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Return Period of Characteristic Discharges from the Comparison between Partial Duration and Annual Series, Application to the Walloon Rivers (Belgium)

Jean Van Campenhout *, Geoffrey Houbrechts, Alexandre Peeters and François Petit

Hydrography and Fluvial Geomorphology, UR Spheres, Department of Geography, University of Liège, Research Centre, 4000 Sart-Tilman, Liège, Belgium; g.houbrechts@uliege.be (G.H.); a.peeters@uliege.be (A.P.); francois.petit@uliege.be (F.P.)

* Correspondence: jean.vancampenhout@uliege.be; Tel.: +32-4-366-52-97

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Abstract: The determination of the return period of frequent discharges requires the definition of flood peak thresholds. Unlike daily data, the volume of data to be processed with the generalization of hourly data loggers or even with an even finer temporal resolution quickly becomes too large to be managed by hand. We therefore propose an algorithm that automatically extracts flood characteristics to compute partial series return periods based on hourly series of flow rates. Thresholds are defined through robust analysis of field observation-independent data to obtain five independent flood peaks per year in order to bypass the 1-year limit of annual series. Peak over thresholds were analyzed using both Gumbel's graphical method and his ordinary moments method. Hydrological analyses exhibit the value in the convergence point revealed by this dual method for floods with a recurrence interval around 5 years. Pebble-bedded rivers on impervious substratum (Ardenne rivers) presented an average bankfull discharge return period of around 0.6 years. In the absence of field observation, the authors have defined the bankfull discharge as the $Q_{0.625}$ computed with partial series. Annual series computations allow Q_{100} discharge determination and extreme floods recurrence interval estimation. A comparison of data from the literature allowed for the confirmation of the value of Myer's rating at 18, and this value was used to predict extreme floods based on the area of the watershed.

Keywords: return period; bankfull recurrence interval; Gumbel methods of moment; graphical method; peaks-over-threshold algorithm; extreme floods analysis

1. Introduction

In many hydrological and geomorphological studies, determining the return period of hydrological events or conversely estimating the discharge value for a given return period is often required. Among the great variety of laws governing statistics and probability used to estimate return period of given discharge value from the series of historical flows (log-normal, log-Pearson, power, exponential, Gumbel, generalized extreme values, Weibull, generalized Pareto, generalized logistic, Poisson distribution …), the Gumbel method was found to be particularly well suited for these types of estimates [1–6].

However, two problems arise: (1) how best to choose between working with either annual series (T_a) or partial series (T_p); (2) which threshold flow should be used to select floods for the partial series method. Annual series do not allow for an estimation of recurrence intervals of bankfull discharge of less than 1 year. This is a problem because such recurrences occur regularly on many rivers in Wallonia, particularly in the Ardenne [7].

In addition, depending on the threshold values used for the partial series method, there are significant differences between the two procedures (T_a and T_p) for predicting a flood with low recurrence [8]. To determine this threshold, a literature review was conducted in order to compare the different threshold values and to confidently select a reliable method based on a series of comparisons and tests.

Most of the previous return period studies were based on daily discharge values because hourly series were too short. Nowadays these records cover often longer than 30 years for some hydrographic stations installed on upland rivers (Wallonia, Belgium). Given that on Ardennian small catchments the most frequent floods are generally shorter than one day, it is preferable to work with hourly discharge data. However, these records represent several hundred thousand unique values, making peak flow identification difficult to calculate manually.

Therefore, an automatic method of calculation in hourly discharge was developed. This method makes it possible to identify hydrological independent events above the threshold and then automatically calculate the characteristic flows.

Most of the hydrology stations used in this paper have hydrologic series covering over more than 30 years, which was essential to decrease the confidence interval of estimated return periods. Indeed, the computation of return periods has to be based on a series of continuous hydrological data over a sufficiently long period of daily flows or hourly flows. Woodyer [9] and Engeland et al. [10] recommend 50-year long series to reduce uncertainties in calculating the recurrence of infrequent floods. The recommendations for the length of hydrological series are usually expressed as daily data. However, unlike other meteorological data such as the amount of rainfall, the autocorrelation of discharge data due to the high resolution [11] will not change the recommendations because the watershed will always have a smoothing effect on the water level. It should be noted that whilst hydrological series with duration between 30 to 50 years can be used, caution should be exercised as the computed recurrences of extreme floods will be less reliable.

As part of this study, the authors have compiled all observations of bankfull discharge of rivers equipped with hydrographic stations. These field observations have supplemented or revised the values presented in the literature [7,12–19]. In addition, these data sets enable prediction of rare events. Given a sufficiently long duration of discharge series, we successfully estimated Q_{100}-flood discharge. Moreover, extreme events have also been compiled, analyzed and compared to Q_{100} estimates. Maximum probable extreme floods were estimated from the catchment area by Guilcher [20] and Réméniéras [21]. Recent data has been compiled using their methodology in order to propose a robust value for the Myer–Coutagne equation [22] for the rivers of Wallonia.

2. Materials and Methods

2.1. Study Sites

The study takes place in Wallonia, the southernmost region of Belgium. This mid-latitude region, with a Cfb climate, i.e., a warm-temperate climate without dry season (oceanic type), according to the updated Köppen–Geiger classification, experiences annual rainfall ranging from 725 mm in westermost Wallonia to 1400 mm in the Hautes Fagnes plateau [23]. In total, 76 hydrographic stations are considered in this study. On the non-navigable rivers these stations are managed by the Aqualim network and for those stations on the navigable waterways the SETHY network is in charge. Both networks are entities of the Public Service of Wallonia (*SPW*). Since the end of the 2000s, Aqualim stations record data in 10-minute intervals which is then aggregated hourly for their use and provision by the manager. The SETHY stations measure the water level hourly. Undisclosed rating curves give hourly discharge data. The catchment area of these limnigraphic stations ranges from 20 to 2910 km^2. The oldest station recording hourly data was installed in 1967; 37 stations offer data starting before 1990, 24 between 1990 and 2000, and 15 after 2000 (Table 1).

The regional classification of stations depends on their location more specifically on their sedimentary heritage, which is directly related to the local geology (Figure 1) of their catchment area [7,24]. Of these stations, 37 have a regional affiliation to the Ardenne with impervious schisto-sandstone substratum of

Cambrian-Ordovician and lower Devonian (nos. 1 to 37). The second group includes rivers located in the Fagne–Famenne region (nos. 38 to 47), a lithological depression eroded into the lower Famennian and Frasnian soft shales. The third group comprises rivers in the Condroz region (nos. 48 to 51) with Carboniferous limestone formations in depressions and Upper Devonian sandstone formations on its ridges. The fourth group encompasses rivers in the Entre-Vesdre-et-Meuse region (nos. 52 to 54). Its geologic substratum is composed of Devonian rocks, Cretaceous deposits and Meuse terraces area, with gravel-bed rivers on moderately permeable substrates.

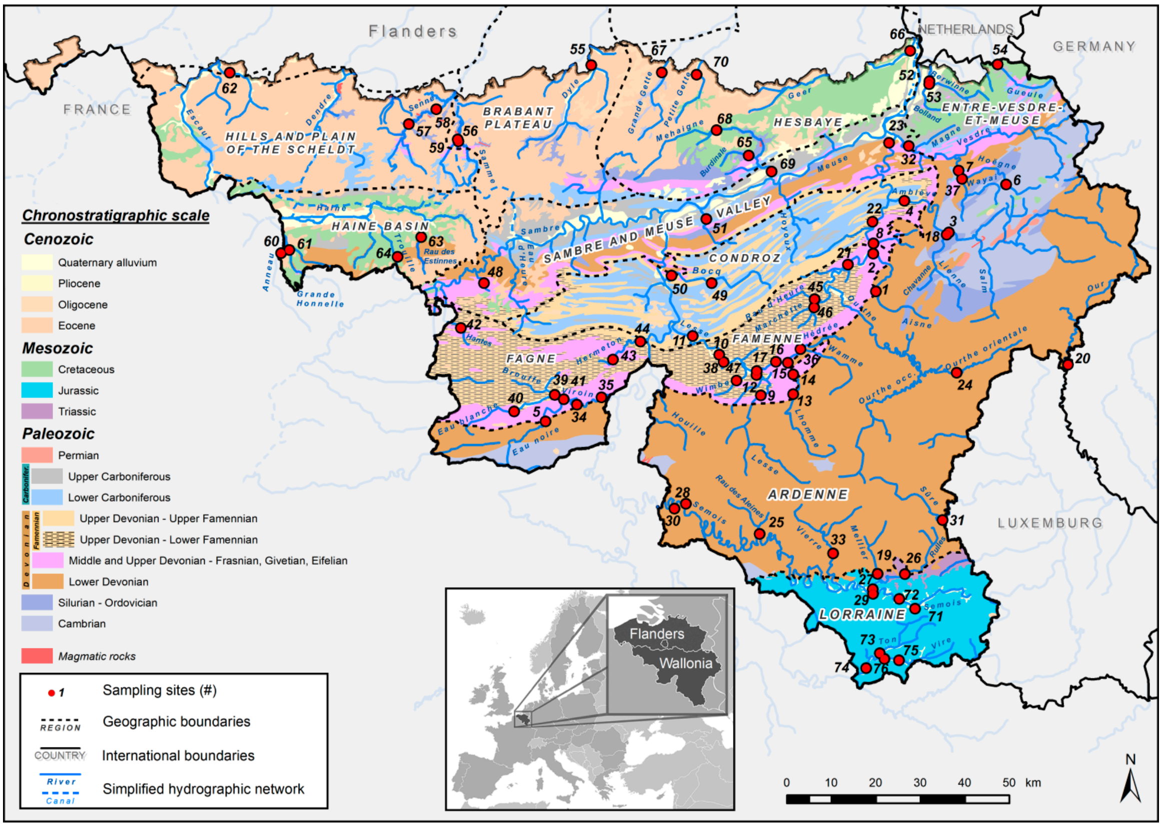

Figure 1. Location of the studied hydrological stations and simplified geological map of Wallonia (according to de Béthune [25] and Dejonghe [26], modified).

The fifth group incorporates the rivers located in the Brabant region (nos. 55 to 59), where substratum is composed of Cambrian-Ordovico-Silurian formations under Eocene and Loessic sandy cover. Hainaut rivers are the sixth group nos. 60 to 64); they are located in a silty area with subsoil composed of Tertiary clay west of the Senne river and Cretaceous formations in the Haine basin. Cretaceous chalk is also found in the Hesbaye region (nos. 65 to 70), covered by a thick layer of loess.

The eighth and last group encompasses Lorraine stations (nos. 71 to 76) with sandy-loaded rivers developed on Triassic and Lower Jurassic deposits of various kinds: conglomerates, marl and sandstone, limestone, and sandy limestone.

2.2. Bankfull Discharges of a Selection of Rivers in the Meuse and Scheldt Basins

Among the characteristics discharges, the bankfull discharge is one of the most important for geomorphological and hydrological reasons [7]; it is indeed an integrator of a large number of basin characteristics [16]. Williams [27] compiled 16 methods for determining this flow while Navratil [28] compared several methods of determination of bankfull discharge magnitude and frequency in gravel-bed rivers. The most common of them are: field observation at a hydrometric station equipped with a stable rating curve, hydraulic geometry of the section [29,30], flood frequency analysis, or a determination through Manning equation. Other authors analyze water level time-series in order to detect the overbank flow [31].

The safest method is to observe the bankfull discharge in the field, preferably in a natural area [27]. We used this way of determination Q_b values for selected rivers.

In most stable alluvial channels, it is generally accepted that the recurrence of Q_b ranges between 1 and 2 years, expressed in annual series [27,32–36]. Dury [37] considered that the return period of Q_b was equal to 1.58 years, the value corresponding to the most probable value of the annual maximum in the Gumbel distribution. Tricart [38] assumed a recurrence of Q_b equivalent to 1.5 years. However, Petit and Daxhelet [12] demonstrated that it increases with catchment size, annual rainfall, contrast of the hydrologic regime, while it decreases with bed load sediment grain size. Amoros and Petts [39] and Edwards et al. [40] estimate the recurrence of Q_b at 1.5 years but closer to one year for rivers with an impervious substrate and closer to 2 years in permeable terrain area. Wilkerson [41] also postulates that the 2-year recurrence flood (Q_2) can be a good estimate of Q_b in absence of field observations.

Table 1. Hydrological parameters of the studied stations.

ID	River	Location	A (km^2)	Station Code	Station Start Date	N_y	Q_b ($m^3 \cdot s^{-1}$)	Specific Q_b ($m^3 \cdot s^{-1} \cdot km^{-2}$)	Sources of Q_b Observation
					ARDENNE Region				
1	Aisne	Erezée	67.4	L6690	1998–12	20	7.3	0.108	Houbrechts (2000) [14]
2	Aisne	Juzaine	183	L5491	1975–03	34	23.8	0.130	Houbrechts (2000) [14]
3	Amblève	Targnon	802.9	S6671	1968–06	20	87.3	0.109	New observation
4	Amblève	Martinrive	1062	S6621	1968–10	45	140	0.132	Houbrechts (2005) [42]
5	Eau Noire	Couvin	176	S9071	1968–03	33	36.9	0.210	New observation (2008)
6	Hoëgne	Belleheid	20	S6526	1993–06	25	10	0.500	New observation (2019)
7	Hoëgne	Theux	189	L5860	1979–02	36	36.8	0.195	Deroanne (1995) [43]
8	Lembrée	Vieuxville	51	L6300	1991–09	26	7.9	0.155	Houbrechts (2005) [42]
9	Lesse	Resteigne	345	L5021	1992–06	46	33	0.096	Franchimont (1993) [44]
10	Lesse	Hérock	1156	L6610	1996–05	23	105	0.091	Bioengineering techniques report (2016)
11	Lesse	Gendron	1286	S8221	1968–01	51	131	0.102	Bioengineering techniques report (2016)
12	Lesse	Eprave	419	L5080	1969–01	41	37	0.088	Petit et al. (2015) [45]
13	Lhomme	Grupont	179.9	L6360	1991–10	22	20	0.111	Franchimont (1993) [44]
14	Lhomme	Forrières	247	L6310	1991–10	24	24.5 [1]	0.099	Computed $Q_{0.625}$
15	Lhomme	Jemelle	276	S8527	1969–01	50	29.7 [1]	0.108	Computed $Q_{0.625}$
16	Lhomme	Rochefort	424.9	L6650	1996–07	22	51.8 [1]	0.122	Computed $Q_{0.625}$
17	Lhomme	Eprave	478	L6360	1992–07	24	60	0.126	Petit et al. (2015) [45]
18	Lienne	Lorcé	147	L6240	1992–09	25	21.3	0.145	Houbrechts (2005) [42] and new authors observation (2008)
19	Mellier	Marbehan	62	L5500	1974–06	39	8.8	0.142	New observation (2008)
20	Our	Ouren	386	L6330	1991–09	26	29.2	0.076	New observation (2005)
21	Ourthe	Durbuy	1285	S5953	1994–12	24	100	0.078	New observation
22	Ourthe	Tabreux	1597	S5921	1970–12	48	160	0.100	Petit & Daxhelet (1989) [12]
23	Ourthe	Sauheid	2910	S5826	1974–01	45	300	0.103	Pauquet & Petit (1993) [46]
24	Ourthe orientale	Houffalize	179	L5930	1979–02	37	21	0.117	Petit et al. (2015) [45]
25	Ruisseau des Aleines	Auby-sur-Semois	88.4	L6990	2003–09	15	13.3	0.150	New observation (2018)
26	Rulles	Habay-la-Vieille	96	L5970	1981–11	33	11	0.115	Petit and Pauquet (1997) [7]
27	Rulles	Tintigny	219	L5220	1971–02	39	24.3	0.111	New observation (2008)
28	Ry du Moulin	Vresse-sur-Semois	61.8	L7000	2003–09	15	5.8	0.094	Jacquemin [47]
29	Semois	Tintigny	380.9	S9561	1974–01	45	40	0.105	New observation (2008)
30	Semois	Membre Pont	1235	S9434	1968–01	51	130	0.105	Petit & Pauquet (1997) [7], Gob et al. (2005) [48]
31	Sûre	Martelange	209	L5610	1975–03	40	32	0.153	Peeters et al. (2018) [19]
32	Vesdre	Chaudfontaine	683	S6228	1975–06	43	120	0.176	Petit & Daxhelet (1989) [12]
33	Vierre	Suxy	219.8	L7140	2003–12	15	19	0.086	New observation (2008)
34	Viroin	Olloy-sur-Viroin	491	L6380	1992–01	26	55	0.112	New observation (2011)
35	Viroin	Treignes	548	S9021	1968–01	45	62	0.113	New observation (2009)
36	Wamme	Hargimont	80	L6370/L7640	2011–06	13	12.1	0.151	New observation (2008)
37	Wayai	Spixhe	93.8	L6790	2002–03	17	25	0.267	New estimate

Table 1. *Cont.*

ID	River	Location	A (km²)	Station Code	Station Start Date	N_y	Q_b ($m^3 \cdot s^{-1}$)	Specific Q_b ($m^3 \cdot s^{-1} \cdot km^{-2}$)	Sources of Q_b Observation
					FAGNE–FAMENNE Region				
38	Biran	Wanlin	51.9	L7190	2004–09	14	6.3	0.121	New observation (2008)
39	Brouffe	Mariembourg	80	S9111	1981–01	38	20	0.250	New observation (2009)
40	Eau Blanche	Aublain	106.2	L6530	1994–03	24	17	0.160	New observation (2011)
41	Eau Blanche	Nismes	254	S9081	1968–01	50	29	0.114	Vanderheyden [49] and new observation (2013)
42	Hantes	Beaumont	92.4	L6880	2003–03	15	15	0.162	New observation
43	Hermeton	Romedenne	115	L5060	1969–02	48	17.3	0.150	New observation (2008)
44	Hermeton	Hastière	166	S8622	1967–09	50	20	0.120	New observation (2008)
45	Marchette	Marche-en-Famenne	48.9	L7120	2003–12	15	7.2	0.147	Petit & Daxhelet (1989) [12]
46	Ruisseau d'Heure	Baillonville	68	L6050	1984–06	29	14	0.206	Louette (1995) [13]
47	Wimbe	Lavaux-Sainte-Anne	93	L6270	1991–08	26	11.7 [1]	0.125	Computed $Q_{0.625}$
					CONDROZ Region				
48	Biesme l'Eau	Biesme-sous-Thuin	79.8	L7180	2004–09	14	6	0.075	New observation
49	Bocq	Spontin [2]	163.6	L7320	2006–04	40	18.3	0.112	Petit et al. (2015) [45]
50	Bocq	Yvoir	230	L5800	1979–02	39	26.3	0.114	Peeters et al. (2013) [50]
51	Samson	Mozet	108.2	L5980	1982–10	26	10.6 [1]	0.098	Computed $Q_{0.625}$
					ENTRE–VESDRE–ET–MEUSE Region				
52	Berwinne	Dalhem	118	L6390	1991–12	24	17	0.144	Houbrechts et al. (2015) [51]
53	Bolland	Dalhem	29.3	L6770	2001–12	17	3.4	0.116	New observation
54	Gueule	Sippenaken	121	L6660	1996–06	22	16	0.132	Mols (2004) [52]
					BRABANT Region				
55	Dyle	Florival	430	L6160	1992–07	23	20.5	0.048	New observation (2011)
56	Samme	Ronquières	135	S2371	1971–08	30	15	0.111	Denis et al. (2014) [53]
57	Senne	Steenkerque	116	L5660	1996–06	40	14	0.121	SPW data
58	Senne	Quenast	169		1977–03	40	19.5	0.115	New observation (2011)
59	Sennette	Ronquières	70	L5670	1977–07	28	6	0.086	SPW data
					HAINAUT Region				
60	Anneau	Marchipont	78.2	L6870	2003–03	15	7.3 [1]	0.094	Computed $Q_{0.625}$
61	Grande Honnelle	Baisieux	121	L5170	1971–01	40	12.4 [1]	0.103	Computed $Q_{0.625}$
62	Rhosnes	Amougies	165	L5412	1972–02	38	19	0.115	SPW data
63	Ruisseau des Estinnes	Estinnes-au-Val	28.7	L7080	2003–11	15	3.0 [1]	0.105	Computed $Q_{0.625}$
64	Trouille	Givry	55.7	L6710	2000–05	19	4.2 [1]	0.075	Computed $Q_{0.625}$
					HESBAYE Region				
65	Burdinale	Marneffe	26.8	L6461	2008–09	10	2.2 [1]	0.082	Computed $Q_{0.625}$
66	Geer	Eben-Emael	452.3	L6340	1991–08	23	11.9	0.026	Mabille & Petit (1987) [54]
67	Grande Gette	Sainte-Marie-Geest	135	L5720	1978–01	41	10	0.074	New observation (2011)
68	Mehaigne	Ambresin	194.7	L6470	1991–12	25	12	0.062	Peeters et al. (2018) [19]
69	Mehaigne	Wanze	352	L5820	1978–12	39	18.1	0.051	Perpinien (1998) [55] at Moha
70	Petite Gette	Opheylissem	134	L6280	1991–08	25	4.8 [1]	0.081	Computed $Q_{0.625}$
					LORRAINE Region				
71	Semois	Chantemelle	89	L5880	1979–01	40	11.1	0.125	New observation (2001)
72	Semois	Etalle	123.9	L6180	1992–09	25	15.2	0.123	New observation (2008)
73	Ton	Virton	89	L6440	1991–08	25	6.5	0.073	New observation (2007)
74	Ton	Harnoncourt	293	L5520	1974–03	44	27.6	0.094	New observation (2008)
75	Vire	Ruette	104	L5600	1975–07	39	21.3	0.205	SPW data and new estimate
76	Vire	Latour	125	L6030	1983–10	34	12	0.096	New observation (2008)

Columns legend: A (km²) is the catchment area at the station location; $Q_{b\ max}$ ($m^3 \cdot s^{-1}$) is field-observed bankfull discharge expressed in hourly flow, [1] except for values computed from partial series ($Q_{0.625}$). [2] The Bocq station at Spontin presents incomplete hydrological data. A correlation with the SETHY station from Bocq at Yvoir was used to complete the data between 1978 and 2018.

Petit and Pauquet [7] with further investigations by Petit et al. [16] proposed a relationship between bankfull discharge and watershed area for pebble-bedded rivers on impermeable substrates (Ardenne's rivers *sensu stricto*, Equation (1)).

$$Q_{b(\text{daily values})} = 0.128A^{0.981} \left(R^2 = 0.961;\ n = 38\right) \quad (1)$$

As this equation is only available for Ardenne's rivers, another type of estimation, based on discharge series and recurrence intervals, will be presented below, applicable to all rivers. It should be noted that this equation was computed from daily discharge series. With the refinement afforded by bankfull discharge values expressed in hourly series resulting from field observations which have been updated since Petit et al. [17] published their data (Table 1), the equation has been significantly updated (Equation (2)).

$$Q_{b(\text{hourly values})} = 0.337A^{0.8244}\left(R^2 = 0.908;\ n = 34\right) \tag{2}$$

2.3. Methods for Flood Return Period Estimation

2.3.1. Graphical Method and Gumbel Distribution

When dealing with flood frequency analysis and recurrence estimation, several methods exist. The simplest method is graphical representation using a straight-line fitting the flood discharge value and the expression of the quantile. This graph linearizes the relation between the quantile x and the cumulative frequency F on a probability scale [56]. Among many two-parameter distributions, the Gumbel law was selected for its ease of use. By inserting the reduced variable u in the expression for the Gumbel distribution ($u = -\ln(-\ln(F))$), it is possible to plot discharge values on the axes x-u and find the best fit straight line. Empirical frequency of a given discharge value can be obtained thanks to the following equation (Equation (3))

$$\hat{F}\left(x_{[r]}\right) = \frac{r-c}{n+1-2c} \tag{3}$$

where n is the sample size, $x_{[r]}$ the value correspoding to the rank r and c a coefficient, usually fixed to 0.5 after Hazen [57] and recommended by Brunet-Moret [58].

Fisher and Tippett [59] developed an analysis of extreme values frequency distribution. It was applied by Gumbel [60,61] in the fields of hydrology and meteorology for discharge and rainfall frequency analysis. The probability density of the Gumbel distribution is described by Equation (4), considering Q as the flow variable.

$$d(Q) = ae^{-e^{-u}}e^{-u} \text{ where } u = a(Q - Q_0) \tag{4}$$

The variable $1/a$ corresponds to the scale parameter, characterizing the spreading of the values. It is calculated from the standard deviation s of the sample (Equation (5)). Parameter Q_0 is a position parameter which corresponds to the distribution mode and is calculated from the mean annual discharge (Q_m) of the series (Equation (6)).

$$\frac{1}{a} = 0.78\ s \tag{5}$$

$$Q_0 = Q_m - \left(0.577\frac{1}{a}\right) \tag{6}$$

The distribution function is represented by Equations (7) and (8).

$$F(Q) = \int_{-\infty}^{Q} d(Q)dQ = e^{-e^{-u}} \tag{7}$$

$$P(Q \leq Q_i) = F(Q_i) = \int_{-\infty}^{Q_i} d(Q_i)dQ_i = e^{-e^{-a(Q_i - Q_0)}} \tag{8}$$

The implementation of the Gumbel distribution can be carried out according to different types of adjustments to calculate the different parameters of the distribution. This results in the estimation of the probability of occurrence of a given flood discharge [62]. Figure 2 presents an example comparing the graphical method of analysing the annual and partial floods of the Aisne River at Juzaine (ID no. 2) and the Gumbel ordinary moment method, which consists in equalizing the actual moments of the flood samples and the theoretical moments predicted by Gumbel's law. This figure shows that for partial series the best method is the graphical method as it gives correct return periods for recurrence under 3.5 years. The graphical method is more appropriate for annual series above this threshold. Tests were made using a large sample of rivers which led to the conclusion that recurrence intervals have to be computed in partial series for a return period under 5 years and an annual series above 5 years. This is because a comparison of the two methods reveals that, in a partial series, the method of ordinary moments moves away from the points displayed when using the graphical method. This 5-year threshold found in this study is consistent with the data found in the literature [63].

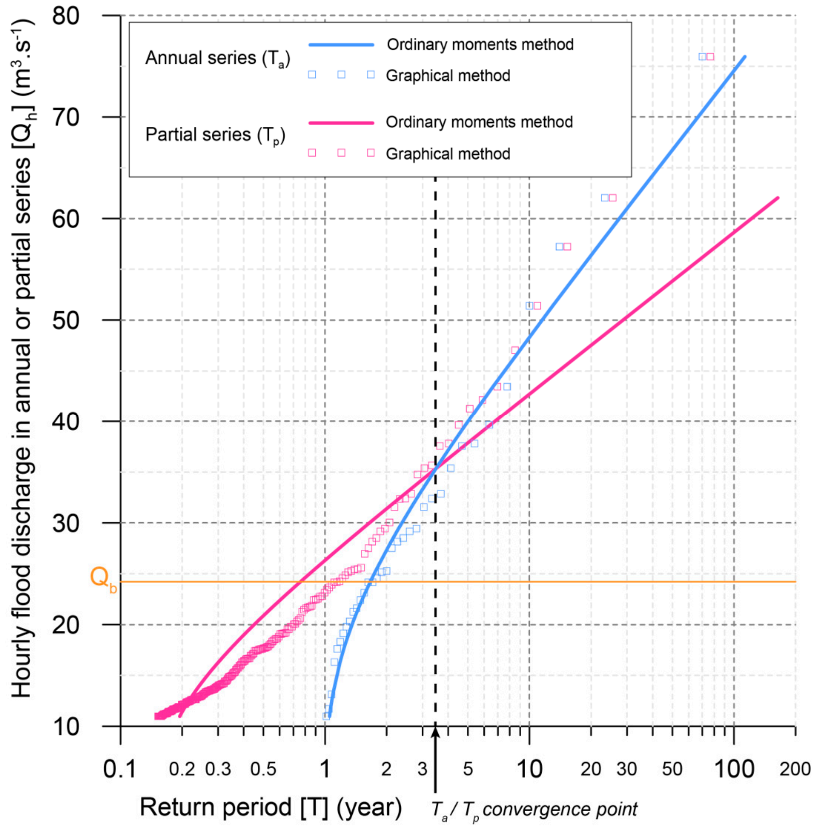

Figure 2. Convergence of annual and partial series—comparison of the method of ordinary moments and the graphical method (example on the Aisne River at Juzaine—station no. 2).

With data samples, the standard estimators of the mean and variance are given by Equation (9) and (10).

$$\overline{Q} = \frac{1}{n}\sum_{i=1}^{n} Q_i \tag{9}$$

$$S^2 = \frac{1}{n-1}\sum_{i=1}^{n}\left(Q_i - \overline{Q}\right)^2 \tag{10}$$

The theoretical expectation and variance of Gumbel's law are given by Equations (11) and (12) respectively. γ is the Euler constant (≅0.577) as reminded by Bernier [64].

$$E(Q) = \frac{1}{a}\gamma + Q_0 \tag{11}$$

$$S^2(Q) = \frac{\pi^2}{6}\left(\frac{1}{a}\right)^2 \tag{12}$$

It is possible to calculate the asymmetric confidence interval of discharges with a given return period by referring to Equation (13) and a chart giving the values T_1 and T_2, respectively the upper and lower limits of the interval [65]

$$Q_i \in (Q_i - T_2\sigma)(Q_i + T_1\sigma) \quad (13)$$

with Q_i, the theoretical discharge of a flood with a return period of i years and σ the standard deviation of the floods sample used.

Using the river stations samples, ensuring the observations are independent of each other, the annual flood series (T_a), corresponding to the maximum annual flood, and the partial flood series (T_p) whose flow is greater than a given threshold were analyzed.

2.3.2. Flood Return Period Calculation in Annual Series

The Gumbel's ordinary moment method was implemented on the series of 76 hydrological stations (Figure 1) spread over the whole territory of Wallonia (see Appendix A). For consistency with the work already conducted in the study area, we have worked in calendar years. A small number of authors undertake work in hydrological years, usually from July to June [66]. In the calculation of annual flood series, the extreme variable used corresponds to the maximum observed annual flow. Because this random variable is independent, it is extremely rare that the maximum flow in one year can either influence the maximum flow in the following year or be influenced by the maximum flow in the previous year. In case any problem is encountered whilst taking measurements at any of the stations (due to technical failure, unstable rating curve, vandalism, ...), any hourly annual series with missing data is only taken into account if: (1) at least 80% of the discharge data is available; and (2) the maximum flood discharge measured during any incomplete year is not lower than the lowest maximum annual flood discharge during the complete years.

2.3.3. Flood Return Period Calculation in Partial Series

As annual series use only the maximum flood discharge per year, Langbein [67] when calculating recurrences with a partial series developed the use of a more extensive flood sample, selecting several flood peaks per year. All floods above a given threshold, independent of each other, are selected as a variable. This leads to the difficulty, when making calculations using a partial series, of determining a discharge threshold above which floods are used; and the time interval between two flood events must be defined in order to consider them independently of each other [2,68]. Indeed, when several flood peaks occur in a short period of time, only the largest peak should be retained [69].

Table 2 presents the thresholds and intervals given by different authors in the literature. For Dunne and Leopold [70], the threshold used for partial series may be the lowest maximum annual flood in the data series. Ashkar and Rousselle [71] propose to use a threshold that is related to the bankfull discharge, also recommended by Pauquet and Petit [46].

For Lang et al. [68], there is no unambiguous threshold value, but rather a range of threshold values leading to similar recurrence calculations. This also applies to the subjectivity of the criterion of flood independence. Physical parameters such as soil saturation in the catchment area modify the responsiveness of rivers to rainfall [72] and therefore the duration of the time interval between two successive peaks [73]. The flood selection methods for partial series recurrence computation are quite variable as shown in Table 2 and depend on time intervals that are either related [66,74] or not related [46,75,76] to the watershed physical parameters. Other authors use iterative statistical tests to select n annual mean flood peaks [77,78]. These works have systematically been carried out on daily flows, which greatly facilitates data analysis.

Table 2. Flow thresholds and time intervals between floods considered as independent in partial series

Threshold	Time Interval	Author(s)
Threshold corresponding to a flow rate with a T_p of 1.15 years	-	Dalrymple, 1960 [80]
Threshold defining a number of 1.65 N of floods where N represents the number of years recorded in the discharge series	Two successive peaks considered as independent if the flow drops to less than two-thirds of the first peak. Interval greater than three times the duration of the flood rise of the first five 'clear' hydrographs in the series	Cunnane, 1973 [76]
Lowest annual maximum flood of the series	-	Dunne and Leopold, 1978 [70]
Two successive peaks considered as independent if flow rate drops below 75% of the discharge of the lowest peak	Peaks separated by at least 5 days + the natural logarithm of the watershed surface (in miles^2)	USWRC, 1976 [74]
Threshold depending on the interval optimized by autocorrelation test	Selection by statistical self-correlation test of flood duration	Miquel, 1984 [73]
Threshold corresponding to a flow rate with partial return period in the range 1.2-2 years	-	Irvine and Waylen [77]
0.6 Q_b	Time interval between two successive maximum flow rates equals to at least four days, separated by a minimum whose value is less than or equal to 50% of the value of the lower of these two maximums	Pauquet and Petit, 1993 [46]; Petit and Pauquet, 1997 [7]
Several methods for estimating the threshold based on a stationarity test of the number of defined floods	-	Lang et al., 1999 [68]
Threshold and time interval defined to obtain between 2 to 5 floods peaks per year		Adamowski, 2000 [78]
Threshold = $\mu_q + 3\sigma_q$ where μ_q is the mean daily flow rate of the series and σ_q is the standard deviation of the daily flow rate according to Rosbjerg et al. [79]	Iterative high-pass filtering of the daily flow rates in order to detect independent peaks	Claps and Laio, 2003 [81]
Threshold = average daily flow rate	3 days	Brodie and Khan, 2016 [75]
-	10 to 15 days depending on watershed area	Karim et al., 2017 [66]

An automatic algorithm has been developed, based on hourly flood series, for extracting floods above a given threshold and selecting independent floods. The VisualBasic script developed in Microsoft Excel extracts temporal flood data (start and end date of the flood, duration, date of the observed maximum flow, time interval from the previous peak and time interval below the threshold between two successive floods). The code of this algorithm (see Appendix B) is available as Supplementary Material and on the website of the Hydrography and Fluvial Geomorphology Research Centre of the University of Liège (http://www.lhgf.uliege.be/). The maximum flow rate of each flood at the hydrograph station above the tested threshold is extracted and some statistical variables, such as the average duration of floods are calculated. Figure 3 shows in graphical form the different time parameters between the successive floods, named A to G in this example.

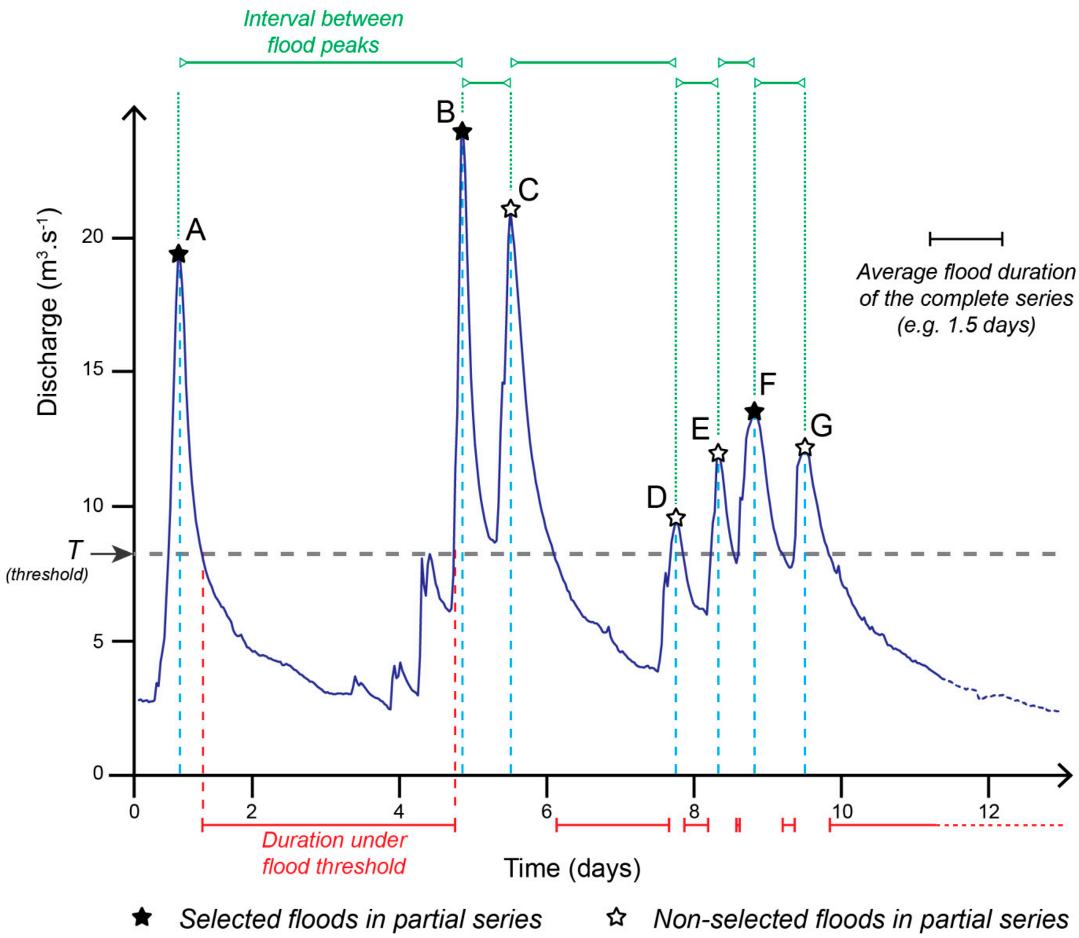

Figure 3. Principle of selection of peaks over threshold (POT) in partial series.

If several peaks are observed successively during the above-threshold period (Figure 3: B and C), only the maximum peak will be used (B). A flood peak that is separated from the previous one by a time interval less than the average duration of all the peak discharges above threshold will not be used in the calculation of the partial series (E and G not retained). In addition, to ensure flood independence in the calculation of partial series, a moving window operating on three successive above-threshold areas (D-E-F or E-F-G for example) will only retain the largest flood (F).

According to the literature, several tests were performed in peaks over threshold (POT) calculation and in the threshold selection: (1) the lowest annual maximum flood of the series [70]; (2) a fraction of the bankfull discharge (from 0.4 to 0.8 Q_b, encompassing the 0.6 Q_b value proposed by Petit and Pauquet [7]); (3) a wide range of specific discharges (from 0.025 to 0.2 $m^3 \cdot s^{-1} \cdot km^{-2}$); (4) several characteristic discharges estimated from hydrologic series; and (5) a discharge threshold defined to obtain around 5 independent flood peaks per year [78].

These methods each have methodological issues [40]. (1) The lowest annual maximum flood is dependent on the length of the hydrological series. A historical severe drought (1976, 2003, or 2018 depending on the location in Belgium [82]) will usually be the lowest annual maximum flood in our data. The designated threshold will be a little too high for stations with hydrologic series that do not go back to this year of severe drought, making recurrences calculated using this incomplete data, when compared with stations with hydrological data including those years of severe drought not comparable with each other. (2) A threshold which is defined from a percentage of the bankfull discharge value (e.g., 0.6 Q_b) is not suitable in the absence of field observations, as the data sometimes do not exist. (3) Specific discharges as threshold for POT calculations are not suitable because permeable and impervious watersheds will show major differences in their specific discharges [83]. (4) A characteristic discharge value such as $Q_{2.33}$ could be set as threshold but it is also dependent on the length of the hydrologic series and the type of fluvial regime and substratum. (5) The best series-length independent estimator we have used is the number of average flood peaks. Adamowski [78] suggests using 2–5 peaks while Cunnane [76] opts for a threshold a number of 1.65 N of flood peaks where N represents the number of years recorded in the discharge series while Lang et al. [68] utilize an equation which will test both the dispersion and the stationarity of the number of floods. We have chosen to set a threshold that gives a value of around 5 independent peak floods after POT selection. As the selection algorithm computer software takes time to run, another type of algorithm has been conceived in order to count all peak floods (dependent and independent) in real time. The threshold that gives 5.5 dependent and independent peak floods per year for each station has been sought; it corresponds to about 5 independent flood peaks per year and does not require the complete operational run of the algorithm (Table 3). This script (see Appendix C) is available in the Supplementary Materials.

Table 3. Return period of characteristic discharges computed for the selection of hydrologic stations

				Annual Series				Partial Series			
ID	**River**	**Location**	**Q_b ($m^3{\cdot}s^{-1}$)**	**Annual Lowest Flood ($m^3{\cdot}s^{-1}$)**	**T_a Q_b (yr)**	**Q_{100} ($m^3{\cdot}s^{-1}$)**	**T_a Q_{hmax} (yr)**	**Threshold for 5.5 Events/yr ($m^3{\cdot}s^{-1}$)**	**T_p Q_b (y)**	**$Q_{0.625}$ ($m^3{\cdot}s^{-1}$)**	**T_a/T_p Conver-Gence Point (yr)**
					ARDENNE Region						
1	Aisne	Erezée	7.3	7.1	1.1	25.8	32	6.30	0.30	9.7	4.0
2	Aisne	Juzaine	23.8	11.0	1.6	74.6	>100	13.15	0.68	23.0	4.0
3	Amblève	Targnon	87.3	78.1	1.4	250.7	75	60.00	0.51	93.6	5.0
4	Amblève	Martinrive	140	74.4	1.6	411.9	54	84.15	0.70	134.9	4.5
5	Eau Noire	Couvin	36.9	26.9	1.4	129.1	37	20.68	0.52	40.1	5.3
6	Hoëgne	Belleheid	10	6.1	1.5	27.6	44	6.05	0.62	9.9	3.5
7	Hoëgne	Theux	36.8	24.2	1.3	132.2	45	25.80	0.33	47.5	7.0
8	Lembrée	Vieuxville	7.9	3.8	1.6	25.7	70	3.62	0.71	7.5	4.0
9	Lesse	Resteigne	33	13.4	1.2	135.2	68	20.39	0.47	38.1	3.4
10	Lesse	Hérock	105	80.5	1.3	397.2	52	69.39	0.46	118.6	3.4
11	Lesse	Gendron	131	58.1	1.6	418.1	65	70.00	0.67	127.3	3.8
12	Lesse	Eprave	37	14.0	1.5	120.1	>300	22.70	0.55	38.6	3.8
13	Lhomme	Grupont	20	7.9	2.0	51.8	29	10.59	1.12	17.0	3.2
14	Lhomme	Forrières	24.5 [1]	15.7	1.5	81.6	35	15.90	0.62	24.5	3.0
15	Lhomme	Jemelle	29.7 [1]	12.4	1.4	87.9	30	17.77	0.62	29.7	3.9
16	Lhomme	Rochefort	51.8 [1]	34.2	1.5	187.5	32	28.11	0.62	51.7	3.0
17	Lhomme	Eprave	60	45.7	1.4	150.7	28	35.70	0.68	58.7	3.4
18	Lienne	Lorcé	21.3	10.5	2.4	52.1	47	10.49	1.28	17.0	6.0
19	Mellier	Marbehan	8.8	6.8	1.1	47.8	64	6.96	0.32	13.3	3.7
20	Our	Ouren	29.2	31.4	1.0	138.4	37	22.10	0.28	46.6	5.5
21	Ourthe	Durbuy	100	61.9	1.4	329.9	74	64.96	0.50	108.8	3.8
22	Ourthe	Tabreux	160	68.1	1.9	450.2	77	73.80	1.03	134.5	3.7
23	Ourthe	Sauheid	300	148.9	1.8	827.3	49	159.92	0.92	263.9	3.7
24	Ourthe orientale	Houffalize	21	9.9	1.9	63.3	~100	9.61	1.01	17.5	3.8
25	Ruisseau des Aleines	Auby-sur-Semois	13.3	7.6	1.0	26.5	23	7.82	1.30	11.3	4.0
26	Rulles	Habay-la-Vieille	11	6.9	1.1	43.5	32	7.80	0.38	14.1	3.7
27	Rulles	Tintigny	24.3	20.3	1.0	74.5	30	17.40	0.33	31.3	20.0
28	Ry du Moulin	Vresse-sur-Semois	5.8	7.3	1.0	31.4	55	6.02	0.31	9.5	2.7
29	Semois	Tintigny	40	34.6	1.1	203.1	>100	34.80	0.29	62.0	4.0
30	Semois	Membre Pont	130	89.0	1.2	555.3	~100	80.90	0.41	162.3	3.5
31	Sûre	Martelange	32	13.9	1.5	107.6	73	11.27	0.81	28.3	3.6
32	Vesdre	Chaudfontaine [2]	120	35.4	2.0	288.1	71	53.14	1.20	98.1	5.0
33	Vierre	Suxy	19	15.3	1.1	92.3	33	11.52	0.41	24.7	3.3
34	Viroin	Olloy-sur-Viroin	55	41.3	1.2	281.5	26	42.38	0.29	85.6	5.8
35	Viroin	Treignes	62	47.4	1.3	259.8	141	43.79	0.37	78.1	3.7
36	Wamme	Hargimont	12.1	9.8	1.3	63.3	89	11.76	0.26	19.4	6.0
37	Wayai	Spixhe	25	14.4	2.0	63.1	>100	11.22	1.41	19.7	3.0
					FAGNE–FAMENNE Region						
38	Biran	Wanlin	6.3	4.2	1.1	30.6	14	3.96	0.35	8.7	3.0
39	Brouffe	Mariembourg	20	7.3	1.9	50.6	75	7.47	1.30	15.7	3.5
40	Eau Blanche	Aublain	17	9.3	1.7	48.4	37	8.03	1.00	14.5	3.2
41	Eau Blanche	Nismes	29	20.1	1.4	96.6	>300	19.70	0.43	33.1	4.3
42	Hantes	Beaumont	15	10.9	1.5	60.2	30	6.42	0.63	14.9	3.5
43	Hermeton	Romedenne	17.3	9.0	1.7	50.5	75	8.61	0.66	17.0	7.5
44	Hermeton	Hastière	20	11.3	1.4	65.2	87	9.53	0.64	19.9	4.0
45	Marchette	Marche-en-Famenne	7.2	6.3	1.0	26.8	34	5.63	0.27	10.3	6.0
46	Ruisseau d'Heure	Baillonville	14	6.9	1.9	32.7	23	4.45	1.28	10.7	8.0
47	Wimbe	Lavaux-Sainte-Anne	11.7 [1]	7.8	1.3	31.7	40	6.68	0.62	11.7	4.0

Table 3. *Cont.*

			Annual Series					Partial Series			
ID	River	Location	Q_b ($m^3 \cdot s^{-1}$)	Annual Lowest Flood ($m^3 \cdot s^{-1}$)	T_a Q_b (yr)	Q_{100} ($m^3 \cdot s^{-1}$)	T_a Q_{hmax} (yr)	Threshold for 5.5 Events/yr ($m^3 \cdot s^{-1}$)	T_p Q_b (y)	$Q_{0.625}$ ($m^3 \cdot s^{-1}$)	T_a/T_p Conver-Gence Point (yr)
					CONDROZ Region						
48	Biesme l'Eau	Biesme-sous-Thuin	6	4.1	1.2	39.5	20	4.24	0.32	9.8	4.0
49	Bocq	Spontin	18.3	4.3	3.3	47.3	>150	5.09	2.99	10.3	4.0
50	Bocq	Yvoir	26.3	5.7	4.3	61.3	>150	6.81	4.53	13.3	4.0
51	Samson	Mozet	10.6 [1]	6.3	1.5	30.3	21	6.00	0.62	10.6	6.5
					ENTRE-VESDRE-ET-MEUSE Region						
52	Berwinne	Dalhem	17	13.3	1.5	60.1	>100	8.72	0.53	18.3	5.5
53	Bolland	Dalhem	3.4	1.7	1.7	11.4	>150	2.07	0.62	3.4	3.7
54	Gueule	Sippenaken	16	14.6	1.1	46.8	39	9.30	0.44	18.1	5.7
					BRABANT Region						
55	Dyle	Florival	20.5	13.5	2.6	31.2	16	12.70	1.77	17.6	20.0
56	Samme	Ronquières	15	9.5	1.5	46.0	>100	8.28	0.66	14.7	4.0
57	Senne	Steenkerque	14	8.8	1.1	51.0	~100	9.18	0.32	18.9	9.0
58	Senne	Quenast	19.5	9.9	1.3	57.4	~100	10.39	0.49	21.3	9.0
59	Sennette	Ronquières	6	4.2	1.2	19.4	68	3.94	0.34	7.9	>50.0
					HAINAUT Region						
60	Anneau	Marchipont	7.3 [1]	2.6	1.8	33.9	79	2.96	0.62	7.3	5.0
61	Grande Honnelle	Baisieux	12.4 [1]	3.3	1.6	46.1	44	5.46	0.62	12.4	4.8
62	Rhosnes	Amougies	19	7.3	5.4 [3]	28.2	50	10.90	3.98	15.0	9.0
63	Ruisseau des Estinnes	Estinnes-au-Val	3.0 [1]	0.6	1.9	15.2	>100	1.26	0.62	3.0	3.6
64	Trouille	Givry	4.2[1]	1.1	1.8	17.6	51	1.69	0.62	4.2	6.2
					HESBAYE Region						
65	Burdinale	Marneffe	2.2 [1]	0.9	1.8	7.6	30	0.92	0.62	2.2	5.5
66	Geer	Eben-Emael	11.9	6.4	2.5	19.6	67	7.59	1.90	10.1	3.8
67	Grande Gette	Sainte-Marie-Geest	10	3.1	1.7	36.3	50	4.68	0.81	8.8	4.0
68	Mehaigne	Ambresin	12	5.8	1.5	29.4	22	7.43	0.49	12.8	10.4
69	Mehaigne	Wanze	18.1	7.2	2.5	39.4	>100	9.10	1.63	14.2	4.5
70	Petite Gette	Opheylissem	4.8 [1]	2.2	8.9 [4]	18.5	>300	2.64	18.46	4.8	4.0
					LORRAINE Region						
71	Semois	Chantemelle	11.1	6.7	1.3	32.9	44	8.05	0.35	13.3	6.4
72	Semois	Etalle	15.2	12.8	1.2	40.2	38	12.48	0.31	18.4	6.5
73	Ton	Virton	6.5	4.7	1.6	12.5	26	4.64	0.59	6.6	~30.0
74	Ton	Harnoncourt	27.6	11.4	2.0	84.4	376	15.31	0.75	25.8	7.0
75	Vire	Ruette	21.3	6.7	3.2	40.4	41	8.01	2.16	15.3	15.0
76	Vire	Latour	12	10.0	1.1	40.4	56	9.69	0.30	15.8	5.8

Column legend: Q_b is the bankfull discharge expressed in hourly flow, [1] except for values computed from partial series ($Q_{0.625}$). [2] The Vesdre River at Chaudfontaine (no. 32) is disturbed by human dams upstream so return periods are not consistent with surrounding stations' values. [3] The Rhosnes River at Amougies and the [4] Petite Gette River at Opheylissem are located in anthropized reaches.

3. Results

3.1. Bankfull Discharge Return Period Analysis

While the computation of the flood frequency in annual series is only dependent upon the lowest annual flood, the newly developed algorithm for extracting peaks over threshold in partial series gave us the possibility to test a greater number of threshold parameters across a wide range of stations. It gives a precise idea of the behaviour of any return period of a given flood discharge value in relationship with the number of flood events per year. This method showed that an average number of 5 independent events per year (corresponding roughly to 5.5 dependent and independent events per year) will give a return period value that is not only consistent with field observation but also less sensitive to a threshold value change.

Tests were performed to assess the statistical utility of working with hourly discharges instead of daily discharges in relation to the area of the catchment. A seasonal difference is noticeable, winter floods require hourly discharge series for watersheds with an area lower than 250 km^2 in Wallonia while summer floods require hourly discharge values for a catchment area of less than 100 to 250 km^2, depending on the area and the fluvial regime.

The analysis of the return period of Q_b by region needs at first an overview of the regional specific bankfull discharge. The lowest values are observed in rivers from Hesbaye with an average specific Q_b of 0.063 $m^3 \cdot s^{-1} \cdot km^{-2}$. Rivers from Brabant, Hainaut, and Condroz regions show average values of 0.096, 0.098, and 0.100 $m^3 \cdot s^{-1} \cdot km^{-2}$ respectively. The rivers from Lorraine exhibit average specific Q_b discharge value of 0.119 $m^3 \cdot s^{-1} \cdot km^{-2}$ while Entre-Vesdre-et-Meuse and Ardenne regions are showing values of 0.131 and 0.132 $m^3 \cdot s^{-1} \cdot km^{-2}$ respectively. Larger values are observed in the region of Fagne and Famenne with 0.156 $m^3 \cdot s^{-1} \cdot km^{-2}$. Two groups are clearly distinctive: the Fagne–Famenne with systematically higher Q_b values, the Hesbaye with systematically lower Q_b. At river scale, some of them clearly stand out. We can cite the ones with a specific bankfull discharge value above 0.2 $m^3 \cdot s^{-1} \cdot km^{-2}$; in Ardenne region: the Eau Noire (no. 5), Hoëgne river (no. 6) and Wayai river (no. 37); in Fagne–Famenne region: Brouffe river (no. 39) and the Ruisseau d'Heure (no. 46). The Hoëgne River at Belleheid (no. 6) appears clearly as an outlier. It is located in a cascade-system reach with a steep profile slope (average: 3.7%) [84]. Its observed Q_b value (~10 $m^3 \cdot s^{-1}$) is equal to the $Q_{0.625}$ computed value (9.9 $m^3 \cdot s^{-1}$). However this value is very different from the 2.4 $m^3 \cdot s^{-1}$ given by the Equation 1 for pebble-bedded rivers on impervious substratum [16]. The Brouffe River located in the Fagne region with a specific Q_b value of 0.250 $m^3 \cdot s^{-1} \cdot km^{-2}$ correspond to an anthropized reach in the vicinity of the gauging station. The other rivers from Fagne–Famenne region show specific Q_b values in the range 0.1–0.2 $m^3 \cdot s^{-1} \cdot km^{-2}$.

Based on the return period computation with an average number of 5 events per year, we used the least square method to find which flood frequency could represent the field-observed bankfull discharge. Tests performed with 65 Q_b values led the authors to consider that the $Q_{0.625}$-flood is the most suitable value, i.e., flood events happening 1.6 times a year. Figure 4 shows that the fit between $Q_{0.625}$ and Q_b does not exhibit the normal regional pattern because the computation is taking into account both the physical features as well as the hydrological parameters. In addition, with their more extensive watershed catchment areas, Ardenne's rivers are those with the largest Q_b in this dataset. A few outliers are detected: no. 49 and no. 50, the Bocq River whose stations suffer from rating curve instability, lack of data and concrete-channelized reaches near hydrographic stations.

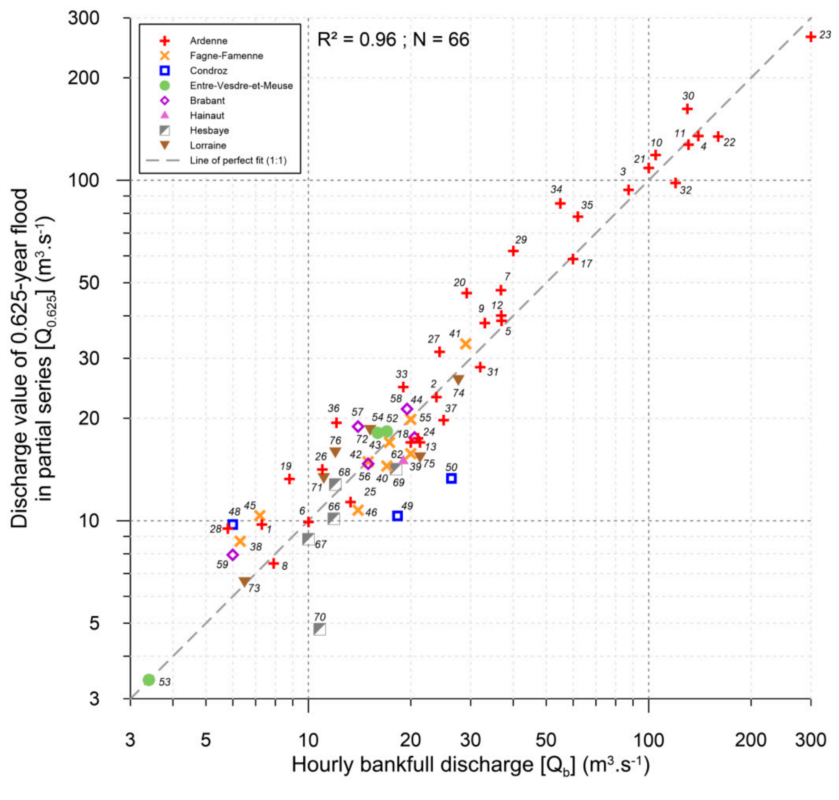

Figure 4. Fit between the discharge value of $Q_{0.625}$ in partial series and the field-observed Q_b.

Tests carried out on the database of selected Walloon rivers have shown a convergence occurring for a return period of 5 years on average (Table 3), as shown by the example of the Aisne at Juzaine (station no. 2—Figure 2). Whilst Ardenne, Condroz, and Fagne–Famenne rivers show a converging value around 4.6 years; in contrast to sand- and silt-bedded rivers of the regions Lorraine and Brabant which present average values of 11.8 and 10.5 respectively. Taking into account these observations, return periods of bankfull discharges will correspond to the value deducted from the partial series if it is less than 5 years, and will be expressed by the value deducted from the annual series above this threshold (see Table 3).

Ardenne rivers present an average bankfull discharge recurrence interval of 0.6 years without clear link to their watershed area. The rivers from Entre-Vesdre-et-Meuse show a value around 0.5 years. Whilst Brabant, Fagne–Famenne and Lorraine rivers have average values of 0.7 years. In contrast, the rivers from Condroz and Hesbaye reach an average bankfull discharge return period of 2.6 and 2.7 years respectively.

Figure 5 maps the return period of field-observed bankfull discharges for all stations where it was evaluated. The most station-populated rivers from our database comprise the Ourthe and the Lesse watershed. Ourthe River and its tributaries present Q_b return period from 0.3 to 1.3 years. Stations located on the main watercourse of the Ourthe have an average value of 0.8 years while Aisne tributary (stations no. 1 and no. 2) and Lienne tributary (station no. 18) show values of 0.30, 0.68 and 1.28 years respectively.

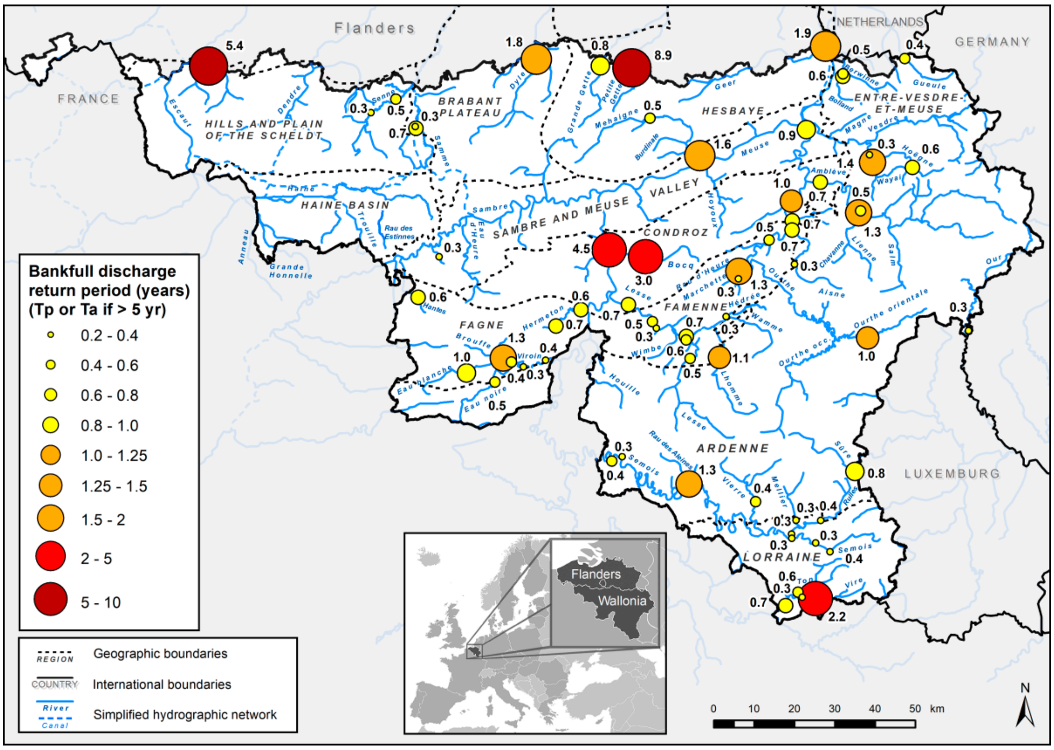

Figure 5. Return period of the observed bankfull discharge (expressed in partial series for values below 5 years and in annual series beyond).

In the case of the Lesse River and tributaries, most of the stations are located in the Famenne region but they have a substratum heritage from the Ardenne region. Except for one station (no. 13, Lhomme at Grupont with 1.13 years), the Lesse River and its tributaries show Q_b return period from 0.3 to 0.7 years.

Viroin River and its tributary the Eau Noire River have Q_b discharge return period between 0.3 and 0.5 years (with Ardenne characteristics) while the Eau Blanche River and Brouffe River, tributary of the Viroin and located in the Fagne region, show return period of 1.0 and 1.3 years respectively.

The Semois catchment and all its studied tributaries present Q_b recurrence interval ranges between 0.2 and 0.4 years, which is consistent with observations and flood alerts from the regional river network manager. The Vire and Ton catchments show bankfull discharge return period from 0.3 to 0.7 years except for the Vire at Ruette (station no. 75) where natural levees increase the value to 2.2 years.

Rivers from Entre-Vesdre-et-Meuse have values between 0.4 and 0.6 years while the Mehaigne catchment presents values from 0.5 years upstream (in the Hesbaye region *sensu stricto*) and 1.6 years downstream in a reach where the watercourse is recharged with pebble bedload due to the local Paleozoic substratum.

In Brabant region, the Senne catchment including the Samme River presents values ranging from 0.3 to 0.7 years. The Geer River and the Dyle River at locations under study present a value of Q_b return period of 1.9 and 1.8 years respectively. The other rivers have not-often experienced bankfull discharge events: the Petite Gette River with a Q_b return period of 8.9 years, the Rhosnes at Amougies with 5.4 years and the Bocq River at two locations (4.5 and 3.0 years). These discharge patterns are directly linked to the high values of the specific discharges values described earlier. The station corresponding to the Vesdre River at Chaudfontaine (no. 32) is not represented in graphs and tables. The calculated return period of its discharges is disturbed by hydroelectric and drinking water dams (Eupen and Gileppe dams).

3.2. Discharge and Return Period of Extreme Floods

Extreme floods were defined on the basis of the maximum hourly discharges recorded during the hydrological data series (see Table 3). The time frame for this recorded data is obviously dependent on the date on which the station was installed and, to a lesser extent, it is sensitive to the stability of the calibration curve [85].

Many authors have compiled databases of extreme floods around the world [86] or for a selection of countries such as the United Kingdom [8] and the United States [87] and relate these extreme discharges with watershed area. Figure 6 shows scatter points from hourly maximum discharges observed in rivers from Wallonia in the recording period, ranging from the longest timeframe of 1968 to 2018, to various other timelines, depending on station installation dates. On the basis of the calculation of the 100-year recurrence interval flood with the annual series (and therefore independently of the previous methodological results), this figure also presents the relationship between the centennial flood (Q_{a100}, computed with Gumbel method's of moments) and watershed area (see Equation (14)).

$$Q_{100} = 3A^{0.7} \tag{14}$$

Figure 6 also shows the extreme discharges estimated during catastrophic flash-flood events in ungauged catchments [88] utilizing a range of methods (specific stream power deducted from mobilized bed load, maximum water level in channel, ...) and the large centennial flood of the Meuse River in 1925–26 in the valley of Liege [89] and a few observations of the well over 50-year return period of the Meuse River flood in Dec. 1993 in the French departments of Ardennes and Meuse [90].

The Myer's formula is an equation (Equation (15)) used in the computation of extreme floods [2,20–22,91].

$$Q_{max} = CA^{a} \tag{15}$$

where Q_{max} is the maximum discharge (in $m^3{\cdot}s^{-1}$), A the watershed area, C the Myer's rating which relates to the physical parameters of the watershed and to the morphoclimatic system and the exponent a = 0.5; the value of this exponent is justified by the fact that, in the presence of a uniform downpour, the total volume flow is proportional to the area of the basin and the concentration time is schematically equivalent to the length of the watercourse [2,92,93]. Myer's ratings, which were recorded following extreme floods in the High Fens range from 16 to 18 [94,95], with pluri-centennial return periods. In Corsica, Gob et al. [96] computed a Coutagne–Myer coefficient close to 30 for the extreme flooding in 1973 in these Mediterranean mountains with their steep slopes. This coefficient exceeds 100 in the Ardèche River and its tributaries during 'Cévenoles' episodes, because it is related both to meteorological and topoclimatological parameters, with the energy of the topographic relief inducing a particular fluvial regime. Differences are partly explained by the more important role attributed to the surface of the basin in Myer's formula, thus accentuating the size differences between watersheds [93].

Sart-Tilman flash-floods, Chefna watercourse and the largest contemporary floods of the Meuse River confirm the Myer's rating of 18 previously proposed on the basis of a more limited number of observations (Figure 6).

From a dataset of peak discharge of extreme floods observed in the last two centuries in 1400 watersheds in the entire world, Francou and Rodier [97] presented an envelope curve based on the given catchment area [88]. Their formula (Equation 16) gives the expected peak flow rate Q (in $m^3 \cdot s^{-1}$) with A, the area of the watershed (in km^2), $Q_0 = 10^6$ and $A_0 = 10^8$. The parameter k is a regionalized parameter and it is equal to 3.5 in the northern oceanic zone.

$$\frac{Q}{Q_0} = \left(\frac{A}{A_0}\right)^{1-\frac{k}{10}} \tag{16}$$

However, their dataset is mainly composed of large watersheds (from ~10 to 5,500,000 km^2) and a huge variability appears in their resulting plot points. They have identified, for any catchment with less than 10, 20-square-kilometre areas, a limit named the "downpour phenomenon" where heavy rainfall associated with runoff can lead to a specific discharge of 10 $m^3 \cdot s^{-1} \cdot km^{-2}$ [97]. Indeed, Francou & Rodier's equation seems most unsuitable for modelling extreme floods for any catchment area below ~100 km^2 with k = 3.5 (Figure 6). A value of 3.9 is needed in order to fit with the extreme discharge values that were observed in watercourses of Wallonia.

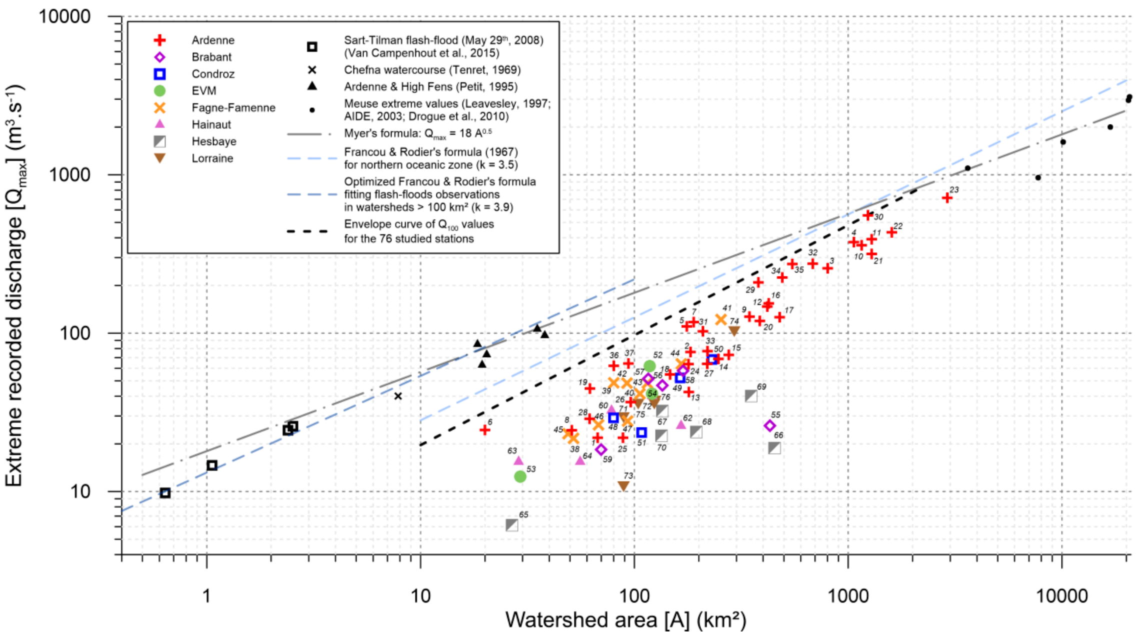

Figure 6. Extreme recorded discharge between 1968 and 2018 in gauged Walloon rivers and the comparison between Myer's formula (with C = 18) and different flash flood in ungauged watershed (Sart-Tilman flash flood, Chefna watercourse and High Fens watercourses) as well as Meuse 1925-26 large inundation; envelope curve of Q_{100} values computed for the 76 studied stations. Francou & Rodier's formula for northern oceanic zone maximum discharge is also shown as well as the optimized k parameter fitting with extreme floods of Walloon rivers.

The Francou and Rodier's equation, taking into account extreme floods for two centuries, is significantly higher than, but parallel, to the Q_{100} envelope curve from our selection of 76 stations. Their estimate of Q_{100} discharge is obviously related to the length of the series of observations and to the extreme events that occurred in the watersheds in this study, given the large spatial disparity in storm precipitation or snowmelt associated with the highest floods. With an average of 31 years of data gathered by the 76 stations studied, the highest floods have an average recurrence of 80 years. Several maximum flow rates are considered as a pluri-centennial flood. The limited length of the hydrologic series does not allow a more robust recurrence interval estimate. As mentioned earlier, Francou and Rodier's envelope curve significantly underestimates the discharge of the flash-floods which occurred in Belgium in both small and large watersheds. These events are markedly better modeled by the Myer's formula.

4. Discussion

With daily series computation of both annual and partial series as datasets, Richards [8] proposed the equation $T_a = T_p + 0.5$. In the analysis of a selection of rivers in different geographical regions in Wallonia (Belgium), this equation turns into $T_a = T_p + 0.83$ (± 0.10 as standard deviation) for bankfull discharge. The flood threshold in partial series has been defined—thanks to a complete analysis of the evolution of the return period value—depending on the average number of flood events per year. Each station has a graphic representation of the area where the calculated return period is stable and corresponds, in our subset, to around five events per year. Comparing this to other studies (see Table 2) which mention a threshold corresponding to a flow rate of either a defined partial return period [77,80] or linked to a number of flood events per year [76,78], we use a threshold (T_p ~ 0.2 years) lower than daily series studies (T_p from 1.15 to 2 years).

As a result of Q_b determination in hourly series and a threshold of T_p ~0.2 years, we have observed that Q_b value could be accurately estimated in absence of field data as the $Q_{0.625}$ discharge in partial series. Wilkerson [41] listed the published Q_b return period of a variety of authors from Europe, USA and Australia. They range from 0.46 to 10 years depending on localization, with average or mode values often reported as being between 1.0 and 2.0 years because annual series are mainly used. Petit [95] mentions that the use of partial series give a better estimation of the reccurence interval of Q_b and this is in the range from 0.4 to 0.7 years in Ardenne rivers with any watershed area of less than 500 km^2. With the same hydrologic series, annual series give for our subset (field-observed data excluding anthropized stations) an average Q_b return period value of 1.5 years (range: 1–2.6 yr) for 59 stations. Later studies have confirmed this value in Southern Italy [98] in annual series. However recent literature lacks values in partial series over a wide selection of stations [7,99,100].

This study takes place more than 20 years after the reference study of Petit and Pauquet [7] for the bankfull discharge recurrence interval in pebble-bedded rivers on impermeable substratum. They found that bankfull discharge recurrence interval for rivers with a hydrographic basin area of less than 250 km^2 in annual series was of the order of 1 year, very close to the value limit which one can obtain by using annual series and values around 1.5 to 2 years in the case of larger Ardenne type rivers [7]. Fagne and Famenne rivers, often characterized by small catchment area due to the morphology of the lithologic depression, show a large specific Q_b. This is a consequence of the fact that they flow over soft shales which are not very resistant to erosion [17,101], and this tends to incise the river more deeply into its bed. However, these rivers exhibit T_p values of around 0.7 years. Bankfull discharge frequency is just a bit more important than that of either the Ardenne rivers (0.6 years) or the Entre-Vesdre-et-Meuse rivers (0.5 years). In the rivers of Hesbaye, a generalized weakness of the flows (e.g., Gette and Geer Rivers) is observed, because precipitation is much lower and anthropogenic withdrawals are far from negligible. Average bankfull discharge return period reaches 2.7 years despite low specific Q_b.

Lorraine rivers have two different lithological contexts: the Ton River and the upstream part of the Semois River flow on Sinemurian sandstone with a stabilized fluvial regime; the downstream part of the Semois River which flows in a depression excavated in the marls, resulting in a highly contrasted regime. The Vire River at the station of Ruette has natural levees inducing a high Q_b return period (2.16 years). Due to their similar substrate to Ardenne watercourses, the rivers of Brabant— which is incised in Cambro-Ordovico-Silurian formations—do not deviate from the relationship defined for the Ardenne. However, rivers such as the Senne, the Dyle are nevertheless very different from the Ardenne rivers, even if they incise the substratum very locally. Very different land use in their catchment can modify the hydrological response to precipitation [102].

The Q_{100}-flood discharge and the return period of extreme floods were analyzed through envelope-curve based on maximum hourly discharges recorded during the hydrological data series in the one hand, as well as literature detailing the available data for flash-floods and extreme floods in Wallonia and surrounding areas. A majority of flood time series are shorter than 50 years. This leads to a mismatch between the length of the flood records and the need for an adequate estimate of the return period, in order to achieve effective and efficient infrastructure design [10]. Increased imperviousness of the landscape tends to increase watershed response to rainfall [102] and heightens the risk of extreme flash-floods [88].

The Myer–Coutagne equation was used with updated data sets on extreme flood discharges in Wallonia. Myer's rating has been confirmed at 18 for extreme (flash-)floods in catchments with an area from 0.6 to 20,000 km^2. The difference between the Q_{100} floods observed in gauged stations and the maximum discharge (Q_{max}) estimated with the Myer's rating varies with the size of the catchments and the length of the hydrographic series.

Climate projections indicate that in many regions of the world the risk of increased flooding or more severe droughts will be higher in the future [103]. While no significant changes were detected in annual rainfall series since an abrupt break in 1909 in Uccle (centre of Belgium) [104], winter precipitations show several increases from 1833–1909, 1910–1987, and 1988–2007. In this changing environment, there is a mismatch between the desire to have long series of data to obtain better estimates of characteristic discharge (minimum annual flood, Q_{100}, ...) and the problem linked to changes in climatological normal—that have to be reassessed over the last 30 years [105]—as prescribed by the World Meteorological Organization.

5. Conclusions

The first purpose of this paper was the development of an algorithm to cope with the large amount of hourly discharge data in return period estimations through the automatic extraction of flood characteristics. The aim was the definition of a non-field-observation flood threshold for POT selection and the computation of a partial series recurrence interval. With the rivers of Wallonia (Belgium), for a compilation of new observations of bankfull discharge, we used a flood threshold corresponding to an average value of five peak events per year. The authors confirmed the recurrence interval of bankfull discharge at 1.5 years, expressed in annual series, as widely presented in the literature. Computation of the return period of bankfull discharge in partial series shows an average value of 0.625 years. Furthermore, tests carried out on the database of selected Walloon rivers have shown a convergence of annual and partial series occurring for a return period of 5 years. Pebble-bedded rivers show a converging value around 4.6 years while sand-bedded and silt-bedded rivers present average values of around 11 years.

Interpretation of Q_b recurrence intervals required an overview of regional characteristics, such as specific bankfull discharge. Sand- or silted-rivers from Hesbaye region present the lowest values of specific bankfull discharge. Pebble-bedded and/or silted rivers from Brabant, Hainaut, and Condroz regions have average specific Q_b around 0.100 $m^3 \cdot s^{-1} \cdot km^{-2}$. Sand-bedded rivers in the Lorraine region and pebble-bedded rivers from Entre-Vesdre-et-Meuse and Ardenne regions present values around 0.125 $m^3 \cdot s^{-1} \cdot km^{-2}$. Rivers on impervious schistose substratum in Fagne and Famenne regions present the highest values (specific Q_b around 0.156 $m^3 \cdot s^{-1} \cdot km^{-2}$).

Hourly flow rate analysis gives the equation $T_a = T_p + 0.83$ (± 0.10) for bankfull discharge of rivers of Wallonia, which could be estimated—in the absence of field data—as the $Q_{0.625}$ discharge in partial series.

Hourly series in this study show, overall, a lower value of recurrence interval (T_p) and a greater dispersion of data points cloud when compared with older studies in the same area and the same rivers with datasets of daily series. Fagne and Famenne rivers exhibit T_p values of Q_b around 0.7 years while Ardenne rivers show average values of 0.6 years. Entre-Vesdre-et-Meuse rivers (0.5 years) and Hesbaye rivers (2.7 years), are respectively the most frequent and less frequent overbank-flooded rivers. Whilst Lorraine rivers, with their complex substratum, show very different T_p values—according to the local materials—and whether or not there are natural levees present.

In the end, the best Gumbel method for estimating recurrence intervals for this set of rivers is the ordinary moment with a POT flood threshold that gives around 5 independent events per year in partial series. Depending on the regional characteristics and flood regimes, the convergence point between partial and annual series has to be sought.

Hourly series from 1968 to 2018 were used to compute Q_{100} discharge and to compare the dimensions of the watershed area. Information on extreme floods was gathered in Wallonia (in both gauged and ungauged catchments) and this was used to compute the value of C, the Myer's rating which relates to the physical parameters of the watershed and to the morphoclimatic system. We could confirm the value of C = 18 with new data over a wide range of watershed area. Difference between the Q_{100} envelope-curve and Myer's curve is best seen in small watersheds because flash-floods are more prone to affecting small catchments with the resulting extreme discharges.

Supplementary Materials: The Microsoft Excel macro files are available online at http://www.mdpi.com/2073-4441/12/3/792/s1. The supplement file named "Macro_Number_of_events_estimation.xlsm" allowing the counting of the number of (dependent and independent) events over a variable threshold. The supplement file named "Macro_Partial_series_calculation.xlsm" allows the calculation of the return period of given discharge based on the partial series.

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Appendix A

Table A1 contains the computed values of characteristic discharges ($Q_{1.5}$, $Q_{2.33}$, Q_5, Q_{10}, Q_{20}, and Q_{50}) calculated with the Gumbel's ordinary moments method for all the studied stations and the $Q_{10/365}$, i.e., the flood discharge that is reached 10 days a year. Table A2 presents the equations of annual and partial recurrence interval calculated with the same method.

Table A1. Characteristic discharges computed for the selection of hydrologic stations

ID	River	Location	Partial Series			Annual Series				
			$Q_{1.5}$ ($m^3{\cdot}s^{-1}$)	Q_2 ($m^3{\cdot}s^{-1}$)	$Q_{2.33}$ ($m^3{\cdot}s^{-1}$)	Q_5 ($m^3{\cdot}s^{-1}$)	Q_{10} ($m^3{\cdot}s^{-1}$)	Q_{20} ($m^3{\cdot}s^{-1}$)	Q_{50} ($m^3{\cdot}s^{-1}$)	$Q_{10/365}$ ($m^3{\cdot}s^{-1}$)
1	Aisne	Erezée	12.0	12.7	13.1	15.3	17.8	20.3	23.4	4.9
2	Aisne	Juzaine	30.2	32.4	33.6	40.0	48.4	56.4	66.8	11.0
3	Amblève	Targnon	117.4	124.7	128.6	146.8	171.9	196.1	227.3	54.0
4	Amblève	Martinrive	172.7	184.3	190.4	226.1	271.1	314.2	370.1	72.8
5	Eau Noire	Couvin	53.4	57.5	59.7	70.0	84.3	98.0	115.8	15.4
6	Hoëgne	Belleheid	12.3	13.0	13.4	16.1	18.8	21.5	25.0	2.7
7	Hoëgne	Theux	60.2	64.1	66.2	73.9	88.0	101.5	119.0	14.6
8	Lembrée	Vieuxville	10.1	10.9	11.3	13.8	16.7	19.4	23.0	2.6
9	Lesse	Resteigne	51.9	56.2	58.4	73.0	88.1	102.5	121.2	24.7
10	Lesse	Hérock	154.0	164.9	170.7	212.6	257.3	300.1	355.6	66.5
11	Lesse	Gendron	167.3	179.7	186.3	224.9	271.7	316.5	374.6	71.7
12	Lesse	Eprave	49.6	53.0	54.8	65.6	78.8	91.5	107.9	26.0
13	Lhomme	Grupont	21.5	22.8	23.6	28.7	34.3	39.6	46.6	9.1
14	Lhomme	Forrières	31.5	33.6	34.8	43.9	53.0	61.8	73.1	14.2
15	Lhomme	Jemelle	37.6	40.1	41.4	49.5	58.8	67.7	79.3	16.4
16	Lhomme	Rochefort	69.1	74.4	77.3	98.7	120.2	140.8	167.5	22.8
17	Lhomme	Eprave	72.2	76.3	78.5	92.0	106.2	119.8	137.4	29.1
18	Lienne	Lorcé	22.2	23.8	24.7	28.2	34.0	39.5	46.7	9.8
19	Mellier	Marbehan	18.0	19.5	20.3	25.1	30.6	35.9	42.7	6.9
20	Our	Ouren	61.3	65.8	68.2	79.3	93.6	107.3	125.1	29.7
21	Ourthe	Durbuy	138.8	148.0	152.9	182.9	218.5	252.6	296.8	72.4
22	Ourthe	Tabreux	177.9	191.3	198.3	242.2	292.5	340.9	403.4	91.1
23	Ourthe	Sauheid	341.7	365.5	378.1	456.6	546.3	632.4	743.8	175.6
24	Ourthe orientale	Houffalize	23.8	25.7	26.7	33.0	40.4	47.4	56.5	10.9
25	Ruisseau des Aleines	Auby-sur-Semois	13.7	14.4	14.7	16.7	19.1	21.4	24.3	8.1
26	Rulles	Habay-la-Vieille	18.7	20.1	20.8	25.0	29.5	33.8	39.4	8.5
27	Rulles	Tintigny	39.3	41.7	43.0	48.1	54.5	60.6	68.6	19.9
28	Ry du Moulin	Vresse-sur-Semois	12.6	13.6	14.1	17.8	21.1	24.2	28.3	5.6
29	Semois	Tintigny	81.7	87.8	91.0	109.7	132.3	154.0	182.1	35.5
30	Semois	Membre Pont	219.6	237.2	246.6	304.3	365.0	423.3	498.8	113.9
31	Sûre	Martelange	40.4	44.2	46.1	57.9	70.0	81.5	96.4	16.9
32	Vesdre	Chaudfontaine	127.0	135.9	140.6	164.1	194.1	222.9	260.2	40.7
33	Vierre	Suxy	34.7	37.7	39.3	49.7	60.0	69.9	82.7	17.9
34	Viroin	Olloy-sur-Viroin	114.4	123.3	128.0	149.0	181.1	211.8	251.7	35.9
35	Viroin	Treignes	102.0	109.4	113.4	138.7	168.0	196.1	232.5	36.5
36	Wamme	Hargimont	24.9	26.6	27.5	31.0	38.8	46.3	56.0	7.5
37	Wayai	Spixhe	25.4	27.2	28.1	35.0	41.8	48.4	56.8	6.3
38	Biran	Wanlin	11.7	12.7	13.2	16.7	20.1	23.3	27.5	2.2
39	Brouffe	Mariembourg	20.8	22.4	23.2	28.5	33.9	39.0	45.7	5.5
40	Eau Blanche	Aublain	19.1	20.5	21.2	26.7	32.0	37.0	43.5	7.4
41	Eau Blanche	Nismes	41.4	44.0	45.4	52.9	63.5	73.7	86.8	16.0
42	Hantes	Beaumont	20.6	22.4	23.3	30.4	37.6	44.6	53.5	4.8
43	Hermeton	Romedenne	22.2	23.8	24.7	27.7	33.2	38.5	45.4	6.0
44	Hermeton	Hastière	26.4	28.5	29.5	35.9	43.0	49.8	58.6	7.9
45	Marchette	Marche-en-Famenne	13.0	13.9	14.3	16.3	18.8	21.3	24.4	2.8
46	Ruisseau d'Heure	Baillonville	14.7	15.9	16.5	19.3	22.6	25.7	29.7	3.5
47	Wimbe	Lavaux-Sainte-Anne	14.7	15.7	16.2	19.0	22.1	25.0	28.8	5.3
48	Biesme l'Eau	Biesme-sous-Thuin	13.8	15.0	15.7	19.6	24.4	29.0	35.0	2.6
49	Bocq	Spontin	14.9	16.4	17.1	22.1	28.2	34.1	41.6	3.8
50	Bocq	Yvoir	19.3	21.2	22.2	28.2	36.2	43.9	53.9	6.5
51	Samson	Mozet	13.6	14.6	15.1	17.0	20.2	23.3	27.3	3.7
52	Berwinne	Dalhem	24.4	26.3	27.4	31.9	38.7	45.3	53.7	4.7
53	Bolland	Dalhem	4.4	4.6	4.8	5.9	7.2	8.5	10.2	1.0
54	Gueule	Sippenaken	23.0	24.5	25.3	29.1	33.4	37.5	42.8	5.1
55	Dyle	Florival	20.1	20.8	21.2	22.6	24.7	26.7	29.3	8.3
56	Samme	Ronquières	18.9	20.2	20.9	25.3	30.3	35.1	41.3	4.1
57	Senne	Steenkerque	24.2	25.9	26.8	29.9	35.0	39.9	46.3	5.1
58	Senne	Quenast	27.2	29.1	30.1	33.7	39.4	44.9	52.0	5.8
59	Sennette	Ronquières	10.3	11.0	11.4	11.2	13.2	15.1	17.6	1.9

Table A1. *Cont.*

ID	River	Location	Partial Series $Q_{1.5}$ ($m^3{\cdot}s^{-1}$)	Q_2 ($m^3{\cdot}s^{-1}$)	$Q_{2.33}$ ($m^3{\cdot}s^{-1}$)	Annual Series Q_5 ($m^3{\cdot}s^{-1}$)	Q_{10} ($m^3{\cdot}s^{-1}$)	Q_{20} ($m^3{\cdot}s^{-1}$)	Q_{50} ($m^3{\cdot}s^{-1}$)	$Q_{10/365}$ ($m^3{\cdot}s^{-1}$)
60	Anneau	Marchipont	11.1	12.3	12.9	15.9	20.2	24.4	29.8	1.5
61	Grande Honnelle	Baisieux	17.2	18.7	19.4	23.2	28.7	34.0	40.9	3.7
62	Rhosnes	Amougies	17.0	17.6	17.9	18.7	21.0	23.2	26.0	6.7
63	Ruisseau des Estinnes	Estinnes-au-Val	4.4	4.9	5.1	6.8	8.8	10.7	13.3	0.6
64	Trouille	Givry	6.0	6.6	6.9	8.0	10.3	12.5	15.4	1.1
65	Burdinale	Marneffe	3.0	3.2	3.3	3.9	4.8	5.6	6.7	0.5
66	Geer	Eben-Emael	11.5	12.0	12.2	13.5	15.0	16.4	18.2	4.9
67	Grande Gette	Sainte-Marie-Geest	12.6	13.7	14.3	18.1	22.5	26.7	32.2	2.4
68	Mehaigne	Ambresin	15.5	16.3	16.7	17.9	20.7	23.3	26.8	5.7
69	Mehaigne	Wanze	17.8	18.9	19.5	22.5	26.6	30.6	35.6	9.0
70	Petite Gette	Opheylissem	6.5	7.0	7.2	8.9	11.2	13.4	16.3	1.6
71	Semois	Chantemelle	16.2	17.1	17.6	19.6	22.8	25.9	29.9	6.4
72	Semois	Etalle	21.8	22.8	23.3	25.5	29.1	32.5	36.9	9.9
73	Ton	Virton	7.6	8.0	8.1	8.4	9.4	10.4	11.6	3.1
74	Ton	Harnoncourt	34.0	36.6	37.9	42.6	52.7	62.4	75.0	13.3
75	Vire	Ruette	19.6	20.9	21.6	24.0	28.0	31.8	36.7	5.4
76	Vire	Latour	19.7	20.8	21.5	24.3	28.2	32.0	36.8	6.9

Table A2. Annual series and partial series equations (ordinary moments method of Gumbel).

ID	River	Location	Annual Series Equation	Partial Series Equation
			$u = a\,(Q - Q_0)$	
1	Aisne	Erezée	u = 0.30 (Q − 10.23)	u = 0.44 (Q − 7.55)
2	Aisne	Juzaine	u = 0.09 (Q − 23.25)	u = 0.14 (Q − 16.31)
3	Amblève	Targnon	u = 0.03 (Q − 96.49)	u = 0.04 (Q − 70.50)
4	Amblève	Martinrive	u = 0.02 (Q − 136.17)	u = 0.03 (Q − 100.69)
5	Eau Noire	Couvin	u = 0.05 (Q − 41.47)	u = 0.07 (Q − 26.01)
6	Hoëgne	Belleheid	u = 0.27 (Q − 10.47)	u = 0.41 (Q − 7.41)
7	Hoëgne	Theux	u = 0.05 (Q − 45.66)	u = 0.08 (Q − 33.75)
8	Lembrée	Vieuxville	u = 0.26 (Q − 7.95)	u = 0.38 (Q − 4.84)
9	Lesse	Resteigne	u = 0.05 (Q − 42.96)	u = 0.07 (Q − 26.32)
10	Lesse	Hérock	u = 0.02 (Q − 123.25)	u = 0.03 (Q − 83.01)
11	Lesse	Gendron	u = 0.02 (Q − 131.40)	u = 0.02 (Q − 86.35)
12	Lesse	Eprave	u = 0.06 (Q − 39.21)	u = 0.09 (Q − 28.02)
13	Lhomme	Grupont	u = 0.13 (Q − 17.44)	u = 0.22 (Q − 12.44)
14	Lhomme	Forrières	u = 0.08 (Q − 25.65)	u = 0.14 (Q − 18.43)
15	Lhomme	Jemelle	u = 0.08 (Q − 30.84)	u = 0.12 (Q − 21.56)
16	Lhomme	Rochefort	u = 0.04 (Q − 55.80)	u = 0.06 (Q − 33.60)
17	Lhomme	Eprave	u = 0.05 (Q − 63.60)	u = 0.07 (Q − 45.50)
18	Lienne	Lorcé	u = 0.13 (Q − 16.67)	u = 0.19 (Q − 12.39)
19	Mellier	Marbehan	u = 0.14 (Q − 14.12)	u = 0.21 (Q − 8.80)
20	Our	Ouren	u = 0.05 (Q − 50.72)	u = 0.07 (Q − 32.51)
21	Ourthe	Durbuy	u = 0.02 (Q − 111.73)	u = 0.03 (Q − 79.98)
22	Ourthe	Tabreux	u = 0.01 (Q − 141.54)	u = 0.02 (Q − 95.65)
23	Ourthe	Sauheid	u = 0.01 (Q − 277.26)	u = 0.01 (Q − 198.68)
24	Ourthe orientale	Houffalize	u = 0.10 (Q − 18.36)	u = 0.16 (Q − 12.09)
25	Ruisseau des Aleines	Auby-sur-Semois	u = 0.32 (Q − 12.01)	u = 0.43 (Q − 9.28)
26	Rulles	Habay-la-Vieille	u = 0.17 (Q − 16.07)	u = 0.22 (Q − 10.38)
27	Rulles	Tintigny	u = 0.12 (Q − 35.35)	u = 0.12 (Q − 23.11)
28	Ry du Moulin	Vresse-sur-Semois	u = 0.23 (Q − 11.20)	u = 0.33 (Q − 7.50)
29	Semois	Tintigny	u = 0.03 (Q − 64.46)	u = 0.05 (Q − 41.32)
30	Semois	Membre Pont	u = 0.01 (Q − 182.82)	u = 0.02 (Q − 107.00)
31	Sûre	Martelange	u = 0.06 (Q − 33.89)	u = 0.08 (Q − 16.74)
32	Vesdre	Chaudfontaine	u = 0.02 (Q − 104.10)	u = 0.03 (Q − 68.43)
33	Vierre	Suxy	u = 0.07 (Q − 29.03)	u = 0.10 (Q − 15.97)
34	Viroin	Olloy-sur-Viroin	u = 0.02 (Q − 84.88)	u = 0.03 (Q − 55.41)
35	Viroin	Treignes	u = 0.03 (Q − 80.07)	u = 0.04 (Q − 52.40)
36	Wamme	Hargimont	u = 0.10 (Q − 15.30)	u = 0.18 (Q − 13.71)
37	Wayai	Spixhe	u = 0.11 (Q − 21.47)	u = 0.17 (Q − 13.74)

Table A2. *Cont.*

ID	River	Location	Annual Series Equation	Partial Series Equation
38	Biran	Wanlin	u = 0.22 (Q − 9.98)	u = 0.32 (Q − 5.40)
39	Brouffe	Mariembourg	u = 0.14 (Q − 17.83)	u = 0.19 (Q − 10.30)
40	Eau Blanche	Aublain	u = 0.14 (Q − 16.27)	u = 0.22 (Q − 10.00)
41	Eau Blanche	Nismes	u = 0.07 (Q − 31.83)	u = 0.12 (Q − 24.15)
42	Hantes	Beaumont	u = 0.10 (Q − 15.99)	u = 0.17 (Q − 8.84)
43	Hermeton	Romedenne	u = 0.14 (Q − 16.63)	u = 0.19 (Q − 11.35)
44	Hermeton	Hastière	u = 0.11 (Q − 21.77)	u = 0.15 (Q − 12.75)
45	Marchette	Marche-en-Famenne	u = 0.29 (Q − 11.17)	u = 0.37 (Q − 7.45)
46	Ruisseau d'Heure	Baillonville	u = 0.23 (Q − 12.80)	u = 0.25 (Q − 6.93)
47	Wimbe	Lavaux-Sainte-Anne	u = 0.25 (Q − 12.86)	u = 0.32 (Q − 8.61)
48	Biesme l'Eau	Biesme-sous-Thuin	u = 0.16 (Q − 9.94)	u = 0.25 (Q − 5.60)
49	Bocq	Spontin	u = 0.12 (Q − 9.86)	u = 0.22 (Q − 6.20)
50	Bocq	Yvoir	u = 0.09 (Q − 12.22)	u = 0.17 (Q − 7.66)
51	Samson	Mozet	u = 0.23 (Q − 10.58)	u = 0.33 (Q − 7.45)
52	Berwinne	Dalhem	u = 0.11 (Q − 18.28)	u = 0.16 (Q − 11.60)
53	Bolland	Dalhem	u = 0.56 (Q − 3.24)	u = 1.04 (Q − 2.40)
54	Gueule	Sippenaken	u = 0.18 (Q − 20.49)	u = 0.20 (Q − 12.92)
55	Dyle	Florival	u = 0.36 (Q − 18.50)	u = 0.39 (Q − 14.84)
56	Samme	Ronquières	u = 0.15 (Q − 15.28)	u = 0.23 (Q − 10.23)
57	Senne	Steenkerque	u = 0.15 (Q − 19.74)	u = 0.18 (Q − 13.14)
58	Senne	Quenast	u = 0.13 (Q − 22.20)	u = 0.16 (Q − 14.80)
59	Sennette	Ronquières	u = 0.38 (Q − 7.29)	u = 0.42 (Q − 5.47)
60	Anneau	Marchipont	u = 0.17 (Q − 7.21)	u = 0.26 (Q − 3.39)
61	Grande Honnelle	Baisieux	u = 0.14 (Q − 12.07)	u = 0.21 (Q − 7.32)
62	Rhosnes	Amougies	u = 0.33 (Q − 14.16)	u = 0.50 (Q − 12.89)
63	Ruisseau des Estinnes	Estinnes-au-Val	u = 0.37 (Q − 2.70)	u = 0.70 (Q − 1.59)
64	Trouille	Givry	u = 0.32 (Q − 3.37)	u = 0.54 (Q − 2.27)
65	Burdinale	Marneffe	u = 0.84 (Q − 2.10)	u = 1.29 (Q − 1.39)
66	Geer	Eben-Emael	u = 0.51 (Q − 10.62)	u = 0.70 (Q − 8.61)
67	Grande Gette	Sainte-Marie-Geest	u = 0.17 (Q − 9.31)	u = 0.27 (Q − 5.77)
68	Mehaigne	Ambresin	u = 0.27 (Q − 12.34)	u = 0.37 (Q − 9.92)
69	Mehaigne	Wanze	u = 0.18 (Q − 14.37)	u = 0.28 (Q − 10.93)
70	Petite Gette	Opheylissem	u = 0.32 (Q − 4.20)	u = 0.59 (Q − 3.04)
71	Semois	Chantemelle	u = 0.23 (Q − 13.09)	u = 0.34 (Q − 10.16)
72	Semois	Etalle	u = 0.21 (Q − 18.42)	u = 0.30 (Q − 14.90)
73	Ton	Virton	u = 0.77 (Q − 6.49)	u = 0.93 (Q − 5.48)
74	Ton	Harnoncourt	u = 0.07 (Q − 22.32)	u = 0.12 (Q − 17.48)
75	Vire	Ruette	u = 0.19 (Q − 16.10)	u = 0.23 (Q − 10.82)
76	Vire	Latour	u = 0.19 (Q − 16.56)	u = 0.26 (Q − 11.74)

The equations correspond to the Gumbel adjustment in the form of $u = a(Q - Q_0)$ where u is a double transformation of the cumulated frequency F(Q), and expressed as $u = -\ln(-\ln F(Q))$. The variable a is the scale parameter estimated through the system of Equations (5) and (6). Q_0 is the form parameter. Available hourly data have been used, from station installation date to 31 December 2018.

Appendix B Visual Basic Code for the Estimation of the Number of Dependent and Independent Peaks over Threshold

The supplement file named "Macro_Number_of_events_estimation.xlsm" contains the VB script allowing the counting of the number of (dependent and independent) events over a variable threshold. It can be open with Microsoft Excel version 2007 at least. Test data are provided as hourly discharge series. The user can adjust the threshold and thus find the number of events per year. In this paper, the threshold has been adjusted to obtain around 5.5 events per year.

```
Sub NbEvents()
' NbEvents Macro
    Range("A1").Select
    Selection.End(xlUp).Select
    Range("C2").Select
    ActiveCell.FormulaR1C1 = "=IF(RC[−1]>=R1C[4],1,0)"
    Range("C2").Select
    Nblines = Application.CountA(Range("A:A"))
```

```
        ZoneFillColumnC = "C2:C" & Nblines
        ZoneFillColumnD = "D3:D" & Nblines
        Selection.AutoFill Destination:=Range(ZoneFillColumnC)
        Range("C2:C14").Select
        Range("D3").Select
        ActiveCell.FormulaR1C1 = "=ABS(RC[−1]-R[−1]C[−1])"
        Range("D3").Select
        Selection.AutoFill Destination:=Range(ZoneFillColumnD)
        Range("D3:D14").Select
        Range("F1").Select
        Columns("F:F").ColumnWidth = 27
        ActiveCell.FormulaR1C1 = "Threshold (m3/s)"
        Range("F2").Select
        ActiveCell.FormulaR1C1 = "Number of Events"
        Range("F3").Select
        ActiveCell.FormulaR1C1 = "Number of years"
        Range("F4").Select
        ActiveCell.FormulaR1C1 = "Number of Events/year"
        Range("F5").Select
        ActiveCell.FormulaR1C1 = "(dependent and independent peaks)"
        Range("G1").Select
        ActiveCell.FormulaR1C1 = "9.999"
        Range("G2").Select
        ActiveCell.FormulaR1C1 = "=SUM(C[−3])/2"
        Selection.NumberFormat = "0"
        Range("G3").Select
        ActiveCell.FormulaR1C1 = "=(COUNT(C[−5])−1)/(24*365.25)"
        Selection.NumberFormat = "0.00"
        Range("G4").Select
        ActiveCell.FormulaR1C1 = "=R[−2]C/R[−1]C"
        Selection.NumberFormat = "0.00"
        Range("G1").Select
    End Sub
```

Appendix C Visual Basic Code for the Calculation of the Partial Series Return Periods

The supplement file named "Macro_Partial_series_calculation.xlsm" contains the VB script allowing the calculation of the return period of given discharge based on the partial series. It can be open with Microsoft Excel version 2007 at least. Test data are provided as hourly discharge series. The user is asked to give the flood threshold and the discharge value of which he wants to know the return period.

```
    Sub Hydrogramsep_Macro()

    Dim i As Long, ID As Long, j As Long, Nom As String
    Dim Threshold As Double
        ID = −1
        j = 2
        Nom = ActiveSheet.Name
        With Sheets(Nom)
```

```
'Ask for threshold value
Threshold = InputBox("Flood threshold (m³/s)")

'Ask for the given flow rate that will be used for the computation of the partial duration series
Q = InputBox("Flow rate for return period computation (Tp − m³/s)")

'Compute min & max date then count number of lines in column A (date)
Dim MinDate As Double, MaxDate As Double

    MinDate = WorksheetFunction.Min(Range("A:A"))
    MaxDate = WorksheetFunction.Max(Range("A:A"))
    Nblines = Application.CountA(Range("A:A"))
    Zone = "C2:C" & Nblines

'Add column Thresholding
    .Cells(1, 3).FormulaR1C1 = "Thresholding"
    Range("C2").Select
    ActiveCell.FormulaR1C1 = "=IF(RC[−1]>=" & Threshold & ",1,0)"
    Range("C2").Select
    Selection.AutoFill Destination:=Range(Zone), Type:=xlFillDefault
    Range(Zone).Select

    'Split the main table in different pages using the ID field (column C)
    For i = 2 To .Range("A1048576").End(xlUp).Row + 1

      If .Cells(i, 3).Value <> ID Then 'Value 3 refers to the column C
        ID = .Cells(i, 3).Value
        If i > 2 Then
          Sheets.Add
          ActiveSheet.Name = ID + ID2 'Creation of a unique sheet name

          .Range("A" & j & ":C" & i - 1).Copy ActiveSheet.Range("A1")
          j = i
          ID2 = ID + i
        End If

      End If
    Next i
    End With

    'Allow delete with alert
    Application.DisplayAlerts = False

    'Copy the first row of the main sheet to the splitted sheets
    For i = 1 To Worksheets.Count - 2

    k = Worksheets.Count

    If i <= k Then GoTo 4 Else GoTo 10
4     Sheets(i).Select
```

```
        'Cells.Select
        Cells.EntireColumn.AutoFit

        'Unselect all

        If Application.WorksheetFunction.Max(Range("C:C")) = 0 Then Worksheets(i).Delete Else
GoTo 8
        'Sort discharge from max to min

    8 Columns("A:C").Select
        Sheets(i).Sort.SortFields.Clear
        Sheets(i).Sort.SortFields.Add Key:=Range( _
          "B:B"), SortOn:=xlSortOnValues, Order:=xlDescending, DataOption:= _
          xlSortNormal
        With Sheets(i).Sort
          .SetRange Range("A:C")
          .Header = xlNo
          .MatchCase = False
          .Orientation = xlTopToBottom
          .SortMethod = xlPinYin
          .Apply
        End With

        Next i

      'Unselect all
    10      Application.CutCopyMode = False

    'Compute the number of sheets in the workbook
    Nbofsheets = Worksheets.Count

    'Allow the overwriting of existing files
    Application.DisplayAlerts = False

    99      Sheets.Add(After:=Sheets(Sheets.Count)).Name = "Floods"

    Sheets("Floods").Cells(1, 1).FormulaR1C1 = "Start date"
    Sheets("Floods").Cells(1, 2).FormulaR1C1 = "End date"
    Sheets("Floods").Cells(1, 3).FormulaR1C1 = "Flood duration (days)"
    Sheets("Floods").Cells(1, 4).FormulaR1C1 = "Maximum flow rate (m3/s)"
    Sheets("Floods").Cells(1, 5).FormulaR1C1 = "Peak date"
    Sheets("Floods").Cells(1, 6).FormulaR1C1 = "Time since previous peak (days)"
    Sheets("Floods").Cells(1, 7).FormulaR1C1 = "Duration below threshold (days)"
    Sheets("Floods").Cells(1, 8).FormulaR1C1 = "Duration of floods >1h"
    Sheets("Floods").Cells(1, 9).FormulaR1C1 = "Max. discharge of floods with duration below
threshold >= average dur. (m3/s)"
    Sheets("Floods").Cells(2, 11).FormulaR1C1 = "Average duration of floods >1h (days)"
    Sheets("Floods").Cells(9, 11).FormulaR1C1 = "Standard dev. of flood discharges (m3/s)"
    Sheets("Floods").Cells(11, 11).FormulaR1C1 = "Average value of flood discharges (m3/s)"
```

```
'Copy the first row of the main sheet to the splitted sheets
For i = 1 To Worksheets.Count - 2

k = Worksheets.Count

If i <= k Then GoTo 15 Else GoTo 20
15      Sheets(i).Select

20 Sheets("Floods").Cells(i + 1, 1).FormulaR1C1 = Sheets(i).Application.WorksheetFunction.
Min(Range("A:A"))
    Sheets("Floods").Columns("A:A").NumberFormat = "dd/mm/yyyy hh:mm"

    Sheets("Floods").Cells(i + 1, 2).FormulaR1C1 = Sheets(i).Application.WorksheetFunction.
Max(Range("A:A"))
    Sheets("Floods").Columns("B:B").NumberFormat = "dd/mm/yyyy hh:mm"

    Sheets("Floods").Cells(i + 1, 3).FormulaR1C1 = Sheets(i).Application.WorksheetFunction.
Max(Range("A:A")) - Sheets(i).Application.WorksheetFunction.Min(Range("A:A"))
    Sheets("Floods").Columns("C:C").NumberFormat = "0.000"

    Sheets("Floods").Cells(i + 1, 4).FormulaR1C1 = Sheets(i).Application.WorksheetFunction.
Max(Range("B:B"))
    Sheets("Floods").Columns("D:D").NumberFormat = "0.000"

    Sheets("Floods").Cells(i + 1, 5).FormulaR1C1 = Sheets(i).Cells(1, 1)
    Sheets("Floods").Columns("E:E").NumberFormat = "dd/mm/yyyy hh:mm"

    Next i

Sheets("Floods").Select
    Cells.Select
    Cells.EntireColumn.AutoFit

    'Count the number of lines in sheet "Floods"
    Sheets("Floods").Select
    NblinesFloods = Application.CountA(Range("A:A"))

    For j = 2 To NblinesFloods

    If j = NblinesFloods Then GoTo 999 Else GoTo 666
666     Sheets("Floods").Cells(j, 6).FormulaR1C1 = Sheets("Floods").Cells(j, 5) -
Sheets("Floods").Cells(j + 1, 5)
        Sheets("Floods").Columns("F:F").NumberFormat = "0.000"

    Sheets("Floods").Cells(j, 7).FormulaR1C1 = Sheets("Floods").Cells(j, 1) - Sheets("Floods").Cells(j
+ 1, 2)
        Sheets("Floods").Columns("G:G").NumberFormat = "0.000"

    Next j
```

```
'Computation of the duration of flood >1h and the max. discharge of floods

999 Sheets("Floods").Select

  Sheets("Floods").Select
  NblinesFloods2 = Application.CountA(Range("A:A"))

Sheets("Floods").Cells(NblinesFloods2, 9).FormulaR1C1 = Sheets("Floods").Cells(Nblines
Floods2, 4)

For m = 2 To NblinesFloods2

Cells(m, 8).Select
ActiveCell.FormulaR1C1 = "=IF(RC[−5]=0,"""",RC[-5])"

Next m

For n = 2 To NblinesFloods2 - 1

Cells(n, 9).Select
ActiveCell.FormulaR1C1 = "=IF(OR(IF(ABS(RC[-3])>=R2C12,1,0),IF(MAX(R[−1]C[−5]:
R[1]C[−5])-MIN(R[−1] C[−5]: R[1]C[−5])>=R9C12,1,0)),RC[−5],"""")"

Next n

Sheets("Floods").Cells(2, 12).FormulaR1C1 = Sheets(i).Application.WorksheetFunction.Average
(Range("H:H"))
  Sheets("Floods").Columns("L:L").NumberFormat = "0.000"

Sheets("Floods").Cells(9, 12).FormulaR1C1 = Application.WorksheetFunction.StDev(Range("I:I"))
Sheets("Floods").Cells(10, 12).FormulaR1C1 = Application.WorksheetFunction.Count(Range("I:I"))
Sheets("Floods").Cells(11, 12).FormulaR1C1 = Application.WorksheetFunction.Average(Range
("I:I"))
  Sheets("Floods").Columns("H:H").NumberFormat = "0.00"

Cells.Select
  Cells.EntireColumn.AutoFit

Sheets.Add(After:=Sheets(Sheets.Count)).Name = "Gumbel_Tp"

Sheets("Gumbel_Tp").Cells(1, 1).FormulaR1C1 = "N ="
Sheets("Gumbel_Tp").Cells(2, 1).FormulaR1C1 = "s ="
Sheets("Gumbel_Tp").Cells(3, 1).FormulaR1C1 = "Qm ="
Sheets("Gumbel_Tp").Cells(4, 1).FormulaR1C1 = "1/a ="
Sheets("Gumbel_Tp").Cells(5, 1).FormulaR1C1 = "a ="
Sheets("Gumbel_Tp").Cells(6, 1).FormulaR1C1 = "Q0 ="
Sheets("Gumbel_Tp").Cells(7, 1).FormulaR1C1 = "Number of hourly data="
Sheets("Gumbel_Tp").Cells(8, 1).FormulaR1C1 = "Number of available years="
Sheets("Gumbel_Tp").Cells(9, 1).FormulaR1C1 = "Number of events per year="
```

```
Sheets("Gumbel_Tp").Cells(11, 1).FormulaR1C1 = "Threshold(m3/s)="
Sheets("Gumbel_Tp").Cells(12, 1).FormulaR1C1 = "Given discharge (m3/s)="
Sheets("Gumbel_Tp").Cells(13, 1).FormulaR1C1 = "Return period Tp of the given disch. (yr)="

Sheets("Gumbel_Tp").Cells(1, 2).FormulaR1C1 = Sheets("Floods").Cells(10, 12)
Sheets("Gumbel_Tp").Cells(2, 2).FormulaR1C1 = Sheets("Floods").Cells(9, 12)
Sheets("Gumbel_Tp").Cells(3, 2).FormulaR1C1 = Sheets("Floods").Cells(11, 12)
Sheets("Gumbel_Tp").Cells(4, 2).FormulaR1C1 = 0.78 * Sheets("Gumbel_Tp").Cells(2, 2)
Sheets("Gumbel_Tp").Cells(5, 2).FormulaR1C1 = 1 / (Sheets("Gumbel_Tp").Cells(4, 2))
Sheets("Gumbel_Tp").Cells(6, 2).FormulaR1C1 = (Sheets("Gumbel_Tp").Cells(3, 2)) − (0.577 * Sheets("Gumbel_Tp").Cells(4, 2))
Sheets("Gumbel_Tp").Cells(7, 2).FormulaR1C1 = Worksheets("Discharges").Range("B:B").Cells.SpecialCells(xlCellTypeConstants).Count - 1
Sheets("Gumbel_Tp").Cells(8, 2).FormulaR1C1 = Sheets("Gumbel_Tp").Cells(7, 2) / (365.25 * 24)
Sheets("Gumbel_Tp").Cells(9, 2).FormulaR1C1 = Sheets("Gumbel_Tp").Cells(1, 2) / Sheets("Gumbel_Tp").Cells(8, 2)
Sheets("Gumbel_Tp").Cells(11, 2).FormulaR1C1 = Threshold
Sheets("Gumbel_Tp").Cells(12, 2).FormulaR1C1 = Q
Sheets("Gumbel_Tp").Cells(13, 2).Formula = "=1/((1-Exp(-Exp(-Gumbel_Tp!B5*(Gumbel_Tp!B12-Gumbel_Tp!B6))))* Gumbel_Tp!B9)"

Sheets("Gumbel_Tp").Cells(2, 2).NumberFormat = "0.000"
Sheets("Gumbel_Tp").Cells(3, 2).NumberFormat = "0.000"
Sheets("Gumbel_Tp").Cells(4, 2).NumberFormat = "0.000"
Sheets("Gumbel_Tp").Cells(5, 2).NumberFormat = "0.000"
Sheets("Gumbel_Tp").Cells(6, 2).NumberFormat = "0.000"
Sheets("Gumbel_Tp").Cells(8, 2).NumberFormat = "0.000"
Sheets("Gumbel_Tp").Cells(9, 2).NumberFormat = "0.000"
Sheets("Gumbel_Tp").Cells(13, 2).NumberFormat = "0.00"

Cells.Select
  Cells.EntireColumn.AutoFit

Sheets("Gumbel_Tp").Cells(12, 2).Select

End Sub
```

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