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1 A method for assessing the influence of rainfall spatial variability on hydrograph
2 modeling. First case study in the Cevennes Region, southern France

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10

11 **Abstract:**

12 Emmanuel *et al.* (2015) proposed rainfall variability indexes intended to summarize the influence of
13 spatial rainfall organization on hydrograph features at the catchment outlet. The present article shows
14 how the proposed indexes may be used in a real-world case study to analyze the influence of spatial
15 rainfall organization on hydrograph modeling. The selected case study is located in the Cevennes
16 Region of southeastern France. The proposed methodology is as follows: the tested flow events are
17 split into two subsets according to the values of their rainfall variability indexes; then, a comparison is
18 drawn between modeled and measured hydrographs separately for each subset. The results obtained
19 suggest that, on average, modeling results based on high-resolution rainfall data are improved for the
20 subset whose rainfall variability influence is expected to be significant according to index values.
21 Though limited to a relatively small number of hydrographs, this case study can be viewed as a first
22 confirmation that the proposed method, based on the rainfall variability indexes of Emmanuel *et al.*
23 (2015), is pertinent to investigating the influence of spatial rainfall variability on hydrograph modeling
24 results.

25 **Keywords:** Spatial rainfall variability, Radar, Spatial rainfall indexes, Hydrograph modeling.

26 **Highlights:**

27 We illustrate one use of rainfall variability indexes in real-world case studies

28 We perform a case-study based in France's Cevennes Region

29 Events were split into two subsets according to rainfall variability indexes

30 The indexes predict events for which high resolution rainfall improves outflow modeling.

31

32 1. Introduction

33 What is the actual influence of spatial rainfall variability on the hydrograph at the catchment outlet?
34 Interest in answering this question has been growing thanks to both the increasing availability of
35 weather radar data and the development of distributed hydrological models. This topic is relevant for
36 both research and practical reasons. On the research side, it contributes to a better understanding of
37 how the spatial variability of rainfall propagates up to the catchment outlet depending on catchment
38 features and, therefore, on the development of adapted modeling strategies. On the operational side,
39 hydrological systems managers would benefit from knowing the conditions under which spatially-
40 detailed knowledge of rainfall and the incorporation of this information into hydrological models may
41 lead to more accurate flood modeling results. Unfortunately, the literature on this topic has revealed
42 contrasting conclusions.

43 The following sample of studies, performed in various contexts and based on various approaches, has
44 concluded that the spatial variability of rainfall exerts a significant impact on modeling results at the
45 catchment outlet: Anquetin *et al.* (2010), Bedient *et al.* (2000), He *et al.* (2013), Looper and Vieux
46 (2012), Sangati *et al.* (2009), Sik Kim *et al.* (2008), Smith *et al.* (2007), Vieux *et al.* (2009), and
47 Zoccatelli *et al.* (2010). Other studies have ascribed a more limited influence to this spatial variability:
48 Adams *et al.* (2012), Brath *et al.* (2004), Cole and Moore (2008), Nicotina *et al.* (2008), Schuurmans
49 and Bierkens (2007), Smith *et al.* (2004), and Tarolli *et al.* (2013); whereas the following studies have
50 observed both influences: Pokhrel and Gupta (2011) confirmed the findings of Obled *et al.* (1994),
51 according to which the influence of the spatial variability of rainfall fields on hydrographs at the
52 catchment outlet can be greatly diminished by the damping effect of routing, thus making the
53 variability difficult to detect. On the basis of 181 French catchments, Lobligeois *et al.* (2014)
54 concluded that a detailed mapping of rainfall fields would be useful for hydrograph modeling in
55 southern France, a region characterized by rainfall fields with a high degree of spatial variability, but
56 not so useful in western France, where catchments are forced by rainfall fields with less spatial
57 variability. Segond *et al.* (2007) analyzed an extensive and detailed dataset from the 1,400-km² Lee
58 catchment in the U.K. (15 years of radar data, 16 rain gauges and 12 flow stations); they concluded

59 that "results show a complex picture", with the influence of spatial rainfall variability being
60 uncorrelated with either catchment scale or response time. In the field of urban hydrology, several
61 studies using different approaches have addressed the influence of spatial rainfall variability on the
62 rainfall runoff modeling of small catchments (i.e. approx. 10 km²); these studies have: proposed a
63 temporal and spatial rainfall resolution adapted to Mediterranean events (Berne *et al.*, 2004), and
64 analyzed both the influence of rainfall uncertainty (Schellart *et al.*, 2012) and the small-scale
65 variability of rainfall (Gires *et al.*, 2012). In sum, it appears that the influence of spatial rainfall
66 variability on hydrograph modeling results depends on a combination of factors, namely: rainfall
67 patterns, catchment characteristics, and runoff generation processes. This question remains an open
68 research subject.

69 The present paper contributes to assessing the influence of spatial rainfall variability on hydrograph
70 modeling results by pursuing the work developed in Emmanuel *et al.* (2015). Based on a simulation
71 approach, these authors identified the conditions under which the spatial variability of rainfall plays a
72 significant role, and they proposed indexes summarizing the influence of spatial rainfall organization
73 on modeled outflow. This paper illustrates how such indexes may be used in a real-world case study
74 for an in-depth analysis of the relation between spatial rainfall variability and modeling results; the
75 case study is situated in the Cevennes Region of southeastern France.

76 The article is organized as follows. Section 2 presents the methodology proposed to assess the
77 influence of spatial rainfall variability on modeling results. Section 3 exposes the Cevennes case study
78 selected to test this method. Next, Section 4 describes the results obtained, while Section 5 offers a
79 discussion of these results. Lastly, Section 6 provides a conclusion on this work.

80 **2. Methodology to identify the influence of spatial rainfall variability on hydrograph modeling**

81 Rainfall-runoff modeling (Renard *et al.*, 2010) is affected by four sources of error: a) errors in rainfall
82 estimates, b) errors in outflow estimates, c) imperfect representation of processes by hydrological
83 models, and d) a miscalibration of model parameters. The combination of these sources of error with
84 influential factors makes it difficult to isolate the influence of spatial rainfall variability, which

85 requires a specific approach. Moreover, it would be helpful for this approach to be applicable to a
86 wide variety of situations in terms of rainfall event features, catchment features and hydrological
87 modeling. Given this context, the following method is being proposed to identify the influence, and
88 this influence alone, of spatial rainfall variability on rainfall-runoff modeling (define as the outflow
89 modeling at the catchment outlet).

90 We consider a set of observed hydrographs, with this set being as broad as possible so as: i) to be
91 representative of varied catchments and rain conditions, and ii) to allow for a statistical analysis
92 differentiating the influence of spatial rainfall variability from the other sources of error.

93 - This set of observed hydrographs is studied by comparing two contrasted rainfall scenarios, i.e.: 1) a
94 fully spatially distributed rainfall assumed to represent the reference situation, and 2) a spatially
95 uniform rainfall equal to the mean value of rainfall over the catchment. The rainfall-runoff model with
96 these two scenarios yields two modeled hydrographs that can be compared to the observed
97 hydrograph, thus providing information on the influence of spatial rainfall variability.

98 - In order to isolate the influence of spatial rainfall variability from the other sources of error, the set of
99 observed hydrographs must be split into subsets as homogeneous as possible with regard to this
100 influence. In assuming that the statistical characteristics of sources of error (b), (c) and (d) are
101 independent of this influence, it is expected that the modeling results obtained on the subsets only
102 differ for rainfall variability reasons.

103 - The splitting of the hydrograph set is based on the rainfall variability indexes proposed by Emmanuel
104 *et al.* (2015); these indexes summarize the expected influence of spatial rainfall variability on the
105 catchment response. In addition, since the indexes have been defined from rainfall fields and
106 catchment characteristics, they are fully independent of the used model.

107 **2.1 Presentation of the rainfall variability indexes used**

108 Emmanuel *et al.* (2015) proposed rainfall spatial variability indexes specifically designed to detect
109 situations for which this variability could exert great influence on the catchment response. They

110 concluded that the proposed indexes offer a similar quantification of the impact of spatial rainfall
111 variability on hydrograph peak time as those developed by Zoccatelli *et al.* (2010, 2011), yet they
112 explain the impact on hydrograph magnitude slightly better.

113 These indexes are based on a comparison between the catchment width function and the rainfall width
114 function. The catchment width function $w(x)$, defined as the portion of the catchment area at a flow
115 distance x from the outlet (Rodríguez-Iturbe and Rinaldo, 1997), is representative of the spatial
116 structure of the catchment (and implicitly of the catchment response for a spatially homogeneous
117 rainfall). This function is intrinsic for a given catchment. The rainfall width function, denoted $w_p(x)$, is
118 defined as the proportion of rainfall on the catchment falling at a flow distance x from the outlet; it
119 combines information on spatial rainfall organization with catchment structure. The influence of
120 spatial rainfall organization on the hydrological response is assessed by comparing the two width
121 functions in their cumulative distribution form. As shown in Figure 1, the first index, denoted VG, is
122 defined as the absolute value of the maximum vertical difference between the two width functions.
123 The second index, denoted HG, is then defined as the corresponding difference between both width
124 functions divided by the length of the longest hydrological path of the catchment. VG values close to
125 zero indicate a rainfall distribution over the catchment displaying weak spatial variability. The higher
126 the VG value, the more concentrated the rainfall over a small part of the catchment. HG values close
127 to 0 reflect a rainfall distribution either concentrated near the catchment centroid position or spatially
128 homogenous. Values less (greater) than 0 indicate that rainfall is distributed downstream (upstream).

129 The rainfall accumulation period suitable for variability index computation must be determined.
130 Emmanuel *et al.* (2015) preconized computing the indexes on the raw rainfall accumulation observed
131 just before the hydrograph peak, i.e. between $[T_Q - \alpha Tr; T_Q]$, with Tr being the catchment response
132 time (usually defined as the time lag between the hydrograph and the hyetogram gravity centers), T_Q
133 the time of the hydrograph peak, and α lying in a [1.5 - 3] range with very low sensitivity to the α
134 value within this range. For the case study therefore, a value of 3 has been set.

135 Let's note that these indexes only partially explain the peak flow deviation due to the spatial variability
136 of rainfall. It is easily understood that the two indexes summarizing this influence cannot replace a
137 hydrological model.

138 [Figure 1 here]

139 2.2 Sorting of hydrographs into subsets

140 Smith *et al.* (2004) had already proposed splitting the tested set of hydrographs into two homogeneous
141 subsets, namely: 1) events for which spatial rainfall variability is expected to exert a significant
142 influence on the observed hydrograph at the catchment outlet; and 2) events for which this variability
143 is expected to exert a weak influence.

144 In assuming the real existence of a continuum of situations between a negligible and a strong
145 influence, we propose herein to proceed with this split based on a unique criterion $C(H_i)$ expressed as:

$$146 \quad C(H_i) = \frac{VG_i^2}{VG_{av}^2} + \frac{HG_i^2}{HG_{av}^2} \quad (1)$$

147 where (VG_i, HG_i) are the rainfall variability indexes associated with hydrograph H_i , and VG_{av} and
148 HG_{av} are the mean index values for all tested hydrographs.

149 The value of $C(H_i)$ is expected to characterize the influence of spatial rainfall variability on the
150 response of the considered catchment for hydrograph H_i . Since its value has been normalized by mean
151 values VG_{av} and HG_{av} , $C(H_i)$ represents the range of rainfall variability influence within the studied
152 set of observed hydrographs.

153 The study of the statistical distribution of criterion $C(H)$ makes it possible to split the set of observed
154 hydrographs into homogeneous subsets combining the hydrographs indicating a similar influence of
155 spatial rainfall variability. It is clear that the number of subsets greatly depends on the variations in
156 $C(H)$, as well as on the size of the studied set of observed hydrographs.

157 2.3 Evaluation of modeling results for the subsets

158 The effects of information on spatial rainfall variability (i.e. high-resolution quantitative precipitation
159 estimates, or QPEs) on modeling results are assessed separately for each subset by comparing two
160 scenarios: 1) "distributed rainfall", whereby the hydrological model is forced by QPEs at the spatial
161 resolution of available radar data, so as to obtain a so-called "distributed hydrograph"; and 2) "average
162 rainfall", whereby the hydrological model is forced by a spatially averaged rainfall field equivalent to
163 the average rainfall intensity over the tested catchment. In this particular instance, the model yields a
164 so-called "spatially averaged hydrograph" (called "average hydrograph" hereafter).

165 Each of the modeled hydrographs (distributed and average) is compared to the observed hydrograph;
166 this comparison is intended to verify whether considering the information on spatial rainfall variability
167 improves the reproduction of the catchment response to rainfall forcing.

168 The hydrograph comparison performed herein focused on peak flows, in accordance with two criteria:
169 the level difference (denoted L_Q), and the time difference (denoted T_Q) between peaks, i.e.:

$$170 \quad L_Q = 100 (Q_{max} - Q_M) / Q_{max} \quad (2)$$

$$171 \quad T_Q = 100 (T_{Q_{max}} - T_{Q_{maxM}}) / T_{Q_{max}} \quad (3)$$

172 with Q_{max} being the maximum value of the observed hydrograph, and Q_M the associated value of the
173 modeled hydrograph (distributed or average) at the same time. $T_{Q_{max}}$ is the time of occurrence of Q_{max} ,
174 while $T_{Q_{maxM}}$ is the time of occurrence of the maximum value of the modeled hydrograph (distributed
175 or average).

176 3. Case study

177 3.1 The Cevennes Region and the selected datasets

178 The Cevennes Region encompasses a medium-elevation mountain range located in the southeastern
179 part of the Massif Central zone (Fig. 2). The southeastern end of this range consists of a plateau and a

180 plain area extending to the Mediterranean coast. The Cevennes Region displays typical Mediterranean
181 climate and is subject to heavy rainfall events during the autumn season, causing flash floods that on
182 occasion have resulted in considerable property damage and losses. Several rivers originate in the
183 Cevennes Mountains and cross the intermediate plain area to empty into the Mediterranean Sea. The
184 area considered in this study includes the catchments of three of these rivers: the Cèze, the Gardons,
185 and the Vidourle (Fig. 2).

186 [Figure 2 here]

187 This region is covered by a network of rain gauges, at a density of roughly 1 gauge per every 150 km²,
188 plus two weather radars providing quantitative precipitation estimates (QPEs) with high spatial (1 km
189 x 1 km) and temporal (5 min) resolutions. Hydrometeorological recordings in this region also benefit
190 from the presence of the Cevennes-Vivarais Mediterranean Hydrometeorological Observatory
191 (Boudevillain *et al.*, 2011), hereinafter referred to as OHMCV (<http://www.ohmcv.fr>). This long-term
192 observatory intends to build an integrated hydrometeorological database of events in the Cevennes-
193 Vivarais zone that generate flash floods. The enhanced observation program conducted as part of the
194 "Hymex-Mistrals" project has also significantly contributed to this data collection effort. The available
195 operational datasets have therefore been submitted to a thorough quality control and can be considered
196 of very good accuracy (Boudevillain *et al.*, 2011). The OHMCV provides several QPE products.

197 For purposes of this study, we used hourly rainfall fields of 1 km x 1 km spatial resolution obtained by
198 the radar - rain gauge merging technique proposed by Delrieu *et al.* (2014); these fields offer a high
199 level of accuracy compared to other QPE products. A time resolution of about 1/3 to 1/5 the catchment
200 response time (Berne *et al.*, 2004) is required to reproduce flood dynamics in hydrograph modeling.
201 This condition is satisfied for most of the considered catchments, even though the hourly time step
202 may appear to be slightly too long for the smallest of them. Nevertheless, since the highly accurate
203 QPE is only available at a one-hour time step, it has been adopted to simulate all hydrographs.

204 The studied area (Cèze, Gardons, and Vidourle catchments) includes 25 stream gauges adapted to high
205 flow measurements and thus able to provide flood hydrographs of sufficiently good quality. These 25

206 stream gauges define the outlets of the 25 basins considered in this study, with upstream catchment
 207 areas ranging from 42 km² to 1,855 km² (median value: 244 km²).

208 For purposes of this case study, the flood hydrographs were selected based on their unit peak flow,
 209 defined as $Q_{\max}/S^{0.8}$ (with Q_{\max} being the peak hydrograph flow and S the surface area of the upstream
 210 catchment). A threshold of 2.5 m³/s/(km²)^{0.8} was set to allow selecting just those rainfall events
 211 causing significant hydrological reactions. This point is important since the CINECAR hydrological
 212 model used herein was designed to model only this category of intense flood events.

213 During the 2007-2012 period selected for this study, 24 flood hydrographs related to 6 rainfall events
 214 reached a unit peak flow exceeding this threshold at one of the 15 stream gauges on the 25 present.
 215 Table 1 lists the number of hydrographs recorded for each event, along with the mean rainfall
 216 accumulations for the associated catchments and the mean surface area of these catchments, some of
 217 which (but not all) are embedded. In case of embedded catchments the drainage areas sufficiently
 218 differ to consider that the results should not be highly correlated. In the following discussion, the
 219 embedded catchments are therefore assumed to be independent.

Event date	Flow gauging station	Total rainfall on the catchment (mm)	Catchment surface area (km ²)
19 October 2008	13990	166	212
	11313	190	665
	11201	161	832
	11861	131	1111
31 October 2008	10749	252	113
	12492	329	162
	12833	292	544
	13113	242	665
	11313	197	665
	11201	169	832
29 December 2008	11861	140	1111
	13990	138	212
	14184	137	501
6 September 2010	14983	133	621
	13990	178	212
29 October 2010	13990	174	212

	14184	170	501
	14983	158	621
	16093	148	794
1 November 2011	12320	513	220
	12492	553	152
	12676	512	246
	12741	499	261
	12833	496	543

Table 1: Characteristics of the selected hydrographs

220

221 3.2 The CINECAR model

222 The distributed CINECAR hydrological model (Naulin *et al.*, 2013; Versini *et al.*, 2010) is based on a
 223 representation of the catchment as a ramified series of stream reaches, to which both left and right-
 224 hand hillslopes are connected. For the sake of simplicity, the hillslopes are depicted by schematic
 225 rectangular shapes, and the river reaches are assumed to have a rectangular cross-section.

226 The Soil Conservation Service-Curve Number (SCS-CN) model is used to compute runoff rates and
 227 the corresponding effective rainfall on hillslopes at each computation time step. The effective rainfall
 228 is then propagated onto both the hillslopes and the downstream river network by either the kinematic
 229 wave model or the Hayami solution for the diffusive wave model (Moussa, 1996). The diffusive wave
 230 model is applied for flood wave attenuation on downstream river reaches with slopes of less than
 231 0.6%, while the kinematic wave model is applied for all other river reaches.

232 Since CINECAR was developed for the purpose of computing hydrographs in ungauged catchments, it
 233 features a very limited number of calibration parameters. The width of river reaches is the main
 234 parameter controlling the transfer function; and the Curve Number (CN) value is the second key
 235 parameter and controls the temporal evolution of runoff rates. This model was applied in 2013 to the
 236 entire Cevennes Region (Naulin *et al.*, 2013) in the aim of producing homogeneous results at the
 237 regional scale; for this reason, no real systematic or site-specific calibration was performed. Given that
 238 the channel widths could not be accurately estimated from available data, a fixed average channel
 239 width w was used: $w = w_o \cdot i^2$, with i being the Strahler order (Horton, 1945; Schumm, 1956) of the
 240 considered reach and w_o an elementary width depending on the return period T of the modeled

241 discharge ($w_o = 4$ m if $T < 2$ years, $w_o = 8$ m if $2 \text{ years} < T < 10$ years, and $w_o = 12$ m if $T > 10$ years).
242 The Manning's n roughness coefficients were assumed to be constant, with their values set at 0.05 for
243 channels and 0.1 for hillslopes. The determination of CN values was based on the USDA method
244 (USDA, 1986), as a function of land use and soil type (Corine Land Cover Database and European
245 Soil Database), as well as of rainfall accumulation over the 5 preceding days.

246 This CINECAR model only depicts rapid runoff and does not include a continuous representation of
247 base flow and soil moisture conditions. It is therefore not suited for modeling low-magnitude floods,
248 which are highly dependent on initial conditions, but rather for modeling the rising limb and peak
249 phases of large flood events. The application of this model to the Cevennes Region was validated with
250 respect to measured data (Naulin *et al.*, 2013). Satisfactory results were derived with an average Nash
251 criterion computed for single flood events equal to 0.49. In addition, a comparative test between
252 CINECAR and a GR4 lumped model (Perrin *et al.*, 2003) was conducted for the Anduze stream gauge
253 on the Gardon River, leading to the conclusion that both models performed similarly for the most
254 intense events.

255 This same model version has been run herein without any adjustments. Based on the initial validation
256 results, it can be considered that the model performs correctly for flood events whose peak discharges
257 exceed $2.5 \text{ m}^3/\text{s}/(\text{km}^2)^{0.8}$: this threshold corresponds to significant (but not exceptional) flood events
258 since it has been exceeded 25 times in 4 years within the considered region. The model's spatial
259 resolution is determined by the hillslope dimensions: the 3 main catchments considered here (Cèze,
260 Gardons, and Vidourle) were divided into 2,282 hillslopes, with a median surface area of 1.5 km^2 . The
261 model can therefore be considered as well suited for taking into account high-resolution information
262 on rainfall and the associated spatial variability often observed in the Cevennes Region.

263 **4. Results**

264 Due to the limited number of hydrographs (24), this sample can be split into two subsets, namely A
265 and B, by adopting a threshold value of $C(H) = 2$, as confirmed in Figure 3.

266

[Fig. 3 here]

267 Among the 24 selected hydrographs, 9 were classified in subset A (with the influence of spatial
268 rainfall variability expected to be significant) and the other 15 hydrographs in subset B (with a weak
269 influence expected). Examples of rainfall accumulations on the tested catchments are shown in Figure
270 4. The associated hydrographs in Figure 5 display the variety of situations that can be encountered. For
271 hydrographs B1 and B2, the hydrological model fails to perform adequately, and the modeling errors
272 appear to be very large when compared to the weak influence of rainfall variability. For instance, for
273 B2, rainfall accumulation is relatively uniform over the catchment, and the value of $C(B_2)$ lies close to
274 0. The distributed and average hydrographs are very similar for this event. Conversely, for A1 and A2,
275 the average rainfall results in an underestimation of the observed hydrograph, whereas the distributed
276 rainfall enables to obtain a model peak value close to the observed value.

277

[Figures 4 and 5 here]

278 The distributions of level and time differences (L_Q , T_Q) computed for the average and distributed
279 hydrographs are compared in Figure 6 for both subsets A and B.

280 For subset B, the distributions of computed L_Q are very similar for the average and distributed
281 hydrographs: the median values are respectively equal to 42.2% vs. 40.5%, with the third quartile
282 equal to 64.4% vs. 63.4%. The distributions of T_Q values are also similar, with median values equal to
283 26.8% vs. 19.2%.

284 In contrast, for subset A, the distributions of computed L_Q seem to differ significantly between average
285 and distributed hydrographs. The box plots are more differentiated, with median values respectively
286 equal to 67.5% vs. 52%, and the third quartile equal to 77.3% vs. 57.8%. Such differences are also
287 observed for T_Q values, with median values equal to 48.2% vs. 29.2%.

288

[Figure 6 here]

289 This result reflects that subset A (regrouping events whose spatial rainfall variability is expected,
290 according to the rainfall indexes, to exert a significant influence) is very different from subset B
291 (events whose spatial rainfall variability is expected to exert a weak influence). For A, the use of
292 distributed rainfall inputs enables to reduce the differences between modeled and observed
293 hydrographs, which in turn confirms that the information on spatial rainfall variability deserves to be
294 taken into account for these rainfall events. For subset B on the other hand, the use of distributed
295 rainfall inputs does not improve hydrograph modeling at the catchment outlet than using average
296 rainfall over the catchment.

297 Figure 6 also illustrates the usefulness of the two subsets A and B. It shows that if all the hydrographs
298 are grouped (i.e. case A+B), the statistical distributions of L_Q (and also T_Q), cannot be clearly
299 distinguished between average and distributed hydrographs. Therefore, considering all the
300 hydrographs together makes it difficult to identify the benefits associated with a detailed spatial
301 resolution on rainfall.

302 Moreover, according to the events analyzed in this case study, the rainfall variability indexes proposed
303 by Emmanuel *et al.* (2015) appear to be helpful in detecting situations where spatial rainfall variability
304 exerts a significant influence on the shape of the hydrograph at the catchment outlet and where
305 information on this variability (high-resolution QPEs) should yield significant improvements in
306 hydrograph modeling results.

307 **5. Discussion**

308 **5.1 Position of the proposed method relative to former contributions**

309 As stated by Pokhrel and Gupta (2011): "there is a clear lack of consensus in the literature regarding
310 the impacts of spatial distribution (of rainfall and parameters) on the streamflow response of a
311 catchment", and this remains so despite the increasing number of studies. Several reasons make this
312 topic a complicated one to address. Since all contributions to this question rely on hydrological
313 modeling, the presence of various sources of error is capable of partially concealing the effect of
314 spatial rainfall variability. The influential factors can never be taken into account in their entirety. For

315 this reason, the contributions to this topic have adopted two distinct approaches, namely real-world
316 case studies on one hand, and simulation studies aiming to avoid difficulties related to modelling
317 errors. This second type of approach includes, for instance, an analysis of the variations in flow
318 simulation due to rainfall field perturbations (Pokhrel and Gupta, 2011) or a comparison of spatial
319 rainfall variability indexes and catchment dampening (Smith *et al.*, 2004). The method proposed
320 herein seeks to take advantage of rainfall variability indexes (initially developed based on simulation
321 results), to facilitate the analysis of real-world case studies. The rainfall variability indexes are used to
322 split the set of considered events into several homogeneous subsets in terms of the expected influence
323 of spatial rainfall variability on modeling results. This influence is then evaluated separately on each
324 subset in order to facilitate the analysis of modeling results.

325 Since this method is based solely on rainfall fields and catchment width function and response time, it
326 remains completely independent of the hydrological modeling employed to produce the hydrographs
327 initially. This specificity helps simplify method application and broaden its scope.

328

329 **5.2 Limitations of the approach**

330 The proposed method can be considered as a form of climatological analysis and thus requires a
331 significant number of observations to reach a robust conclusion. In addition, the case study has
332 focused on a given context (climatology, catchment features, etc.). These two aspects limit the
333 significance of the conclusions drawn. Fortunately, the development of weather radar data for
334 hydrological modeling and the increasing availability of weather radar databases should expand
335 applications of the method to a variety of contexts in order to gain experience with the efficiency and
336 robustness of the method. In particular, one key point of its application seems to be the statistical
337 distribution of criterion $C(H)$, which is used as the basis for splitting the set of observed hydrographs
338 into homogeneous subsets. It would be interesting to learn more about this statistical distribution as a
339 function of the considered context. Furthermore, the influence of spatial rainfall variability is not
340 binary, i.e. weak vs. significant, but instead more continuous. Segmenting the dataset into a larger
341 number of subsets would thus also be beneficial in capturing this continuity.

342

343 **5.3 Possible future applications of the method**

344 Addressing the aforementioned issues would require applying the proposed method to a larger set of
345 case studies. More specifically, the method could now be used to complement the analysis of previous
346 real-world studies, e.g. the study by Lobligeois *et al.* (2014), who performed a climatological analysis
347 of the influence of spatial rainfall variability based on 3,620 flood events over 181 catchments.

348 In the future, the proposed method could also be used to compare several modeling approaches,
349 including lumped and distributed models, instead of comparing two rainfall data scenarios with a
350 distributed model. Based on this same procedure of separating hydrographs into subsets, a comparison
351 of respective model performance in both situations might illustrate the advantages offered by a
352 calibrated lumped model in situations of limited rainfall variability and moreover suggest how these
353 advantages may be counterbalanced using a distributed model in the case of high rainfall variability.

354 Lastly, the classification method presented may help practitioners identify catchments for which the
355 development of distributed rainfall-runoff modeling should be promoted, or where lumped models
356 appear to be a good option thanks to a sufficiently limited rainfall heterogeneity. The separation of
357 events into subsets may also be used to derive different parameter sets of lumped models, once again
358 depending on the level of rainfall heterogeneity. Moreover, this separation step may be of great
359 assistance in real-time applications, by identifying events whose high rainfall variability causes
360 concerns over the validity of outflow predictions based on lumped models and thereby enabling a
361 switch to distributed models (if available).

362

363 **6. Conclusion**

364 The objective of this study has been to present and test a method designed to identify the influence of
365 spatial rainfall variability on hydrograph modeling results. This method makes use of the rainfall
366 variability indexes developed by Emmanuel *et al.* (2015) in proposing a criterion representative of the
367 expected influence of spatial rainfall variability on the hydrograph at the catchment outlet. The method

368 has been tested on a case study grouping 24 hydrographs recorded on 15 catchments of various surface
369 areas in the Cevennes Region (southeastern France) from 2008 to 2012. According to the spatial
370 rainfall variability index values, the tested flood events were classified into two subsets, combining
371 respectively: i) the hydrographs expected to be significantly affected by rainfall variability (subset A);
372 and ii) the hydrographs expected to be weakly affected by this variability (subset B). Once examined,
373 the modeling results revealed that on average the influence of taking spatial rainfall variability into
374 account differs rather significantly for the two subsets: the added value is clear in the case of subset A,
375 whereas the added value was not so evident in the case of subset B.

376 This case study has therefore illustrated the value of the proposed method in identifying the events for
377 which the rainfall spatial variability should be taken into account for hydrograph modeling. The two
378 spatial rainfall variability indexes used herein appear to be capable of detecting situations where
379 spatial rainfall variability exerts a significant influence on catchment response. Their main advantage
380 lies in a computation, based on the raw rainfall field and the catchment characteristics, thus making it
381 possible to separate rainfall events independently of the model being tested. This separation step
382 appears here to be of great benefit in better analyzing and understanding modeling results. It may
383 prove helpful in a large number of practical applications, for in-depth analyses of lumped model
384 performance and, if necessary, as support for the decision to switch to distributed modeling.

385 This study however needs to be extended to a much larger and more varied set of catchments and
386 rainfall events in order to acquire a broader perspective on the influence of spatial rainfall variability.

387

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396

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487

Figure1

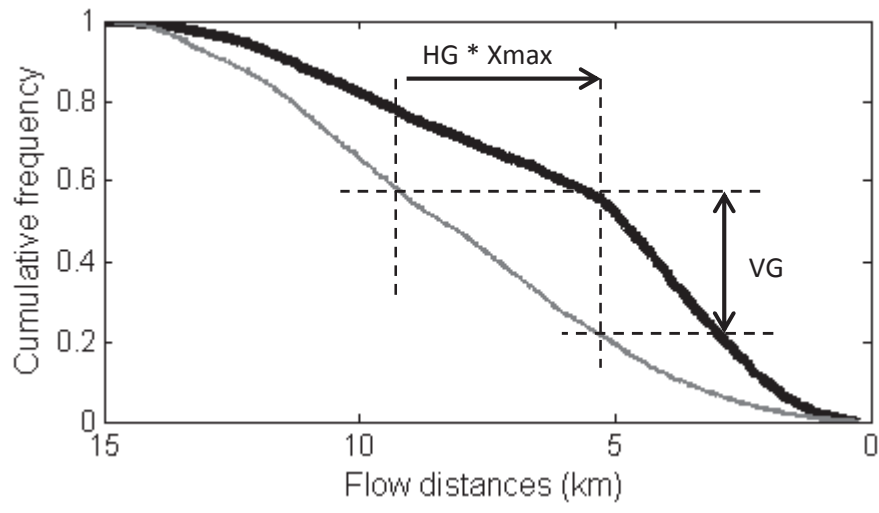


Figure2
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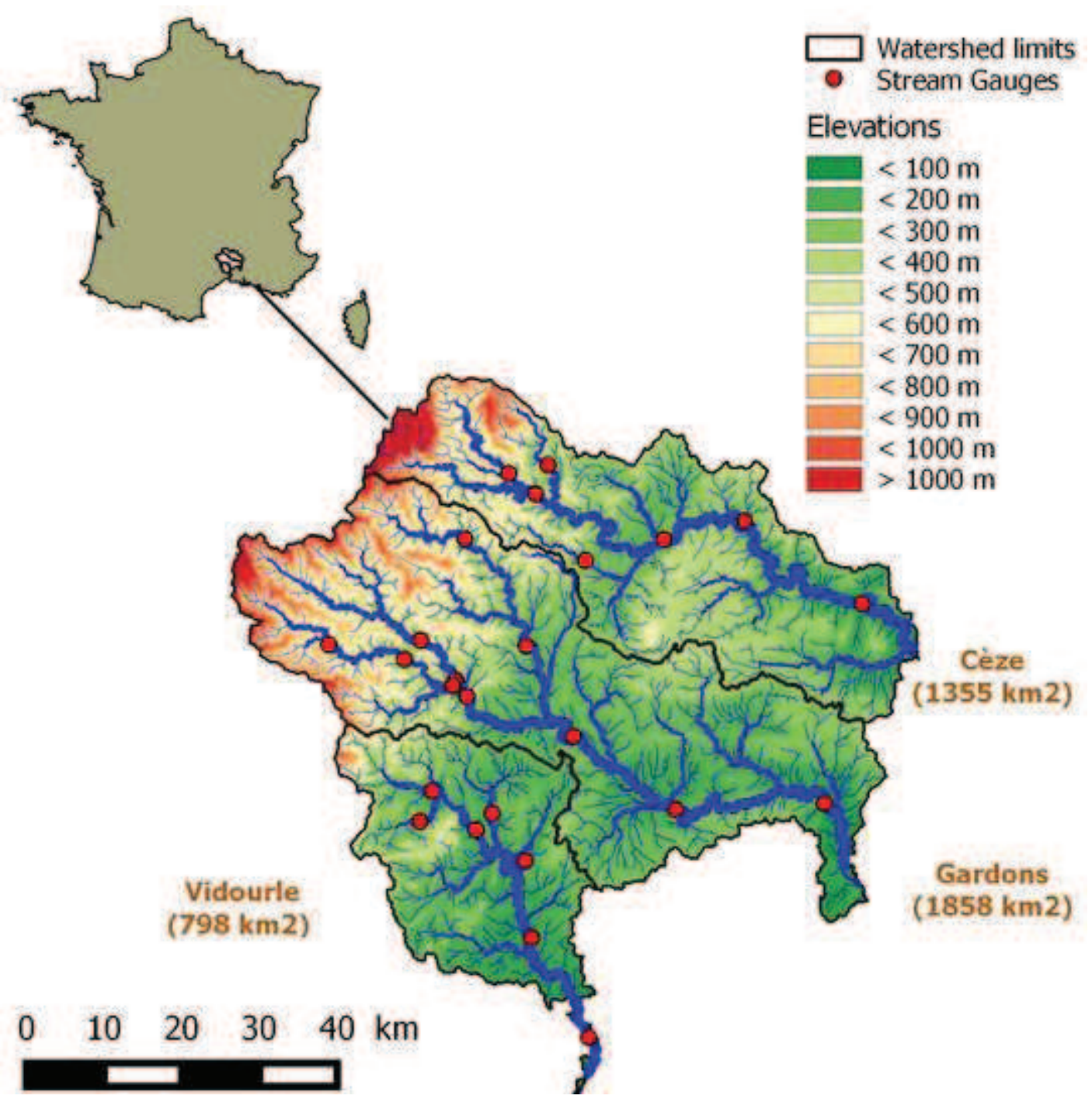


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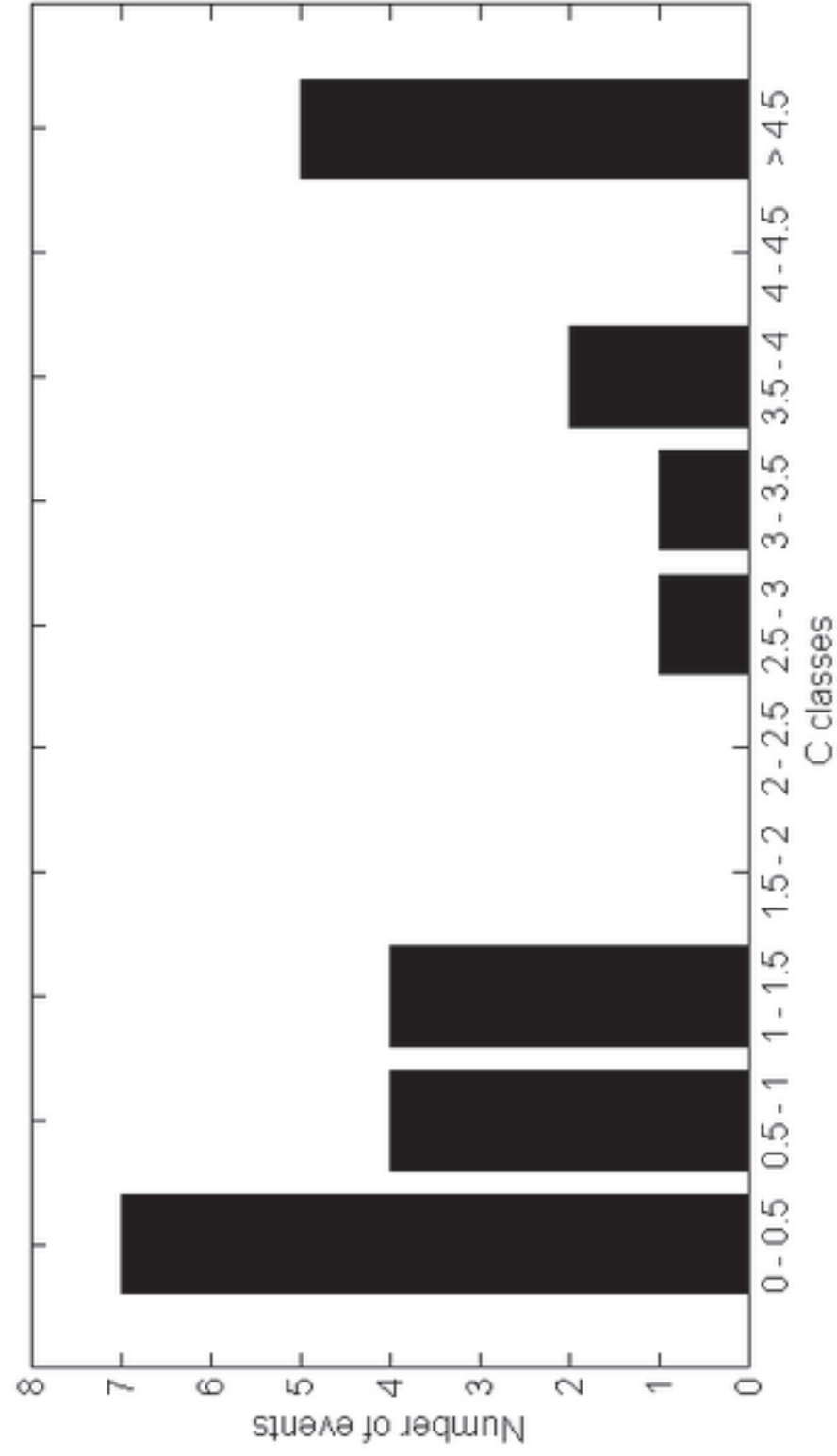
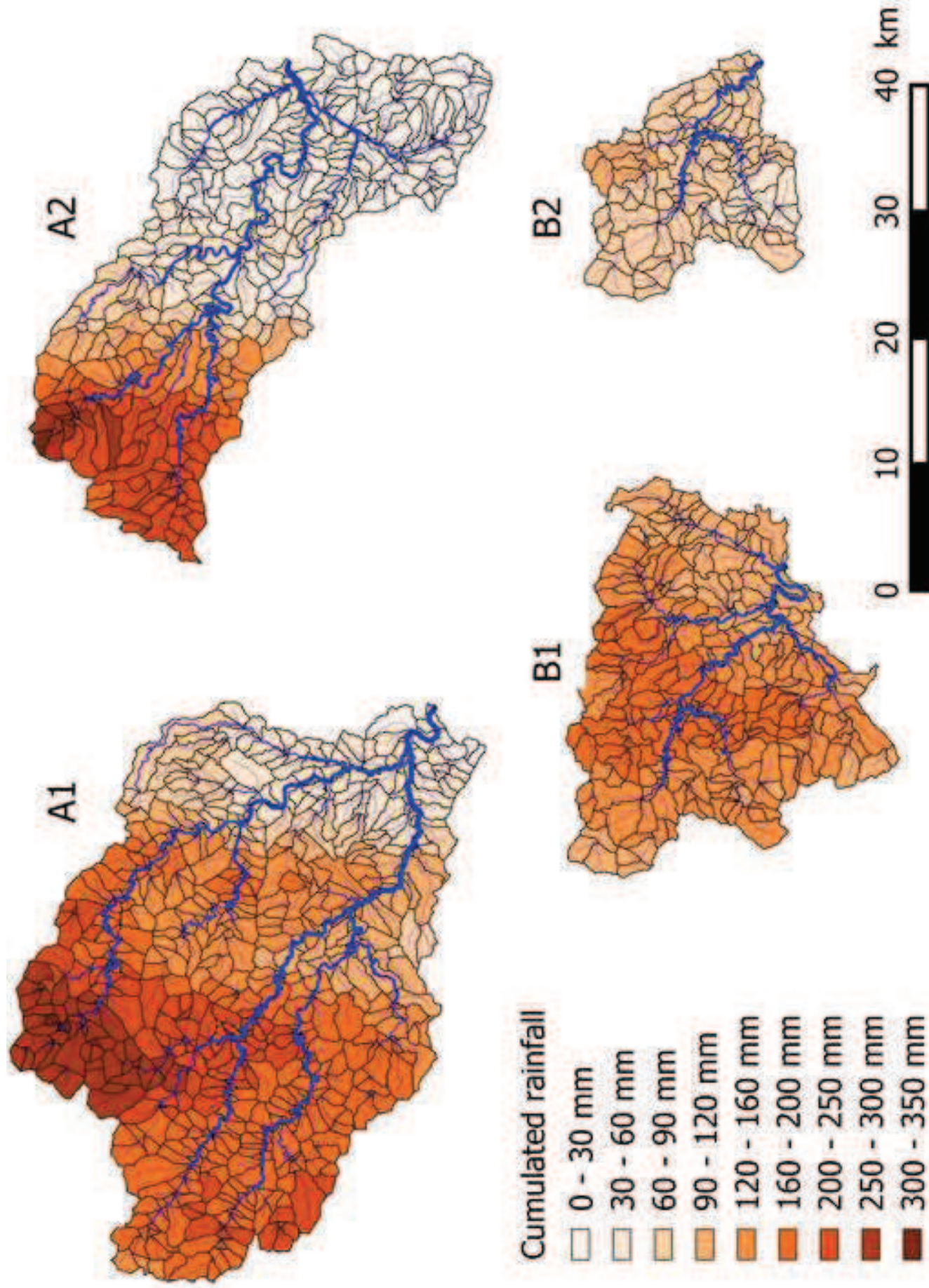


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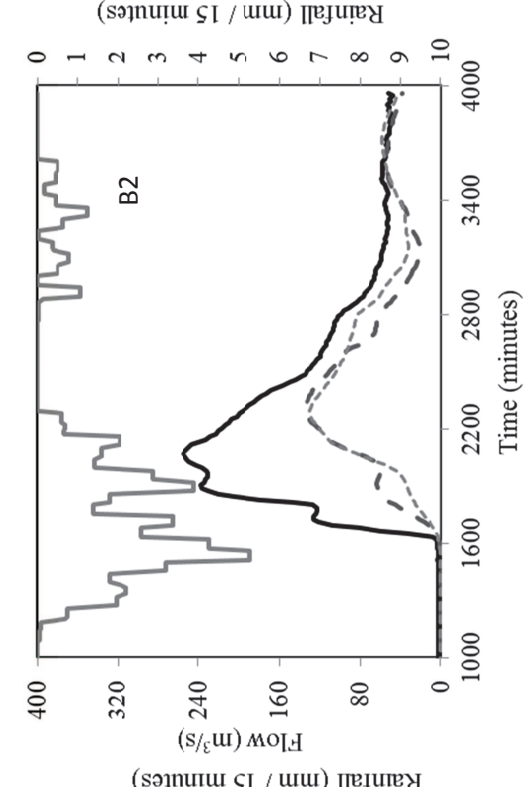
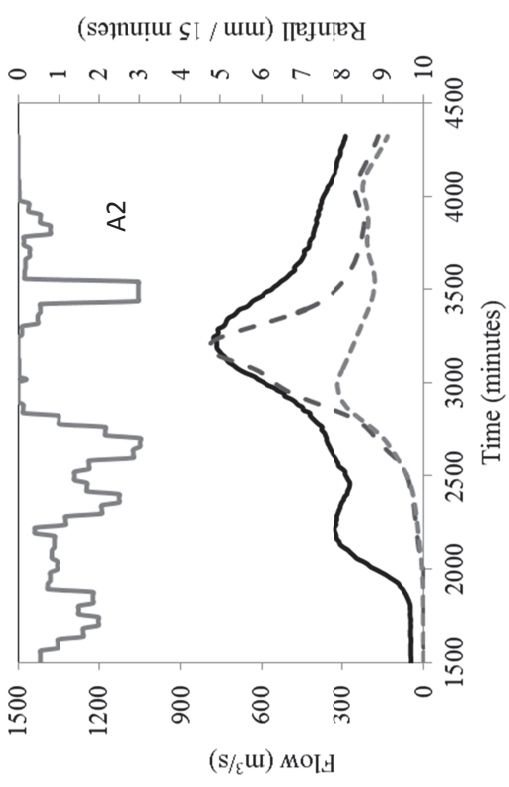
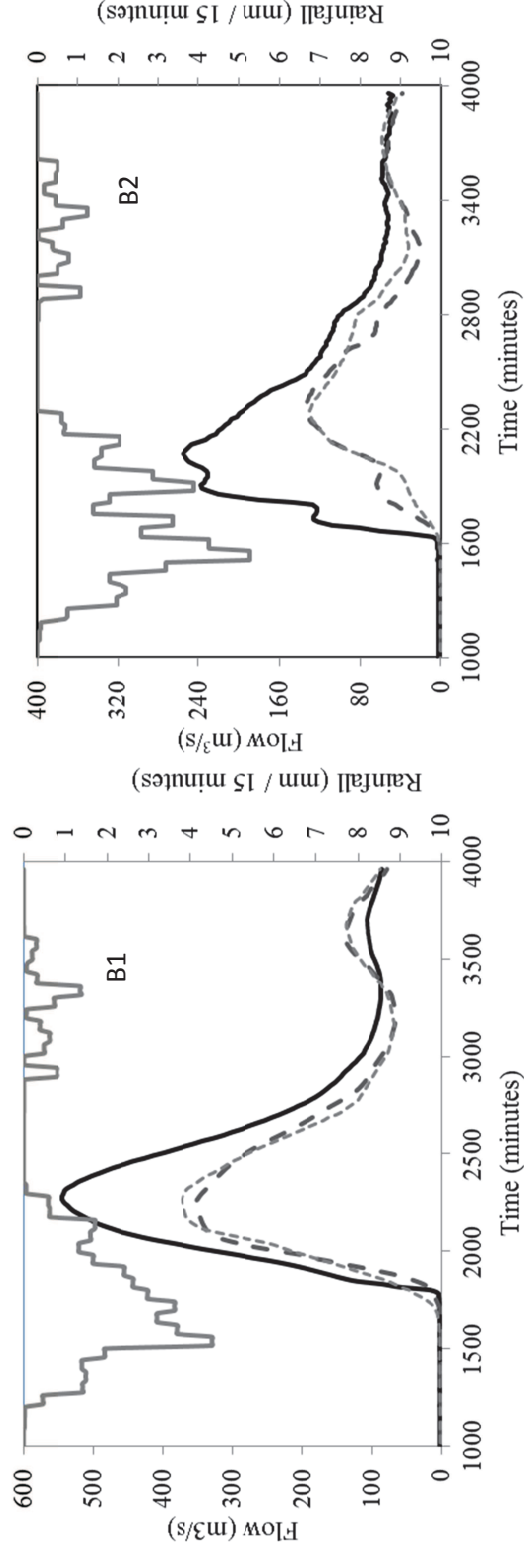
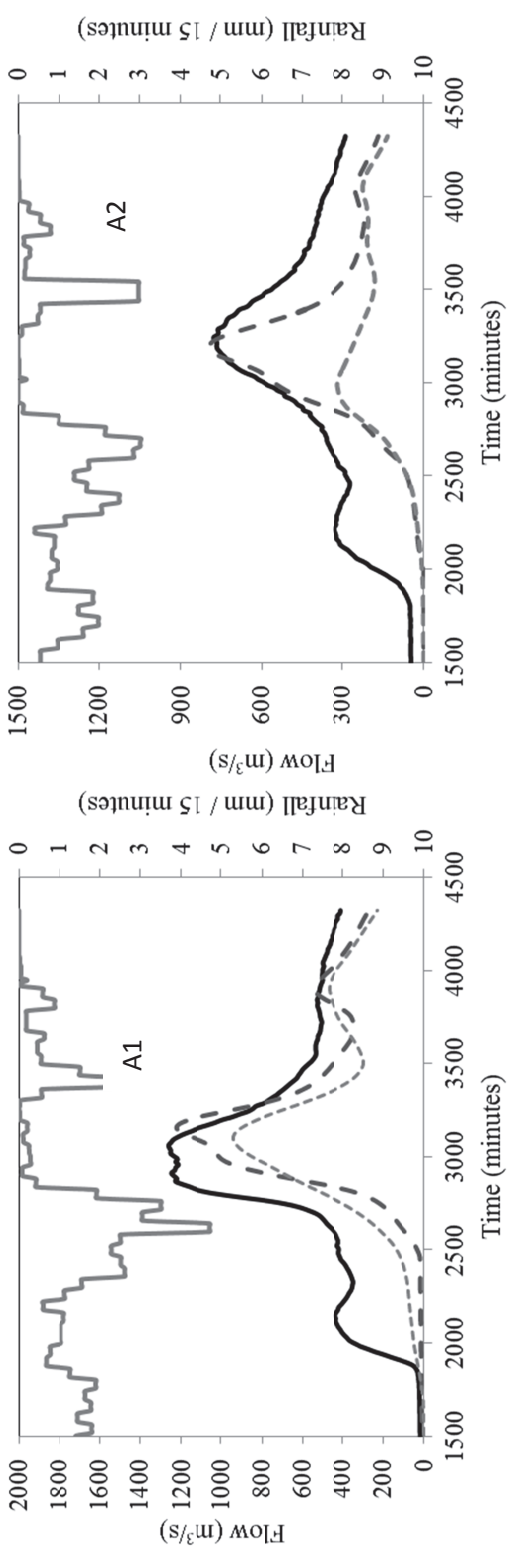


Figure 5

Figure6a
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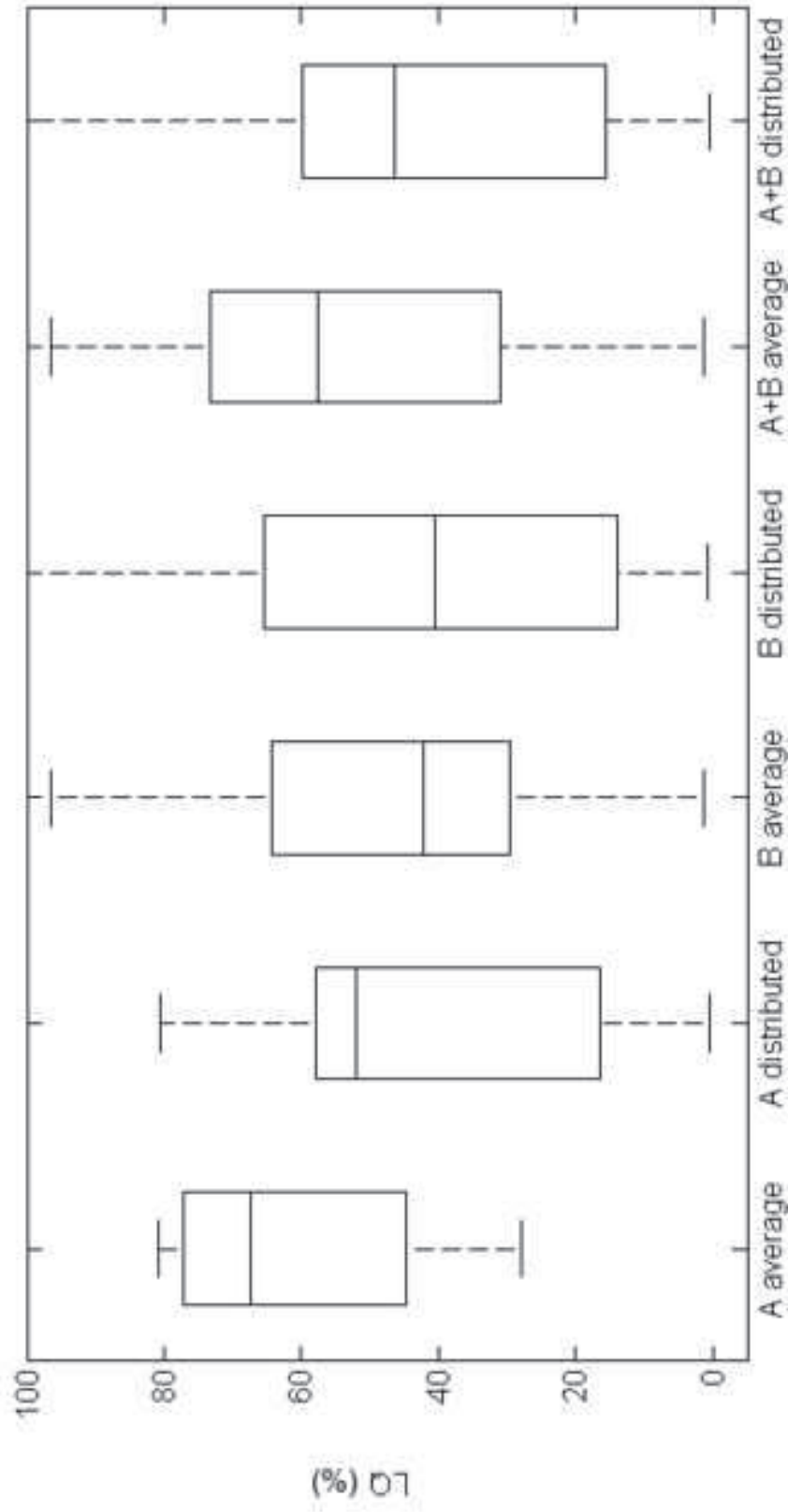


Figure6b
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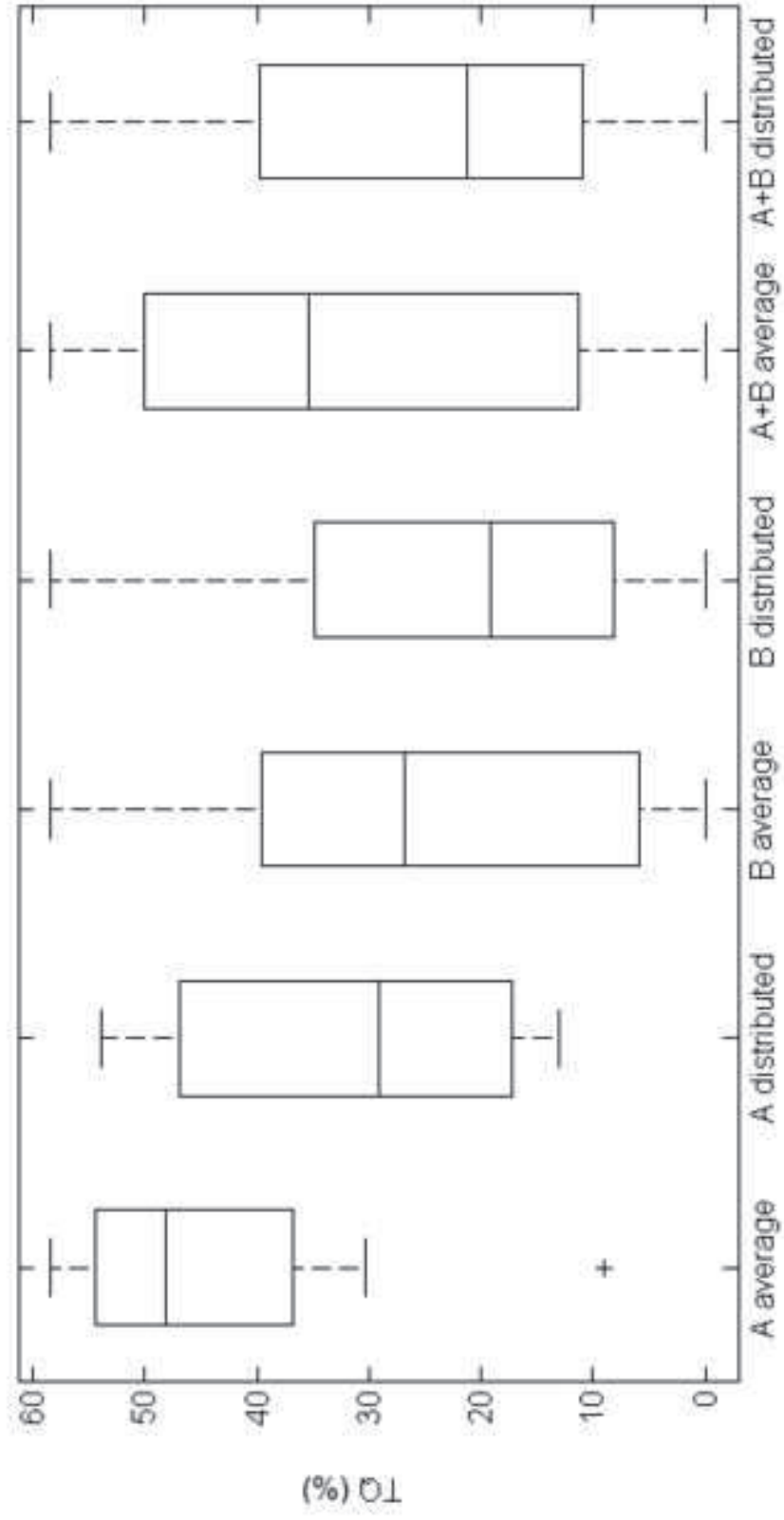


Figure captions:

Figure 1: Computation principle applied to rainfall variability indexes VG and HG based on the catchment width function (thin line) and rainfall width function (thick line). X_{max} is the length of the longest hydrological path on the catchment.

Figure 2: Location of the tested catchments in the Cevennes Region (southeastern France)

Figure 3: Number of events per C classes.

Figure 4: Representation of rainfall accumulation (in mm) computed over a $3Tr$ duration before the hydrograph peak, with Tr being the catchment response time. A1 and A2 occurred on 31 Oct 2008, over respectively a 1,096-km² and a 665-km² catchment with $C(A1) = 1.36$ and $C(A2) = 10.0$. B1 and B2 occurred on 29 Oct 2010, over respectively a 501-km² and a 212-km² catchment with $C(B1) = 0.23$ and $C(B2) = 0.06$.

Figure 5: Examples of comparisons between observed (solid line), distributed (dashed line) and average (dotted line) hydrographs. A1 and A2 are hydrographs classified in the "sensitive to spatial rainfall variability" sample. B1 and B2 are hydrographs classified in the "relatively insensitive to spatial rainfall variability" sample.

Figure 6: Comparison of the distributed and average modeled hydrographs to the observed hydrographs, based on the L_Q (a) and T_Q (b) criteria, for both subsets A and B and the entire A+B dataset. The box plots represent the first quartile, median, third quartile and minimum and maximum values. An outlier has also been plotted individually (the "+" sign).