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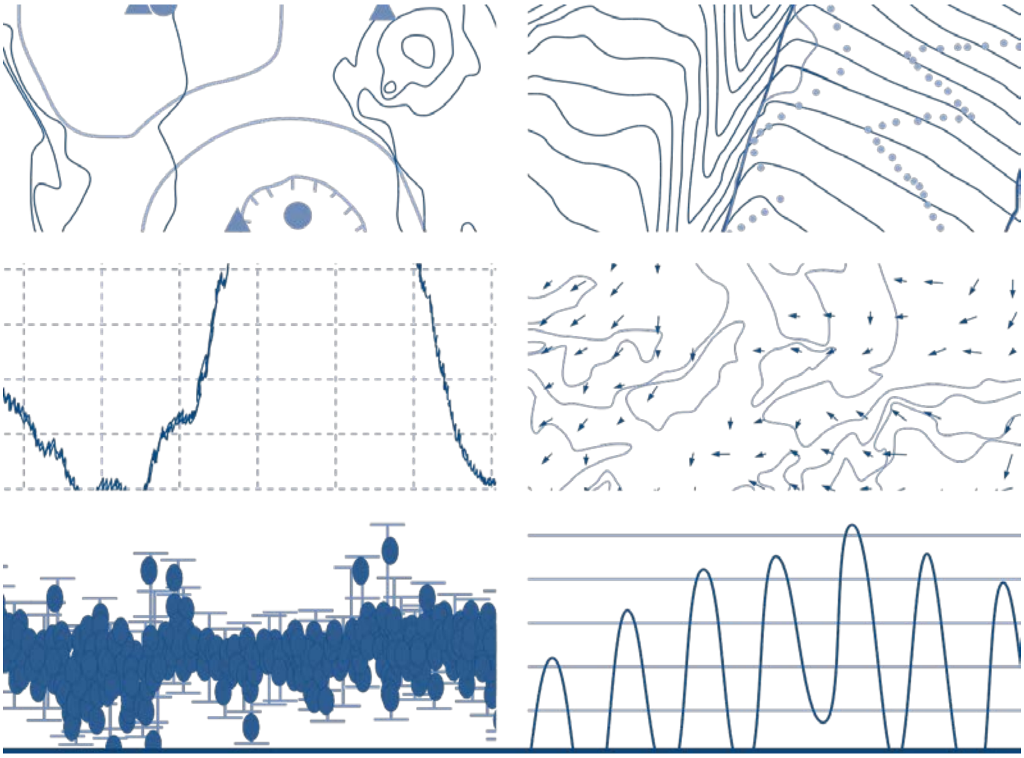

Regional Flood Frequency Analysis: Application to partly glacierized and/or groundwater-fed catchments

Philippe Crochet

Report

VÍ 2015-009

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Report

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Summary:

This study explores the application of the index flood method for estimating design floods at ungauged sites for rivers whose basins are partly glacierized and/or with substantial groundwater contribution to streamflow. The method is developed with observed flood data at available gauging stations in the studied region in Iceland. Results indicate that the method is capable of estimating flood quantiles with reasonable accuracy at most tested sites.

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Contents

1 Introduction

Flood frequency analysis is a prerequisite in flood risk assessment studies and for the design of various hydraulic structures. Often, flood quantile estimates are required at locations where streamflow series are very short or where no data are available, making a direct estimation impossible. Regional flood frequency analysis such as the index flood method (IFM) (Dalrymple, 1960) offers a solution to this problem. The idea is to trade space for time and compensate for the lack of information at the site of interest by using flood data from other sites, located within the same homogeneous region with respect to flood characteristics. The IFM has for instance been used by Burn (1990), GREHYS (1996a, 1996b), Hosking & Wallis (1997), Malekinezhad *et al.* (2011a, 2011b), Zaman *et al.,* (2012), among many others.

The IFM has successfully been evaluated in various regions of Iceland, e.g. in the Westfjords, Tröllaskagi and neighboring areas (Crochet, 2012a, b; Crochet & Þórarinsdóttir, 2014) and in eastern Iceland (Crochet & Þórarinsdóttir, 2015). This study is a continuation of this work. The capacity of the IFM to estimate design floods at ungauged locations is now evaluated for river basins having substantial glacier coverage and/or substantial groundwater contribution to streamflow. The report is organized as follows. Section 2 presents the study area and data. Section 3 describes the methodology. Section 4 presents the results and Section 5 concludes the report.

2 Study area and data

2.1 River basins

Rivers in Iceland are often classified according to the origin of flow (Rist, 1990): direct runoff (D), spring-fed (L), glacier-fed (J) and whether they flow through lakes (S). Twelve river basins were selected for this study (Fig. 1). Ten of them are partly glacierized and with a variable groundwater contribution to flow whereas the other two are non-glacierized but mostly spring-fed. Table 1 summarizes their main characteristics.

2.2 Streamflow data

Annual maximum flow (AMF) series were used to conduct the regional flood frequency analysis. The study is concerned by floods of hydro-meteorological origin only. AMF series were extracted for each hydrological year (taken here from Sept 1 to Aug 31), from monthly maximum instantaneous flow series. Years with more than two missing months were omitted. As the AMF of year 1999 at gauging stations vhm102 and vhm233 was strongly suspected to be caused by a jökullhlaup, the 2nd largest annual flow was selected for this year. One must bear in mind that uncertainties related to the validity of the rating curves, used to convert measured water level into discharge, can lead to uncertainties in discharge calculations, especially for high discharge values. Figure 2 presents the time of occurrence of AMF at each gauging station. One can see that for gauging stations vhm59, vhm64, vhm66, vhm116, vhm144, vhm145, vhm167, vhm235 and vhm238, the AMF is mainly occurring between November and May, whereas for vhm102, vhm162 and vhm233, which are primarily of glacial origin, the AMF is mainly occurring between June and September.

2.3 Meteorological data

Gridded daily air temperature at 2 m above ground (Crochet & Jóhannesson, 2011) and precipitation (Crochet, 2013) calculated on a 1x1 km grid for the period 1961–2014, were used in the study.

2.4 Other data

A 1x1 km digital elevation model derived from a 500 m DEM (Icelandic Meteorological Office, National Land Survey of Iceland, Science Institute, University of Iceland, and National Energy Authority. 2004), a soil map from the Agricultural University of Iceland and a map of the bedrock geology from the Icelandic Institute of Natural History (Jarðfræðikort af Íslandi - Berggrunnur - 1:600.000 - NI_J600v_berg_2.utg) were also used in this study.

Table 1. Main characteristics of river basins used in this study.

River / Gauging station	Name	Type	Area (km^2)	Mean elevation (m a.s.l)	Percentage glacier	Mean annual precipitation (mm) (1961-2014)	Period for streamflow data
vhm59	Ytri-Rangá	L	622	365	0	1564	1961–2014
vhm64	Ölfusá	L+D+J+S	5687	480	12.2	2003	1950–2014
vhm66	Hvítá (Borgarfirði)	L+J	1577	653	21	1585	1951–2014
vhm102	Jökulsá á Fjöllum	J+L+D	5094	863	29.3	908	1965–2014
vhm116	Svartá	L	524	652	0	658	1985–2014
vhm162	Jökulsá á Fjöllum	J+L	2023	1139	57.5	1107	1985–2014
vhm233	Kreppa	J+D	817	936	39.9	983	1985–2014
vhm235	Hvítá (Árnessýslu)	L+J+D	1650	719	21.8	1858	1991–2014
vhm238	Skjálfandafljót	L+D+J	2172	823	6.2	822	1987–2014
vhm144	Austari-Jökulsá	D+J+L	1089	872	14.6	1102	1971–2014
vhm145	Vestari-Jökulsá	D+J+L	844	751	11.3	924	1971–2014
vhm167	Austari-Jökulsá	D+J	553	916	28.8	1208	1985–2014

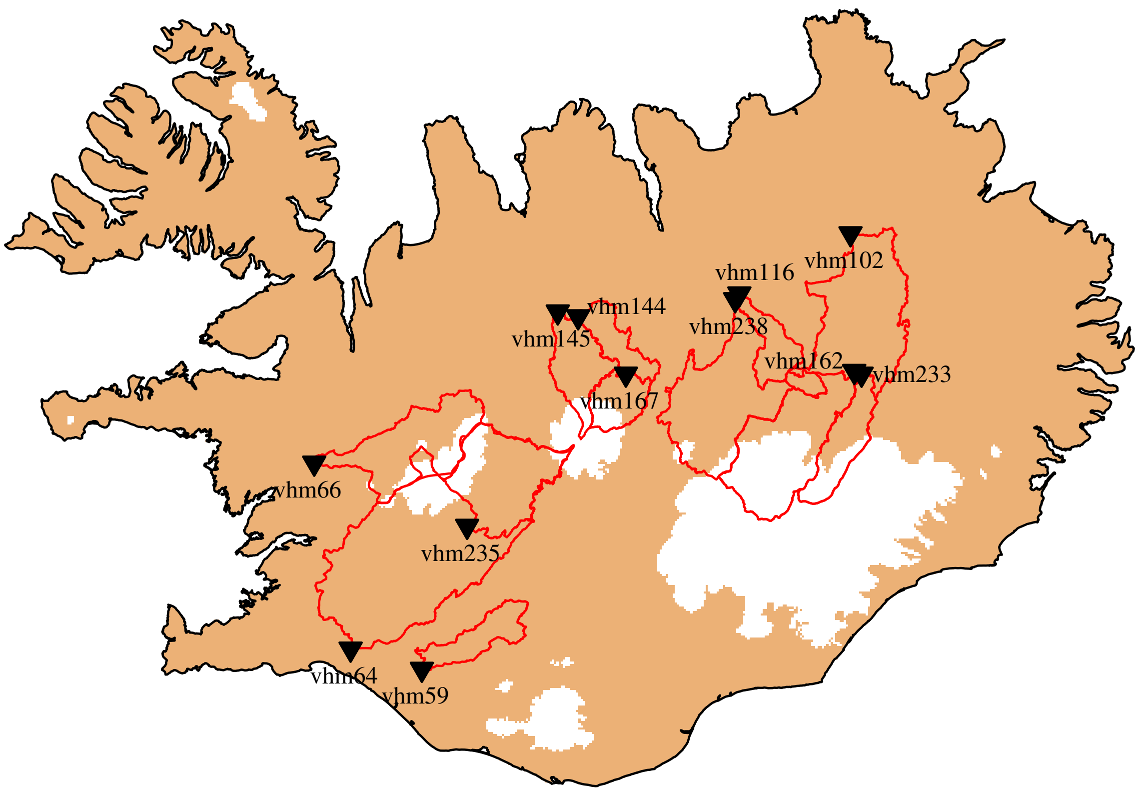

Figure 1. Location of river basins.

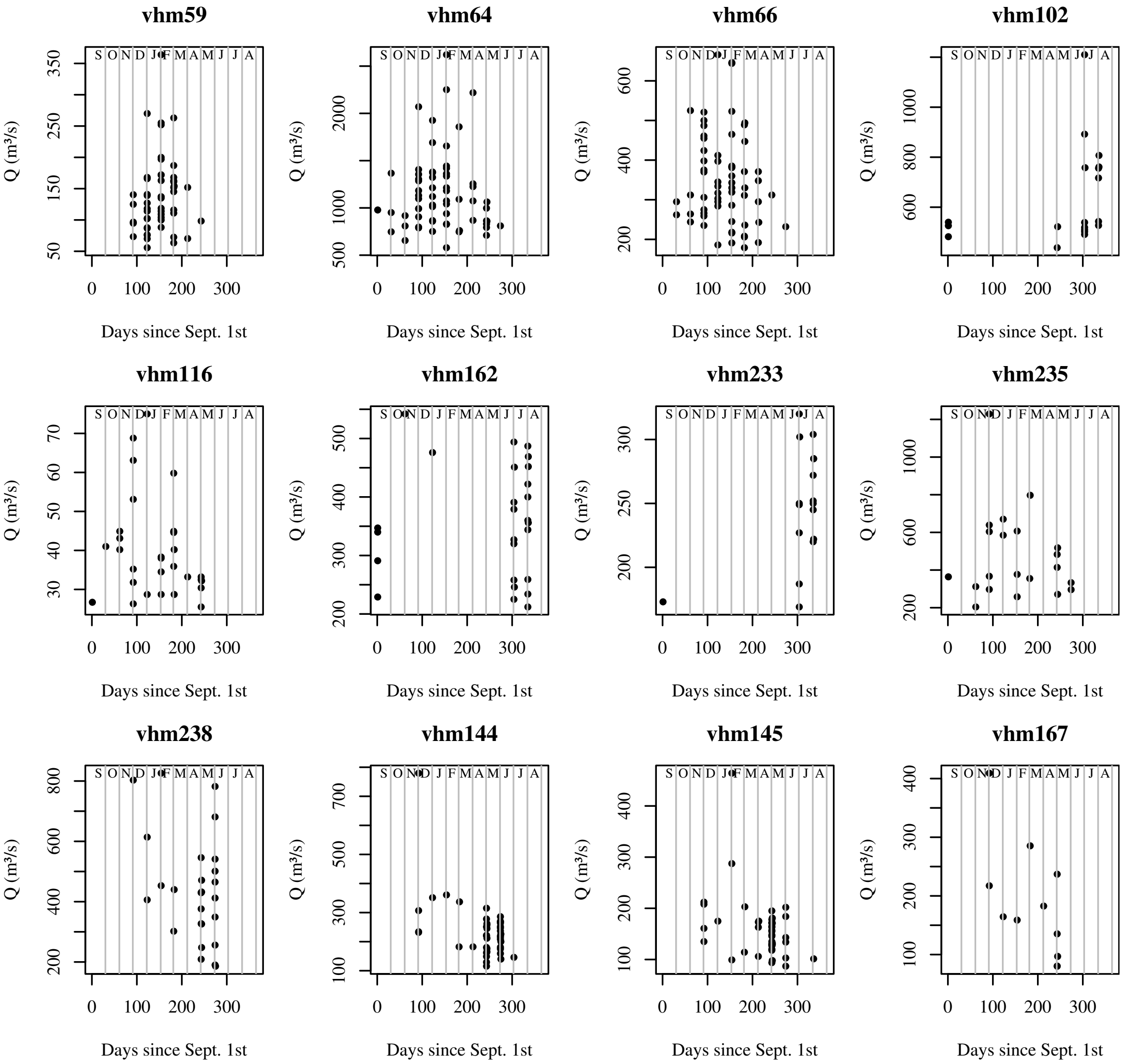

Figure 2. Time of occurrence for annual maximum flow.

3 Index flood method

3.1 General principle

The method has already been described in Crochet (2012a, 2012b) and Crochet & Þórarinsdóttir (2014, 2015) and is briefly summarised here. The index flood method (IFM) is used to estimate the T-year flood quantile at ungauged locations or at gauged sites with short records, using available flood data taken from gauged sites located within the same homogeneous region. The flood generating mechanisms are supposed to be the same. This study is focused on floods of hydro-meteorological origin, without distinguishing between rain or snowmelt floods. The catchments are assumed to be natural and without flow alteration. The method assumes that within a homogeneous region, flood data are drawn from the same frequency distribution, apart from a scaling factor. The method involves two major steps: i) the identification of a group of homogeneous catchments with respect to flood statistics and ii) a regional estimation method for estimating the flood frequency distribution at each site of interest, called target site, gauged or ungauged, within the homogeneous region.

The so-called region of influence (ROI) approach (Burn 1990) was used to identify homogeneous groups of catchments, i.e. catchments considered sufficiently similar to produce a similar hydrologic response with respect to extreme flow. With this technique, a potentially unique "region" is defined and associated to each target catchment. Once a homogeneous group of catchments has been preliminary identified, the degree of homogeneity of the candidate "region" with respect to extreme flow statistics is tested with the H-statistics (Hosking & Wallis, 1993) (see also Crochet, 2012b). Once the candidate region has been accepted as sufficiently homogeneous with respect to flood statistics, the flood frequency distribution of the target site is estimated by rescaling a dimensionless regional flood frequency distribution or growth curve, $q_R(D,T)$, common to all sites of the homogeneous region, with the so-called index flood, $\mu_i(D)$, of the target site:

$$\widehat{Q}_i(D,T) = \mu_i(D) q_R(D,T), \tag{1}$$

where $\widehat{Q}_i(D,T)$ is the estimated flood quantile, i.e. the T-year flood peak discharge averaged over duration D, at site i. The regional growth curve, $q_R(D,T)$, is the ratio of $Q_i(D,T)$ to the index flood $\mu_i(D)$ and is derived by pooling the AMF series from all gauged sites belonging to the homogeneous region. In this study, instantaneous floods (D=0) are only considered.

The index flood, $\mu_i(D)$, is defined here by the mean of the AMF. If the target site is gauged, $\mu_i(D)$ can be estimated by the sample mean, whereas for ungauged target sites, $\mu_i(D)$ needs to be indirectly estimated. This step is usually performed by assuming that $\mu_i(D)$ is a function of catchment characteristics ($C_{i,k}$) (not necessarily the same ones than those used in the identification of the homogeneous region):

$$\widehat{\mu}_i(D) = f(C_{i,k}), k = 1,n. \tag{2}$$

where k denotes the kth catchment characteristic. Multiple linear regression is often used to infer the model parameters (see for instance Grover et al., 2002).

3.2 Flood frequency distribution and parameter estimation method

The Generalized Extreme Value (GEV) distribution (Jenkinson, 1955) was adopted to model the flood frequency distribution from the AMF series:

$$Q(D,T) = \begin{cases} \varepsilon + \frac{\alpha}{\kappa}(1 - [-\ln(1-1/T)]^{\kappa}) & \text{if } \kappa \neq 0 \\ \varepsilon - \alpha \ln(-\ln(1-1/T)) & \text{if } \kappa = 0 \end{cases} \tag{3}$$

where ε is the location parameter, α is the scale parameter and κ is the shape parameter. The method of probability weighted moments (PWM) proposed by Hosking *et al.* (1985b) was adopted to fit the individual GEV distributions at each site and the parameters of the regional growth curve ($q_R(D,T)$) were estimated with the GEV/PWM regionalization algorithm proposed by Hosking *et al.* (1985a), as in Crochet (2012a, 2012b) and Crochet & Þórarinsdóttir (2014, 2015).

3.3 Evaluation statistics

The IFM was evaluated assuming that the target site was totally ungauged. A cross-validation strategy was developed. Each of the twelve gauged sites presented in Fig. 1 was in turn considered as the ungauged "target" site *i* for which flood quantiles were required. The IFM was recursively developed without using the AMF data from that site, and then used to infer the index flood ($\mu_i(D)$) and flood quantiles ($Q_i(D,T)$) at that site. Estimated index flood ($\widehat{\mu_i}(D)$) and flood quantiles ($\widehat{Q_i}(D,T) = \widehat{\mu_i}(D) q_R(D,T)$) were then compared to the reference index flood and flood quantiles, calculated with AMF observations available at the target site.

The ability to predict the index flood at ungauged sites was evaluated by calculating the following statistics:

- Relative root mean squared error ($RMSE_\mu$)
- Mean absolute error (MAE_μ)
- Nash-Sutcliffe efficiency (NS_μ) (Nash & Sutcliffe, 1970)

With

$$RMSE_\mu(\%) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{\widehat{\mu_i}(D) - \mu_i(D)}{\mu_i(D)}\right)^2} x100 \tag{4}$$

$$MAE_\mu(m^3/s) = \frac{1}{N}\sum_{i=1}^{N}|\widehat{\mu_i}(D) - \mu_i(D)| \tag{5}$$

$$NS_\mu = 1 - \frac{\sum_{i=1}^{N}\left(\widehat{\mu_i}(D) - \mu_i(D)\right)^2}{\sum_{i=1}^{N}\left(\mu_i(D) - E[\mu_i(D)]\right)^2} \tag{6}$$

where $\mu_i(D)$ is the reference index flood at target site i defined by the arithmetic mean of observed AMF, and N the total number of target sites.

Each statistics was ranked from best (1) to worst (24) and the average rank calculated.

Reference and estimated flood quantiles were compared at each target site, for average recurrence intervals T of 2, 5, 10, 20, 50 years. The quality of the estimation was evaluated by calculating the relative root mean squared error of the quantile estimates for each site, and then the average over all sites was calculated ($RMSE_T$):

$$RMSE_T(\%) = \frac{1}{N}\sum_{i=1}^{N}\sqrt{\frac{1}{L}\sum_{l=1}^{L}\Big(\frac{Q_i(D,T_l)-\widehat{Q}_i(D,T_l)}{Q_i(D,T_l)}\Big)^2} x100 \tag{7}$$

where $Q_i(D,T_l)$ is the reference flood quantile at gauged site i and return period T_l, calculated with the GEV distribution fitted to the observed AMF series and $\widehat{Q}_i(D,T_l)$ is the estimated flood quantile, calculated with the IFM ($\widehat{Q}_i(D,T) = \widehat{\mu}_i(D)q_R(D,T)$). $RMSE_T$ was ranked from best to worst and the model giving the lowest $RMSE_T$ was selected to estimate flood quantiles at ungauged sites.

4 Results

4.1 Delineation of homogeneous regions

The following eleven catchment characteristics (calculable anywhere in Iceland) were considered for the identification of homogeneous regions with the ROI technique:

- Logarithm of catchment area ($Log(A)$)
- Mean catchment altitude (Z)
- Ratio between actual catchment area and area of circular catchment of perimeter L
- Percentage of glacierized area (G)
- Percentage of bedrock geology type ($Geol$)
- Percentage of soil type ($soil$)
- Mean annual precipitation (P) (1961-2014)
- Mean timing of annual maximum snowpack (SWE_m) (1961-2014)
- Mean snow cover fraction on May 1st (SCF) (1961-2014)
- Timing of annual maximum mean daily input water supply (W_m) (1961-2014)
- Normalized mean monthly input water supply ($NW(j), j = 1,..,12$) (1961-2014)

Daily precipitation was split into rain or snow according to a temperature threshold. A simple temperature-index melt model that relates air temperature to snow and ice melt rates was used to estimate the snowpack evolution and glacier melt. Input water supply (W) was estimated as the sum of rain and snowmelt (and ice melt). The mean daily input water supply (W_m) was calculated for each calendar day between 1961 and 2014.

A minimum of five sites ($M \geq 5$) was required to compose a homogeneous region. After an extensive investigation where various combinations of catchment characteristics were tested, the following four catchment attributes were finally selected to conduct the delineation of homogeneous groups of catchments with the ROI technique:

- Mean catchment altitude (Z)
- Percentage of glacierized area (G)
- Percentage of bedrock geology type ($Geol$)
- Mean annual precipitation (P) (1961-2014)

Table 2 presents the homogeneous groups of catchments associated to each target catchment. The catchments are ordered from most similar to least similar.

Table 2. Homogeneous groups of catchments associated to each target catchment, according to the ROI technique.

Target catchment	ROI
vhm59:	vhm66, vhm238, vhm102, vhm235, vhm116, vhm233
vhm64:	vhm235, vhm66, vhm238, vhm144, vhm102, vhm145
vhm66:	vhm144, vhm145, vhm235, vhm238, vhm102, vhm233
vhm102:	vhm233, vhm238, vhm162, vhm66, vhm144, vhm235
vhm116:	vhm102, vhm238, vhm233, vhm59, vhm66
vhm162:	vhm102, vhm233, vhm238, vhm66, vhm144, vhm235, vhm145
vhm233:	vhm102, vhm238, vhm162, vhm66, vhm144, vhm235
vhm235:	vhm66, vhm144, vhm102, vhm238, vhm145, vhm233
vhm238:	vhm102, vhm144, vhm66, vhm145, vhm233, vhm235
vhm144:	vhm145, vhm66, vhm238, vhm102, vhm235, vhm233
vhm145:	vhm144, vhm66, vhm238, vhm235, vhm102
vhm167:	vhm102, vhm238, vhm144, vhm233, vhm66

4.2 Regional growth curves

The validity of the candidate homogeneous regions delineated by the ROI technique (see Table 2), was analyzed by studying the homogeneity of the associated regional growth curves derived from observed AMF series, through the calculation of the H-statistics (Hosking & Wallis, 1993). Regions with values of H-statistics above 2 are regarded as potentially non-homogeneous in relation to the regional growth curve. The M' most similar sites (with $M' \geq 3$) giving the lowest H-statistics, among the M pre-selected ones (with $M \geq 5$), were selected for the calculation of the growth curves, $q_R(D,T)$. The selection was conducted by eliminating one site at the time, starting from the least similar one, back to the 4th most similar one, leaving the three most similar ones. Table 3 presents the H-statistics obtained with and without target site. Appendix I presents the regional growth curves calculated with the M' selected gauging stations, to be compared to Table 2 giving the list of M pre-selected sites. Results confirm that for most target sites, the groups of river basins selected for applying the IFM are homogeneous with respect to flood statistics ($H \leq 2$), except those associated to vhm59 and vhm116 ($H > 2$), which are both spring-fed rivers (cf. Table 1). For these two river basins, there is a possibility that the delineated surface drainage areas do not reflect the contributing areas with respect to groundwater, which may explain the heterogeneity of the associated groups of river basins delineated with the ROI technique.

Table 3. H-statistics associated to the ROI of each target catchment. See associated regional growth curves in Appendix I.

Target catchment	H-statistics without target catchment	H-statistics with target catchment
vhm59:	2.17	2.31
vhm64:	0.534	0.553
vhm66:	–0.086	0.179
vhm102:	1.7	1.99
vhm116:	3.73	2.94
vhm162:	1.48	2.03
vhm233:	1.32	2.16
vhm235:	0.203	0.743
vhm238:	–0.259	0.253
vhm144:	0.156	–0.454
vhm145:	0.13	–0.398
vhm167:	0.848	1.69

4.2.1 Index flood modelling

Too few gauged sites were available in the studied region for developing a multiple linear regression between index flood and catchment characteristics. Simple models were therefore developed by combining several catchment characteristics into one single variable. Twelve variables, V, were defined:

- Variable no. 1: $V = (A)$
- Variable no. 2: $V = (L)$
- Variable no. 3: $V = (A/L)$
- Variable no. 4: $V = (A/Z)$
- Variable no. 5: $V = (AP)$
- Variable no. 6: $V = (AP/Z)$
- Variable no. 7: $V = (AP/L)$
- Variable no. 8: $V = (AP/(ZL))$
- Variable no. 9: $V = (AP_m)$
- Variable no. 10: $V = (AP_m/Z)$
- Variable no. 11: $V = (AW_m)$
- Variable no. 12: $V = (AW_m/Z)$

Where P_m is the mean annual maximum catchment-averaged precipitation for the period 1961–2014, W_m is the mean annual maximum input water supply for the period 1961–2014 and other catchment characteristics are defined in Section 4.1. Variables no. 1–4 include physiographic catchment characteristics only, whereas variables no. 5–12 combine physiographic and climatic characteristics.

Two groups of models were defined between the index flood $\mu(D)$ and V. The first twelve models, (1–12), were defined assuming a power-form relationship between $\mu(D)$ and V:

$$\mu(D) = \theta_0 V^{\theta_1} \tag{8}$$

and the next twelve ones, (13–24), were defined assuming a linear relationship between $\mu(D)$ and V:

$$\mu(D) = \theta_0 + \theta_1 V \tag{9}$$

where V is one of the twelve variables defined previously and $\theta = (\theta_0, \theta_1)$ is the vector of model parameters, estimated by ordinary least squares (OLS) regression. A logarithmic transformation was first applied for models 1–12 prior to infer the model parameters. The reference index flood $\mu(D)$ at each site was taken as the arithmetic mean of observed AMF series. These models were calibrated for each target site, treated as ungauged, i.e. by using all catchments belonging to the homogeneous region associated to the target site (cf. Table 2) but without using the data from the target site in question. The models were then used to estimate $\mu(D)$ at each of the twelve gauged sites (cf. Fig. 1), alternatively treated as ungauged, and for which the catchment characteristics (and therefore V) are known.

Figure 3 summarizes the results of the comparison between reference and estimated index floods and Appendix II presents the scatter plots. For each catchment, one can see that several index flood models perform relatively similarly. One can also see that there usually is one model at least providing an acceptable estimate of $\mu(D)$ for each catchment, i.e. close to or within the 95% CI of the reference $\mu(D)$. However, as one cannot a-priori know which model will perform best at ungauged catchments, one of the candidate models has to a-priori be selected on the basis of results obtained at gauged catchments, through the cross-validation procedure.

As previously discussed in Crochet (2012a, 2012b) and in Crochet & Þórarinsdóttir (2014, 2015), different factors can contribute to the development of a poor index flood model, leading to poor estimates of $\mu(D)$ at ungauged catchments. Firstly, the model may be inappropriate to describe the spatial variations of $\mu(D)$ in the region under study, even though the region is homogeneous. Secondly, the degree of hydrological similarity between the target catchment and the homogeneous region is too poor. Thirdly, the index flood model is applied to a catchment whose characteristics are beyond the range of characteristics for which the model was developed. Finally, sampling variability can affect the quality of the index flood model, e.g when $\mu(D)$ has been estimated on different periods of time at the different gauging sites.

According to the three selected criteria (cf. Section 3.3 and Appendix II), the best results are obtained with model no. 5 ($\widehat{\mu}(D) = \theta_0(AP)^{\theta_1}$), ($RMSE_\mu = 54\%$, MAE_μ=52 m^3/s, NS_μ=0.95). When this model is considered, results indicate that $\widehat{\mu}(D)$ is usually within or close to the 95% confidence interval (CI) of the reference $\mu(D)$ for gauging stations vhm64, vhm102, vhm162, vhm233, vhm235, vhm144, and vhm167, slightly biased for vhm59, vhm66, vhm238 and vhm145 and very biased for vhm116 (cf. Fig. 3). The gauging station vhm116 is located on a spring-fed river. Part of its runoff flows through a lake and surface and groundwater drainage areas do not necessarily coincide. This could explain the difficulty for the different models to estimate $\mu(D)$ at that site with available information at other selected sites. Note also that the H-statistics obtained for the homogeneous group of catchments associated to vhm116 is the highest (cf. Table 3), which indicates potential heterogeneity with respect to flood statistics and partly explains the difficulty of estimating $\mu(D)$ at that site with the IFM.

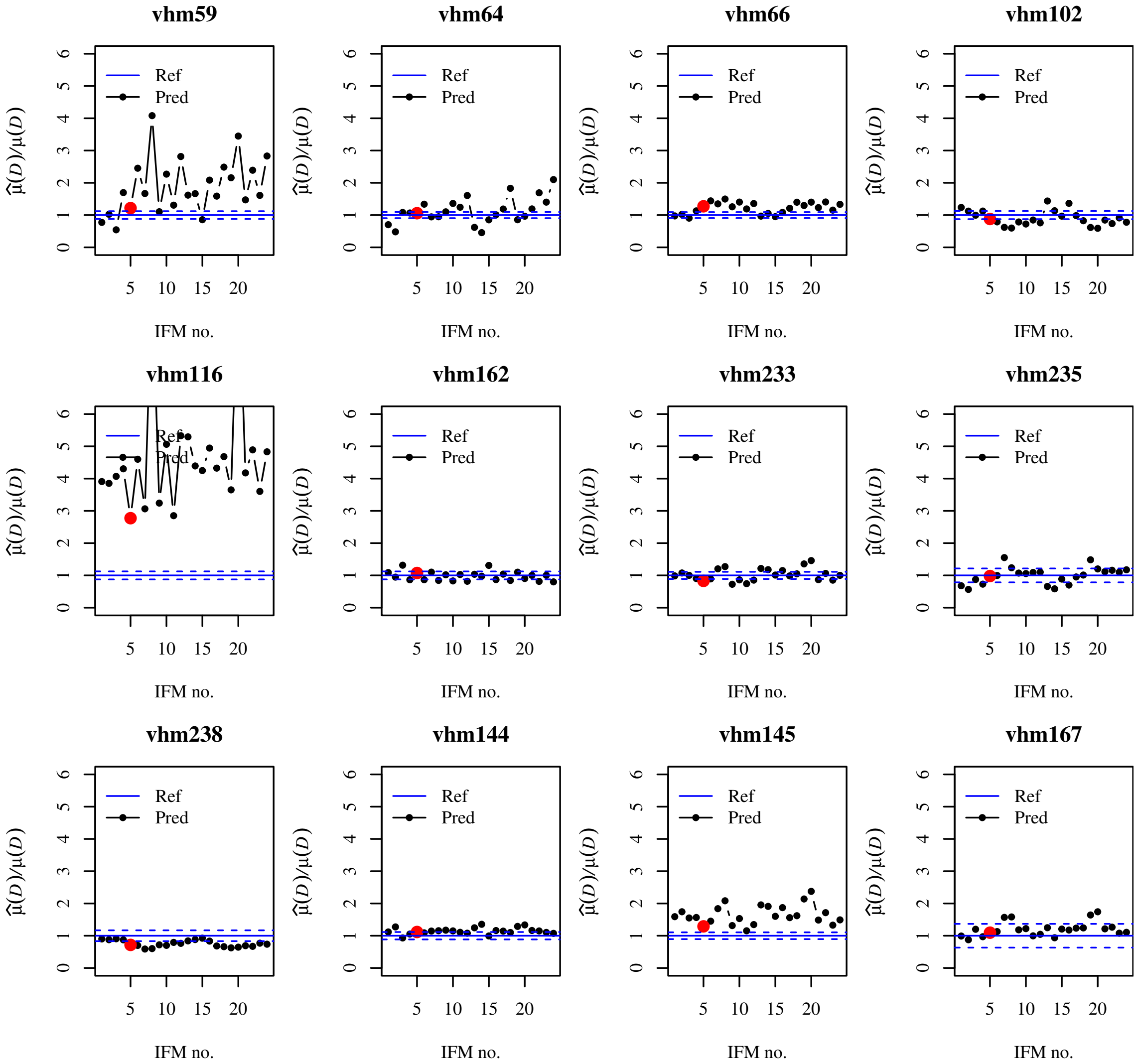

Figure 3. Index flood estimation, $\widehat{\mu}(D)$, at each gauged site treated as ungauged, using index flood models 1–24 (Eqs. 8 and 9 applied with variables 1–12). Ratio between estimated and reference index flood (solid black line). The solid blue line corresponds to the reference index flood (Ratio=1), estimated as the arithmetic mean of the observed AMF sample and the dashed blue lines the 95% CI derived from the GEV distribution. Large red symbol indicates overall best model.

4.2.2 Flood quantile estimation

The twenty four different index flood models proposed in this study were used to estimate $\mu(D)$ and then the flood quantiles at each target site, treated as ungauged (cf. Eq. 1). The relative RMSE ($RMSE_T$, see Section 3.3) calculated on five quantiles (T=2, 5, 10, 20 and 50 years) summarizes the overall quality of these estimates (Fig. 4) and gives a comparison of their respective performances. The flood quantile estimation error depends on the quality of i) the index flood model (Eqs. 8 and 9 applied with variables 1–12) and ii) the regional growth curve, $q_R(D,T)$. As a consequence, the best results are not necessarily obtained with the best index flood model, because of compensating errors such as an over- (under-) estimation of the catchment growth curve ($q_i(D,T)$) by the regional growth curve ($q_R(D,T)$) and an under- (over-) estimation of the true index flood ($\mu_i(D)$) by the estimated index flood $\widehat{\mu_i}(D)$. However, the dominating source of error is often the quality of $\widehat{\mu_i}(D)$.

According to $RMSE_T$, the best results are obtained with index flood model no. 5 ($\widehat{\mu}(D) = \theta_0(AP)^{\theta_1}$), ($RMSE_T$=31.5%). This model was already identified as providing the best index flood estimate ($\widehat{\mu}(D)$). Figures 5 to 7 present the reference and estimated flood frequency distributions obtained at each gauged site, treated as ungauged, considering the index flood model no. 5. When this model is used, the estimated quantiles are relatively unbiased in average and are usually within the 95% CI of the reference quantiles in a majority of target sites. As expected, poor quantile estimates are obtained for catchments where $\widehat{\mu}(D)$ is most biased, e.g. vhm116.

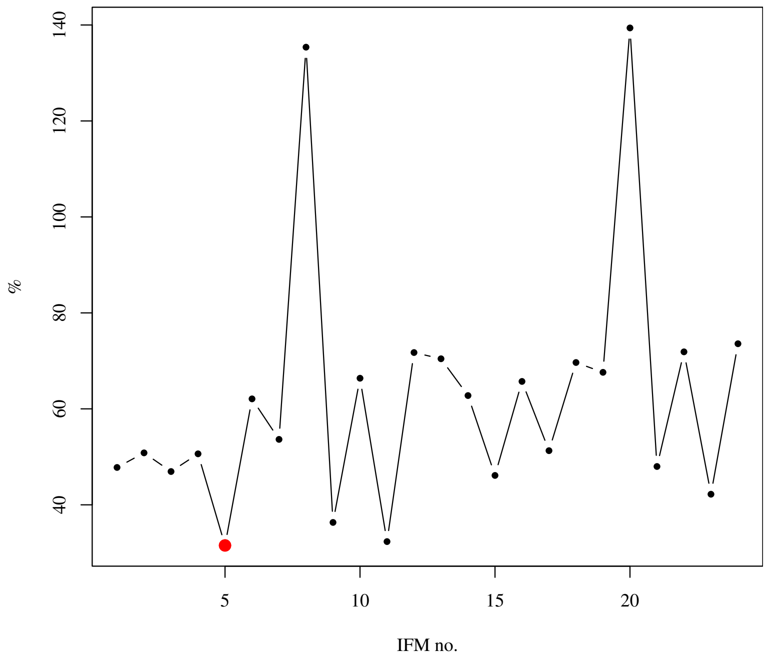

Figure 4. Estimated instantaneous flood quantiles with the IFM, at gauged sites treated as ungauged. Mean relative quantile RMSE ($RMSE_T$) for the different index flood models. Large symbol corresponds to the model giving the best results.

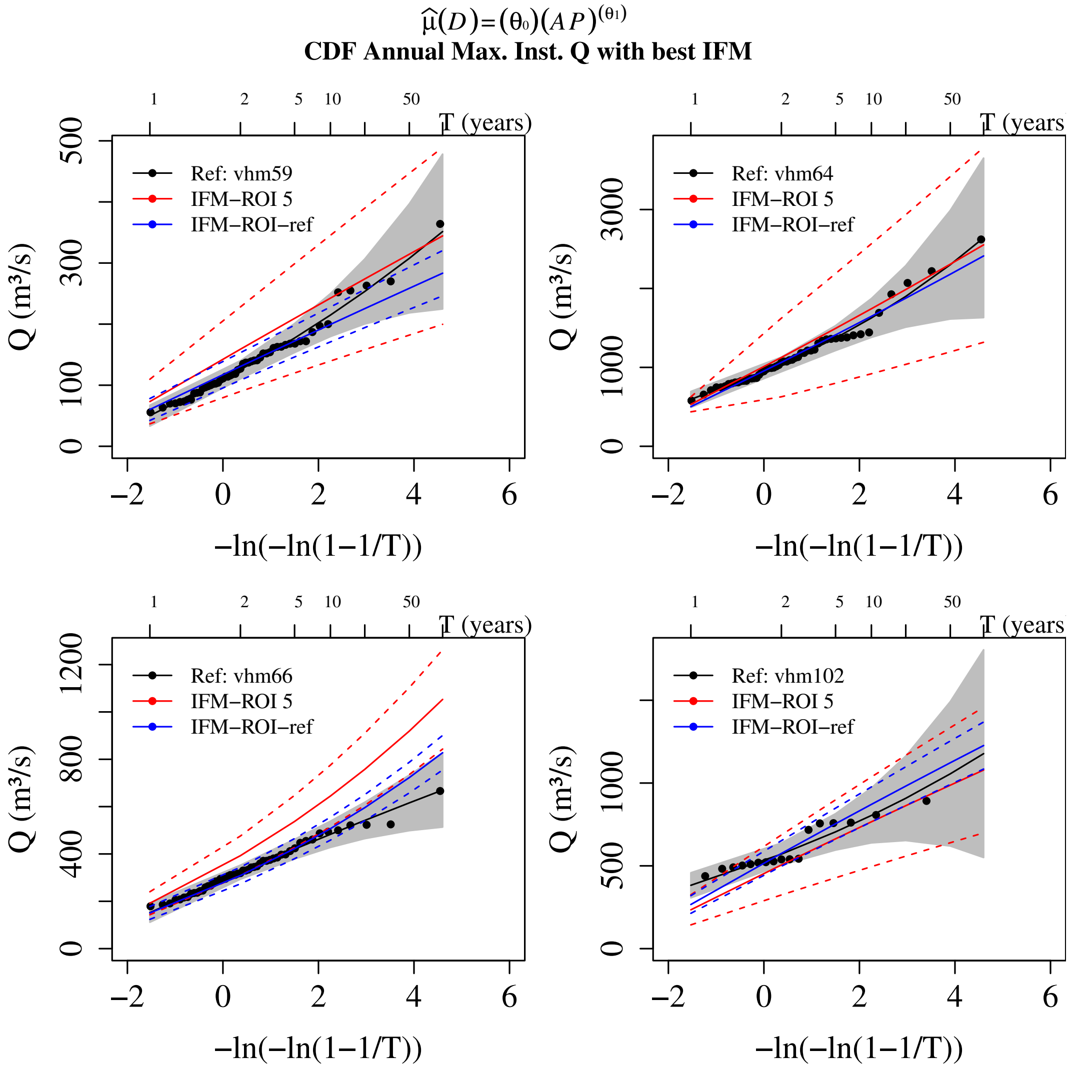

Figure 5. AMF frequency distributions ($Q(D,T)$ vs. T) at target sites treated as ungauged, using best overall index flood model ($\widehat{\mu}(D) = \theta_0(AP)^{\theta_1}$): vhm59 (top-left), vhm64 (top-right), vhm66 (bottom-left), vhm102 (bottom-right). Solid black line corresponds to the reference GEV distribution fitted to the observed AMF sample. Grey shaded region corresponds to the reference 95% CI. Red solid line corresponds to the IFM-based distribution assuming that the target site is ungauged ($\widehat{\mu}(D) = \theta_0(AP)^{\theta_1}$). Blue solid line corresponds to the IFM-based distribution assuming that the target site is gauged (i.e. when $\mu(D)$ is estimated by the arithmetic mean of the observed AMF sample). Coloured dashed lines correspond to the IFM-based 95% CI (See Crochet, 2012a).

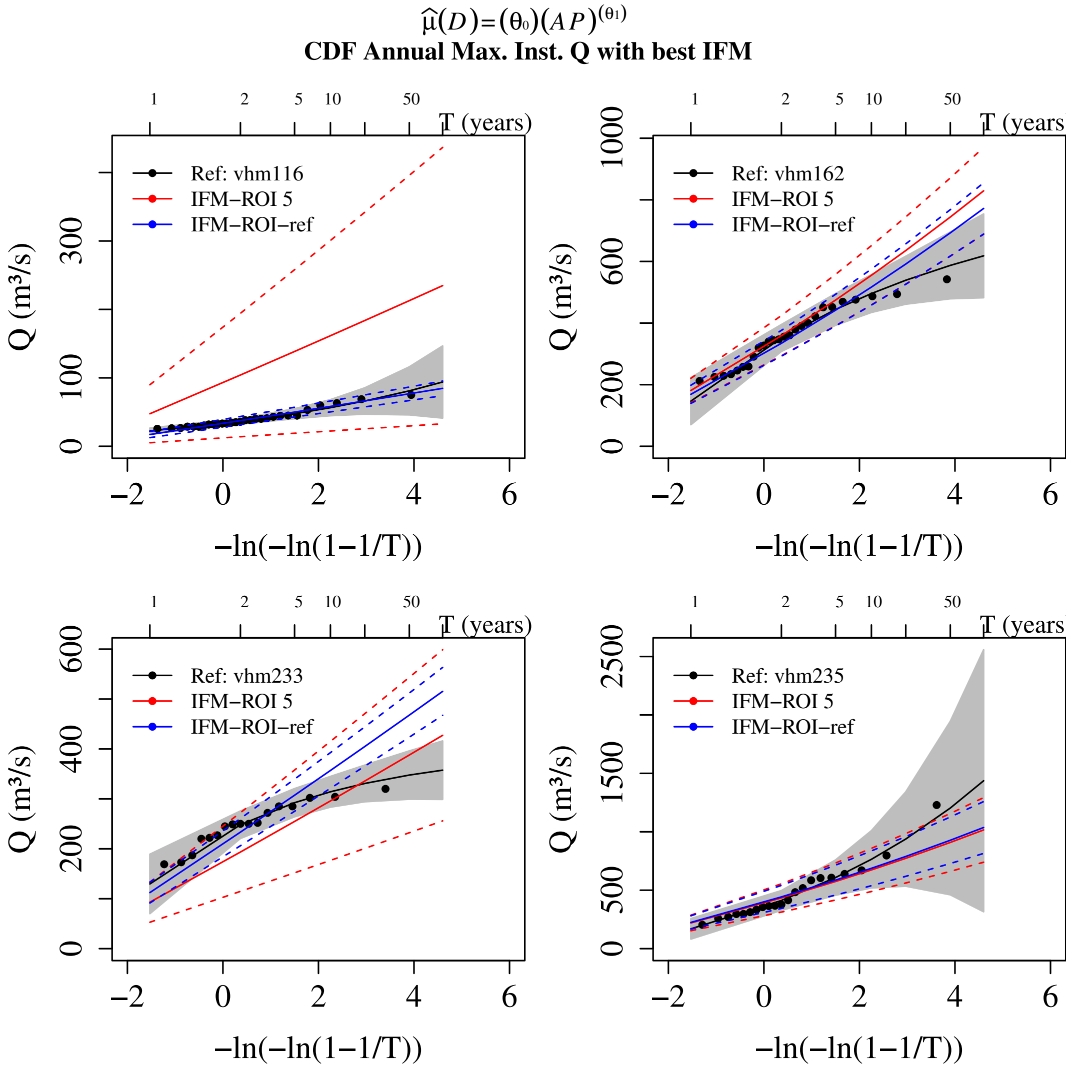

Figure 6. As Fig. 5 but for vhm116 (top-left), vhm162 (top-right), vhm233 (bottom-left), vhm235 (bottom-right).

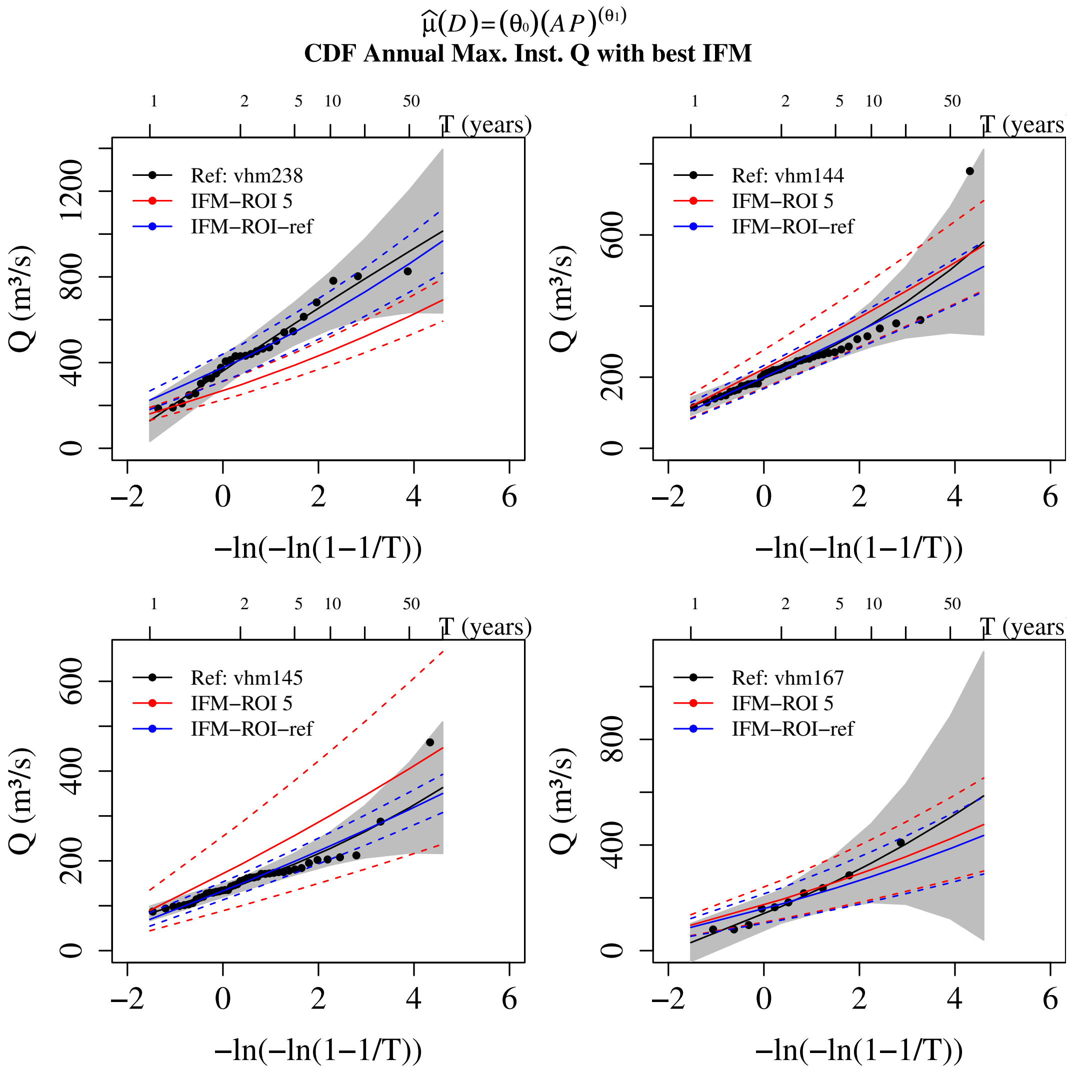

Figure 7. As Fig. 5 but for vhm238 (top-left), vhm144 (top-right), vhm145 (bottom-left), vhm167 (bottom-right).

5 Conclusion

Lack of data is one of the most difficult challenges that hydrologists and engineers face in flood risk assessment studies and in the design of hydraulic structures. The IFM offers a solution for the calculation of design floods, at locations where flood data are too few or not available to allow a direct estimation. The idea is to trade space for time, i.e. to pool flood data from different gauged sites belonging to the same homogeneous region with respect to flood statistics, in order to infer design floods at the required target location. The goal of this study was to test the applicability of the IFM for partly-glacierized river basins and/or river basins with large groundwater contribution to streamflow. Results indicate a good potential for the method in this type of rivers, assuming no known flow alteration or regulation.

However, the development of a robust IFM can also be challenging when too few gauged sites are available to define a homogeneous region. An alternative possibility in such a case could be to calibrate a distributed hydrological model on the catchment in question, if a gauged site is available, simulate flow series at the ungauged target site, extract the AMF series and then build the flood frequency distribution from these simulated series. If the target catchment is totally ungauged, making the hydrological model calibration difficult, then hybrid methods such as the one proposed by Crochet & Þórarinsdóttir (2014, 2015) could also be considered.

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Appendix I - Identification of homogeneous groups of catchments obtained with the ROI technique and associated growth curves

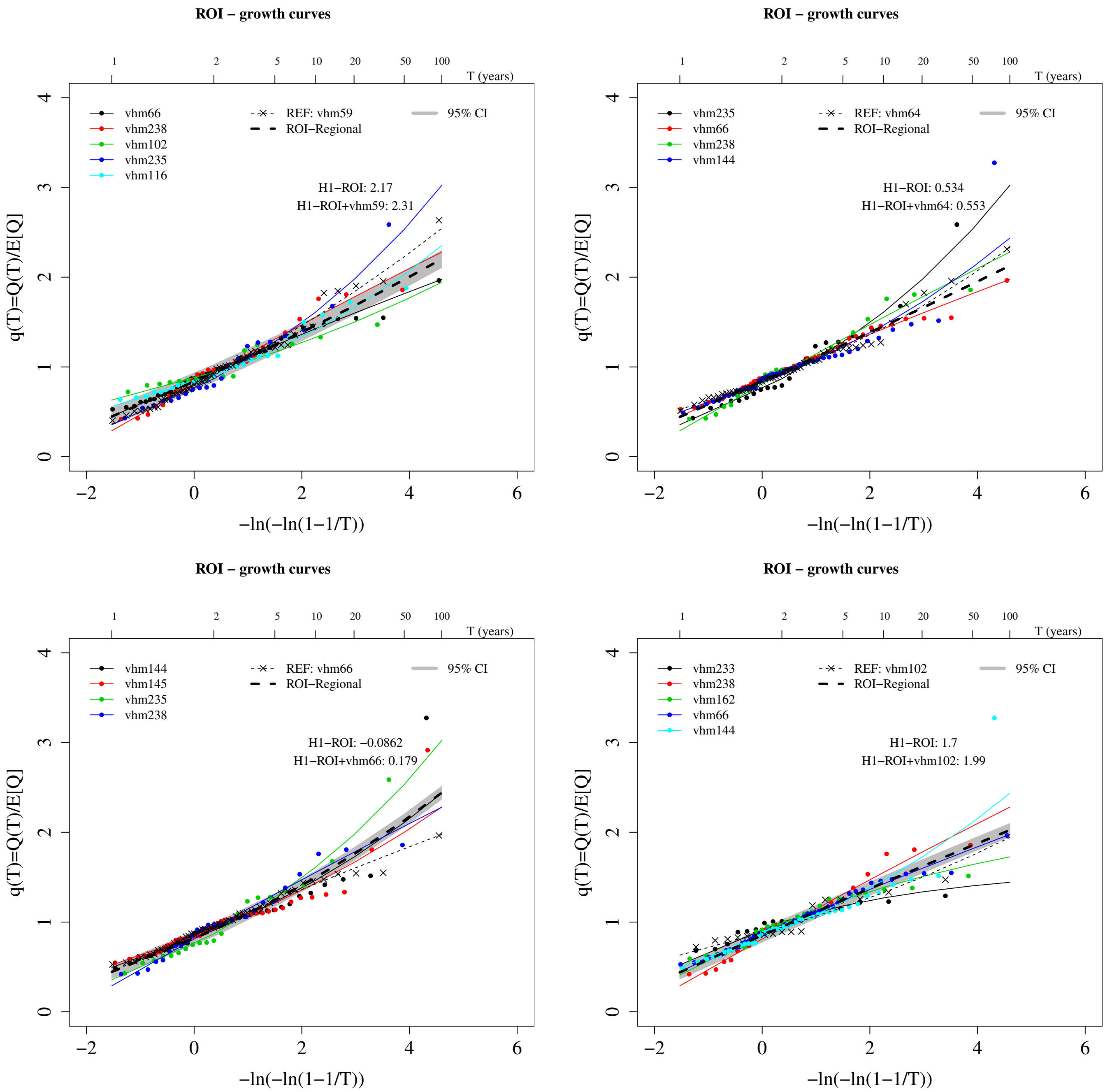

Figure I.1. Homogeneous groups of catchments identified with the ROI technique, associated to vhm59 (top-left), vhm64 (top-right), vhm66 (bottom-left), vhm102 (bottom-right) and corresponding regional and individual growth curves. Thick dashed line corresponds to the regional growth curve.

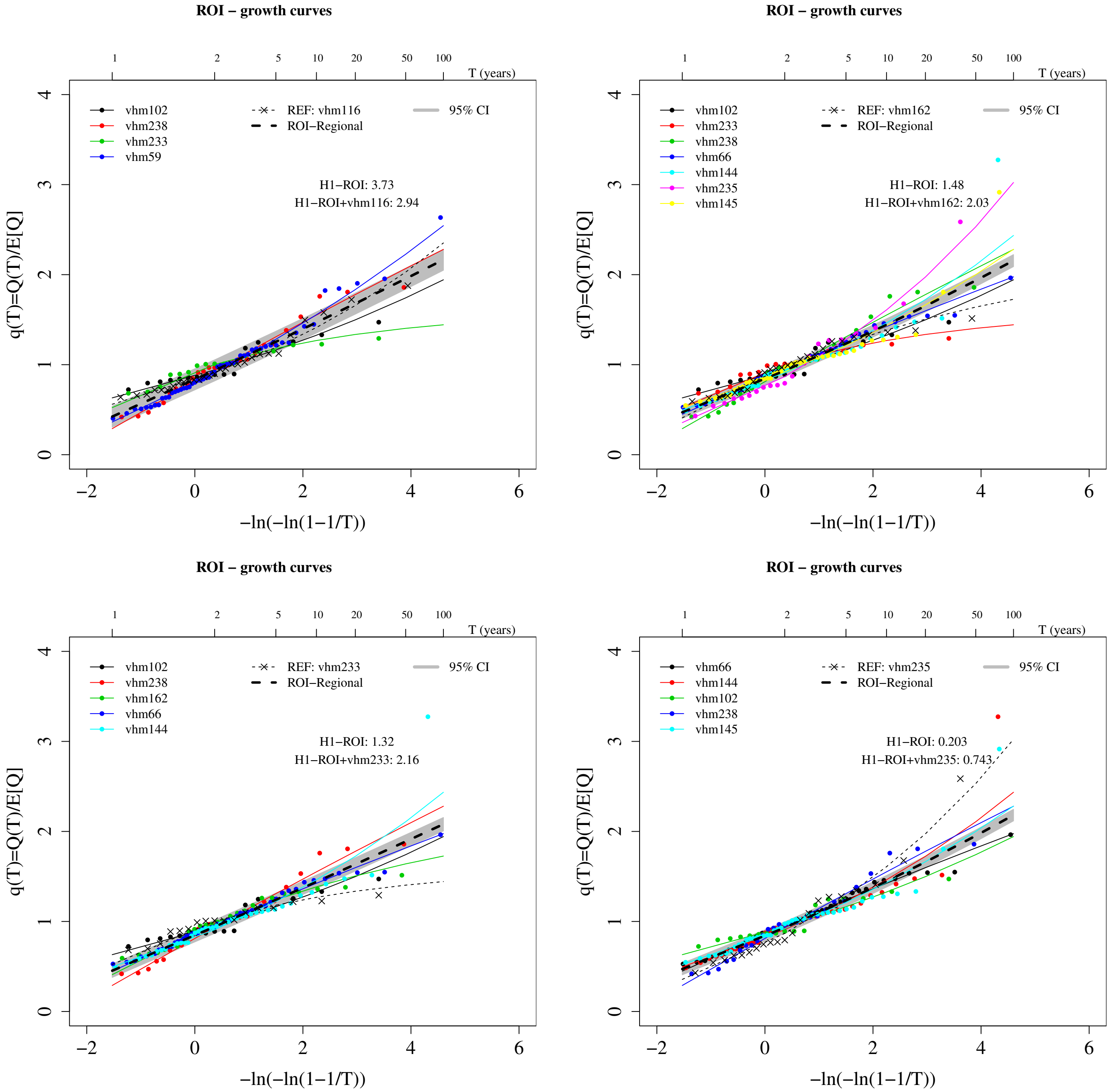

Figure I.2. As Fig. I.I but for vhm116 (top-left), vhm162 (top-right), vhm233 (bottom-left), vhm235 (bottom-right).

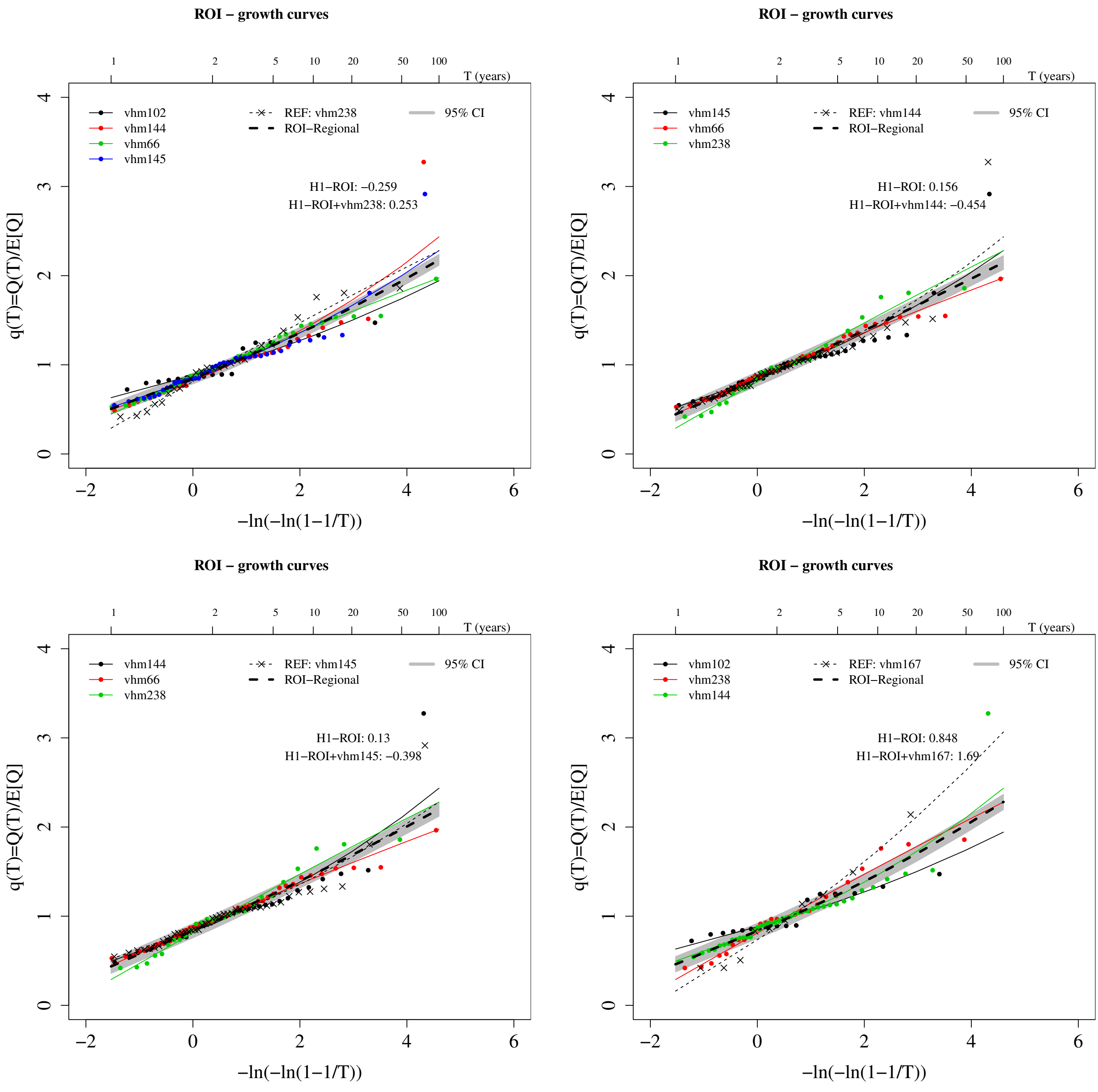

Figure I.3. As Fig. I.I but for vhm238 (top-left), vhm144 (top-right), vhm145 (bottom-left), vhm167 (bottom-right).

Appendix II - Index flood estimation at gauged sites treated as ungauged.

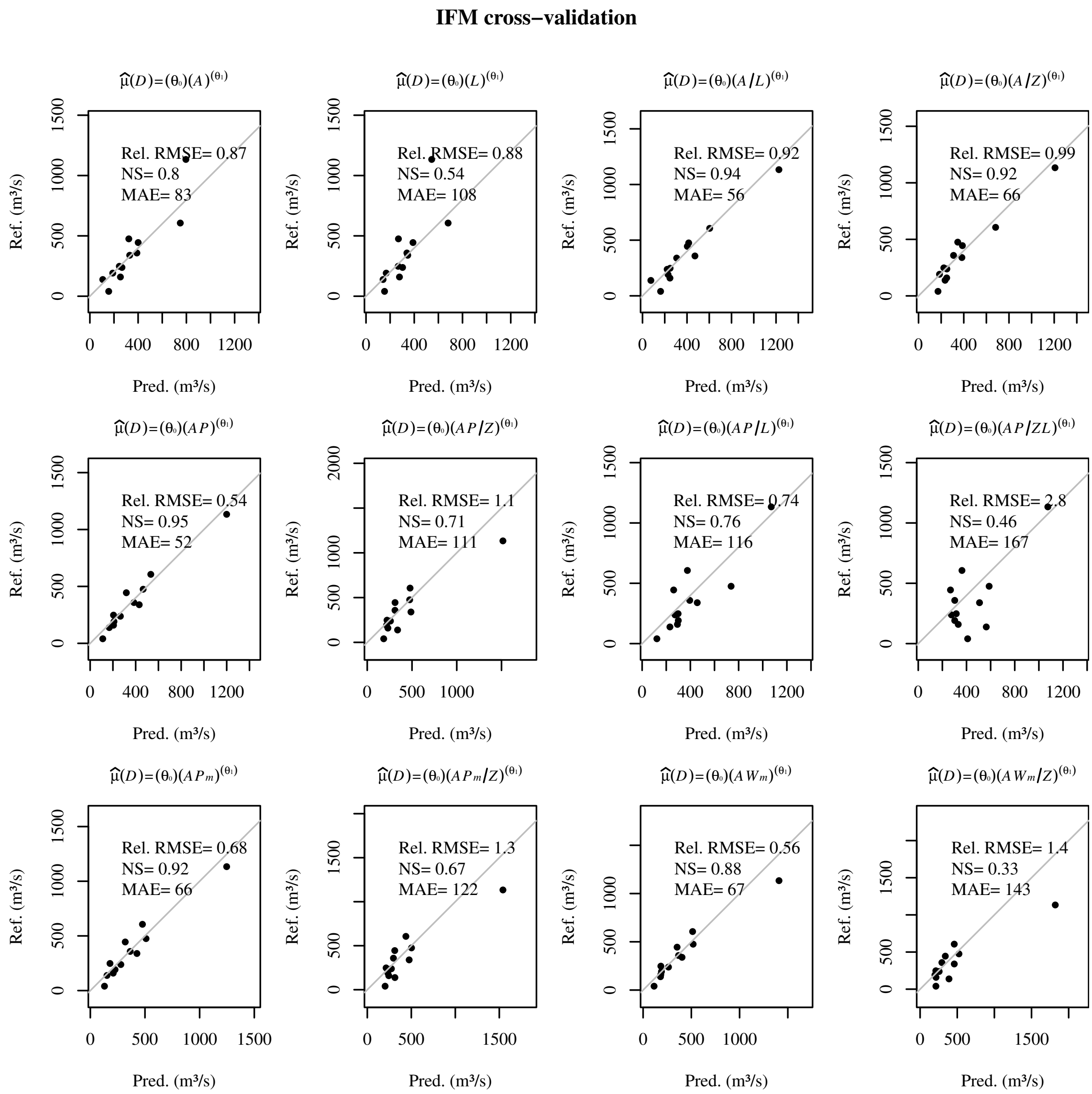

Figure II.1. Cross-validation: Reference versus predicted index flood at gauged sites treated as ungauged, using a power-relationship between index flood and catchment characteristics (V): $\widehat{\mu(D)} = \theta_0 V^{\theta_1}$, (see Section 4.2.1). Models 1–12.

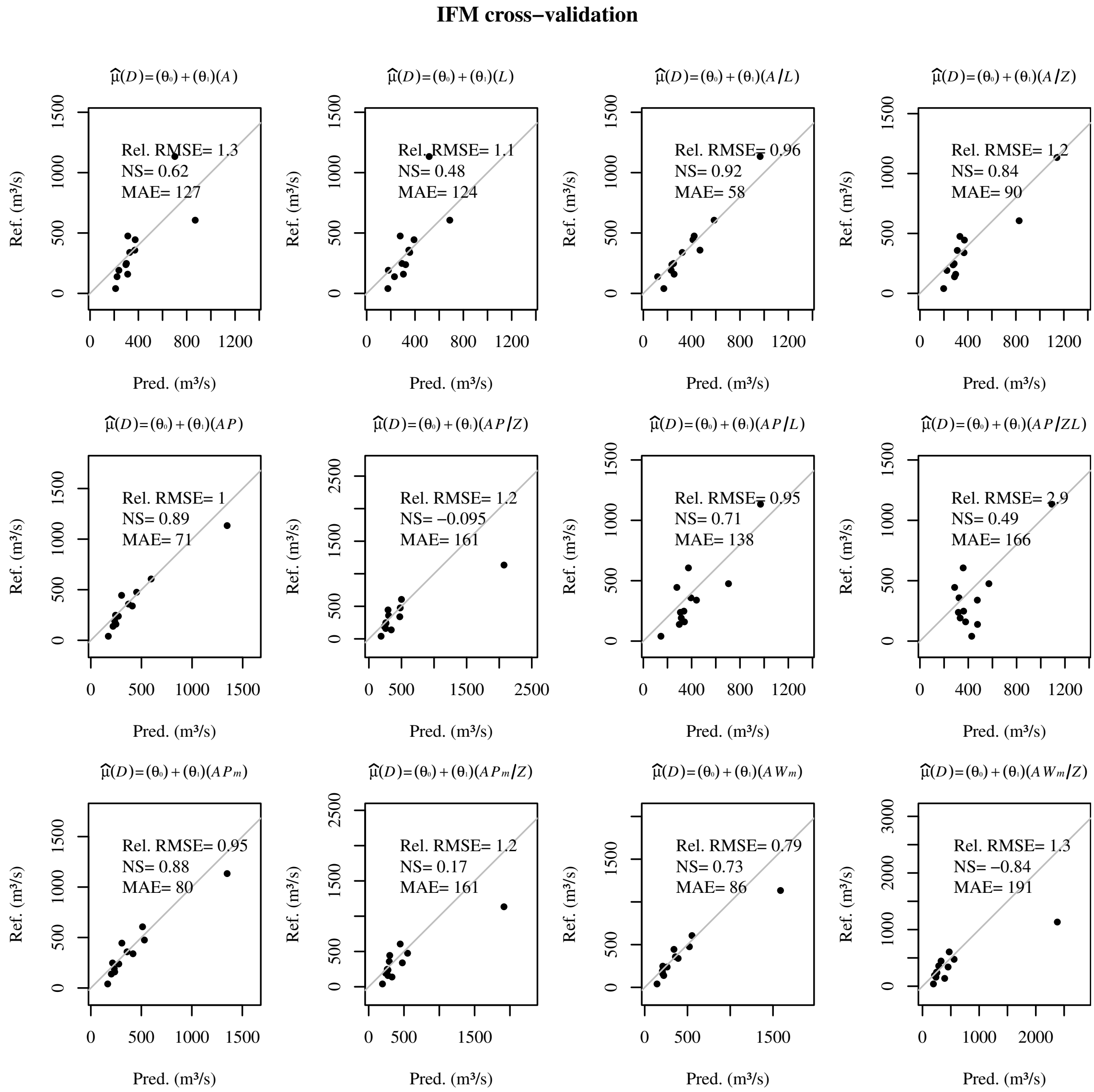

Figure II.2. As Fig II-1 but considering a linear relationship: $\widehat{\mu(D)} = \theta_0 + \theta_1 V$. *Models 13–24.*