., 2004b. Use of a geomorphological transfer
719 function to model design floods in small hillside catchments in semiarid Tunisia. *J. Hydrol.*,
720 287(1): 197-213. <https://doi.org/10.1016/j.jhydrol.2003.10.001>

721 Ogilvie, A., Belaud, G., Massuel, S., Mulligan, M., Le Goulven, P., Calvez, R., 2018. Surface water
722 monitoring in small water bodies: potential and limits of multi-sensor Landsat time series.
723 *Hydrol. Earth Syst. Sci.*, 2018: 1-35. <https://doi.org/10.5194/hess-2018-19>

724 Ogilvie, A., Le Goulven, P., Leduc, C., Calvez, R., Mulligan, M., 2016. Hydrological response of a semi-
725 arid catchment to rainfall events and water and soil conservation works (Merguellil
726 catchment, central Tunisia). *Hydrol. Sci. J.*, 61(2): 441-453.
727 <https://doi.org/10.1080/02626667.2014.934249>

728 Oudin, L., Andréassian, V., Mathevet, T., Perrin, C., Michel, C., 2006. Dynamic averaging of rainfall-
729 runoff model simulations from complementary model parameterizations. *Water Resour.*
730 *Res.*, 42(7). <https://doi.org/10.1029/2005wr004636>

731 Parajka, J., Viglione, A., Rogger, M., Salinas, J.L., Sivapalan, M., Blöschl, G., 2013. Comparative
732 assessment of predictions in ungauged basins - Part 1: Runoff-hydrograph studies. *Hydrol.*
733 *Earth Syst. Sci.*, 17(5): 1783-1795. <https://doi.org/10.5194/hess-17-1783-2013>

734 Pomeroy, J., Spence, C., Whitfield, P., 2013. Putting prediction in ungauged basins into practice. *Can.*
735 *Water Resour. Assoc. Alberta*, 375 p.

736 R Development Core Team, 2017. R: A Language and Environment for Statistical Computing.

737 Rigon, R., Bancheri, M., Formetta, G., de Lavenne, A., 2016. The geomorphological unit hydrograph
738 from a historical-critical perspective. *Earth Surf. Process. Landf.*, 41(1): 27-37.
739 <https://doi.org/10.1002/esp.3855>

740 Robinson, J.S., Sivapalan, M., 1996. Instantaneous response functions of overland flow and
741 subsurface stormflow for catchment models. *Hydrol. Process.*, 10(6): 845-862.
742 [https://doi.org/10.1002/\(SICI\)1099-1085\(199606\)10:6<845::AID-HYP375>3.0.CO;2-7](https://doi.org/10.1002/(SICI)1099-1085(199606)10:6<845::AID-HYP375>3.0.CO;2-7)
743 Robinson, J.S., Sivapalan, M., Snell, J.D., 1995. On the relative roles of hillslope processes, channel
744 routing, and network geomorphology in the hydrologic response of natural catchments.
745 *Water Resour. Res.*, 31(12): 3089-3101. <https://doi.org/10.1029/95wr01948>
746 Rodríguez-Iturbe, I., Valdés, J.B., 1979. The geomorphologic structure of hydrologic response. *Water*
747 *Resour. Res.*, 15(6): 1409-1420. <https://doi.org/10.1029/WR015i006p01409>
748 Seiller, G., Roy, R., Anctil, F., 2017. Influence of three common calibration metrics on the diagnosis of
749 climate change impacts on water resources. *J. Hydrol.*, 547: 280-295.
750 <https://doi.org/10.1016/j.jhydrol.2017.02.004>
751 Sivakumar, B., 2007. Dominant processes concept, model simplification and classification framework
752 in catchment hydrology. *Stoch. Environ. Res. Risk Assess.*, 22(6): 737-748.
753 <https://doi.org/10.1007/s00477-007-0183-5>
754 Sivapalan, M., Takeuchi, K., Franks, S.W., Gupta, V.K., Karambiri, H., Lakshmi, V., Liang, X., McDonnell,
755 J.J., Mendiondo, E.M., O'Connell, P.E., Oki, T., Pomeroy, J.W., Schertzer, D., Uhlenbrook, S.,
756 Zehe, E., 2003. IAHS decade on Predictions in Ungauged Basins (PUB), 2003-2012: Shaping an
757 exciting future for the hydrological sciences. *Hydrol. Sci. J.*, 48(6): 857-880.
758 <https://doi.org/10.1623/hysj.48.6.857.51421>
759 Skøien, J.O., Blöschl, G., Laaha, G., Pebesma, E., Parajka, J., Viglione, A., 2014. rtop: An R package for
760 interpolation of data with a variable spatial support, with an example from river networks.
761 *Comput. & Geosci.*, 67: 180-190. <https://doi.org/10.1016/j.cageo.2014.02.009>
762 Skøien, J.O., Merz, R., Blöschl, G., 2006. Top-kriging - geostatistics on stream networks. *Hydrol. Earth*
763 *Syst. Sci.*, 10(2): 277-287. <https://doi.org/10.5194/hess-10-277-2006>
764 Sneath, P.H.A., 1957. The application of computers to taxonomy. *Microbiology*, 17(1): 201-226.
765 Snell, J.D., Sivapalan, M., 1994. On geomorphological dispersion in natural catchments and the
766 geomorphological unit hydrograph. *Water Resour. Res.*, 30(7): 2311-2323.
767 <https://doi.org/10.1029/94wr00537>
768 Spence, C., Whitfield, P.H., Pomeroy, J.W., Pietroniro, A., Burn, D.H., Peters, D.L., St-Hilaire, A., 2013.
769 A review of the Prediction in Ungauged Basins (PUB) decade in Canada. *Can. Water Resour.*
770 *J.*, 38(4): 253-262. <https://doi.org/10.1080/07011784.2013.843867>
771 Surkan, A.J., 1969. Synthetic hydrographs: effects of network geometry. *Water Resour. Res.*, 5(1):
772 112-128. <https://doi.org/10.1029/WR005i001p00112>
773 Tarantola, A., 1987. *Inverse Problem Theory: Methods for Data Fitting and Model Parameter*
774 *Estimation*. Elsevier, Amsterdam, 644 p.
775 Tarantola, A., Valette, B., 1982. Inverse problems= quest for information. *J. Geophys.*, 50(3): 150-170.
776 Tremblay, Y., Rousseau, A.N., Plamondon, A.P., Lévesque, D., Jutras, S., 2008. Rainfall peak flow
777 response to clearcutting 50% of three small watersheds in a boreal forest, Montmorency
778 Forest, Québec. *J. Hydrol.*, 352(1-2): 67-76. <https://doi.org/10.1016/j.jhydrol.2007.12.028>
779 Wang, C., Gupta, V.K., Waymire, E., 1981. A geomorphologic synthesis of nonlinearity in surface
780 runoff. *Water Resour. Res.*, 17(3): 545-554. <https://doi.org/10.1029/WR017i003p00545>
781 Wood, E.F., Sivapalan, M., Beven, K., Band, L., 1988. Effects of spatial variability and scale with
782 implications to hydrologic modeling. *J. Hydrol.*, 102(1-4): 29-47.
783 [https://doi.org/10.1016/0022-1694\(88\)90090-x](https://doi.org/10.1016/0022-1694(88)90090-x)
784 Woods, R., Sivapalan, M., 1999. A synthesis of space-time variability in storm response: Rainfall,
785 runoff generation, and routing. *Water Resour. Res.*, 35(8): 2469-2485.
786 <https://doi.org/10.1029/1999WR900014>

787