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## Relevance of an at-site flood frequency analysis method for extreme events based on stochastic simulation of hourly rainfall.

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1 **Title: Relevance of an at-site flood frequency analysis method for extreme events based on**  
2 **stochastic simulation of hourly rainfall.**

3 Titre: Pertinence d'une méthode de prédétermination des crues basée sur la simulation stochastique  
4 de pluies horaires

5  
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15  
16 **Abstract:**

17 Extreme events are rarely observed, so their analysis is generally based on observations of more  
18 frequent values. The relevance of flood frequency analysis (FFA) method depends on its capability  
19 to estimate the frequency of extreme values with reasonable accuracy using extrapolation. A FFA  
20 method based on stochastic simulation of flood event is assessed based on its reliability and  
21 stability. For such an assessment, different training/testing decompositions are performed for a set  
22 of data from more than 1,000 gauging stations. We showed that the method enables relevant  
23 “predictive” estimates, e.g. by assigning correct return periods to the record values that are  
24 systematically absent in calibration data sets. The model is also highly stable vis-a-vis the sampling.  
25 This characteristic is linked to the use of regional statistical rainfall data and a simple rainfall-runoff  
26 model that requires calibrating only one parameter.

27 **Résumé:**

28 Les événements extrêmes sont par nature rarement observés, c'est pourquoi leur estimation est  
29 généralement basée sur l'observation de valeurs plus courantes. La pertinence d'une méthode de  
30 prédétermination des événements extrêmes dépend donc de sa capacité à raisonnablement  
31 extrapoler les distributions de fréquences vers les valeurs extrêmes. Dans cette étude, une méthode  
32 de prédétermination de crues basée sur la simulation de scénarios de pluies horaires, est évaluée sur  
33 sa capacité à produire des estimations justes et stables. Cette évaluation s'appuie sur différents tests  
34 d'échantillonnage sur les périodes de calage et de validation, appliqués sur un jeu de données  
35 conséquent (plus de 1000 stations). Nous montrons que la méthode est capable de fournir une  
36 estimation pertinente sur les événements extrêmes bien que ceux-ci soit systématiquement ôtés de la  
37 période de calage. La méthode montre aussi une grande stabilité face à l'échantillonnage. Cette  
38 caractéristique est liée à l'utilisation d'une information statistique régionale sur la pluie et à la  
39 simplicité de la modélisation hydrologique paramétrée par un seul paramètre.

40 **Keywords:** extreme events, stochastic model, flood frequency analysis.

41 **Mots clés:** événements extrêmes, modèle stochastique, prédétermination des crues

42 **1 Introduction**

43

1 To plan a risk prevention strategy, it is necessary to examine the hydrometeorological variability in  
2 an entire region. This analysis has many operational applications, e.g. mapping flood-prone areas  
3 (European Flood Directive 2007/60/EC), designing hydraulic structures (Lavabre et al. 2009), and  
4 defining the frequency of hydrometeorological events for natural disaster assessments or alert  
5 methods (Javelle et al. 2010). Hydrologists have developed many flood frequency analysis (FFA)  
6 methods. The development of these methods is often influenced by the availability of observation  
7 data and by the specific hydrometeorological characteristics. In Europe, the FloodFreq COST  
8 ES0901 Action (<http://www.cost-floodfreq.eu/>) has identified most well-know FFA methods,  
9 including methods which enable an initial estimate of rainfall risk used as input for more or less  
10 empirical rainfall-runoff modelling approaches (Willems et al. 2012), and those which estimate  
11 hydrological risk directly from hydrometric data (Castellarin et al. 2012). All these methods are  
12 generally presented in Hydrology reference books (Chow et al. 1988, Lang and Lavabre 2007,  
13 Llamas 1993).

14 Broadly speaking, purely statistical methods are to fit a probability distribution law directly to the  
15 empirical frequency distribution of the hydrological variable studied. The choice of probability  
16 distributions used to estimate flood flows is distributions based on the Extreme Value Theory  
17 (Coles 2001). The probability distributions used the most often in flood frequency analysis include  
18 the Generalized Extreme Value (GEV) distribution (Hosking and Wallis 1993), the Generalized  
19 Pareto (GP) distribution and the Three-Parameter Lognormal (TPLN) distribution. These three  
20 probability distributions are used on site in favourable observation conditions (Klemes 1993). At  
21 sites where observation data are inadequately gauged or nonexistent, regional approaches are used,  
22 namely a regional flood frequency analysis (RFFA). These include values observed on  
23 neighbouring sites to increase the size of the sample of observations, using either the index flood  
24 method (Darlymple 1960) or other RFFA (Hosking and Wallis 1993, Stedinger and Tasker 1985,  
25 Hosking and Wallis 1997, Ribatet et al. 2007, Merz and Blöschl 2005)).

26 Extrapolating frequency distributions to extreme values is still problematic, however, because  
27 hydrological phenomena are strongly nonlinear (Katz et al. 2002). Calibrating a model based on  
28 frequent observations does not guarantee extrapolation to extreme values. This is why certain purely  
29 statistical methods rely on estimation of rainfall variability to extrapolate flow probability  
30 distribution (Guillot and Duband 1967, Margoum et al. 1994).

31 By construction, simulation approaches use rainfall data. They have been developed especially to  
32 fulfil the temporal data requirements associated with design floods (Eagleson 1972). Such  
33 approaches mimic some of the statistical properties of rainfall observations and the rainfall/runoff  
34 relationship in order to generate rainfall and runoff series that can be used subsequently as observed  
35 series. These simulated series, which are becoming increasingly common, are then used to extract  
36 the desired hydrological characteristics (i.e. quantiles), and can also be used to test the failure of  
37 hydraulic structures when subjected to extreme events (Lavabre et al. 2010). Simulation approaches  
38 are used more and more (Li et al. 2014). Models differ according to the type of rainfall generator or  
39 rainfall-runoff model used (Blazkova and Beven 2004, Cadavid et al. 1991, Onof et al. 2005, Shen  
40 et al. 1990), a summary of which is presented in the article (Boughton and Droop 2003). In France,  
41 there are two simulation approaches, one developed by Electricité de France (EdF) (Paquet et al.  
42 2013), and the other, by Irstea (Arnaud and Lavabre 2002, Aubert et al. 2013) (SCHADEX and  
43 SHYREG respectively).

1 A complete nationwide database on the estimation of flood flow quantiles has been produced due to  
2 the implementation of the SHYREG method (Aubert et al. 2013, Organde et al. 2013).

3 This method was also evaluated in comparison with other FFA and RFFA methods, as part of a  
4 nationwide research project (ANR Extraflo project, <https://extraflo.cemagref.fr>) (Kochanek et al.  
5 2013). The project involved establishing evaluation indexes to assess method relevance. This article  
6 presents (§2) the SHYREG method (calibration of hourly rainfall generator and hydrological  
7 model), (§3) data and stability and reliability indexes and (§4) its reliability and stability  
8 performance over a broad sampling of data, (§5) before discussing the method's inherent  
9 characteristics that lead to such performance.

## 11 2 The SHYREG method

### 12 2.1 The principle

13 The SHYREG method is a simplified version of the SHYPRE (Simulated HYdrographs for flood  
14 PRobability Estimation) method (Arnaud and Lavabre 2002), adapted for the purposes of regional  
15 flood flow studies. Both these frequency analysis methods are based on process simulation.  
16 SHYPRE was first developed to simulate catchment flood scenarios. It couples a stochastic hourly  
17 rainfall generator (Arnaud and Lavabre 1999, Cernesson et al. 1996, Arnaud et al. 2006, Cantet et  
18 al. 2010, Cantet and Arnaud 2014) with a rainfall-runoff model. In this way the model generates a  
19 set of flood hydrographs, which can then be used to empirically deduce the frequency distribution  
20 of peak and maximum mean flows over different durations. The analysis of this even-based of peak  
21 approach focuses on hourly rainfall events selected from daily criteria (all daily rainfalls of the  
22 event are greater than 4 mm and one of them must exceed at least 20 mm). In France, the number of  
23 such events was mapped and varies between 3 and 25 events per year. In order to generate 1,000  
24 years of flood events, we generate the number of events per year for each year (using the Poisson  
25 distribution law) and the associated independent rainfall events. These are transformed into flood  
26 events, which are associated to a simulation of 1,000 year period.

27  
28 The SHYREG (SHYpre REGionalised) method was developed after the SHYPRE method, and is  
29 based on the same principle, but was adapted to simplify the initial approach and thus facilitate its  
30 regionalization (Aubert et al. 2013, Organde et al. 2013) in order to estimate flood frequencies on  
31 un-gauged basins. It is implemented in two steps:

- 32 • **Regionalizing the hourly rainfall generator.** The rainfall model was regionalized for all  
33 French territory, including the tropical islands of Reunion (Aubert et al. 2014), Martinique  
34 and Guadeloupe. Its regional application is based on the use of daily rainfall data, which are  
35 more broadly available than hourly data. This regionalization process is detailed in a  
36 methods guidebook and articles (Arnaud and Lavabre 2010, Arnaud et al. 2008b). It relies  
37 on the mapping of three characteristic daily rainfall variables (for intensity, duration, and  
38 frequency) to calibrate the hourly rainfall generator. These three variables, estimated for two  
39 seasons<sup>1</sup>, were determined based on 2,812 rain gauge stations on French territory and then  
40 mapped, taking local environmental and topographical characteristics into account (Arnaud

---

<sup>1</sup> The hourly rainfall generator is calibrated for two seasons: the summer (from June to November)  
and the winter (from December to May). By this way, we distinguish the long events with low  
rainfall intensity and the short events characterized by high quantity of rainfall.

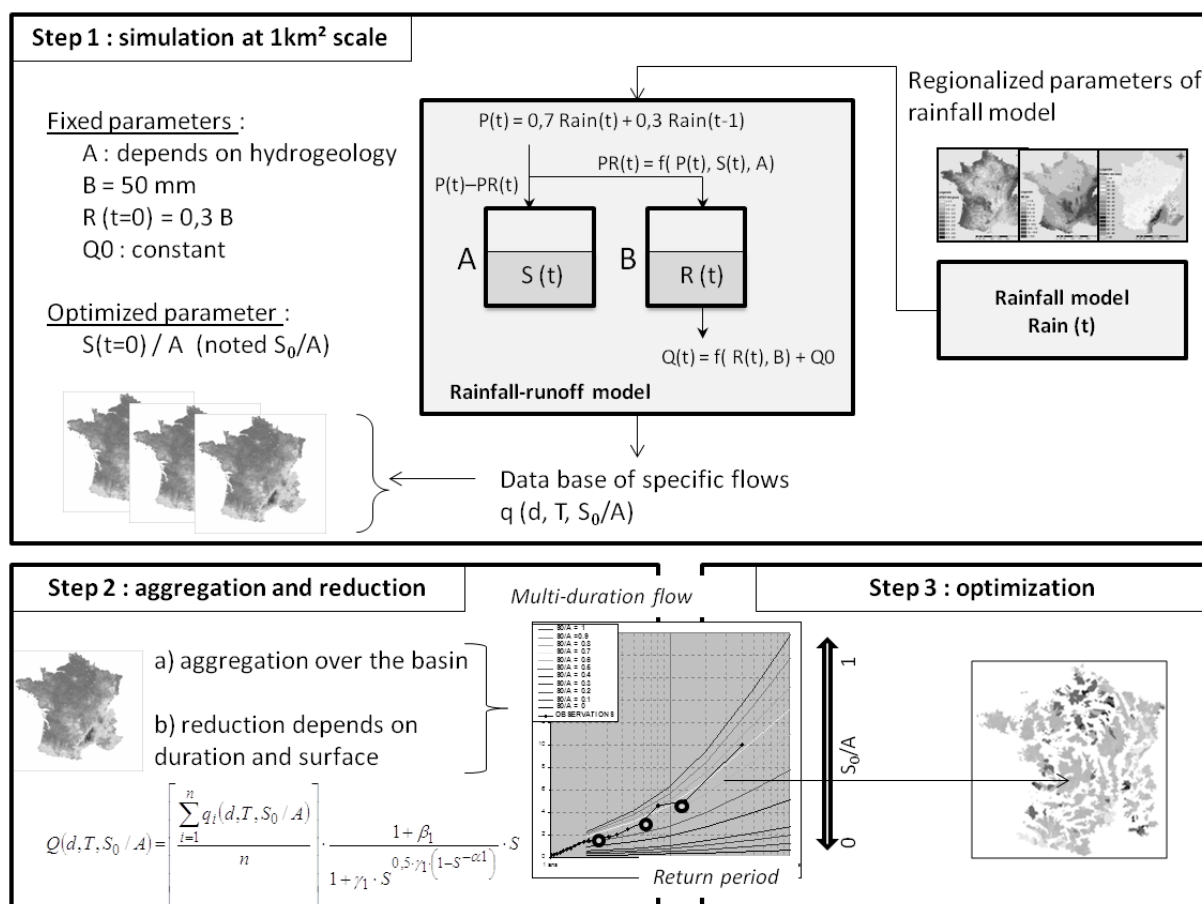
1 et al. 2008a). The regionalized parameters are used to parameterize the hourly rainfall  
2 generator and the hourly rainfalls simulated are transformed into flood according to  
3 hydrological model. The simulated hourly rainfall time series also serve to establish a  
4 rainfall risk database (intensity-duration-frequency curves for the entire territory).  
5

- 6 • **Regionalizing the rainfall-runoff model.** We chose to convert hourly rainfall into flood  
7 flow at a pixel resolution of 1 km<sup>2</sup>. The use of pixels is necessary because of the point-wise  
8 nature of rainfall generator (this is not a rainfall field/spatial generator), while also  
9 simplifying the rainfall-runoff model. Regionalization is a two-phase process. First, the  
10 rainfall generator parameters are set to the local values of the pixel, then hourly rainfall  
11 events over the pixel are generated and transformed into flood events through with a  
12 simplified rainfall-runoff model (described below). Simplifying the model involves using a  
13 single parameter. The flood scenarios are used to obtain flow quantiles for each km<sup>2</sup> (called  
14 further specific flows). In order to estimate river flow quantile, specific flow quantiles are  
15 cumulated for all the pixels in the associated catchment. Then an areal reduction factor is  
16 used to take into account simultaneously the rainfall areal reduction and the flood routing,  
17 and depends only on catchment surface area and the duration examined. This function,  
18 described in the paragraph below, is unique for any given region. Only one calibration for  
19 the rainfall-runoff model is necessary in order to regionalize this method (Organde et al.  
20 2013).  
21

22 This article presents the performance of the local version of SHYREG, calibrated on gauged  
23 catchments. The focus of the research is not the regionalization process, but rather the calibration of  
24 the method for a wide range of catchments and the resultants of the quantile estimation.  
25

## 26 2.2 Method calibration

27 Calibrating the SHYREG method consists in determining which rainfall-runoff model parameters  
28 should be used in order to most closely match the frequency distributions for the flows observed at  
29 gauged stations. The calibration steps are described in Fig. 1.



1  
 2 **Figure 1: SHYREG method calibration principle**

3  
 4 The first step is to generate specific flow quantiles for each 1 km<sup>2</sup> pixel. In this way, independent  
 5 hourly rainfall events are simulated at each pixel, using regionalized parameters from the rainfall  
 6 generator. These hourly rainfall events are converted into independent flood events using a simple  
 7 rainfall-runoff model, in which some parameters are fixed (in part because the model is being used  
 8 on 1 km<sup>2</sup> pixel).

9 The hydrological model is of the Irstea GR type ([www://cemagref.fr/webgr/](http://www://cemagref.fr/webgr/)). It consists of two  
 10 reservoirs and a unit hydrograph (Arnaud et al. 2011) and is used in event mode to convert the  
 11 hourly rain scenarios into flood scenarios at pixel scale. After testing the different structures, we  
 12 selected those that performed the best in the flood modelling of 12 small basins (each about 1 km<sup>2</sup>  
 13 area). Thus, we chose to fix most of the model parameters except the first reservoir's initial  
 14 recharge level. The model's rainfall input first goes through a simple unit hydrograph that  
 15 distributes the rainfall in two one-hour time steps: 70% in the first time step and 30% in the second..  
 16 The capacity of the first reservoir A was set as a function of the main hydrogeological classes  
 17 determined according to the territory (Aubert et al. 2013). The capacity of reservoir B was set at 50  
 18 mm (during the summer) and at 100 mm (during the winter), and its initial recharge level R at 30%  
 19 of B's capacity. Reservoir B is the second routing function after the unit hydrograph for modelling  
 20 transfer occurring on 1 km<sup>2</sup> pixels. Reservoir A's initial recharge level (S<sub>0</sub>/A) is therefore the only  
 21 variable parameter (varying from 0 to 1). Simulations are performed for different S<sub>0</sub>/A values; then  
 22 flood events are simulated for each of those values, at each pixel. The flood quantiles are extracted  
 23 empirically from these simulated events. Base flow (Q<sub>0</sub>) is added to the generated flows. Q<sub>0</sub>



1 corresponds to the estimate of mean monthly specific flow, obtained using the LOIEAU regional  
 2 method for estimating water resources (Folton and Lavabre 2006, Folton and Lavabre 2007). While  
 3 this value is often negligible compared to simulated flood flows, it needs to be factored in when  
 4 calibrating the method, because it enables distinguishing between surface runoff and subsurface  
 5 runoff, thus avoiding a calibration bias.

6 The generated flood events are assigned to a simulation period. and analyzed empirically to  
 7 calculate the flood quantile values. Since the number of events per year is known (it is one of the  
 8 rainfall model parameters), there is a correspondence between the empirical frequency and the  
 9 return period (in year). The flood quantiles are read directly from the empirical distribution for  
 10 return periods that are 100 times shorter than the simulation period to ensure the stability of the  
 11 empirical frequencies. For example, to obtain millennial quantiles, the equivalent of 100,000 years of  
 12 rainfall events is simulated and the 1000yr-quantiles are estimated by the 100<sup>th</sup> highest value. This  
 13 task is performed for each of the 550,000 pixels that cover the metropolitan France. The spatial  
 14 variability of specific flows for a same duration, a same return period and a same  $S_0/A$  value is  
 15 mainly caused by the variability of simulated rainfall, then by the size of reservoir  $A$ , and finally, to  
 16 a lesser extent, by the base flow  $Q_0$ . The second step is to calculate the flood quantiles at gauged  
 17 catchment outlets for different  $S_0/A$  parameter values. For each catchment and each  $S_0/A$  value, the  
 18 runoff on catchment pixels is cumulated. This value is then reduced by a function that depends on  
 19 catchment surface area and mean flow duration (Aubert 2012, Fouchier 2010). This function allows  
 20 factoring in areal reduction of rainfall and flood routing simultaneously. It is represented by  
 21 equations (1) and (2):

$$Q(d \geq 24h, T, S_0/A) = \bar{q}_d \cdot f_1(S) \cdot S \quad (1)$$

$$Q(d < 24h, T, S_0/A) = Q(24h, T, S_0/A) + [\bar{q}_d - \bar{q}_{24}] \cdot f_2(S) \cdot S$$

(2)

with the terms  $\bar{q}_d = \left[ \frac{\sum_{i=1}^n q_i(d, T, \frac{S_0}{A})}{n} \right]$  and  $f_i(S) = \frac{1 + \beta_i}{1 + \gamma_i \cdot S^{0.5 \cdot \gamma_i \cdot (1 - S^{\alpha_i})}} \cdot S$

where  $n$  is the number of 1 km<sup>2</sup> pixels contained on the catchment;  $S$  is catchment area in km<sup>2</sup>;  
 $Q(d, T, S_0/A)$  is mean flow (of duration  $d$  and return period  $T$ ) calculated at the catchment outlet ( $d=0$   
 for peak flow) for a given  $S_0/A$  value;  $q_i(d, T, S_0/A)$  is the mean flow of duration  $d$  and return  
 period  $T$ , simulated for a catchment pixel ( $d=0$  for peak flow) for a given  $S_0/A$  value. Parameters  $\alpha_1$ ,  
 $\alpha_2$ ,  $\beta_1$ ,  $\beta_2$ ,  $\gamma_1$  and  $\gamma_2$  are assumed constant over the metropolitan France and were calibrated in a  
 preliminary study with calibration data. This study showed that calibration period does not  
 influence parameter's value estimated over the French territory and  $\alpha_1$ ,  $\alpha_2$ ,  $\beta_1$ ,  $\beta_2$ ,  $\gamma_1$  and  $\gamma_2$  values  
 are fixed. In this way the  $Q(d, T, S_0/A)$  flows are obtained for each catchment.

The areal reduction factor is modelled by the functions  $f_1(S)$  and  $f_2(S)$  presented in Figure 2.  
 $f_1(S)$  represents areal reduction of flow averaged over more 24 hours, and  $f_2(S)$  represents areal  
 reduction of the difference between flow average over less than 24 hours and flow averaged on 24  
 hours.

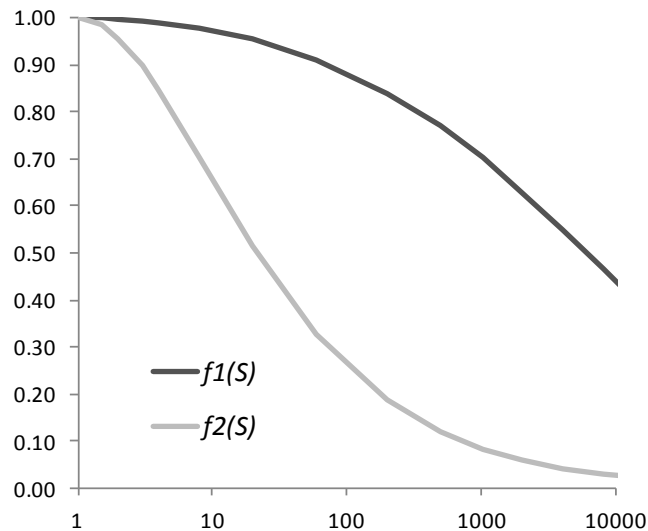


Figure 2 : representation of the areal reduction function.

The third step is the actual calibration of the method and consists in finding the  $S_0/A$  value that minimizes the deviations between the six quantiles obtained from observations (peak flows and mean daily runoff for 2-, 5- and 10-years return periods) and the same six quantiles provided by the SHYREG method. The quantiles from observations are estimated by fitting a GEV probability distribution for which the value of the shape parameter is imposed between 0 and 0,4. The choice of probability distribution is relatively insignificant as long as you are dealing with observed frequencies ( $T < 10$  years). For each gauged catchment, then, the SHYREG method can be calibrated by optimizing a single parameter, on which the regionalization process will rely to apply the method over the entire drainage network (including ungauged environments).

Setting local parameters concerns only the rainfall yield (production), via the calibration of the  $S_0/A$  parameter. When it is calibrated, this parameter also allows offset the assumptions made about the other parameters (fixed or regional parameter) which have been set. Since this is not a continuous method, we assumed that the rainfall events, which are generated independently, always occur in a system where the initial state is the same, and given by the parameter  $S_0/A$ .

### 3 Flow data and assessment index

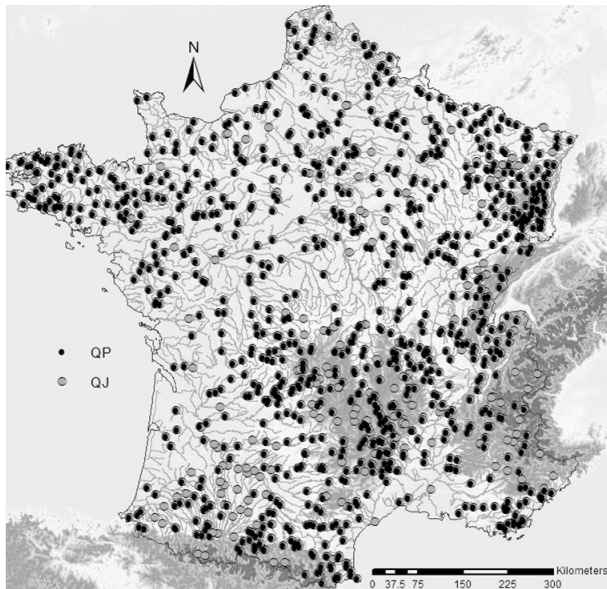
#### 3.1 The data

Even if the SHYREG method was designed as a multivariate approach, the present article focuses on only two flood characteristics: peak flow and daily runoff. The data analyzed are runoff series recorded at 1,172 gauging stations in the metropolitan France for which catchment areas range from 10 to 2000 km<sup>2</sup>. While these series are available in daily time steps, only 605 of them also provide instantaneous runoff series, which are usually observed over shorter periods. These stations, shown in Fig.3, were chosen within the framework of the ANR Extraflo<sup>2</sup> project, from the national Hydro database for the most part, but also from database of Electricity de France (16 stations). They were chosen for their rating curve quality (high level of water deemed satisfactory by the observation

<sup>2</sup> The purpose of the ExtraFlo project (Extreme Rainfall and Floods), funded by the French national research agency ANR, was to establish a comparison framework of methods for estimating extreme rainfall and flood in France.



1 manager) and for their observation period (long enough to provide significant statistics: more than  
2 20 years for all stations, with a median of 40 years). Highly specific stations (heavily karstic or  
3 anthropised catchments) were excluded (Organde et al. 2013). Some of the station selection criteria  
4 are based on tests, like trends and step-changes tests, defined in article (Renard et al. 2008).  
5



6  
7 *Figure 3: Locations of the catchment outlets studied, with gray points showing daily time steps (QJ) only*  
8 *and black points showing instantaneous time steps (QP).*

### 9 10 3.2 Assessment index

11  
12 The framework developed for the ANR Extraflo project was used to assess the SHYREG method.  
13 This framework defines a decomposition strategy to differentiate between the calibration (training  
14 set) and validation (testing set) periods described in the following paragraph. It also defines the  
15 indexes used to assess the methods' results. A thorough description of this assessment platform is  
16 given by the article (Renard et al. 2013).

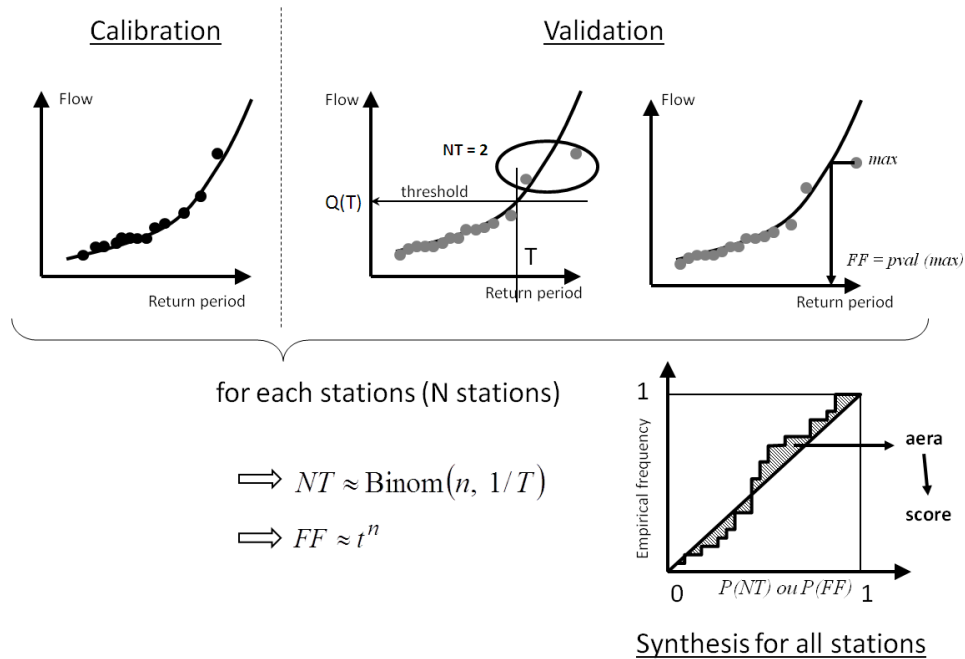
17  
18 This article rapidly describes some of these indexes, which were used to assess method reliability  
19 and stability.

20 Two performance indexes are designed to evaluate the goodness-of-fit with particular care for the  
21 extreme part of the distribution. These indexes allow judging the reliability of a given method on a  
22 whole territory, assessing the ability of a model to assign correct exceedance probabilities for  
23 several stations. These indexes are (Fig.4 shows how these are determined):

- 24 - The index  $NT$  is based on the number of quantile excesses: it verifies if the number of  
25 observation above a  $T$ -year quantile estimated by a given method is consistent with the  
26 empirical quantile level. The theoretical distribution of said number of observations is then  
27 identified by a binomial distribution for parameters  $n$  (number of years of observation) and  
28  $1/T$  (annual frequency of success) (Renard et al. 2013).
- 29 - The index  $FF$ , which is used e.g. by (England et al. 2003, Garavaglia et al. 2011),  
30 corresponds to the frequency a method gives for the highest observed value in  $n$  years of  
31 observation. Under the reliability assumption, the theoretical distribution of this index is

1 characterized by a Beta( $n,1$ ) distribution with parameter  $n$  (number of years of observation)  
 2 (Kumaraswamy 1980).

3  
 4



5  
 6

Figure 4: Calculation principle for reliability indexes  $NT$  and  $FF$

8

9 First the method is calibrated on the observations from the calibration set (black curves and black  
 10 dots in Fig.4). The values for the indexes  $NT$  and  $FF$  are then calculated based on the observations  
 11 in the validation set (gray dots). By inverting the theoretical probability distributions for these index  
 12 (binomial for  $NT$  and beta for  $FF$ ), their probability of occurrence are obtained,  $P(NT)$  and  $P(FF)$ ,  
 13 which should follow a uniform probability if the model is reliable. The reliability of the methods is  
 14 determined by the deviation between the observed probability and the theoretical probability for the  
 15 indexes  $NT$  and  $FF$  (the graph at the bottom of Fig.4). If the frequency distributions for the  $P(NT)$   
 16 and  $P(FF)$  align around the bisector –ie- close to a uniform law., then the method has no systematic  
 17 bias. Graphical analysis shows the nature of the biases of the method. If the distribution is below the  
 18 bisecting line, then the method tends to underestimate flood quantiles; whereas if it is above, then  
 19 the method tends to overestimate flood quantiles on the studied territory. When the distribution  
 20 appears as a 'S' curve, it means that the method is over-parameterized.

21

22 The stability of a frequency analysis method is linked to its ability to produce similar results when it  
 23 is calibrated on different samples. In order to determine the stability of a method, a model  
 24 calibration is performed independently on two different data samples ( $C1$  and  $C2$ ) leading to two  
 25 quantile estimations ( $Q_{C1}$  et  $Q_{C2}$ ). Then the relative deviations between the quantiles for different  
 26 return periods ( $T$ ) and at each site ( $i$ ) can be estimated (equation (3)) (Garavaglia et al. 2011).

$$27 \quad SPAN^{(i)}(T) = 2 \cdot \frac{|Q_{C1}^{(i)}(T) - Q_{C2}^{(i)}(T)|}{Q_{C1}^{(i)}(T) + Q_{C2}^{(i)}(T)} \quad (3)$$

28 A stable method is then characterized by an index  $SPAN$  close to 0.

1 The graphical analysis of the different indexes can be synthesized by calculating scores, which are  
2 based on calculations of the area between the observed distribution and the theoretical distribution  
3 (bisecting line) for each index (Fig.4). By standardizing this area, it is possible to make all scores  
4 vary between 0 (poor performance) and 1 (perfect performance) (Renard et al. 2013).

### 6 3.3 Decompositions

7 To assess the method's performance, statistical decompositions were performed on the observation  
8 years. For method reliability, the observation years were split into two samples: a calibration sample  
9 consisting of a random sampling of the years used to calibrate the method, and a validation sample  
10 composed with the rest of the years. For reliability, three decompositions were performed:

- 11 - C50V50: out of 519 daily runoff series (and of 605 instantaneous runoff series) with at least  
12 40 years (respectively 20 years) of observations, 50% of the years were used for calibration  
13 and 50% of the years were used for validation;
- 14 - C33V66: out of 519 daily runoff series (and of 605 instantaneous runoff series) with at least  
15 40 years (respectively 20 years) of observations, 33% of the years were used for calibration  
16 and 66% of the years were used for validation
- 17 - CVrecord: out of 1,143 stations with at least 15 years of data, method calibration was  
18 performed on the complete series without the year of record, and validation was performed  
19 on the complete series including the year of record (in this case is not a random sampling).

20 For method stability, the years were decomposed into two calibration sub-samples having the same  
21 size:

- 22 - Calibration sub-samples 1 (C1), the years on which the method was calibrated,
- 23 - Calibration sub-sample 2 (C2), with the same sample size as C1, also used to calibrate the  
24 method.

25  
26 Because method stability could depend on the amount of data available, several decompositions  
27 were performed using sample size for both periods, over 10, 15 and 20 years. The decompositions  
28 were labelled CC\_10, CC\_15, and CC\_20, respectively, and required gauging stations with  
29 minimum observation periods of 20, 30 and 40 years, respectively. Due to the lengths of runoff  
30 series, decomposition was performed only on daily data for which the observation periods were  
31 longer. On this basis, the number of available stations was 1,122 stations with more than 20 years of  
32 data, 848 stations with more than 30 years of data, and 432 stations with more than 40 years of data.  
33

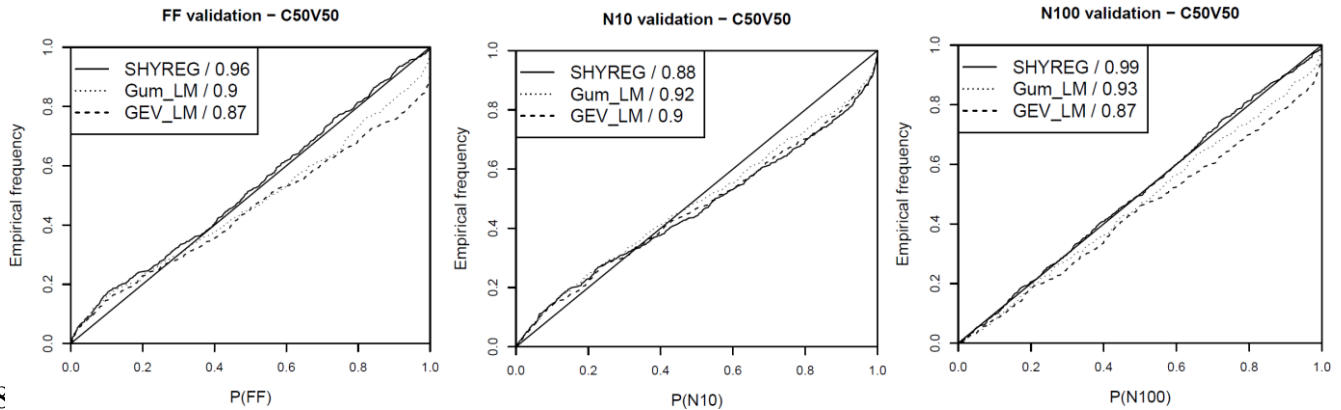
## 35 4 Results

36 The SHYREG method's performance was analyzed by viewing the frequency distributions for  
37  $P(NT)$  and  $P(FF)$  and stability index  $SPAN$  and computing the corresponding scores (indicated in  
38 the graph legend). To put the results of the SHYREG method into perspective, we compared these  
39 results to those obtained with two other usual statistical models in France: the Gumbel distribution  
40 (2 parameters) and the GEV distribution (3 parameters), for which the parameters are estimated by  
41 the L-Moments method. This comparison is far from being exhaustive, and serves only to put the  
42 results into perspective compared to simple, well-known methods. First we present the results for  
43 daily flow estimates.  
44

#### 1 4.1 The method's reliability

2 To judge the method's reliability the  $FF$  and the  $NT$  indexes has been used. The index  $NT$  was  
 3 calculated for 10- and 100-year return periods (values  $N10$  and  $N100$ ). The graphs in Fig.5 show the  
 4 index frequency distributions for the three models that were compared (SHYREG, Gumbel  
 5 distribution and GEV distribution), obtained at the C50V50 decomposition validation stations. The  
 6 index for each curve is indicated in the upper left-hand corner.

7



8

Figure 5: Frequency distribution for  $P(FF)$  (a),  $P(N10)$  (b) and  $P(N100)$  (c)

9 The values of  $FF$  and  $N100$  represent the capacity of the models to assign accurate frequencies to  
 10 extreme values. The value of  $N10$  determines the ability to exceed rare values. In the case of  
 11 extreme values, the values of SHYREG's reliability index are very good. The two statistical models  
 12 also perform well. The frequency distribution analysis of  $P(FF)$ , however, reveals a tendency of the  
 13 purely statistical models to underestimate the frequency of the highest records in some cases (curve  
 14 below the bisecting line). Assigning a  $P(FF)$  of 1 is particularly problematic, since the record  
 15 observed over the validation period is deemed "improbable". This was the case for 19 stations out  
 16 of the 519 analyzed, when calibrating a GEV distribution based on the calibration sample. The GEV  
 17 distribution has three calibration parameters, so it can be calibrated as closely as possible to the  
 18 empirical distribution (and presents the risk of over-fitting). If the empirical distribution has no  
 19 extreme values, it is likely that the proposed extrapolation will underestimate the probability of  
 20 observing a high value. The extrapolation to rare frequencies proposed by the SHYREG method, on  
 21 the other hand, is linked directly to the extrapolation proposed by the rainfall model, in combination  
 22 with the rainfall-runoff model's saturation capacity. This characteristic seems preferable in  
 23 proposing a more reliable extrapolation to extreme values.

24

#### 25 4.2 The method's stability

26

27 Method stability was determined by analyzing the distribution of the index  $SPAN$ , estimated from  
 28 the quantiles for the 10-, 100- and 1,000-year return periods ( $SPAN10$ ,  $SPAN100$  and  $SPAN1000$ ).  
 29 The graphs in Fig.6 show the results obtained using two 20-year calibration periods (decomposition  
 30 CC\_20).  
 31

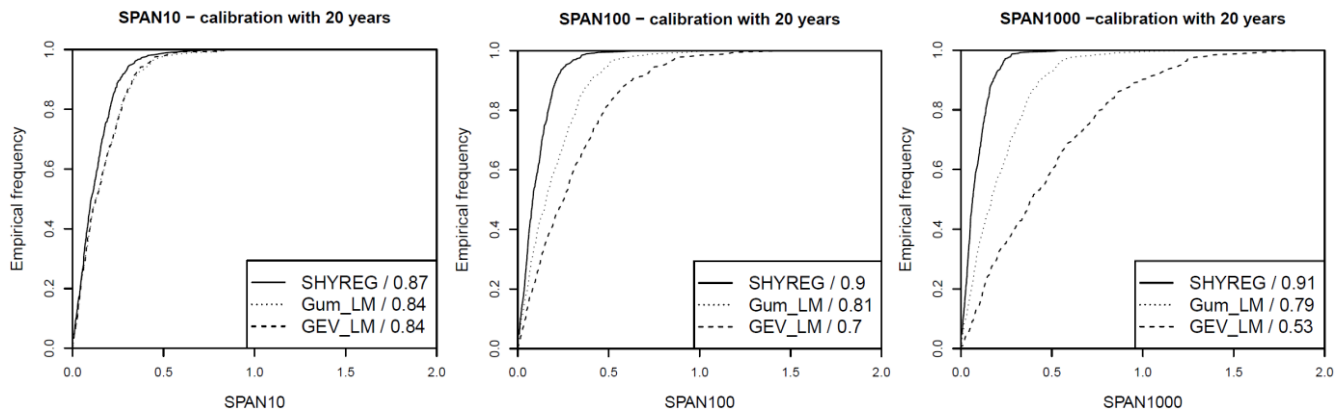


Figure 6: Frequency distribution for index SPAN computed from the quantiles for 10-year (a), 100-year (b) and 1,000-year (c) return periods.

4 The methods are generally less stable when dealing with the longest return periods. The instability  
 5 is even greater for the methods that are calibrated using a larger number of parameters. For instance,  
 6 fitting a GEV distribution (3 parameters) is less stable than fitting a Gumbel distribution (2  
 7 parameters). For the SHYREG method, fitting the method at site relies only on the calibration of a  
 8 single parameter that represents catchment production in a simplified way. It is clearly  
 9 representative of average catchment behaviour and will be weakly influenced by the calibration  
 10 sample. This is also why calibrating this parameter is based on fit of current flood quantiles (T = 2,  
 11 5 and 10 years). The extrapolation stability is then linked to the stability of both the rainfall  
 12 generator and the rainfall-runoff relationship. Rainfall generator stability was also analyzed under  
 13 the ANR Extraflo project. The stability of the SHYREG method's rainfall generator was shown to  
 14 be especially stable (Carreau et al. 2013), in agreement with the results of (Muller et al. 2009)  
 15 showing that the confidence intervals for the quantiles provided by the hourly rainfall generator are  
 16 relatively narrow.

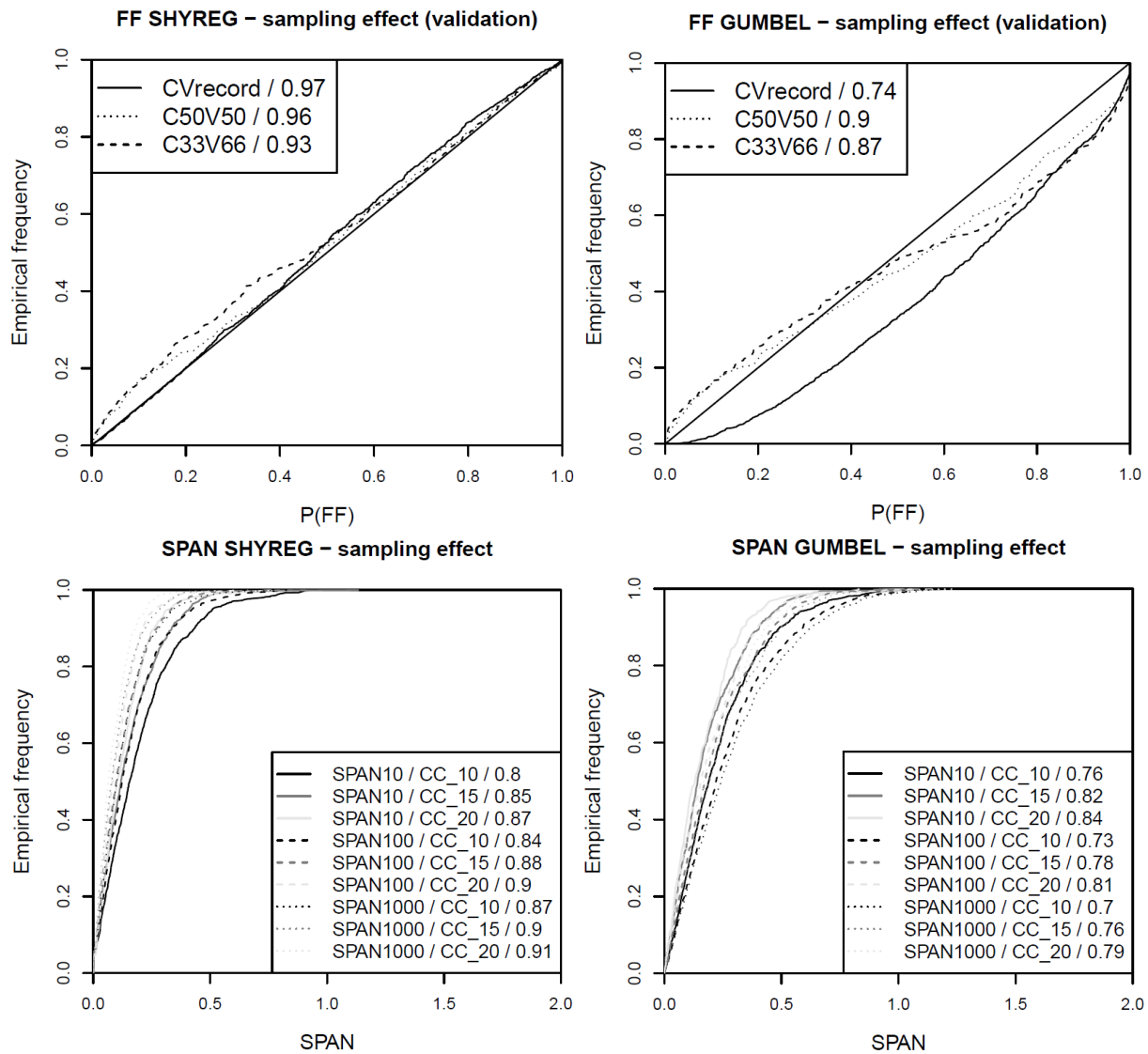
17

### 18 4.3 Sampling effect

19 The SHYREG method's performances are analyzed with respect to the size of period sampling. The  
 20 reliability is compared on the C33V66, C50V50 and CVrecord decompositions presented above.  
 21 The stability is tested on decompositions CC\_10, CC\_15 and CC\_20 to analyze the impact of  
 22 calibration sample size on the method's stability. To put these results into perspective, we present  
 23 only the results obtained with a Gumbel distribution fit. The choice of a Gumbel distribution has  
 24 been motivated by its better stability than that of GEV distribution and so, more challenging.

25





2  
 Figure 7: Sampling effect on the SHYREG method's performance and comparison with that of a Gumbel distribution.

5 Graph (a) in Fig.7 shows that the SHYREG method is not highly sensitive to the sampling period.  
 6 However, we must remember that in the case of the C33V66 decomposition, we have at least 13  
 7 years of calibration. The most interesting result is that the method has very good reliability index  
 8 even if the highest value is systematically omitted from the calibration sample. The absence of such  
 9 a record value in the calibration sample does not create a bias in the SHYREG method's extreme  
 10 value estimates. This is particularly significant given of the problems that can occur with  
 11 measurement of extreme flood data. The analysis of (b) in Fig.7 shows that a 2-parameter  
 12 distribution is much more sensitive to sampling, in particular when the highest value is omitted  
 13 from the sample. In that case, the model almost systematically underestimates the probability of  
 14 extreme flood occurrence. SHYREG provides more "predictive" extrapolations. This is linked to  
 15 the method's heavy reliance on regional rainfall data. Since the rainfall-runoff relationship is not  
 16 highly sensitive to knowledge of an extreme event (the rainfall-runoff model must be parameterized  
 17 independently of rainfall), the method has the capability to calibrate itself correctly despite the  
 18 absence of extreme values in the calibration sample. This is not the case for a method that use only  
 19 on runoff data, especially if it is calibrated at site and if it have a lot of parameters. That is why



1 methods that use only on runoff must factor in regional runoff data (Darlymple 1960, Hosking and  
 2 Wallis 1997, Ribatet et al. 2007, Ouarda et al. 2008).

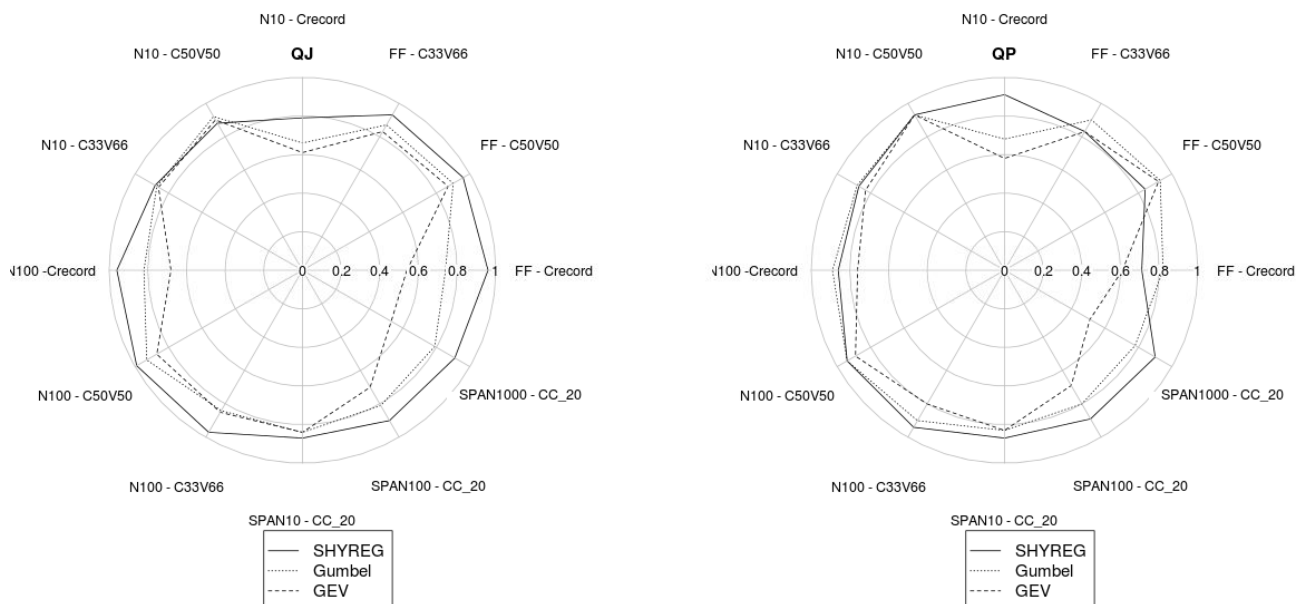
3 The sampling effect on stability is logical. Graphs (c) and (d) in Fig.7 show that longer the  
 4 calibration period is, greater the stability is. The length of the calibration period has no real impact  
 5 in the SHYREG's method, whatever the return period. For a Gumbel distribution, stability  
 6 decreases when the return period increases and when the calibration period decreases. These results  
 7 are even more marked with the 3-parameter distribution as GEV.

8

#### 9 4.4 Multivariate approach

10 The SHYREG method is a multivariate method. For the same calibration and simulation, it provides  
 11 flood quantiles for different durations from peak flow to 3-day flood volumes. The radar charts in  
 12 Fig. 8 summarize the scores obtained when both daily flows QJ (left) and peak flows QP (right).  
 13 The outer-most curves show the best performance.

14



15

16 **Figure 8:** Method's score for daily flow and peak flow estimates.

17 For peak flows, the observations of mean daily flows remain valid. However, there is a slight  
 18 decrease in SHYREG performance for reliability criteria estimates, because the method slightly  
 19 overestimates (by roughly 5-10%). The method shows the same stability characteristics. The peak-  
 20 flow results for a statistical distribution (Gumbel or GEV) are similar to those for daily flows.

21

22 The results obtained here show that the method performs well with respect to its capacity to  
 23 estimate flood quantiles for different durations. This is especially noteworthy because the  
 24 performance of multivariate approaches tends not to be as good as that of univariate approaches  
 25 where the parameters can be calibrated for each variable of interest (Gräler et al. 2013).

26

#### 27 4.5 Sensitivity to the modelling hypothesis

28 The stability characteristics of the SHYREG method are linked to the fact that the rainfall-runoff  
 29 model has few parameters. Calibrating the method relies on a single parameter,  $S_0/A$ . The other  
 30 parameters used in rainfall-runoff models are either fixed values, or regional parameters that are

1 prescribed by the method's modelling hypotheses and therefore not considered as at-site fitting  
 2 parameters. To see the impact of modelling hypotheses on the method's results, different model  
 3 versions are tested. To avoid overloading the analysis, we present only the tests with a potential  
 4 impact on the method's asymptotic behaviour. These tests involve the parameters associated with  
 5 the method's equifinality issues as presented by (Aubert 2012, Aubert et al. 2013).

6  
 7 The table below lists the hypotheses that were tested for the regionally estimated parameters. In  
 8 particular the parameterization of the production reservoir *A*, which can influence the asymptotic  
 9 behaviour of the method towards extreme values, is discussed.

| Test      | Value of <i>A</i>      | Drainage of <i>A</i> | $Q_0$                     |
|-----------|------------------------|----------------------|---------------------------|
| Final     | Hydrogeology dependent | No drainage          | Factored in               |
| Variant 1 | Max (200 mm, PJ100)    | No drainage          | Factored in               |
| Variant 2 | Max (200 mm, PJ100)    | With drainage        | Factored in               |
| Variant 3 | Max (200mm, PJ100)     | With drainage        | Not factored in $Q_0 = 0$ |

11

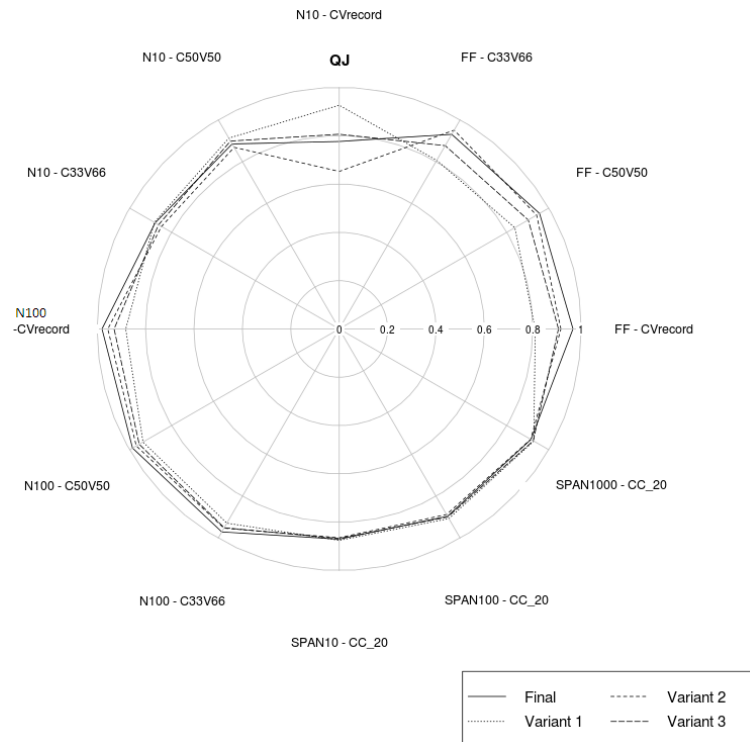
*Table 1. Summary of hypotheses tested for regional parameters of rainfall-runoff model.*

13

- 14 - The value of reservoir *A*: In one version of the approach, the maximum capacity of  
 15 production reservoir *A* was parameterized as a function of the 100-year daily rainfall (*PJ100*  
 16 in mm) (Organde et al. 2013). This value was optimized for each catchment on data of  
 17 calibration years and a link with the hydrogeology was established. The value of reservoir *A*  
 18 was then regionalized as a function of the hydrogeology. This process is only weakly  
 19 influenced by station sampling, because the hydrogeology link is relatively weak and serves  
 20 only to establish key value classes according to hydrogeologically homogeneous regions.  
 21 Still, it does help to enhance the method's performance, in particular on catchments in  
 22 Northern France (Aubert 2012) with high retention capacity.
- 23 - Drainage of reservoir *A*: there is no drainage of reservoir *A*, and this could result in its  
 24 saturation during an event. A version taking drainage into account was tested, with drainage  
 25 parameterized as being proportional to the capacity of *A* (Organde et al. 2013). This relation  
 26 avoids regionalizing an additional parameter.
- 27 - Factoring in base flow  $Q_0$ : the method did not initially take base flow into account. When  
 28 the method was adapted to a wider range of hydrological conditions, a base flow was  
 29 factored in to improve method calibration. Improvements were subsequently observed,  
 30 especially on catchments that are heavily influenced by subsurface exchange and snow melt  
 31 (Aubert 2012).

32

33 The radar charts in Fig.9 provide a synthesis of SHYREG's scores as a function of the different  
 34 rainfall-runoff modelling hypotheses.



1  
 2 **Figure 9:** SHYREG method's score for different rainfall-runoff modelling hypotheses used in the method.

3 The modelling hypotheses have a moderate impact on SHYREG's performance. The impact mainly  
 4 concerns the extreme values, seen through the evolution of the *FF* score. The *N10* and *N100* values  
 5 are less sensitive to the modelling hypotheses. However, the method's stability does not change  
 6 whatever the hypothesis made. The method's calibration parameter  $S_0/A$  takes on different 'optimal'  
 7 values as a function of the hypotheses tested on the rainfall-runoff model's production. These  
 8 values serve to provide identical estimates for the common values ( $T < 10$  years) used to calibrate the  
 9 model. On the other hand, extrapolations to extreme values can be more variable, although certain  
 10 configurations can compensate. For instance, Variant 2 is able to reach the performance of the Final  
 11 model by introducing a drainage process into the production reservoir. Variant 1 resulted in a  
 12 smaller average capacity for reservoir *A* than the initial model, causing the reservoir to saturate  
 13 more rapidly. Adding a drainage process helps compensate for the saturation. Variant 3 serves to  
 14 confirm the advantage of taking into account an initial flow, even if the gain is relatively small. So  
 15 here, we are verifying that SHYREG's chosen modelling hypotheses have no impact on the  
 16 method's stability, and a relatively small impact on its reliability.

17  
 18 **5 Discussion**

19 It is difficult to validate flood frequency analysis methods at only one station, due to the lack of  
 20 observation data on extreme values. The original methodology used in this article allows assessing  
 21 methods by compiling statistics over a large number of stations. Comparison with other standard  
 22 hydrological approaches (fitting a probability distribution on annual maximum flows) also helps to  
 23 put into perspective the performance of the SHYREG method. The methods are first assessed for  
 24 their reliability. If the values of the reliability indexes are weak then the method is unreliable,  
 25 because of systematic biases for example. If the reliability criteria are good, you cannot affirm that  
 26 the method is reliable but only that it is not incorrect. This is due to the criteria that cannot detect  
 27 random biases in a method (it can only detect systematic biases). So, in the case of random biases,

1 good reliability value can be due to hazard. However, a method containing this type of random bias  
2 will be detected by its poor stability performance.

3 The SHYREG method has good reliability criteria. Among methods with good reliability criteria,  
4 the method with the greatest stability is to be preferred. This is also the case for SHYREG method,  
5 where the good stability characteristics are due to the small number of parameters (only one  
6 parameter) it requires and the type of approach. It would appear that an approach based on rainfall  
7 data use leads to particularly relevant flood flow extrapolation.

8  
9 The SHYREG method was also assessed within the larger framework of the ANR Extraflo project,  
10 where additional statistical methods, e.g. regional ones, were compared. It emerged that only  
11 approaches that take regional data into account can lead to reliability and stability results close to  
12 those of the SHYREG method (Kochanek et al. 2013). The benefits of these RFFA are now  
13 emphasized by many authors. These results of ANR Extraflo project showed that SHYREG method  
14 has the same benefits as RFFA.

15  
16 Despite its good performance, the method needs improvement. In particular, the use of a unique  
17 runoff reduction factor for the whole French territory is a strong assumption and need to be  
18 improved in the future. In this way, we are working to impose coefficients by large hydro-climatic  
19 areas.

## 20 21 22 **6 Conclusion**

23 This study demonstrates the performance of an extreme flood estimation method by simulation. The  
24 SHYREG method is designed to analyze flood flows of all durations (from peak flow to 3-day flood  
25 volumes) based on the calibration of a single parameter characterizing catchment production. The  
26 SHYREG method was applied to French territory and regionalized; it is currently in operational use  
27 to estimate extreme flood flows (Aubert et al. 2013).

28 Split-sample test procedures were used to assess the method based on its “predictive” performance.  
29 Statistical reliability and stability criteria were calculated for different sampling configurations. To  
30 put the results into perspective, they were compared with those from standard statistical models in  
31 use that are based on parametric probability distributions fitted on peak annual flow data (Gumbel  
32 distribution and GEV distribution).

33  
34 The results show that the SHYREG method is highly stable. The method’s stability is linked to the  
35 fact that it relies on the regional statistical features of the data and on a simple rainfall-runoff model.  
36 Calibrating the method on a catchment is done using a single parameter. The other parameters are  
37 set *a priori* on a regional basis, independently of the rainfall data that is available for the catchment  
38 under consideration.

39  
40 The method’s reliability indexes have very good values, better than those found with the standard  
41 statistical methods that were tested. A supplementary study showed that to obtain reliability criteria  
42 as good as SHYREG’s, you would need to use a regional statistical distribution (Kochanek et al.  
43 2013). The method’s reliability is linked to the type of approach, which proposes an estimation of  
44 extreme flows based on regional extreme rainfall data. This type of rainfall data as provided by the

1 method was also found to be reliable and stable (Carreau et al. 2013). It was also demonstrated that  
2 the method enables relevant “predictive” estimates, e.g., by assigning correct return periods to the  
3 record values missing from the calibration data.

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28 **Tables:**  
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| Test      | Value of A             | Drainage of A | $Q_0$                     |
|-----------|------------------------|---------------|---------------------------|
| Final     | Hydrogeology dependent | No drainage   | Factored in               |
| Variant 1 | Max (200 mm,PJ100)     | No drainage   | Factored in               |
| Variant 2 | Max (200 mm,PJ100)     | With drainage | Factored in               |
| Variant 3 | Max (200mm ,PJ100)     | With drainage | Not factored in $Q_0 = 0$ |

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31 Table 1. Summary of hypotheses tested for regional parameters of rainfall-runoff model.

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- 2 **Figure captions.**
- 3 Figure 1: SHYREG method calibration principle
- 4 Figure 8 : representation of the areal reduction function.
- 5 Figure 3: Locations of the catchment outlets studied, with gray points showing daily time steps (QJ)
- 6 only and black points showing instantaneous time steps (QP).
- 7 Figure 4: Calculation principle for reliability parameters NT and FF
- 8 Figure 5: Frequency distribution for reliability criteria P(FF) (a), P(N10) (b) and P(N100) (c)
- 9 Figure 6: Frequency distribution for SPAN stability criteria computed from the quantiles for 10-
- 10 year (a), 100-year (b) and 1,000-year (c) return periods.
- 11 Figure 7: Sampling effect on the SHYREG method's performance and comparison with that of a
- 12 Gumbel distribution.
- 13 Figure 8: Method's score for daily flow and peak flow estimates.
- 14 Figure 9: SHYREG method's score for different rainfall-runoff modelling hypotheses used in the
- 15 method.
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