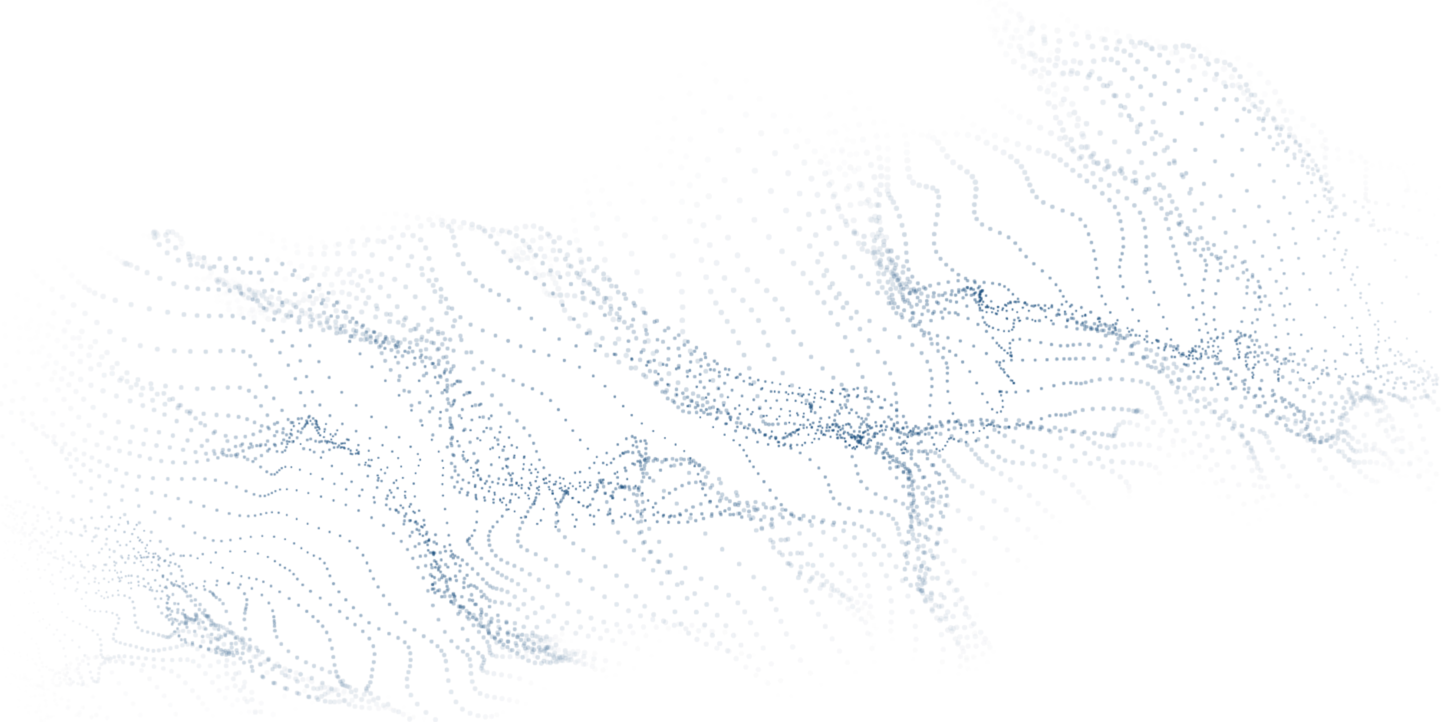
Veðurstofa Íslands

Design flood estimates from daily runoff simulations using the Icelandic Reanalysis (ICRA): expanding the methodology to ungauged catchments

Andréa-Giorgio R. Massad
Bergur Einarsson
Tinna Þórarinsdóttir



Greinargerð

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1 Introduction

In Iceland, periods of extreme rainfall have led to numerous damaging floods, including a flash flood in Siglufjörður in August 2015, widespread flooding in southeast Iceland in September 2017, as well as recent rainfall-induced landslides in Seyðisfjörður in December 2020. The latter example was caused by record-breaking rainfall amounting to almost 570 mm over five days. Extreme flood estimates are important in the design of infrastructure subject to flowing water, particularly in urban areas and along transport routes.

In 2020, a study reassessed precipitation return levels in Iceland, resulting in a new national map of 24-hour precipitation thresholds for a 5-year event (Massad *et al*., 2020). The study also presented intensity-duration-frequency curves for numerous locations in Iceland. These curves describe the relationship between rainfall intensity, rainfall duration, and return periods, making them useful in the design of hydrological infrastructure, including highways, stormwater drains, bridges, and culverts. This project was then followed by a study funded by Vegagerðin (Massad *et al*., 2022) with the aim of estimating extreme values based on simulated runoff from the ICRA reanalysis data. In this research, runoff from the ICRA dataset was converted into a discharge and compared to measurements from 41 stations around Iceland. A cluster-based correction system was calculated to correct systematic overestimation in the simulated dataset. Then, an Extreme Value Analysis resulted in closer return levels between observations and simulations after applying the correction. Overall, these results showed that extreme discharge values based on catchment-accumulated runoff from the ICRA dataset was able to simulate the observed high discharge after correction.

The findings of this study represent an initial methodology that could successfully assess design-flood values for ungauged catchments throughout the country. Indeed, extreme runoff estimates from ungauged catchments are challenging and represent one of the leading problems in flood hydrology. In several recent studies, Veðurstofan has investigated flood forecasting in ungauged catchments, including simulations using the WaSIM hydrological model in the Westfjords and Tröllaskagi regions (Crochet and Þórarinsdóttir, 2014). An index-flood method was also tested in the Eastfjords, leading to promising initial results (Crochet and Þórarinsdóttir, 2015). With the increasing dependence on Iceland’s road infrastructure, combined with the uncertainties of rapid climate change, there is a need to develop updated design-flood methods for rapid and widespread assessments.

Building on the 2022 research project, the goal here is to calculate flood estimates in the 41 aforementioned catchments, using the ICRA-simulated runoff, and also calculate those return levels for 20 ungauged catchments using the same method. Additionally, daily discharge timeseries are simulated by the rainfall-runoff hydrological model airGR and new return levels are calculated to compare with the previously obtained results.

2 Catchment selection

This research being a continuation of the 2022 study, the same gauged catchments are being used. This amounts to 41 watersheds, which are shown in red on Figure 1, with the location of the gauges and VHM number also indicated on the map. Various classifications exist to distinguish those rivers, and it is generally assumed that four types of rivers exist in Iceland: direct-runoff rivers (lying on old, impermeable bedrock), spring-fed rivers (lying on newer bedrock), glacial rivers and lake rivers. However, in reality, classifying the rivers is not that straight-forward, and they are often considered to be a combination of several types. Similarly to the 2022 study, the gauged stations associated with the river Skaftá are not used in this work, as jökulhlaup happen there often, making the discharge series particularly challenging to work with.

The main novelty of this study is that 20 ungauged catchments are added to the analysis, with catchments selected all around the country, as shown in blue on Figure 1. Individual maps were created for each ungauged catchment and shown on Figure 2.a – 2.d. These watersheds were hand-picked, with the only condition being that they have an area superior to 25 km^2 so that they include at least three gridpoints from the ICRA domain. The idea was to cover parts of the country that are currently poorly gauged (Fjarðará, Hellisfljót, Nýjadalsá, Ólafsfjarðará). When possible, rivers which seem of particular interests for Vegagerðin were selected. This is the case for Sléttuá, Flókadalsá and Lágadalsá that are currently flowing under old, one-way bridges. Some others were picked because of new road plans (Steinavötn, in the eastern part of Snæfellsness), or the possibility of future construction plans in the Highland region (Hellisá, Gilsá, Jökulgiskvísl). Overall, Figure 1 shows that combining this selection of gauged and ungauged watersheds leads to a good spatial coverage of the rivers in Iceland.

Table 1 shows the main characteristics of the ungauged catchments, including their area, aspect ratio, longest flow-path, mean elevation, and geological properties. The size of the selected catchment is quite diverse, ranging from 38.4 km^2 (Nýjadalsá) to 730.5 km^2 (Midfjarðará). Three catchments have a mean elevation above 700 m a.s.l. (Hornafjarðarfljót, Jökulgilskvísl, Nýjadalsá), and six are partially covered by glaciers (Hornarfjarðarfljót, Jökulsá í Lóní, Nýjadalsá, Steinavötn, Gilsá, Jökulgilskvísl).

In the end, a total of 61 catchments are used in this study.

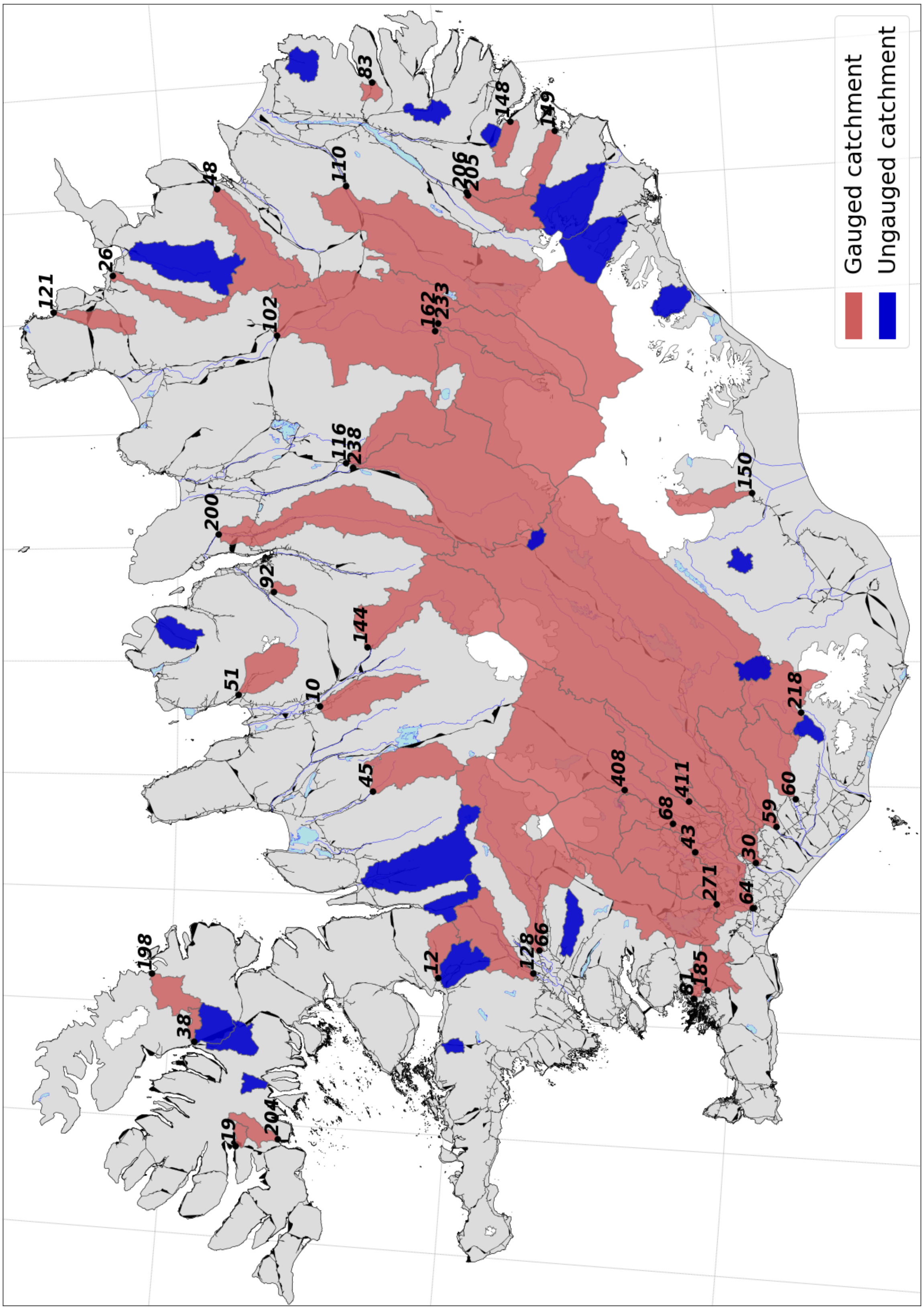


Figure 1 – Catchments selected for this study. Gauged catchments used for the 2022 study are shown in red, ungauged catchments are represented in blue.

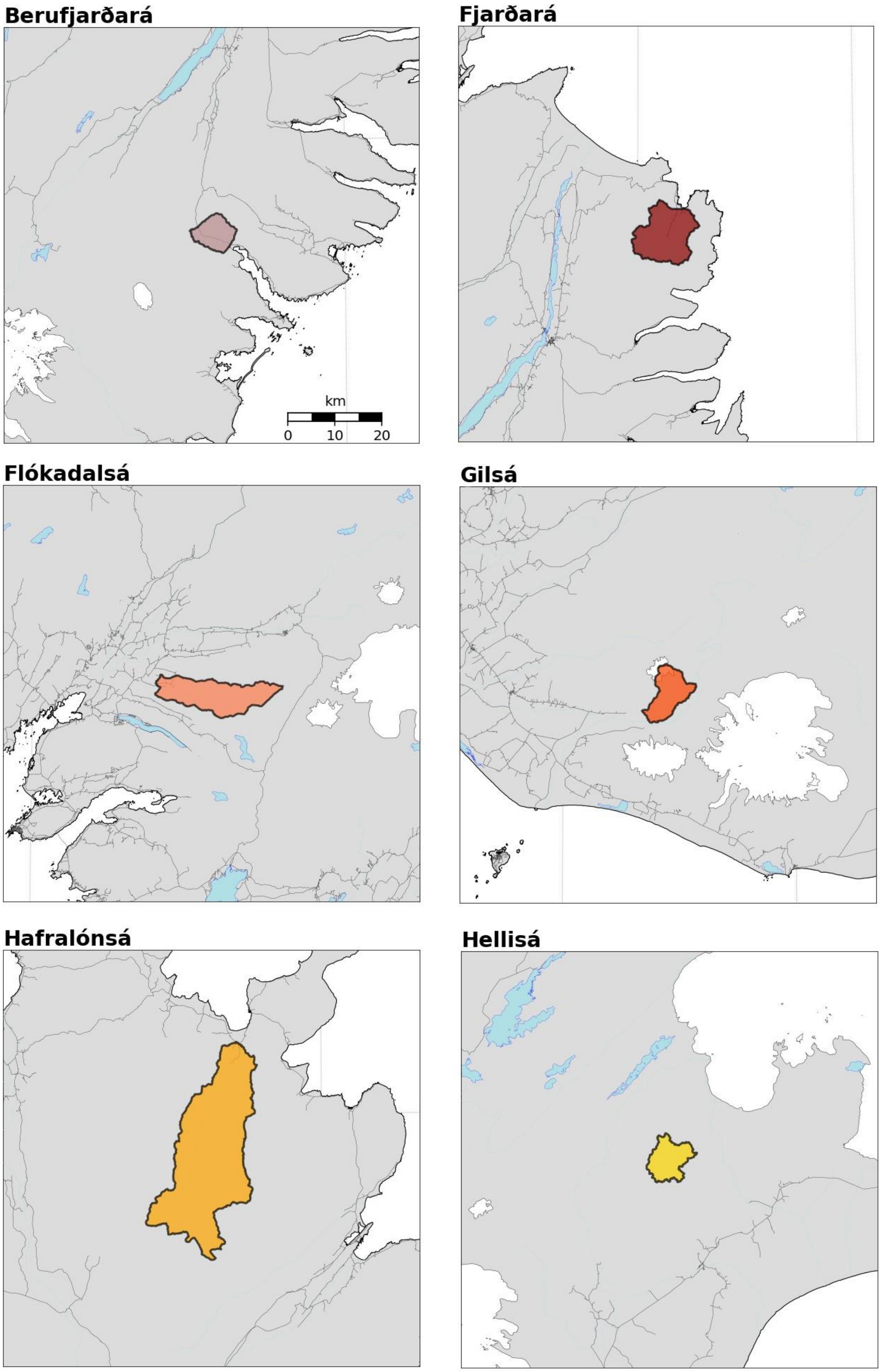


Figure 2.a – Outlines of the ungauged catchments selected for this study (1/4). Scale is only shown for Berufjarðará but is the same for all catchments.

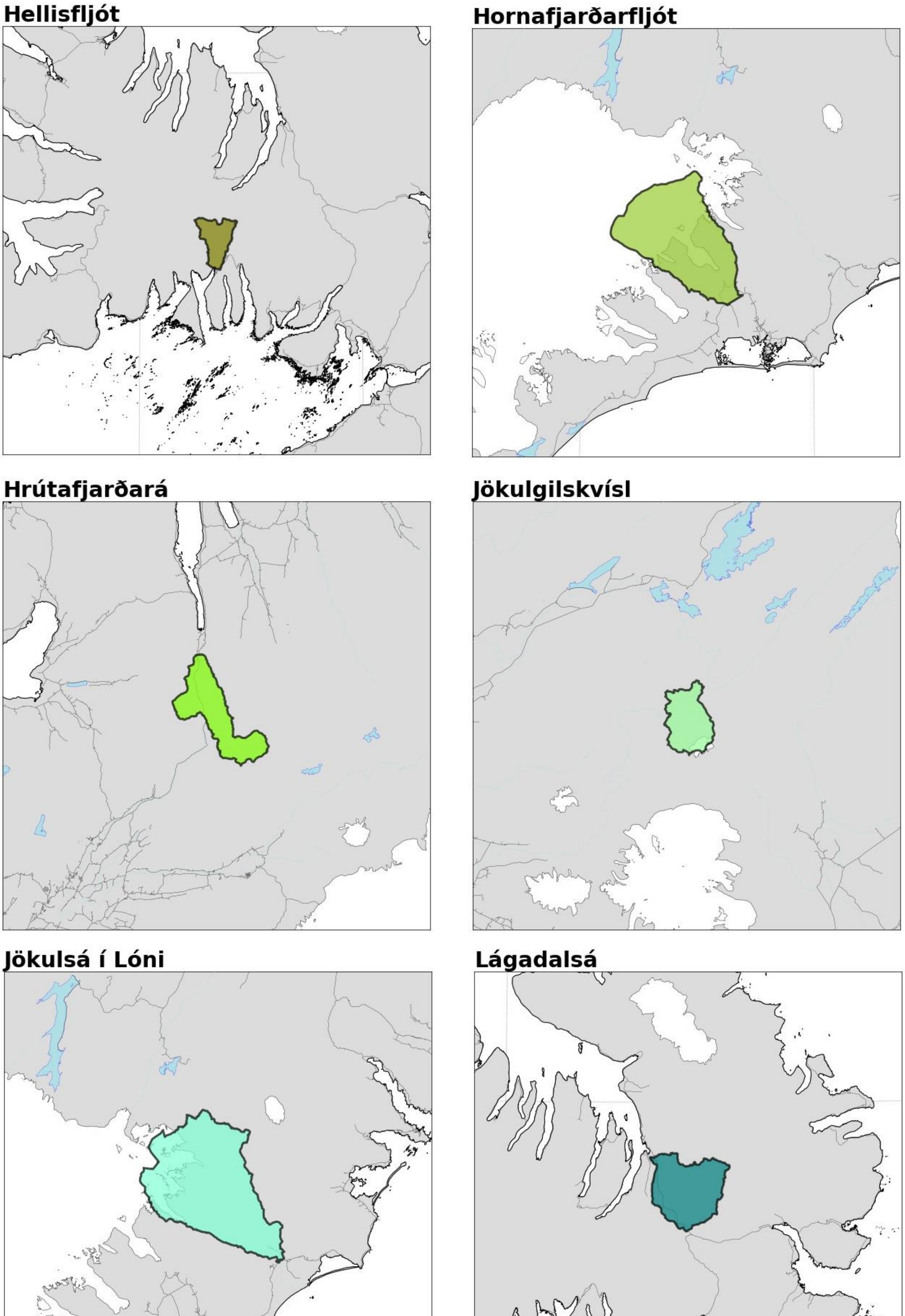


Figure 2.b – Outlines of the ungauged catchments selected for this study (2/4).

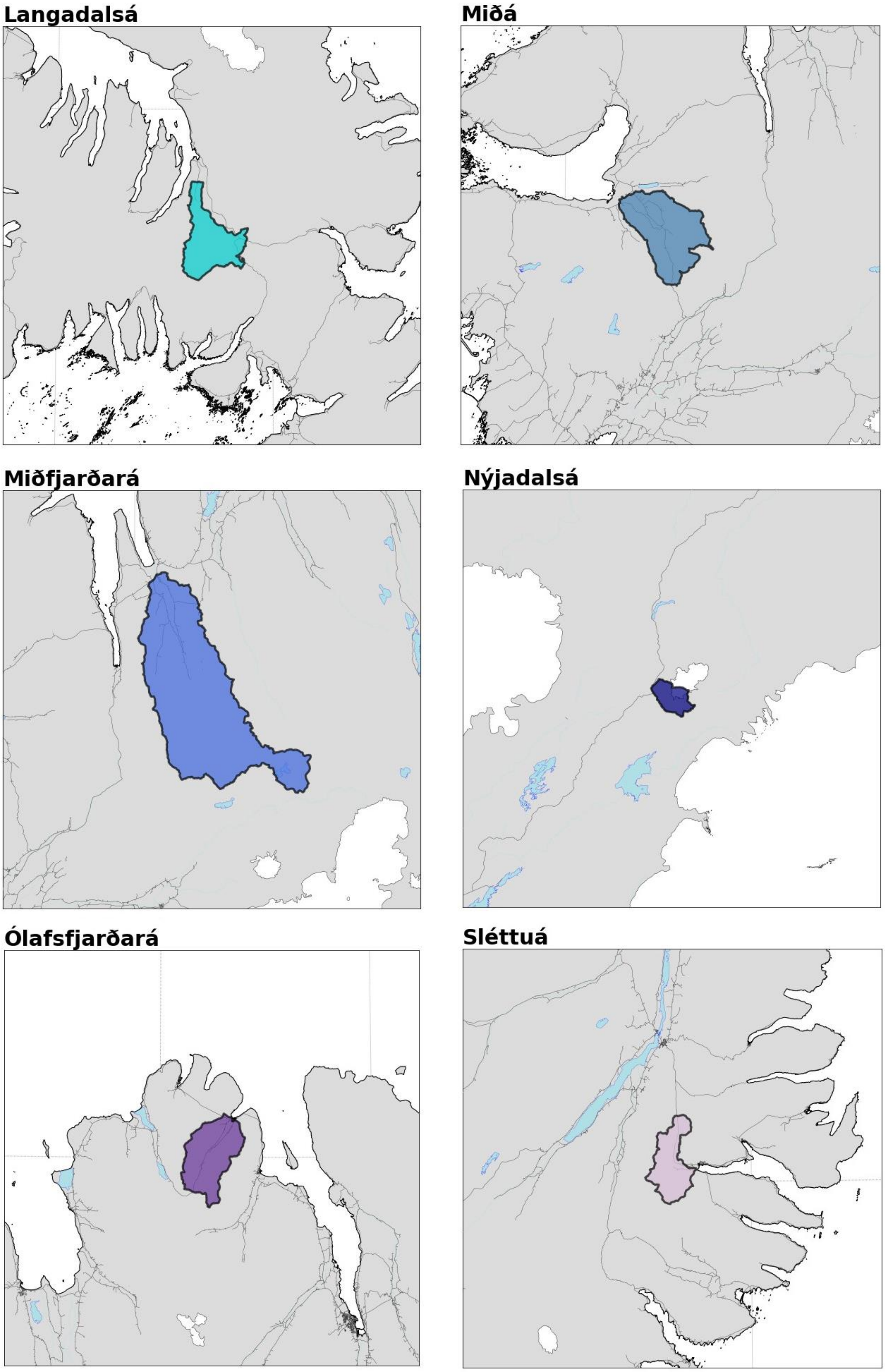
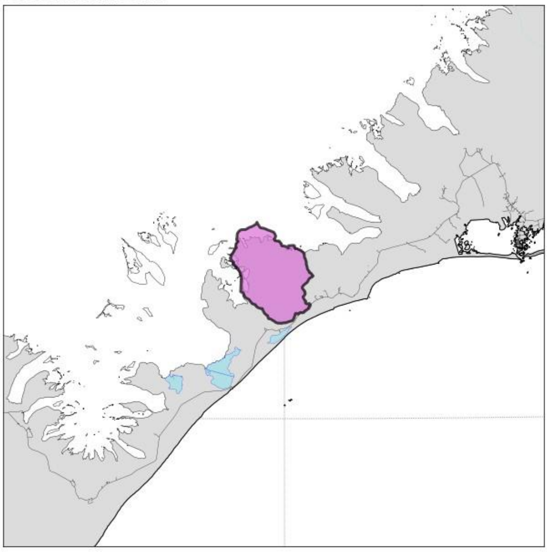


Figure 2.c – Outlines of the ungauged catchments selected for this study (3/4).



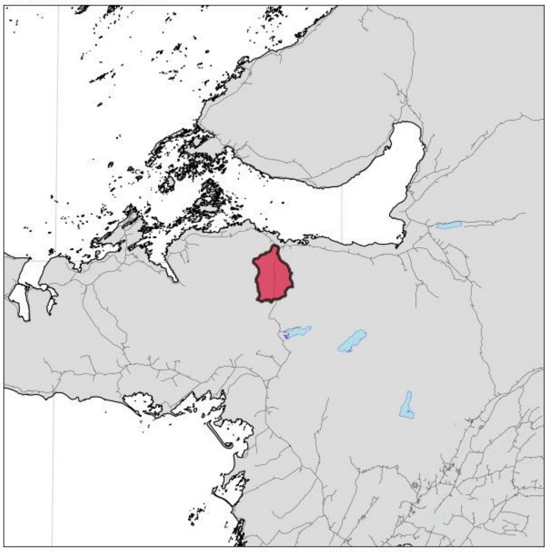


Figure 2.d – Outlines of the ungauged catchments selected for this study (4/4).

Table 1 – Main characteristics of the ungauged catchments used for the cluster analysis.

	Area *km^2*	**Aspect ratio**	**Longest flowpath** *m a.s.l.*	**Average Elevation** *m a.s.l.*	**Glacial cover** *%*	**Old bedrock** *%*	**Young bedrock** *%*	**Total Bedrock** *%*
Berufjarðará	51.3	1.21	15,256	562	0	0	100	100
Fjarðará	126.5	1.06	18,139	361	0	0	100	100
Flókadalsá	141.1	3.22	35,585	357	0.11	72.5	27.4	99.9
Gilsá	70.8	1.43	22,097	622	13.5	78.2	8.4	86.5
Hafralónsá	545.2	2.32	61,735	395	0	14	86	100
Hellisá	64.7	1.19	18,229	542	0	96.3	3.7	100
Hellisfljót	51.4	1.37	14,711	375	0	0	100	100
Hornafjarðarfljót	403.6	1.44	41,579	798	62.1	5.8	31.7	37.5
Hrútafjarðará	160.8	2.07	37,847	329	0	0	100	100
Jökulgilskvísl	107.3	1.49	23,809	816	11	7.7	81.3	89
Jökulsá í Lóni	513.6	1.45	53,786	698	25	3.7	71.3	75
Lágadalsá	179.7	1.06	27,165	390	0	0	100	100
Langadalsá	147.9	1.83	31,086	363	0	0	100	100
Miðá	217.3	1.48	29,833	322	0	4	96	100
Miðfjarðará	730.5	2.2	75,201	326	0	4	96	100
Nýjadalsá	40.7	1.67	14,786	1,128	18.2	78.7	3	81.7
Ólafsfjarðará	155.7	1.7	24,378	493	0	0	98.4	98.4
Sléttuá	105.3	1.85	18,808	564	0	0	100	100
Steinavötn	140.2	1.43	23,484	554	18.1	8.9	73.7	81.9
Svínafossá	38.4	1.52	11,960	156	0	0.5	99.5	100

3 Data

3.1 Measurements from the gauging station network

Since the first gauging stations were set up in Iceland, the gauging network has expanded to record most of the major rivers in the country, allowing for high resolution measurements down to 10-minute intervals. River discharge is not measured directly: the gauges measure the water level, which is then converted into a discharge using flow rating curves. The rating curves are measured at the gauge location through cross-section of the river and establish the correspondence between water level and discharge. The rating curves are updated regularly, as river path and characteristics change over time.

For this study, daily averaged discharge measurements from a total of 41 gauging stations are used (Figure 1, red catchments). These are the same stations that were used in the 2022 study, and were previously used for testing and calibrating the hydrologic model airGR (Atlason *et al.*, 2021) as well as for the analogue forecast set up for Vegagerðin (Priet-Mahéo *et al.*, 2020). For further information on the timeseries available as well as the catchment characteristics, refer to Table 1 and 2 from Massad *et al.* (2022).

3.2 Simulated discharge from the ICRA dataset

The operational numerical weather prediction (NWP) system used by the Icelandic Meteorological Office (IMO) is the non-hydrostatic HARMONIE–AROME model levels (Bengtsson *et al.*, 2017). In 2017, the model was used to reanalyse atmospheric conditions in Iceland at hourly time-steps between September 1979 and August 2017. This dataset, known as the Icelandic Reanalysis (ICRA) dataset (Nawri *et al.*, 2017), has a horizontal resolution of 2.5 × 2.5 km and 65 vertical levels, for a total of 66,181 terrestrial points over Iceland.

As in most NWP systems, runoff is not a direct output from the model, but it is a combination of the rainfall rate, the rate of evaporation and the melting parameter. Moreover, it should be noted that the melting variable is also an indirect product of the model resulting from the combination of sleet- and snowfall rates, sublimation, and snow water equivalent. Therefore, in total, six variables need to be extracted from the reanalysis in order to estimate the daily runoff. Runoff values were then summed over all grid-points within the catchment outlines in order to get for each catchment a single daily runoff timeseries covering nearly 40 years of reanalysis.

To compare with the discharge timeseries from the gauges, the simulated daily runoff needs to be converted into a simulated discharge for each catchment. This is done with the following formula:

$$Q(m^3 s^{-1}) = \frac{runoff(mm) * 0.001 * cell\ area(m^2)}{60 * 60 * 24}$$

The main assumption is that all the simulated runoff reaches the river within the day and no infiltration occurs. This approximation is not expected to work similarly in all the watersheds: it is assumed to give good results for small, direct-runoff catchments, but lead to larger errors for catchments with a strong groundwater component, or with water reservoirs such as lakes or meres.

In this study, the focus is on extreme discharge values. Hence, even if a time lag exists between observed and simulated discharge (as a result from the fact that the runoff does not reach the river within the day), it is not expected to heavily affect the flow analysis as the focus is on peak values, and not on the time of occurrence.

4 Cluster Analysis

3.2 Methodology and previous results

Over the years, several types of classifications have been developed with the aim of grouping rivers together according to their type. In 2014, rivers were classified based on the geology of the catchments and the presence of lakes and meres (Stefánsdóttir *et al.,* 2014), while Rist (1990), and Hróðmarsson and Þórarinsdóttir (2018) based their classification on observations made over more than 50 years of field measurements. More recently, a hierarchical cluster analysis has been used to categorize rivers in groups that share more similarities than with any other rivers from other groups. This analytic method was previously used by Crochet (2012) and was adapted for Icelandic rivers in previous projects funded by Vegagerðin (Priet-Mahéo *et al.*, 2019 and 2021; Massad *et al*. 2022). According to Demirel and Kahya (2007), the Ward's method based on Euclidean distances is better suited when performing a cluster analysis for hydrological data.

In the 2022 study, the cluster analysis was carried out on 44 stations, both on discharge measurements, and on simulated discharge as calculated from the ICRA dataset. In order to work with a homogeneous set of data, the time period from 2007 to 2017 was used, and discharge data were combined in three different ways, each method reflecting a different behaviour of the river: its seasonality, range of discharge (through flow-duration curves*)* and storage capacity (through mass curves*)*. For further details and examples, see the 2022 technical report, Section 3.1. Additionally, several catchment characteristics (see Table 2 in the 2022 study) were added to complete the analysis.

Results from the cluster analysis based on the original gauged rivers are shown both on a dendrogram (Figure 3.a) and on a map (Figure 4.a). While this analysis was carried out only on the simulated discharge of the gauged catchments, the ungauged watersheds also appear on the map, in purple. In order to directly compare the results from the ungauged areas, the results shown on Figure 4.a differ slightly from the map shown in Figure 4 in the 2022. Indeed, results were then only shown for catchments that clustered similarly after the analysis was carried out on both measured and simulated discharge. That lead to the exclusion of seven catchments (VHM 30, VHM 60, VHM 64, VHM 218, VHM 144, VHM 66, VHM 26) that were left for further analysis. Here, on Figure 3, those seven catchments are included as the focus is on the results of the clustering based on simulated discharge only, since this is the only dataset available for the ungauged rivers. It should also be noted that the three jökulhlaup rivers appear in the dendrogram on Figure 3.a. but not on the map on Figure 4.a. Those three rivers were this time discarded from the new study before working on the cluster analysis, which make the two dendrograms not directly comparable.

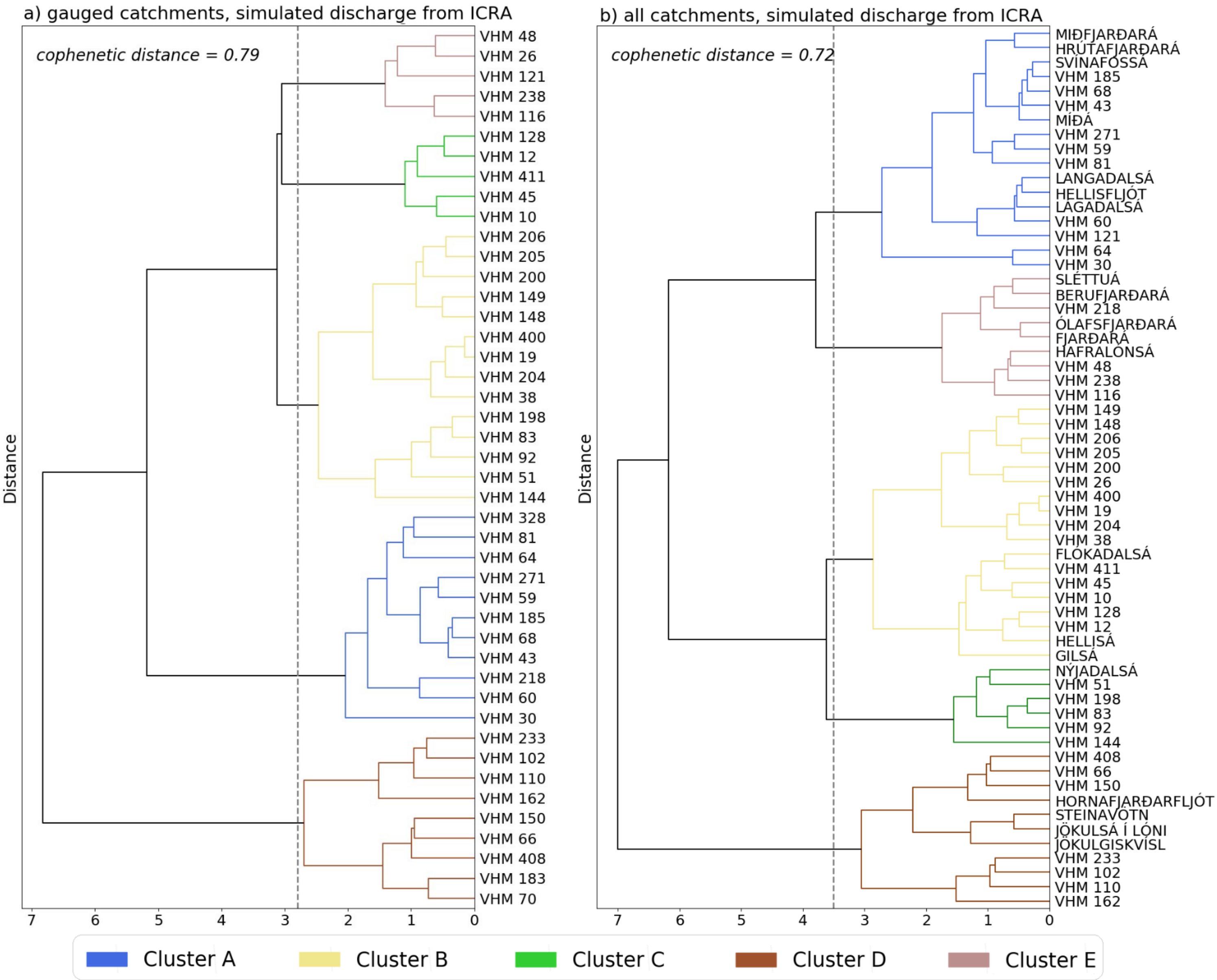


Figure 3 – Dendrograms resulting from the cluster analysis of simulated discharge timeseries for (a) the gauged rivers from the 2022 study, and (b) for all the rivers, gauged and ungauged.

3.2 Results including the ungauged catchments

After obtaining discharge timeseries from the ICRA dataset for the 20 ungauged rivers, the same methodology was carried out to include the ungauged catchments to the analysis: flow-duration and mass curves, as well as seasonality timeseries were obtained, and added to the cluster analysis with the 41 simulated discharge timeseries from the gauged rivers. Additional catchment information as shown in Table 1, were combined to the characteristics from the gauged catchment (Table 2 in the 2022 study), and the hierarchical cluster analysis performed.

Results from the dendrogram are shown on Figure 3.b. The cophenetic distance is an indicator of the correlation between distance and cophenetic matrices resulting from the cluster analysis, with in this case a value of 0.72. As it approaches 1, it can be concluded that the clustering was carried out successfully.

To keep consistency with the previous study, it was decided to only keep five clusters:

- *Cluster A:* VHM 185, VHM 68, VHM 43, VHM 271, VHM 59, VHM 81, VHM 60, VHM 121, VHM 64, VHM, 30, and the ungauged rivers Miðfjarðará, Hrútafjarðará, Svínavötn, Miðá, Langadalsá, Hellisfljót, Lágadalsá.
- *Cluster B:* VHM 149, VHM 148, VHM 206, VHM 205, VHM 200, VHM 26, VHM 400, VHM 19, VHM 204, VHM 38, VHM 411, VHM 45, VHM 10, VHM 128, VHM 12, and the ungauged rivers Flókadalsá, Hellisá, and Gilsá.
- *Cluster C:* VHM 51, VHM 198, VHM 83, VHM 92, VHM 144, and the ungauged river Nýjadalsá.
- *Cluster D:* VHM 408, VHM 66, VHM 150, VHM 233, VHM 102, VHM 110, VHM 162, and the ungauged rivers Hornafjarðarfljót, Steinavötn, Jökulsá í Lóni and Jökulgilskvísl.
- *Cluster E:* VH 218, VHM 48, VHM 238, VHM, 116, and the ungauged rivers Sléttuá, Berufjarðará, Ólafsfjarðará, Fjarðará, and Hafralónsá.

It should also be noted that when changing the number of members in the cluster analysis, the new groups are not directly the same when comparing both maps, although rivers seem to cluster similarly for the most part. Rivers change from one cluster to the next usually when they were in close vicinity with the next hierarchical cluster in the first place. This is the case for instance for rivers in Cluster B and C on Figure 3.a. that are now part of the same group in Cluster B on the new analysis on Figure 3.b.

Those new results are also shown on a map (Figure 4.b), with the ungauged area appearing with black borders for emphasis. As for the 2022 study, rivers were generally classified according to river types, and weather conditions. Cluster A mostly gathers spring-fed rivers, some of them originating from glacial rivers. Most gauged rivers in this cluster are located on the southwestern part of Iceland, but that does not apply to the ungauged rivers, which are for example in the Westfjords. On the dendrogram, Cluster B and C are quite close, and it is reflected by the type of stations that belong to them. These are mostly mountainous or heathland catchments, many direct-runoff catchments, but some with more storage than others. New catchments like Nýjadalsá for instance fits correctly into that category. Cluster D comprises glacial rivers, and all watersheds are partially covered by glaciers, which is also the case of the ungauged rivers (Jökulsá í Lóni, Jökulgilskvísl, Steinavötn, Hornafjarðarfljót). Cluster E is more difficult to estimate, especially after adding the ungauged catchments. The gauged ones tend to have a spring-fed component which is not as clear after the ungauged catchments have been added to the cluster analysis. The timing of the seasonal discharge peak could be the reason the catchments clustered together, although it should also be noted that this cluster contains more ungauged catchments than gauged rivers.

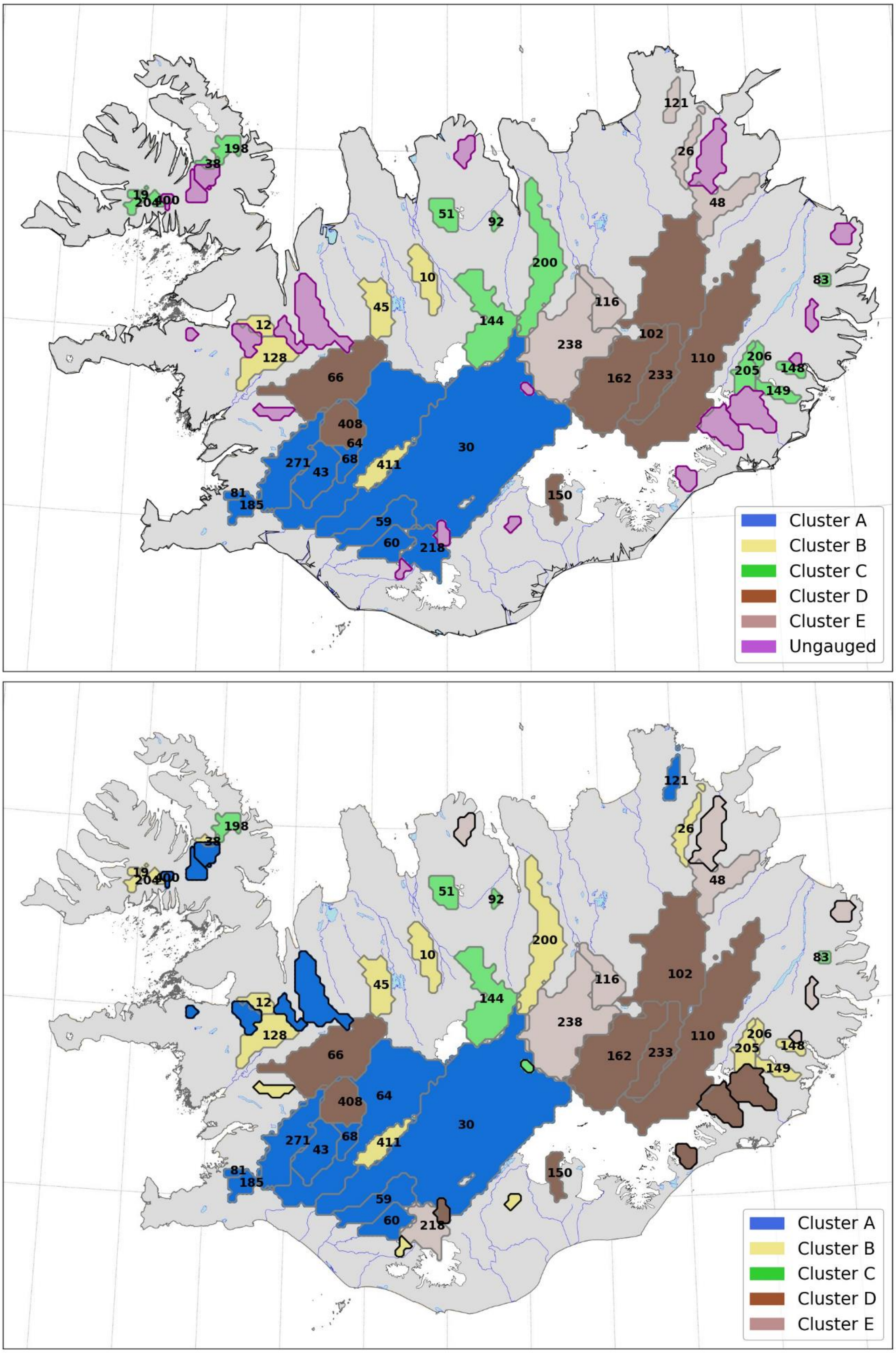


Figure 4 – Map of Iceland including catchments that clustered similarly after analysis of the simulated discharge for (a) the gauged rivers from the 2022 study, and (b) for all the rivers, gauged and ungauged.

5 Extreme Value Analysis

5.1 Methodology

Extreme Value Analysis (EVA) is a statistical discipline used to predict the occurrence of rare events by assessing their frequency from the most extreme values of a dataset. EVA allows the calculation of return levels associated with periods that can be much longer than the length of the timeseries available for the analysis. Two approaches exist: the Peak-over-Threshold method and the Block Maxima method. In this study, only the latter method is used, as in recent hydrological projects at IMO (Pagneux *et al.*, 2017, 2018 and 2019; Þórarinsdóttir *et al.*, 2021; Massad *et al.*, 2022).

The Block Maxima approach consists of dividing the timeseries into non-overlapping periods of equal size and retaining only the maximum values within each period. When dealing with hydrological data, it is common to use the maximum daily values from each calendar year. A new timeseries that includes only the maxima is thus generated and referred to as an Annual Maxima Series (AMS). Under extreme value conditions, the AMS follows a General Extreme Value (GEV) family of distribution, and it is then possible to estimate the return level associated to a specific return period.

For more details, see Coles (2001), and the summary in Section 4.1 in Massad *et al.* (2022).

5.2 Correction of the simulated discharge from the gauged stations

In the 2022 study, it appeared clearly that the discharge as calculated from the runoff of the ICRA dataset was not directly usable, but needed to be scaled to match more closely the values from the observations. To do so, a coefficient of proportionality was calculated for each station by comparing the daily ranked discharge above the 95th, 90th and 75th percentile. These coefficients were then averaged over all the stations that clustered together, so that in the end, each cluster had a corresponding scaling factor that could be applied to its simulated discharge to match more closely the measurements from the other stations that belonged to the same group.

That method assumes that if rivers belong to one group from the cluster analysis, it is likely that the missing part when calculating the discharge from the ICRA runoff is comparable for all rivers in that group. For instance, for a cluster that is comprised of groundwater-fed rivers were a large part of the runoff infiltrates, the scaling factor is likely to be smaller than for direct-runoff catchments where most runoff goes directly into the river.

While that method is not perfect, results in the 2022 study showed greatly improved results for the simulated discharge, and it was therefore decided to expand it in this study and apply it to ungauged catchments to obtain corrected flood estimates.

5.2.1 Updated correcting factors

New results are shown in Figure 5, in histograms. On the figure, each cluster is represented by a panel, and within a cluster, values of the coefficients of proportionality are shown individually for each station. For this study, the values of these coefficients are based on the daily discharge above the 95th percentile. A coefficient of proportionality equal to 1 means there is no difference between simulated and observed discharge. Above 1, the mean observed values are higher than the simulations; under 1, the mean simulated values are higher than the measurements.

Mean values for each cluster are not directly comparable to the values of the 2022 study as the new cluster analysis changed the members within each group. However, results are still within the same range, with mean values comprised between 0.35 (Cluster A) and 0.58 (Cluster B) against 0.33 (Cluster E) and 0.58 (Cluster B) in the previous study (see Figure 9 in the 2022 study).

On Figure 5, for Clusters C and E, it can be noted that the coefficients of proportionality are quite homogeneous for all the stations. This is not the case for Cluster A, B, and D, as some stations appear as outliers. For instance, within Cluster A, the small value of the coefficient calculated for VHM 185 can be explained: the catchment is very porous and is known to have a lot of water infiltrating, justifying why only a small portion of the simulated runoff ends up in the river. The opposite effect can be seen in VHM 68: the gauge is located downstream of a catchment where a lot of groundwater is present which comes out at the station. In Cluster B, two rivers stand out compared to the other stations: VHM 205 and VHM 206. This can be explained by the fact that these two catchments are quite small, direct-runoff rivers that imply a more straight-forward conversion of the ICRA runoff into a discharge. Moreover, when analysing their flow-duration curves, for both stations the all-time maximum daily discharge values are outliers when compared to the other high values, which consequently influences the large value of their individual correcting factor.

The new mean coefficients of proportionality can then be used as scaling factors for the rest of the study.

5.2.2 Scaled flow-duration curves

In order to adjust the simulated high discharge for each station to better fit the measurements, daily discharge values calculated from the ICRA runoff are multiplied by the mean coefficient of proportionality from the belonging cluster. This scaling is shown on Figure 6 on the flow-duration curves of five gauged rivers, one from each cluster. Only the 5% highest daily values are shown on the figure. For each plot, flow-duration curve is shown in blue when based on the measurements, in brown when based on the non-corrected simulated discharge, and in red after applying the mean scaling factor. Therefore, to obtain the corrected ICRA values, the ICRA runoff is multiplied by 0.35 for the stations belonging to Cluster A, 0.58 for stations from Cluster B, and so on.

It was decided to show on Figure 6 both stations that have an individual coefficient close to the mean value of its cluster of belonging (VHM 48 and VHM 83), and stations with an individual coefficient far from the mean value (VHM 185, VHM 205 and VHM 408). Results for stations VHM 48 and VHM 83, after scaling down the simulated discharge, give values extremely close to the flow-duration curve based on the measurements. For VHM 185 and VHM 498, even though their individual scaling factors are quite far from the mean values of their respective clusters (0.08 against 0.35, and 0.09 against 0.43, respectively), scaling down the simulated discharge still leads to significant improvement. The only two stations that do not benefit from the scaling are VHM 205 and VHM 206. As stated earlier, these two smalls direct-runoff catchment have a simulated discharge matching the measurements very well, and do not need any correction. It is apparent on Figure 6, with the red curve reaching much lower values than what was measured.

Overall, most rivers (39 out of 41) benefit from scaling down the simulated discharge from the ICRA runoff. It is therefore expected that using the same factor to correct the discharge from the ungauged areas will lead to results that are closer to reality, in the absence of any measurements to validate the results. Simulated discharge were multiplied by 0.35 for rivers Miðfjarðará, Hrútafjarðará, Svínavötn, Miðá, Langadalsá, Hellisfljót and Lágadalsá; by 0.58 for rivers Flókadalsá, Hellisá and Gilsá; by 0.49 for river Nýjadalsá; by 0.43 for Hornafjarðarfljót, Steinavötn, Jökulsá í Lóni and Jökulgilskvísl; and by 0.33 for rivers Sléttuá, Berufjarðará, Ólafsfjarðará, Fjarðará and Hafralónsá. Results for five ungauged rivers (one for each cluster) are shown on Figure 7, with the flow-duration curve based on the original simulated discharge shown in brown, and after applying the scaling factor in red.

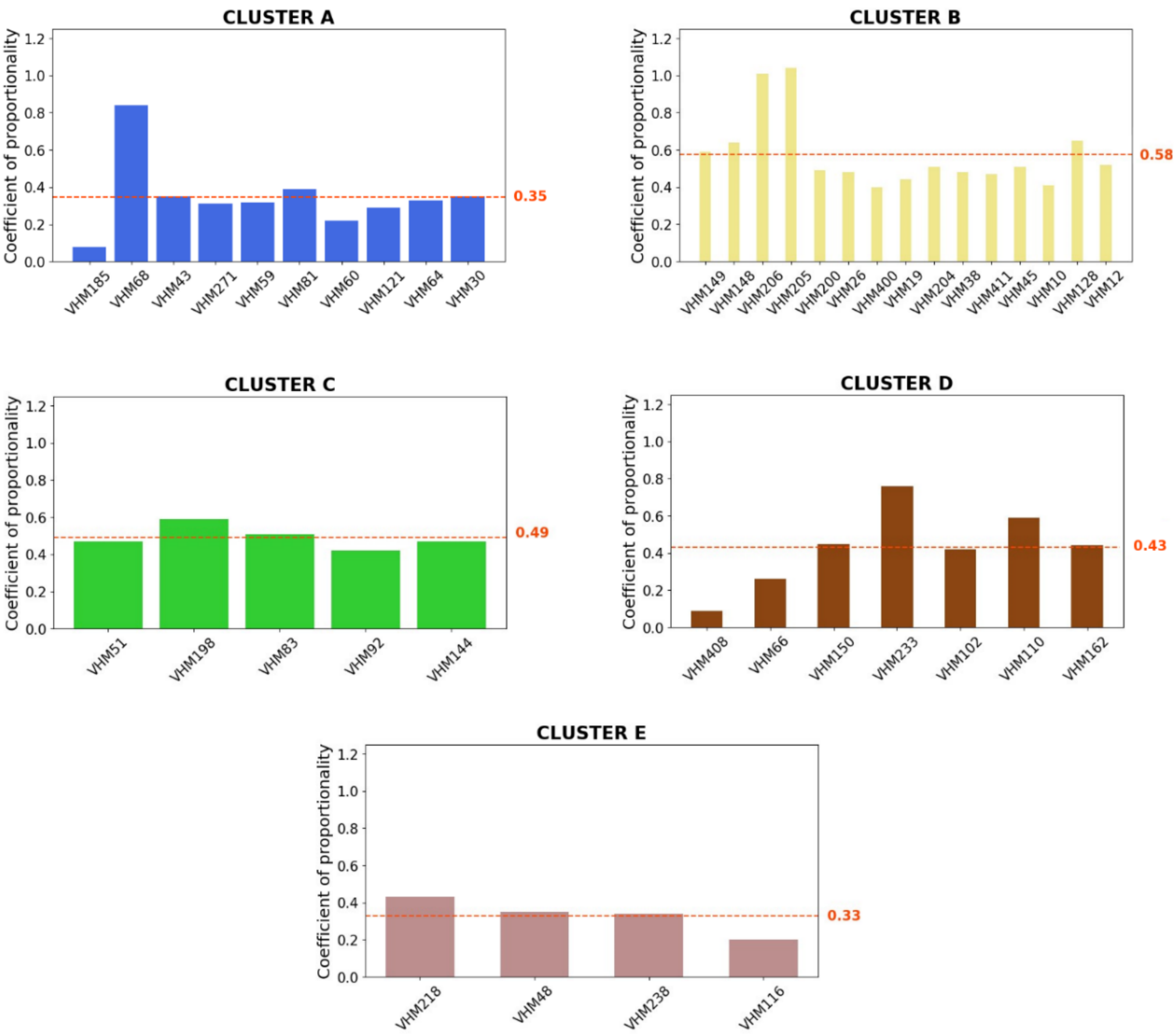


Figure 5 – Histograms showing coefficients of proportionality for each station and based on daily discharge values above the 95th percentile. Stations are shown by cluster, and mean coefficients averaged among all stations are represented by the dashed lines. The colours of the bars were chosen to match the colour of the clusters in Figures 3 and 4.

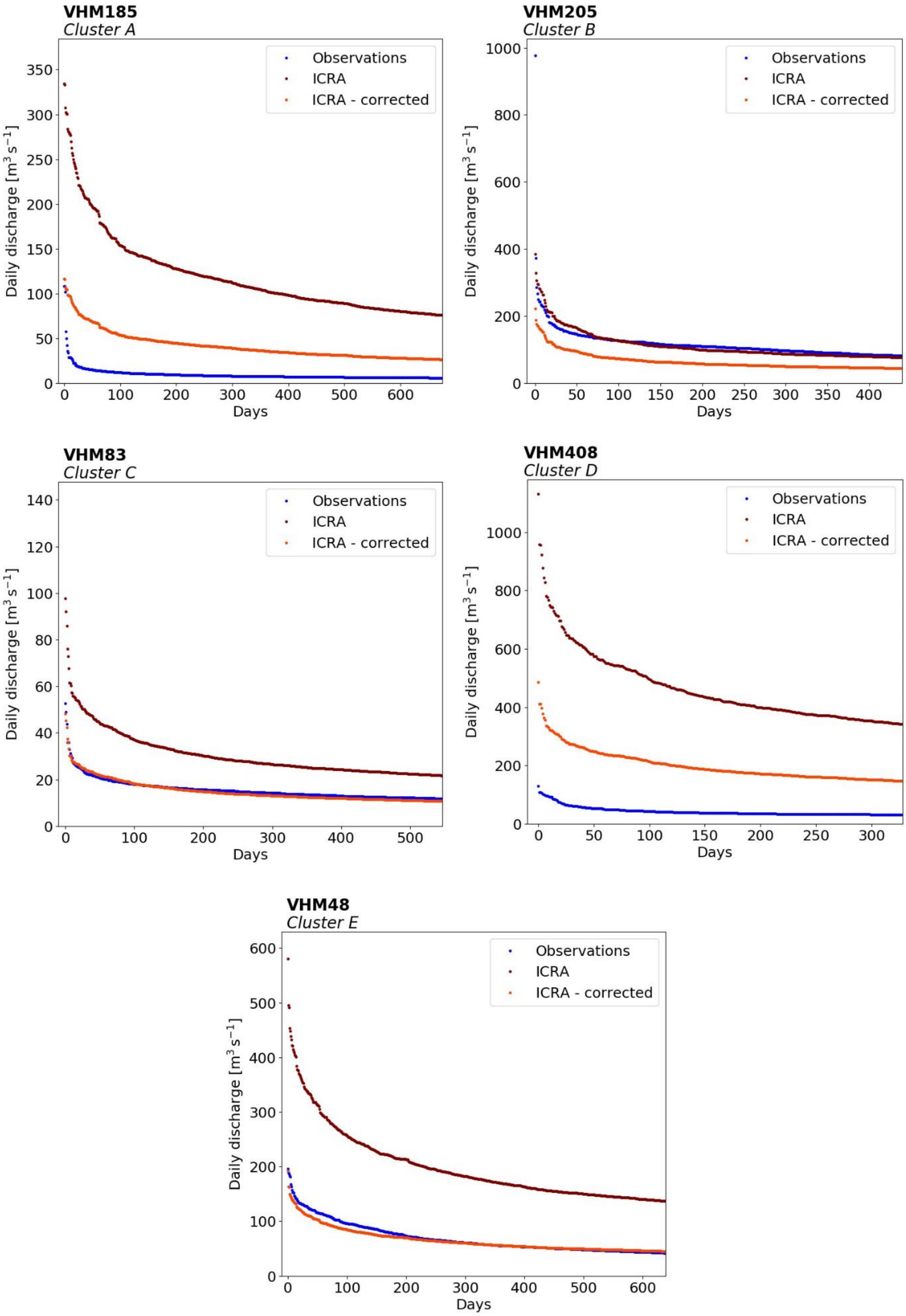


Figure 6 - Flow-duration curves for five gauged rivers including the 5% highest values. Discharge values are based on observations (blue), and based on the ICRA dataset before (brown) and after applying the corresponding cluster's scaling factor (red).

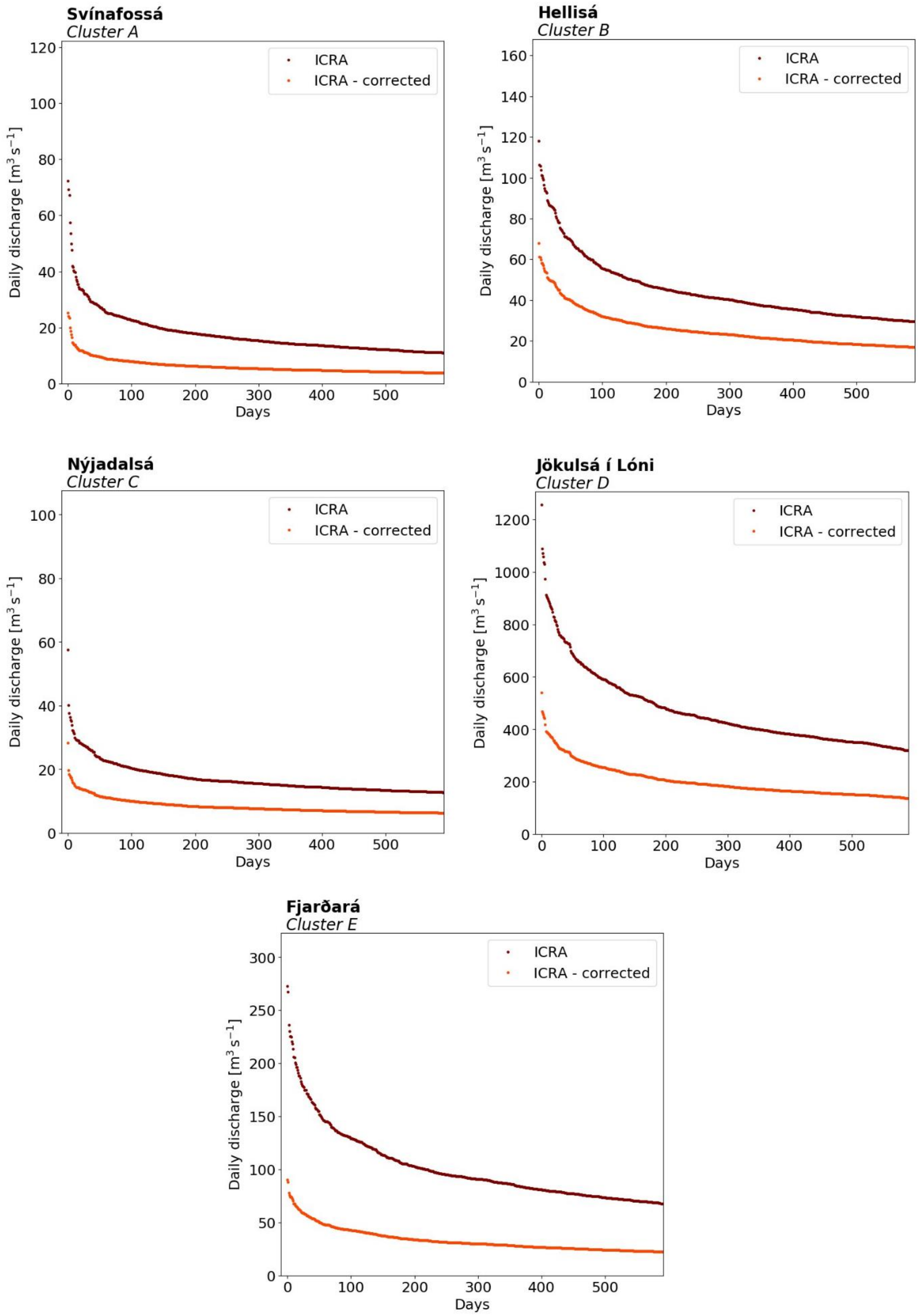


Figure 7 - Flow-duration curves for five ungauged rivers including the 5% highest values. Discharge values are based on the ICRA dataset before (brown) and after applying the corresponding cluster's scaling factor (red).

5.3 Flood analysis

5.3.1 Flood analysis for the gauged catchments

In order to obtain flood estimates for the gauged rivers, the Block Maxima method is applied both on measured and simulated discharge, before and after applying the correction factor. For each river, the correction coefficient depends on which cluster it belongs to, and is applied to the timeseries before the EVA. Daily flood return levels with a 10-, 25-, 50-, 100-, 200-, and 500-year return period are calculated for all gauging stations.

Three examples are shown in Table 2, for stations VHM 83, VHM 185 and VHM 205 (Results for other rivers are shown in Appendix I). Those rivers were picked from the histogram for the diversity of results they display. In the case of VHM 83, the mean correcting factor for its cluster of belonging (0.49) is very close to the individual correcting factor (0.51). Therefore, it clearly appears from the table that results after scaling the dataset are very close to the results obtained from the measurements. This is further illustrated by Figure 8 which displays the return-level plot for VHM 83. In those figures, discharge values are plotted against the return periods on a logarithmic scale. Here, values from the measured AMS between years 1980 and 2016 are represented by the blue dots. A straight line shows the fit between this data and return periods, and horizontal dashed lines indicate the values for the 25-year flood. The same is done for discharge derived from the ICRA dataset on the top plot in red, and for simulated discharge after correction on the lower plot in orange. In the case of this station, after scaling the data, the value of the daily return-value with a 25-year return period is 45 $m^3\ s^{-1}$, which is extremely close to the one obtained from the measurements (43 $m^3\ s^{-1}$) and more realistic than based on the uncorrected simulated discharge (92 $m^3\ s^{-1}$).

VHM 185, as previously discussed, is lacking infiltration when the runoff is converted into a discharge, which explains why the correcting factor is so low, compared to other stations that belong to the same cluster. Therefore, it is expected that the return levels after correction are not as close to the measurements as for VHM 83. This is indeed what can be seen from Table 2 and Figure 9. However, even if the corrected return levels are not lowered enough in order to reach the values based on the measurements, it is still a considerable improvement from before applying the correcting factor.

VHM 205 serves as a counterexample, as it is, with VHM 206, one of the two stations that do not benefit from correcting the simulated discharge, as can be seen from Table 2 and Figure 10. In that case, applying the mean correcting factor only lowers the return levels even more, while they were already inferior to the one obtained from the observations in the first place.

In order to easily assess the results for all the gauged rivers, a closeness coefficient (*CC*) is used to determine how well the simulated values match the measurements:

$$CC = \frac{\min(obs, sim)}{\max\,(obs, sim)} \times 100$$

This coefficient quantifies how close the simulated value is to the observed one, independently of whether the value is higher or lower than the observation, and can be used as a percentage match between two values of a same event. On Figure 11, the coefficients are shown for each gauged river for the 25-year return period before (top) and after (bottom) correction. Using the scaling factor improves the results in 34 cases out of 41. Similar results are found for other return periods (32 out of 41 for the 200-year flood, not shown here). Moreover, for the 25-year flood, seven stations have a *CC* above 75% before correction against 16 after correcting the runoff.

Table 2 – Return levels (m^3 s^{-1}) for stations VHM 83 (top), VHM 185 (middle), and VHM 205 (bottom). Results are based on the measured discharge, simulated discharge from the ICRA runoff, and simulated discharge from the ICRA runoff after correction. Values are given for a 10-, 25-, 50-, 100-, 200-, and 500-year return period.

<u>VHM 83 - Fjarðará</u>

Return-period	**Return levels *(m^3 s^{-1})***		
	Observations	**ICRA**	**ICRA, corrected**
10 years	37	78	39
25 years	44	92	45
50 years	50	102	50
100 years	56	111	55
200 years	61	121	60
500 years	68	134	66

<u>VHM 185 - Holmsá</u>

Return-period	**Return levels *(m^3 s^{-1})***		
	Observations	**ICRA**	**ICRA, corrected**
10 years	42	313	109
25 years	56	356	124
50 years	65	389	135
100 years	75	421	146
200 years	85	452	157
500 years	97	494	172

<u>VHM 205 - Kelduá</u>

Return-period	**Return levels *(m^3 s^{-1})***		
	Observations	**ICRA**	**ICRA, corrected**
10 years	376	316	182
25 years	482	372	214
50 years	560	414	238
100 years	637	455	262
200 years	715	496	286
500 years	817	550	317

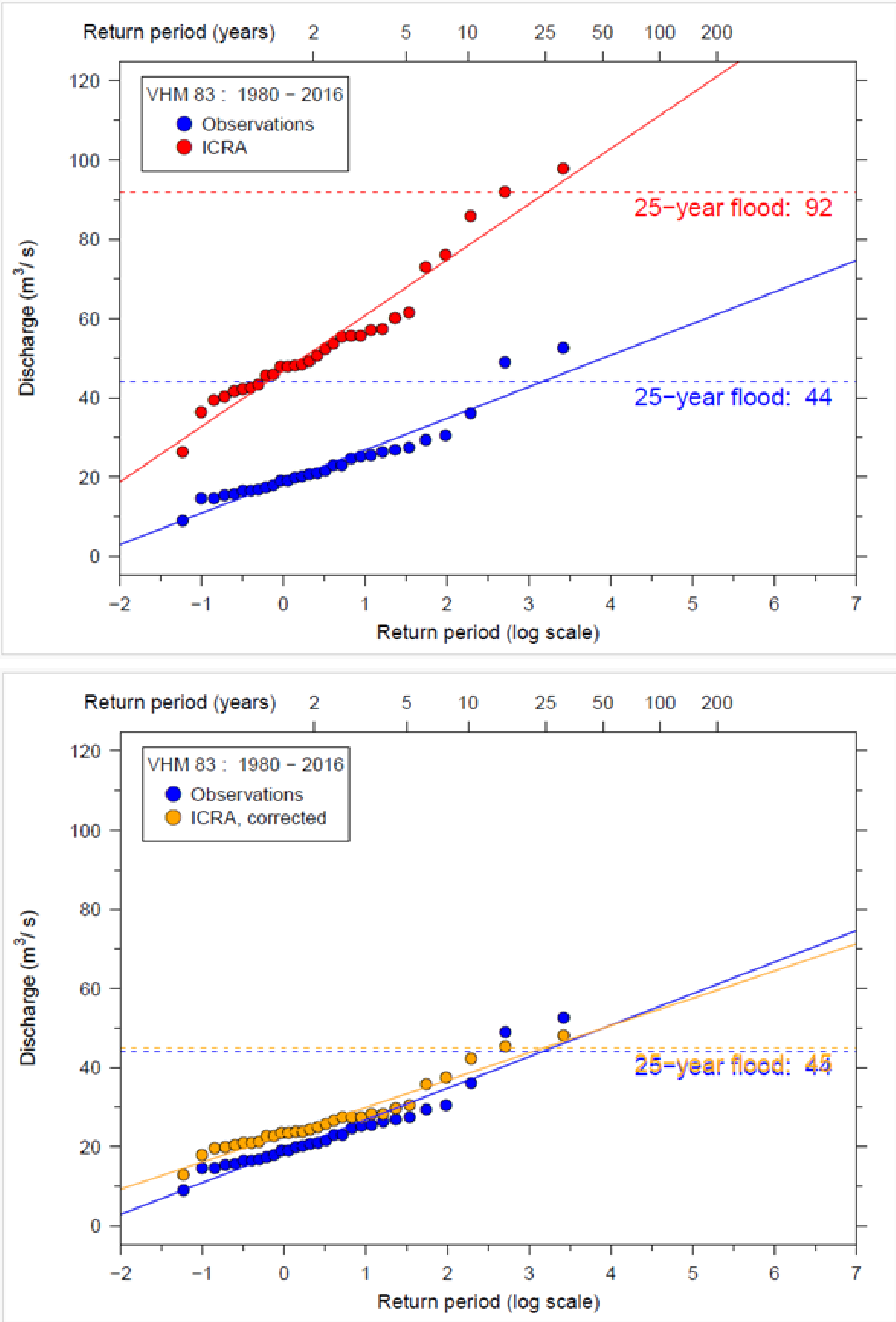


Figure 8 – Return level plot for station VHM 83, based on observations (blue), simulations before (red) and after correction (orange). Dashed-lines show the 25-year return level for the different datasets.

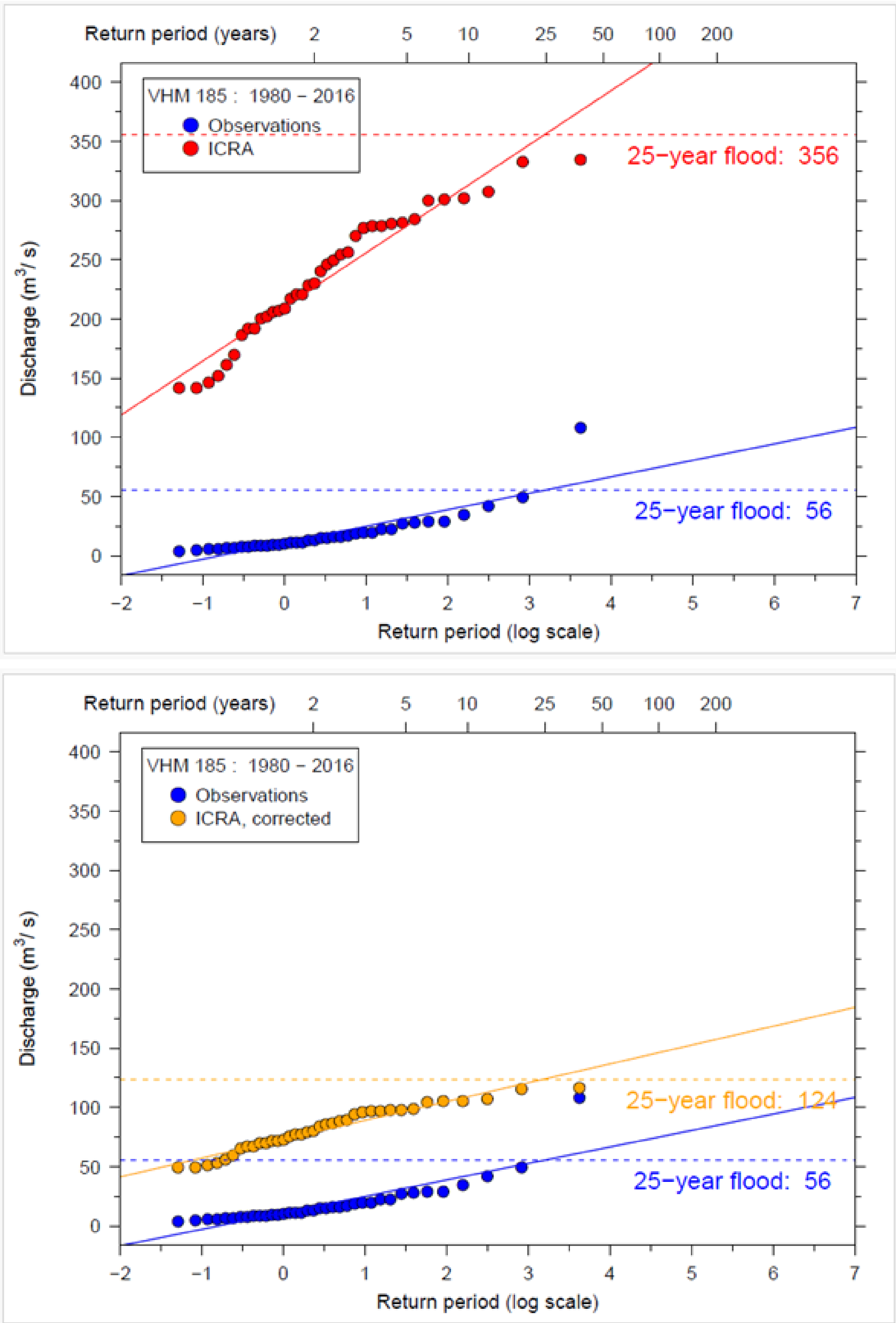


Figure 9 – Return level plot for station VHM 185, based on observations (blue), simulations before (red) and after correction (orange). Dashed-lines show the 25-year return level for the different datasets.

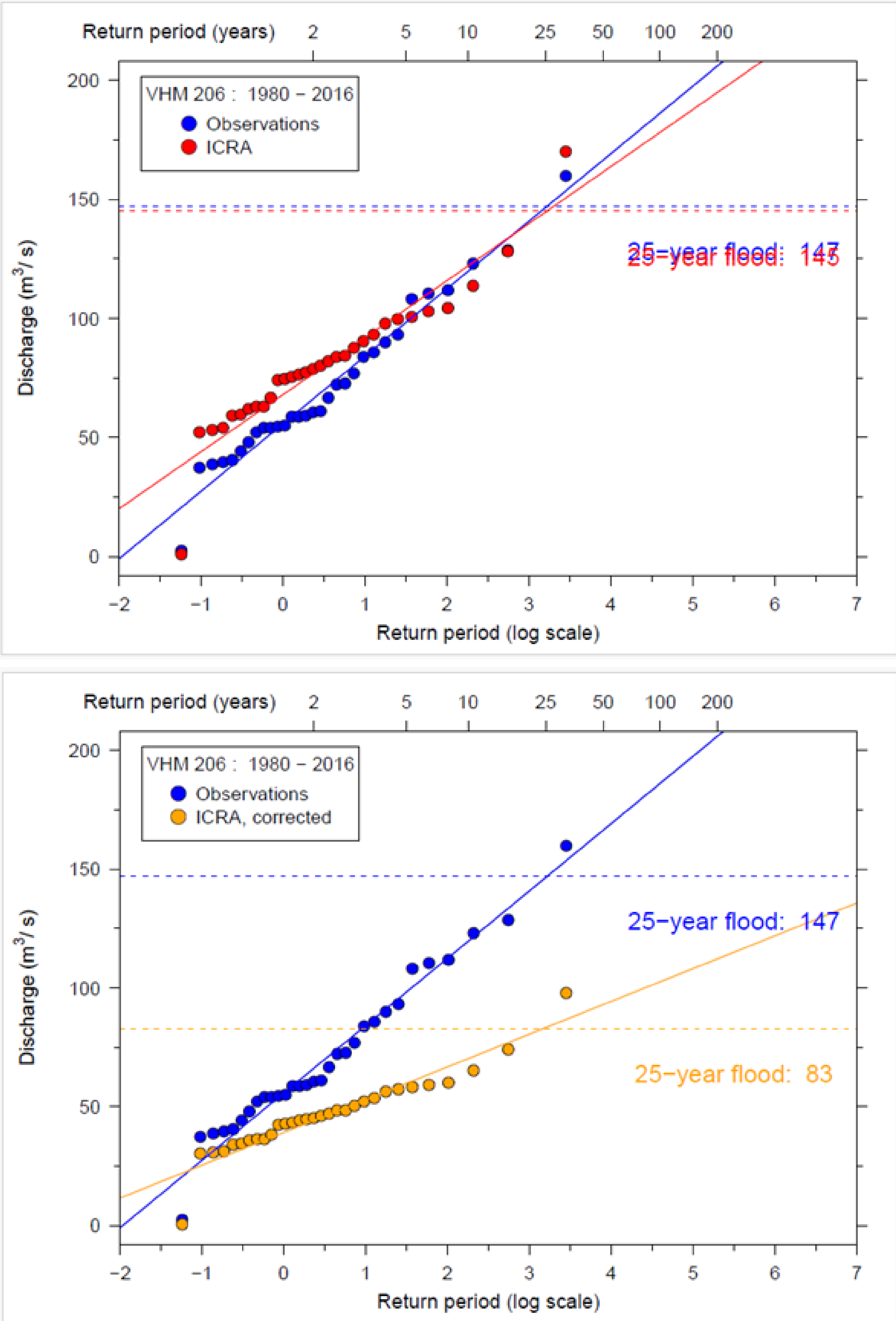


Figure 10 – Return level plot for station VHM 205, based on observations (blue), simulations before (red) and after correction (orange). Dashed-lines show the 25-year return level for the different datasets.

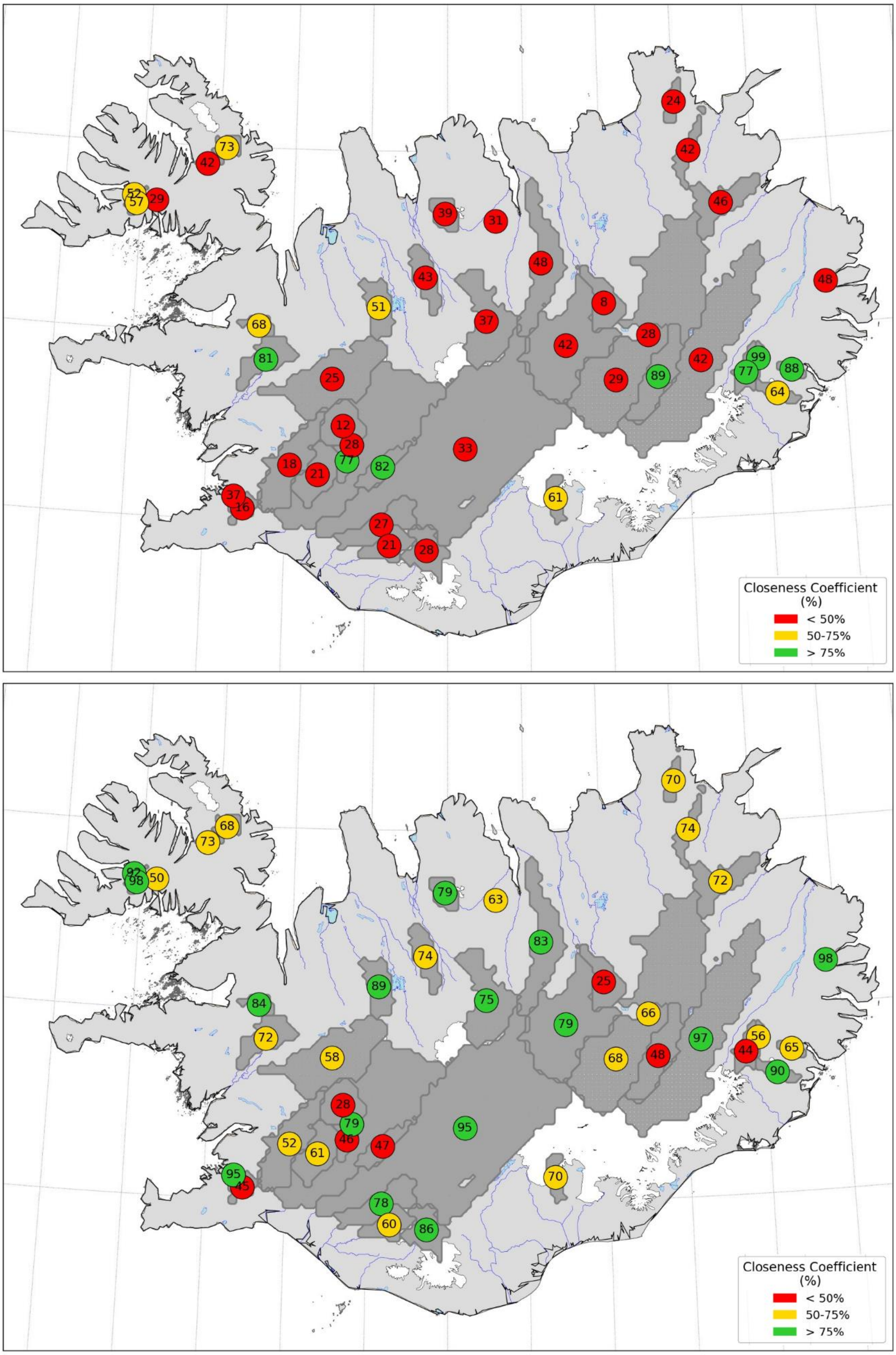


Figure 11 - Closeness Coefficient map comparing 25-year flood return level between observation and ICRA before (top) and after (bottom) applying the correcting factor.

The new flood estimates can also be compared to the early results obtained in four catchments (VHM 148, VHM 149, VHM 205, VHM 206) by the Index Flood Method (Crochet and Þórarinsdóttir, 2015). This method showed that return levels were slightly overestimating the reference values for these four rivers, but results were very close. Those four catchments are not the ones benefitting from the scaling of the ICRA the best, as can be seen from Figure 11 and the return level tables in Appendix I, which led to underestimated values for the 25-year flood when compared to the results obtained from the measurements.

5.3.2 Flood analysis for the ungauged catchments

The same methodology is then applied to ungauged areas. For each river, two AMS are created: one based on the simulated discharge from the ICRA runoff, the other based on the same simulated discharge, but scaled down by the corresponding coefficient. The EVA is then carried out on the timeseries, and new daily flood estimates are obtained.

Those results are compiled in Table 3 after applying the correction. For comparison purposes, results before correction are shown in Appendix II. Return-level plots are also produced and shown for rivers Miðfjarðará (Cluster A), Hafralónsá (Cluster E), Hellisá (Cluster B), and Jökulsá í Lóni (Cluster D) in Figure 12. Return level plots for the other ungauged rivers are shown in Appendix II.

As expected, those results vary significantly whether the correcting factor is applied or not and the lack of reference provided by the measurements for the gauged catchments makes it difficult to assess the quality of the results. However, considering the success of the method for the gauged stations, it is likely that the results after applying the correction are closer to reality than when applied on the AMS from uncorrected discharge.

Table 3 – Return levels ($m^3 s^{-1}$) for all ungauged rivers. Results are based on the simulated discharge from the ICRA runoff after correction.

	10-year	**25-year**	**50-year**	**100-year**	**200-year**	**500-year**
Berufjarðará	24	27	30	33	36	39
Fjarðará	79	90	98	105	113	123
Flókadalsá	51	58	64	69	75	82
Gilsá	41	48	52	57	62	68
Hafralónsá	169	196	217	237	257	284
Hellisá	61	70	76	82	88	96
Hellisfljót	27	32	35	38	41	46
Hornafjarðarfljót	479	543	591	639	686	748
Hrútafjarðará	48	56	62	68	73	81
Jökulgilskvísl	73	84	92	100	108	119
Jökulsá í Lóni	452	516	564	611	659	721
Lágadalsá	53	62	68	74	81	89
Langadalsá	73	87	96	106	116	128
Miðá	78	93	104	115	126	140
Miðfjarðará	105	118	127	136	146	158
Nýjadalsá	19	22	24	26	28	31
Ólafsfjarðará	63	73	80	87	94	103
Sléttuá	47	54	60	65	70	77
Steinavötn	161	180	195	209	223	242
Svínafossá	19	23	26	28	31	34

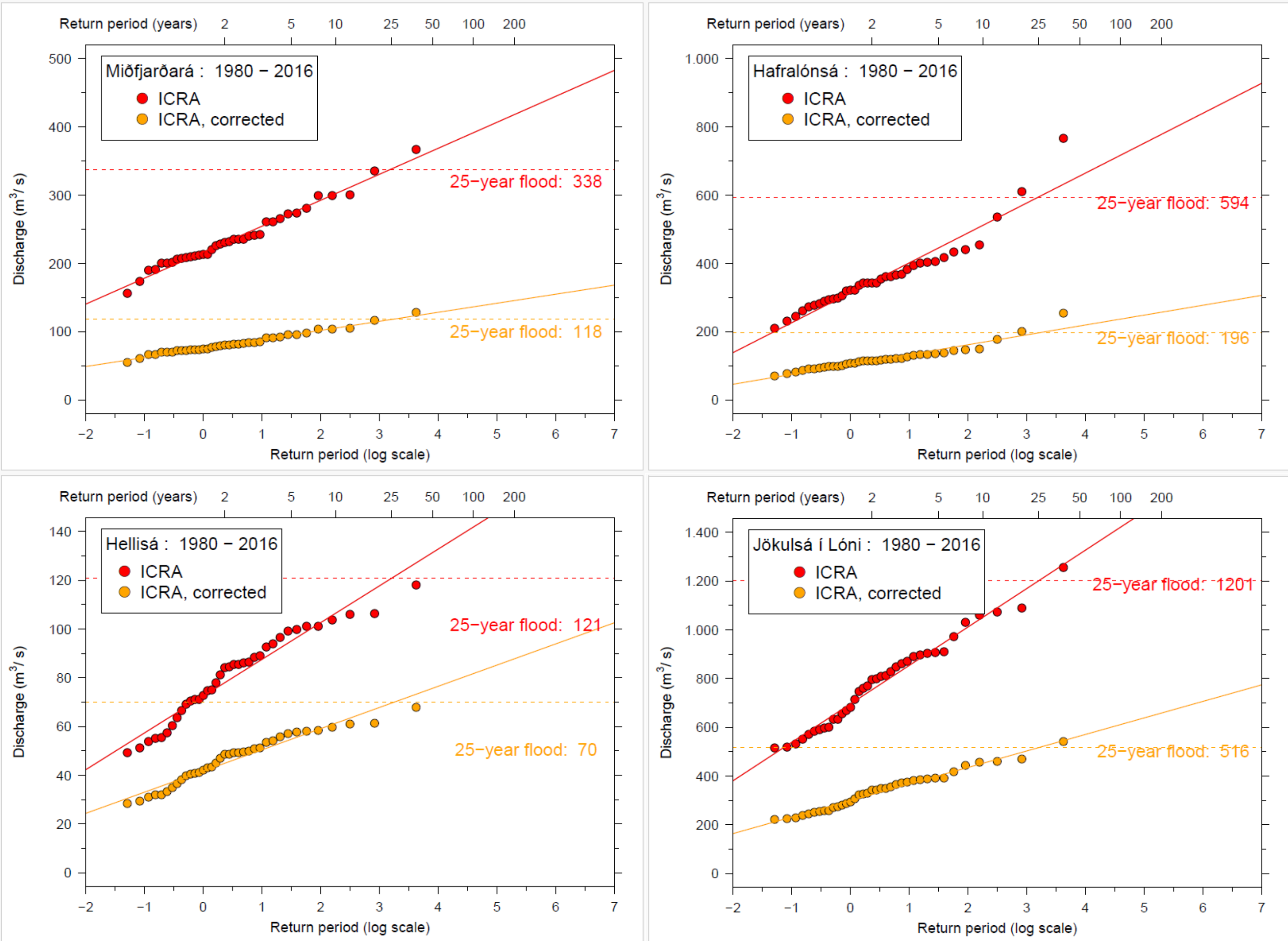


Figure 12 – Return level plot for ungauged rivers Miðfjarðará, Hafralónsá, Hellisá, and Jökulsá í Lóni, based on simulations of daily discharge before (red) and after correction (orange). Dashed-lines show the 25-year return level for the different datasets.

6 Discharge from the airGR runoff-rainfall model

6.1 Presentation

6.1.1 The GR6J model

AirGR is a series of rainfall-runoff models that can be applied either in a lumped or semi-distributed way. The suite of GR hydrological models was developed by INRAE (Institut National de Recherche pour l'Agriculture, l'alimentation et l'Environnement) and the models are available in R packages (Coron *et al.,* 2017; 2020).

In this study, following the works of Atlason *et al.* (2021) and Priet-Mahéo *et al.* (2021), the GR6J model (Pushpalatha *et al.*, 2011) is used along with the CemaNeige module (Valéry, 2010) for handling the simulation of snow accumulation and melt. GR6J runs with a daily time-step and uses six parameters for calibration and optimisation (see Table 4, parameters X1 – X6). Two extra parameters are used for the CemaNeige module (see Table 4, CNX1 and CNX2). All parameters are defined within a range of possible values and are optimised using the automatic ASA (Adaptive Simulated Annealing) optimisation method (Ingber, 2000; Ingber *et al*., 2012).

Table 4 – Parameters for the GR6J model and the CemaNeige.

Model	**Parameter**	
GR6J	**X1**	production store capacity [mm]
	X2	intercatchment exchange coefficient [mm d^{-1}]
	X3	routing store capacity [mm]
	X4	unit hydrograph time constant [d]
	X5	intercatchment exchange threshold [-]
	X6	exponential store depletion coefficient [mm]
CemaNeige	**X1**	weighting coefficient for snowpack thermal state [-]
	X2	degree-day melt coefficient [mm $°C^{-1}$ d^{-1}]

6.1.2 Input data

Three types of data are required as inputs to run the airGR model:

- ***Catchment characteristics:*** area and hypsometric curves are needed for each catchment. Those data were previously calculated by Atlason *et al.* (2021) and Priet-Mahéo *et al.* (2021), using ArcGIS.
- ***Meteorological data:*** daily evaporation, precipitation, and temperature timeseries were created using mean or accumulated values of the parameters, as simulated by the ICRA dataset.
- ***Gauge measurements:*** in order to use them as input data, the discharge measurements need to be converted from m^3 s^{-1} into mm day^{-1}, which can easily be done by scaling it with the area of the catchment.

6.1.3 Running the model

As previously mentioned, airGR is available as R packages, and is rather straightforward to implement. For this study, one gauged river from each cluster was selected: VHM 43, VHM 144, VHM 149, VHM 233 and VHM 238.

The first phase – and the longest – is the calibration phase. With the GR6J model, the user needs to create the input data that will feed the optimisation script. The user also needs to specify the number of elevation layers to create the CemaNeige module inputs. After a few tests, it was decided to use the default value of five elevation layers, since the results did not change when trying a different number (not shown here). The script then calls the calibration file that tries different ranges for each parameter and determines the value of the statistical criteria under the tested conditions. In this study, it was decided to use the Nash-Sutcliffe Efficiency coefficient (NSE), by analogy with the previous works done at IMO with airGR. Once the NSE reaches its maximum value, the optimisation will stop. This typically takes a few hours, depending on the wideness of the testing ranges for the parameters.

The second phase is the validation, where values of the eight parameters corresponding to the highest NSE are retrieved and used to simulate the discharge over the validation period. In some cases, the highest NSE value corresponds to several set of parameters, although it usually does not lead to major differences in the results.

6.2 Results

6.2.1 Calibration and validation of the selected rivers

For this study, it was decided to calibrate the rivers over a five-year period, from 01.01.2007 to 01.01.2012, with the exception of VHM 149 that was already calibrated from previous research over a period of six years (2007 – 2013).

For each catchment, validation was then carried over the whole period covered by both measurements and the ICRA dataset. For VHM 43, VHM 144 and VHM 149, this period spans from 01.09.1980 to 31.12.2016, with a spin up between 01.01.1980 to 01.09.1980. For VHM 233, the validation started on 01.09.1985, and for VHM 238 on 01.09.1988, and also ended on 31.12.2016. A spin up from January to September was also used for both these rivers.

NSE coefficients for the five catchments are shown both for the calibration and the validation periods on Figure 13. On the map, the catchments are coloured according to their cluster, similarly to Figure 4. NSE values appear in green when results are considered very good (above 0.75), in yellow when the results are considered good (between 0.35 and 0.75), and in red when the model fails to simulate the river flows successfully (under 0.35). In this case, all the catchments show good to very good results, both for the calibration and validation period. Best results are obtained for VHM 233 (with both NSE values equal or above to 0.75), and VHM 149. With a calibration of 0.65 and a validation of 0.55, VHM 238 is the river that is the least successfully simulated by the model, but both results are still considered as good.

To further illustrate those results, Figure 14 shows the hydrographs for the whole validation period for the five rivers. For VHM 144, VHM 149, and VHM 233, while the simulated discharge follows the general patterns of the measurements, results from airGR underestimate the highest peaks, which is especially notable for VHM 233. This is expected to lead to lower flood estimates, as the EVA only focus on the highest discharge peaks. For VHM 43 and VHM 238, the opposite can be seen, with an overestimation by the model.

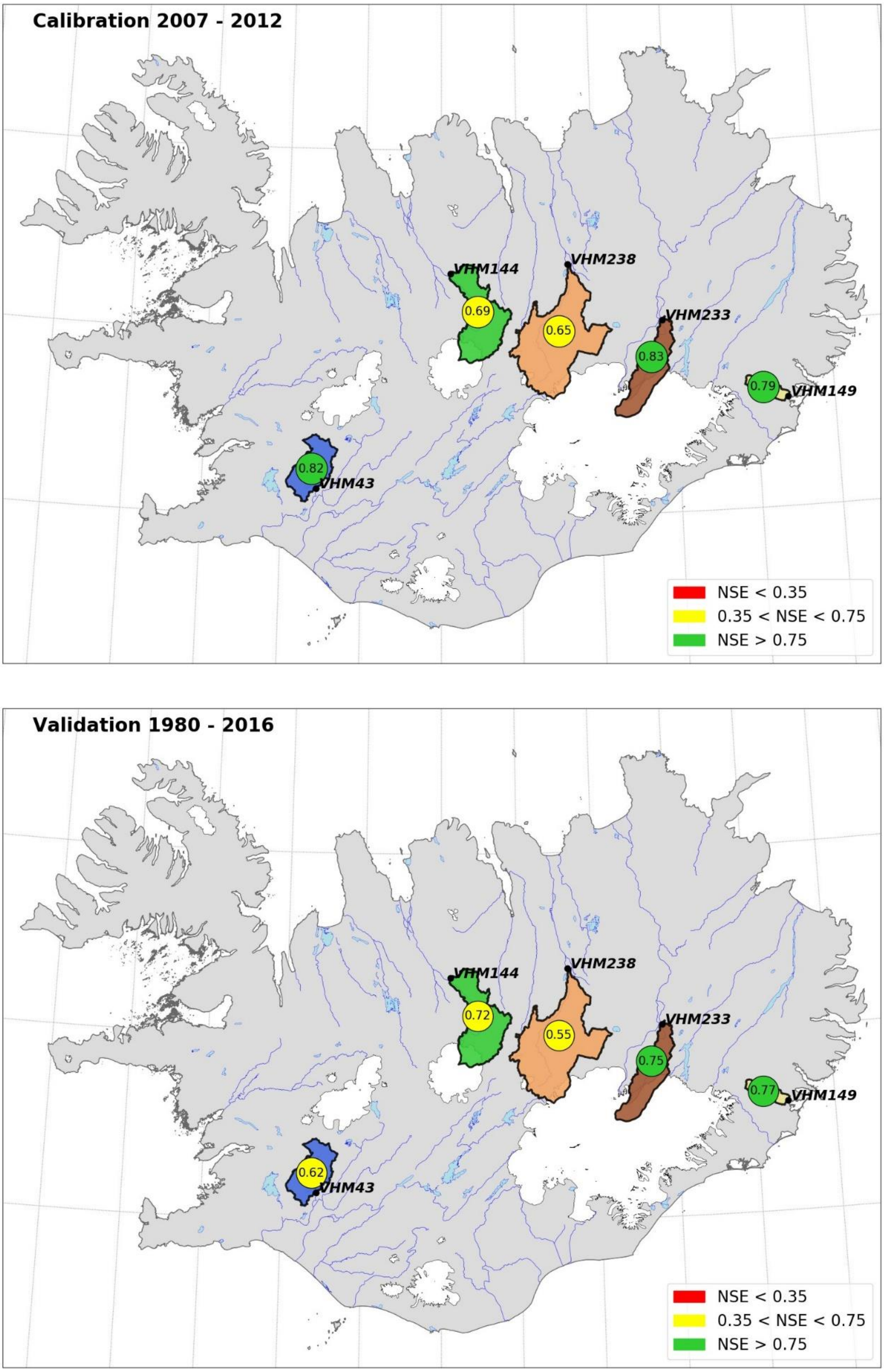


Figure 13 - Maps of Iceland with the selected catchments, with NSE values after calibration (top) and validation (bottom). The colours of the catchments match the colours used for the cluster analysis shown on Figure 4.

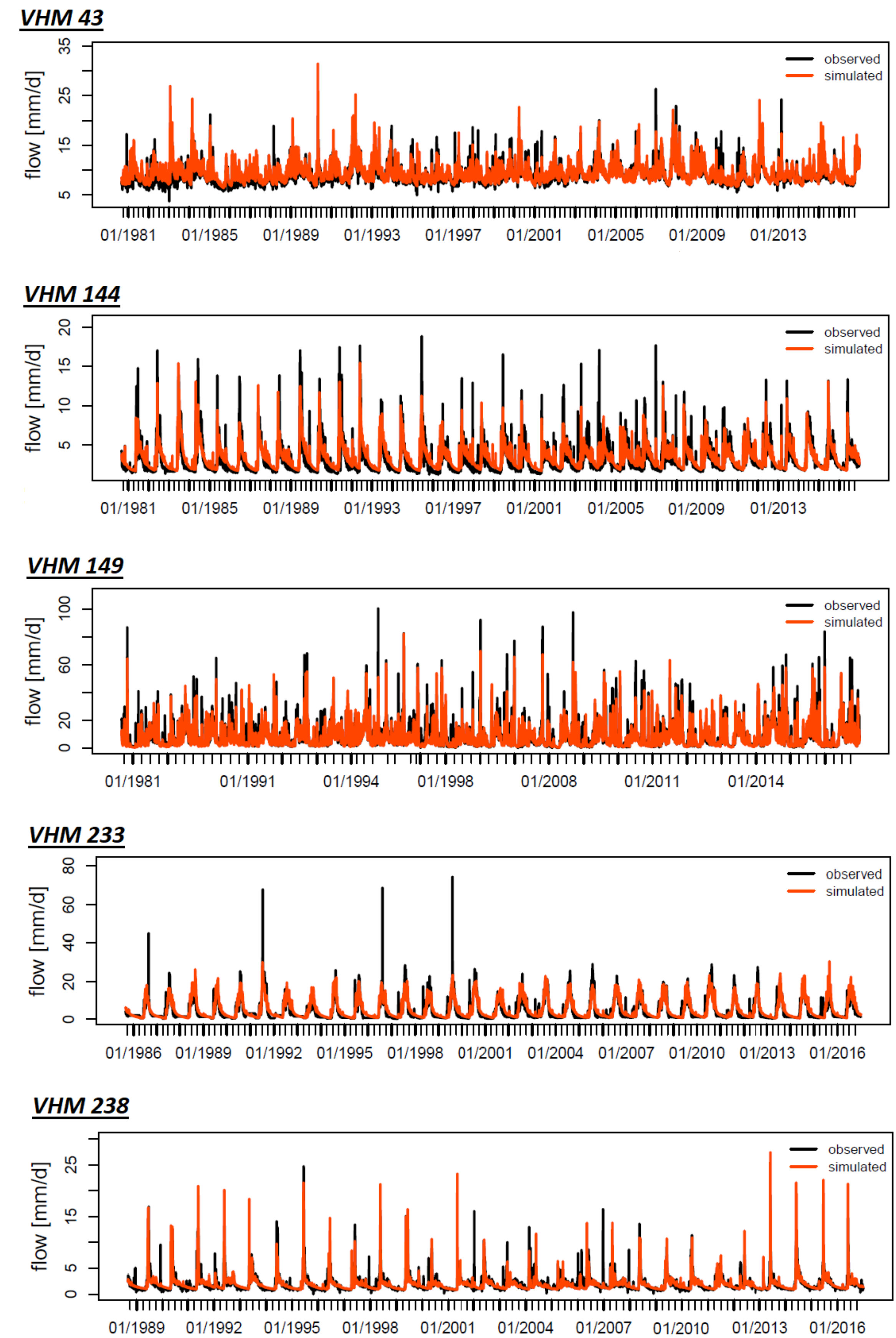


Figure 14 – Measured (black) and simulated (red) discharge for five catchments over the validation periods.

6.2.2 Flood estimates from airGR

After running airGR for the five rivers, new discharge timeseries were created. From these timeseries, AMS were calculated and the Block Maxima method applied to calculate daily discharge with a 10-, 25-, 50-, 100-, 200-, and 500-year return period. Results are shown on Table 5 for the five rivers. In order to make the comparison easier with the results from the measurements, the return levels calculated earlier from measurements are also shown.

Results show that for most rivers, the return levels calculated from airGR give values within the same range than from the observations. This is especially true for VHM 43 with a 10-year flood value of 181 mm when running airGR, and a value of 163 mm from the measurements. For VHM 233, the simulated results are very underestimated, with a 50-year flood of 307 mm from airGR, which is less than half the return level obtained from the measurements. Even though the station scored a high NSE coefficient over the whole validation period (0.75), it appeared from Figure 13 that the peak values were underestimated by airGR, explaining why those return levels are too low.

These results are further illustrated by Figure 15 which shows return level plots similar to Figure 8, 9, 10, and 11. On the plots, results from airGR are shown in green, and results from the measurements in blue. The coloured dots show the AMS, and for most stations, results from airGR are quite good, notably for VHM 233 which explains the high NSE score shown on Figure 13. However, for this river, the four highest observations (all above 400 mm) are weighing on the parameters of the GEV distribution, which ends up giving very different return level values.

Table 5 – Return levels (m^3 s^{-1}) for all ungauged rivers. Results are based on the simulated discharge from the GR6J model (top table) and from the observations (bottom table).

GR6J SIMULATIONS						
	10-year	**25-year**	**50-year**	**100-year**	**200-year**	**500-year**
VHM 43	181	209	230	250	270	297
VHM 144	171	195	212	230	247	270
VHM 149	157	180	196	213	230	252
VHM 233	251	283	307	330	354	385
VHM 238	593	716	808	899	990	1109
MEASUREMENTS						
	10-year	**25-year**	**50-year**	**100-year**	**200-year**	**500-year**
VHM 43	163	182	195	209	223	241
VHM 144	222	252	274	296	318	347
VHM 149	202	237	263	288	314	347
VHM 233	456	568	652	735	818	927
VHM 238	468	565	636	708	779	873

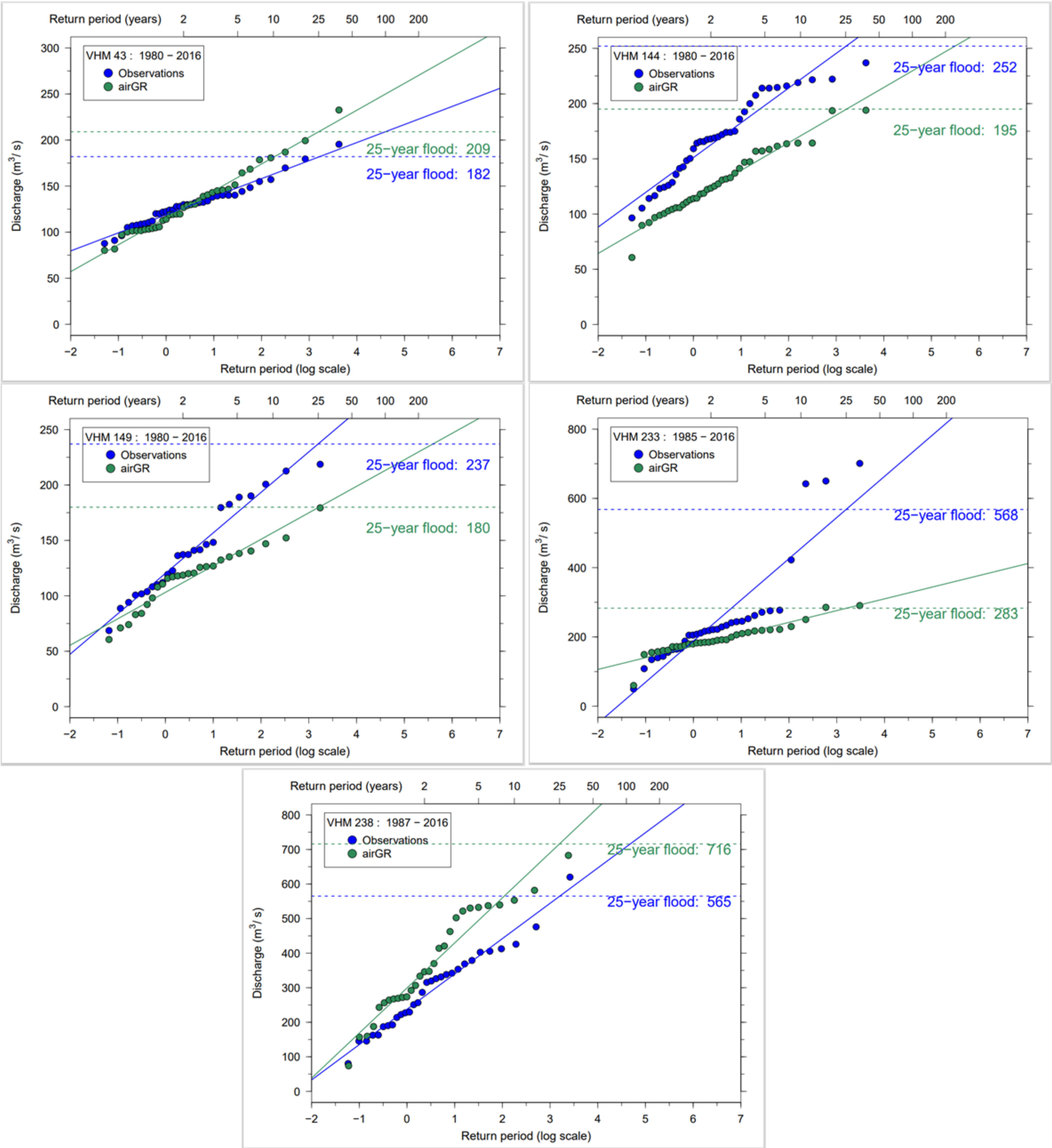


Figure 15 – Return level plot for five rivers, based on simulations from the GR6J model (green) and the measurements (blue). Dashed-lines show the 25-year return level for the two datasets.

7 Conclusion

Building on the 2022 research project, the goal of this research was to calculate flood estimates in 41 gauged catchments using the ICRA-simulated runoff, and also calculate those return levels for 20 ungauged catchments using the same method. Additionally, daily discharge timeseries were simulated by the rainfall-runoff hydrological model airGR for five rivers, and new return levels were calculated to compare with the previously obtained results.

In the first place, ungauged watersheds were selected to add to the 2022 analysis, with catchments being hand-picked all around the country. These rivers were chosen with the only condition being that they have an area superior to 25 km^2 so that at least three gridpoints from the ICRA domain can be included. Parts of the country that are currently not well gauged were favoured, and when possible, rivers that seem of particular interests for Vegagerðin were selected.

After obtaining discharge timeseries from the ICRA dataset for the ungauged rivers, a hierarchical cluster analysis was carried out on the simulated data for both gauged and ungauged catchments. This clustering used flow-duration and mass curves, as well as seasonality timeseries and physical catchments characteristics in order to categorize rivers in groups that share more similarities than with any other rivers from other groups. A dendrogram was produced, and five clusters were identified, with each cluster combining both gauged and ungauged rivers.

Similarly to the 2022 study, new correcting factors were calculated based on the measurements in order to scale the ICRA runoff in order to match the observations better. While this was done individually for each station based on the 95th percentile discharge values, a mean correcting factor for each cluster was calculated and therefore applied to the discharge timeseries of the ungauged catchments.

An EVA was then performed for the gauged rivers using the Block Maxima method on both observed and simulated timeseries, before and after correction. Return levels were presented in tables, and return-level plots. For 34 rivers out of 41, the 25-year flood benefitted from the correction on the simulated discharge. Return levels were then calculated for the ungauged catchments using the same methodology.

Finally, the airGR rainfall-runoff model was used to simulate timeseries for five gauged rivers. Calibrated over a period of five years, the simulated discharge showed good results with NSE values for the validation period ranging from 0.55 to 0.75. After retrieving the AMS from the discharge simulated by the hydrological model, flood estimates were calculated using the same EVA than in the rest of the study. With the exception of one river that failed to simulate the highest discharge correctly, return levels based on the airGR model gave values in the same range than the ones previously obtained from the measurement timeseries, making it a promising tool for flood analysis.

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Appendix I. Flood estimates for the gauged catchments

Return levels ($m^3\ s^{-1}$) for all gauged rivers shown in the following tables. Results are based on the measured discharge, simulated discharge from the ICRA runoff, and simulated discharge from the ICRA runoff after correction. Values are given for a 10-, 25-, 50-, 100-, 200-, and 500-year return period.

VHM 10 - Svartá

Return-period	**Return levels** ***($m^3\ s^{-1}$)***		
	Observations	**ICRA**	**ICRA, corrected**
10 years	82	199	115
25 years	96	224	129
50 years	106	242	139
100 years	116	260	150
200 years	127	278	160
500 years	140	302	174

VHM 12 - Haukadalsá

Return-period	**Return levels** ***($m^3\ s^{-1}$)***		
	Observations	**ICRA**	**ICRA, corrected**
10 years	98	150	86
25 years	119	174	100
50 years	134	191	110
100 years	149	209	120
200 years	164	227	131
500 years	184	250	144

VHM 19 - Dynjandisá

Return-period	**Return levels** ***($m^3\ s^{-1}$)***		
	Observations	**ICRA**	**ICRA, corrected**
10 years	29	59	34
25 years	35	67	38
50 years	39	72	42
100 years	43	78	45
200 years	47	84	48
500 years	52	91	52

VHM 26 - Sandá

Return-period	Return levels *($m^3 s^{-1}$)*		
	Observations	**ICRA**	**ICRA, corrected**
10 years	108	259	149
25 years	128	302	174
50 years	143	334	192
100 years	157	365	210
200 years	172	397	229
500 years	191	438	253

VHM 30 - Þjórsá

Return-period	Return levels *($m^3 s^{-1}$)*		
	Observations	**ICRA**	**ICRA, corrected**
10 years	1499	4750	1653
25 years	1775	5391	1876
50 years	1981	5866	2041
100 years	2184	6338	2206
200 years	2387	6809	2369
500 years	2655	7429	2585

VHM 38 - Þverá

Return-period	Return levels *($m^3 s^{-1}$)*		
	Observations	**ICRA**	**ICRA, corrected**
10 years	26	64	37
25 years	32	77	44
50 years	36	86	50
100 years	40	95	55
200 years	45	105	60
500 years	50	117	67

<u>VHM 43 - Brúará</u>

Return-period	Return levels *(m^3 s^{-1})*		
	Observations	**ICRA**	**ICRA, corrected**
10 years	163	748	260
25 years	182	853	297
50 years	195	931	324
100 years	209	1109	351
200 years	223	1086	378
500 years	241	1188	413

<u>VHM 45 - Vatnsdalsá</u>

Return-period	Return levels *(m^3 s^{-1})*		
	Observations	**ICRA**	**ICRA, corrected**
10 years	107	217	125
25 years	129	252	145
50 years	145	278	160
100 years	160	303	175
200 years	176	329	189
500 years	197	362	209

<u>VHM 48 - Selá</u>

Return-period	Return levels *(m^3 s^{-1})*		
	Observations	**ICRA**	**ICRA, corrected**
10 years	191	442	146
25 years	229	496	164
50 years	258	537	177
100 years	286	577	190
200 years	314	617	204
500 years	351	670	221

VHM 51 - Hjaltadalsá

Return-period	**Return levels *(m^3 s^{-1})***		
	Observations	**ICRA**	**ICRA, corrected**
10 years	87	226	111
25 years	100	256	126
50 years	110	279	137
100 years	119	301	148
200 years	129	324	159
500 years	141	353	174

VHM 59 – Ytri-Rangá

Return-period	**Return levels *(m^3 s^{-1})***		
	Observations	**ICRA**	**ICRA, corrected**
10 years	137	517	180
25 years	161	593	206
50 years	178	650	226
100 years	196	707	246
200 years	213	763	265
500 years	236	837	291

VHM 60 – Eystri-Rangá

Return-period	**Return levels *(m^3 s^{-1})***		
	Observations	**ICRA**	**ICRA, corrected**
10 years	101	490	171
25 years	118	567	197
50 years	131	624	217
100 years	144	681	237
200 years	157	737	256
500 years	174	811	282

VHM 64 - Ölfusá

Return-period	Return levels (*m^3 s^{-1}*)		
	Observations	**ICRA**	**ICRA, corrected**
10 years	1386	5109	1178
25 years	1599	5784	2013
50 years	1758	6286	2187
100 years	1916	6783	2361
200 years	2072	7279	2533
500 years	2279	7933	2761

VHM 66 - Hvitá

Return-period	Return levels (*m^3 s^{-1}*)		
	Observations	**ICRA**	**ICRA, corrected**
10 years	347	1432	616
25 years	410	1652	710
50 years	456	1815	781
100 years	503	1977	850
200 years	549	2138	920
500 years	609	2351	1011

VHM 68 - Tungufljót

Return-period	Return levels (*m^3 s^{-1}*)		
	Observations	**ICRA**	**ICRA, corrected**
10 years	168	226	79
25 years	202	264	92
50 years	227	291	101
100 years	252	319	111
200 years	277	347	121
500 years	310	383	133

VHM 81 - Úlfarsá

Return-period	**Return levels** ***($m^3\ s^{-1}$)***		
	Observations	**ICRA**	**ICRA, corrected**
10 years	17	46	16
25 years	20	54	19
50 years	23	60	21
100 years	25	66	23
200 years	28	71	25
500 years	31	79	28

VHM 83 - Fjarðará

Return-period	**Return levels** ***($m^3\ s^{-1}$)***		
	Observations	**ICRA**	**ICRA, corrected**
10 years	37	78	39
25 years	44	92	45
50 years	50	102	50
100 years	56	111	55
200 years	61	121	60
500 years	68	134	66

VHM 92 - Bægisá

Return-period	**Return levels** ***($m^3\ s^{-1}$)***		
	Observations	**ICRA**	**ICRA, corrected**
10 years	17	55	27
25 years	20	65	32
50 years	22	72	35
100 years	24	79	39
200 years	25	86	42
500 years	28	96	47

VHM 102 – Jökulsá á Fjöllum

Return-period	**Return levels *(m^3 s^{-1})***		
	Observations	**ICRA**	**ICRA, corrected**
10 years	730	2618	1126
25 years	842	2958	1272
50 years	924	3210	1380
100 years	1006	3460	1488
200 years	1087	3709	1595
500 years	1195	4038	1736

VHM 110 – Jökulsá á Dal

Return-period	**Return levels *(m^3 s^{-1})***		
	Observations	**ICRA**	**ICRA, corrected**
10 years	870	2125	914
25 years	1026	2461	1058
50 years	1142	2711	1166
100 years	1257	2958	1272
200 years	1371	3205	1378
500 years	1522	3530	1518

VHM 116- Svartá

Return-period	**Return levels *(m^3 s^{-1})***		
	Observations	**ICRA**	**ICRA, corrected**
10 years	32	355	117
25 years	34	410	135
50 years	36	450	149
100 years	38	490	162
200 years	40	530	175
500 years	42	583	192

VHM 121 - Ormarsá

Return-period	Return levels ($m^3 s^{-1}$)		
	Observations	**ICRA**	**ICRA, corrected**
10 years	40	162	56
25 years	46	188	66
50 years	51	208	72
100 years	55	227	79
200 years	60	246	86
500 years	66	271	94

VHM 128 - Norðurá

Return-period	Return levels ($m^3 s^{-1}$)		
	Observations	**ICRA**	**ICRA, corrected**
10 years	410	522	300
25 years	497	617	356
50 years	561	688	397
100 years	625	759	437
200 years	689	829	478
500 years	773	922	531

VHM 144 – Austari-Jökulsá

Return-period	Return levels ($m^3 s^{-1}$)		
	Observations	**ICRA**	**ICRA, corrected**
10 years	222	590	290
25 years	252	686	338
50 years	274	758	373
100 years	296	829	408
200 years	318	900	443
500 years	347	993	489

<u>VHM 148 - Fossá</u>

Return-period	Return levels *($m^3 s^{-1}$)*		
	Observations	**ICRA**	**ICRA, corrected**
10 years	152	184	106
25 years	184	208	120
50 years	208	227	131
100 years	231	245	141
200 years	255	263	151
500 years	285	287	165

<u>VHM 149 - Geithellnaá</u>

Return-period	Return levels *($m^3 s^{-1}$)*		
	Observations	**ICRA**	**ICRA, corrected**
10 years	202	321	185
25 years	237	371	214
50 years	263	409	235
100 years	288	446	257
200 years	314	483	278
500 years	347	532	306

<u>VHM 150 - Djúpá</u>

Return-period	Return levels *($m^3 s^{-1}$)*		
	Observations	**ICRA**	**ICRA, corrected**
10 years	288	508	219
25 years	352	573	246
50 years	400	620	267
100 years	447	668	287
200 years	495	715	397
500 years	557	777	334

VHM 162 – Jökulsá á Fjöllum

Return-period	Return levels *(m^3 s^{-1})*		
	Observations	**ICRA**	**ICRA, corrected**
10 years	408	1449	623
25 years	481	1642	706
50 years	536	1785	767
100 years	591	1927	829
200 years	645	2068	889
500 years	716	2255	970

VHM 185 - Hólmsá

Return-period	Return levels *(m^3 s^{-1})*		
	Observations	**ICRA**	**ICRA, corrected**
10 years	42	313	109
25 years	56	356	124
50 years	65	389	135
100 years	75	421	146
200 years	85	452	157
500 years	97	494	172

VHM 198 – Hvalá

Return-period	Return levels *(m^3 s^{-1})*		
	Observations	**ICRA**	**ICRA, corrected**
10 years	206	301	148
25 years	247	339	167
50 years	277	368	181
100 years	307	396	195
200 years	337	424	208
500 years	376	461	227

VHM 200 - Fnjóská

Return-period	Return levels *(m^3 s^{-1})*		
	Observations	**ICRA**	**ICRA, corrected**
10 years	392	859	495
25 years	479	996	574
50 years	543	1098	632
100 years	607	1199	690
200 years	671	1299	748
500 years	755	1432	825

VHM 204 - Vatnsdalsá

Return-period	Return levels *(m^3 s^{-1})*		
	Observations	**ICRA**	**ICRA, corrected**
10 years	76	141	81
25 years	91	161	93
50 years	102	175	101
100 years	114	190	109
200 years	125	204	118
500 years	140	223	129

VHM 205 - Kelduá

Return-period	Return levels *(m^3 s^{-1})*		
	Observations	**ICRA**	**ICRA, corrected**
10 years	376	316	182
25 years	482	372	214
50 years	560	414	238
100 years	637	455	262
200 years	715	496	286
500 years	817	550	317

VHM 206 - Fellsá

Return-period	**Return levels** $(m^3\ s^{-1})$		
	Observations	**ICRA**	**ICRA, corrected**
10 years	120	122	70
25 years	147	145	83
50 years	166	161	93
100 years	186	178	103
200 years	206	195	112
500 years	232	217	125

VHM 218 - Markarfljót

Return-period	**Return levels** $(m^3\ s^{-1})$		
	Observations	**ICRA**	**ICRA, corrected**
10 years	188	662	219
25 years	215	756	249
50 years	234	825	272
100 years	254	893	295
200 years	273	962	317
500 years	299	1052	347

VHM 233 - Kreppá

Return-period	**Return levels** $(m^3\ s^{-1})$		
	Observations	**ICRA**	**ICRA, corrected**
10 years	456	564	242
25 years	568	637	274
50 years	652	691	297
100 years	735	746	321
200 years	818	799	344
500 years	927	870	374

VHM 238 - Skjálfandafljót

Return-period	Return levels *(m^3 s^{-1})*		
	Observations	**ICRA**	**ICRA, corrected**
10 years	468	1186	391
25 years	565	1360	449
50 years	636	1490	492
100 years	708	1618	534
200 years	779	1747	576
500 years	873	1916	632

VHM 271 - Sog

Return-period	Return levels *(m^3 s^{-1})*		
	Observations	**ICRA**	**ICRA, corrected**
10 years	227	1214	422
25 years	250	1386	482
50 years	268	1513	527
100 years	285	1640	571
200 years	303	1766	615
500 years	326	1933	673

VHM 400 - Vattardalsá

Return-period	Return levels *(m^3 s^{-1})*		
	Observations	**ICRA**	**ICRA, corrected**
10 years	35	122	70
25 years	40	140	80
50 years	45	153	88
100 years	49	166	96
200 years	53	180	103
500 years	59	197	113

__VHM 408 - Sandá__

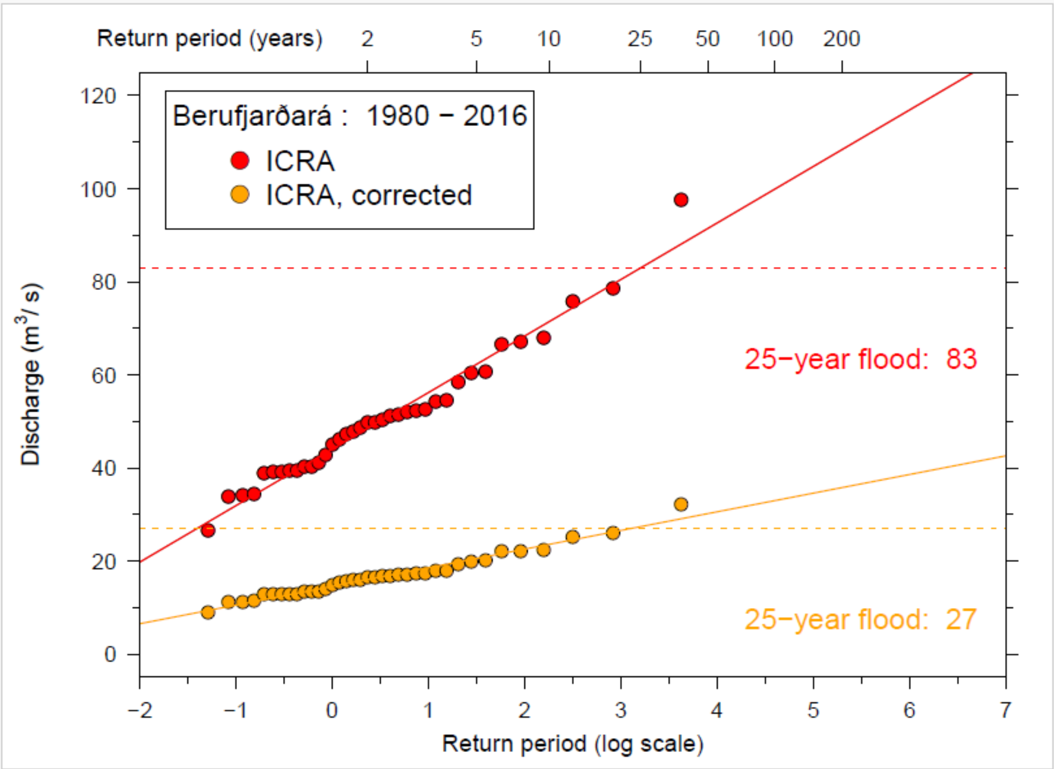
Return-period	Return levels *(m^3 s^{-1})*		
	Observations	**ICRA**	**ICRA, corrected**
10 years	112	1016	437
25 years	140	1155	497
50 years	160	1258	541
100 years	180	1360	585
200 years	200	1463	629
500 years	227	1597	687

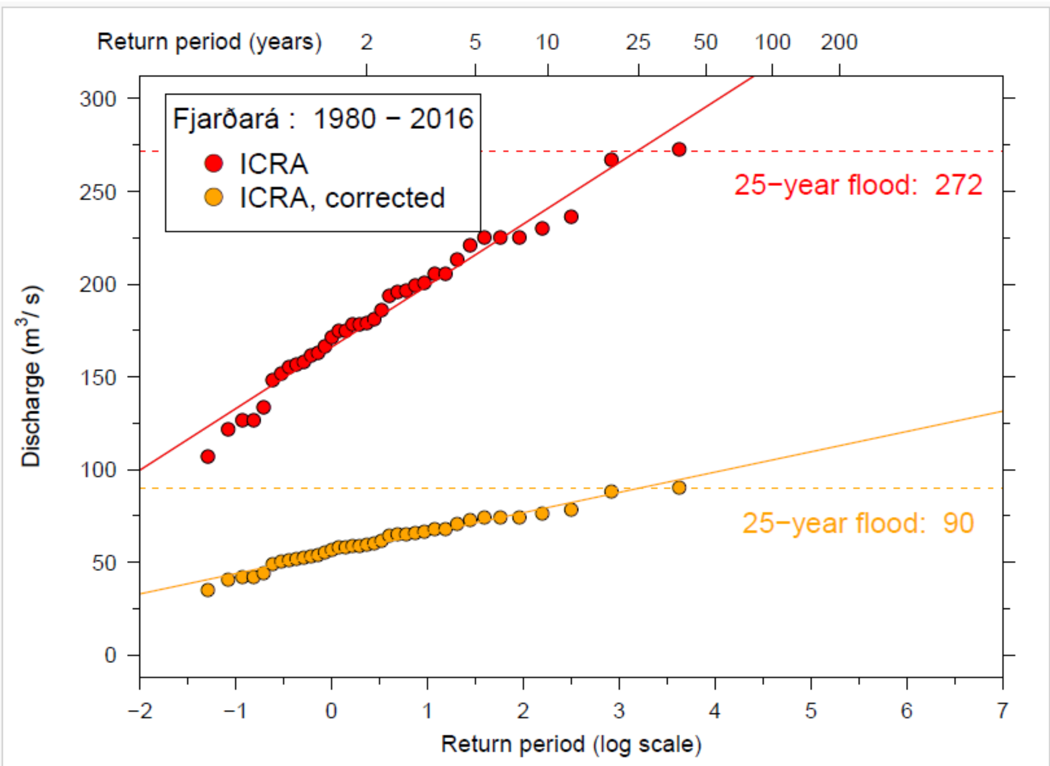
__VHM 411 – Stóra Laxá__

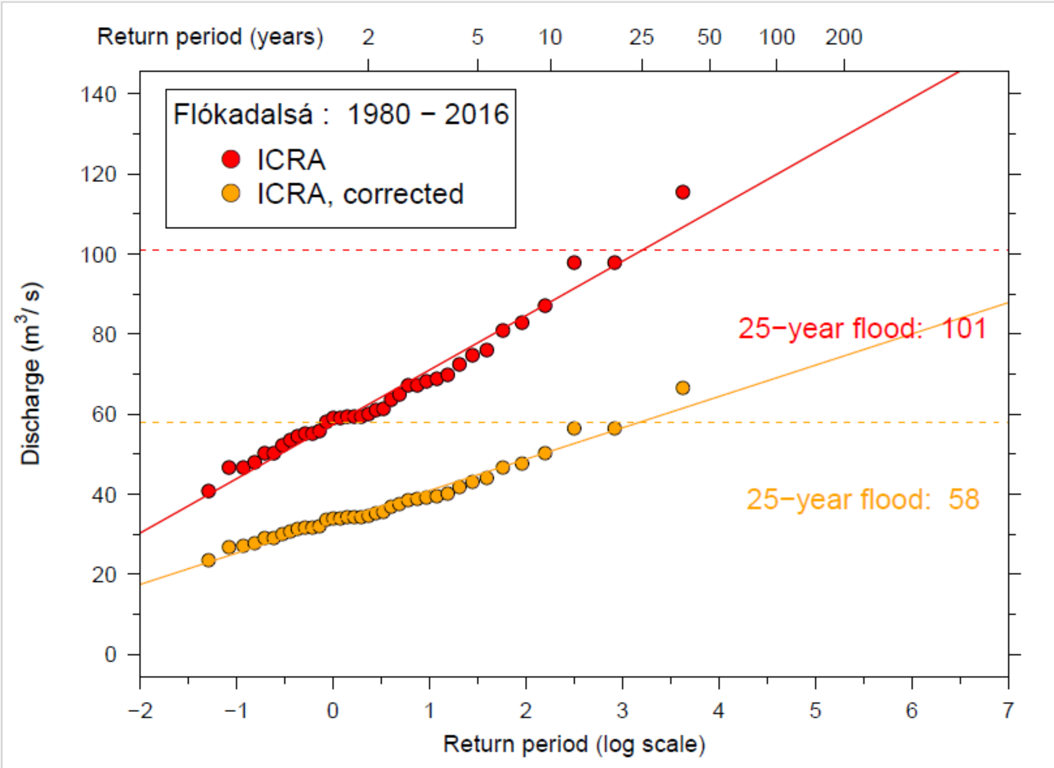
Return-period	Return levels *(m^3 s^{-1})*		
	Observations	**ICRA**	**ICRA, corrected**
10 years	409	377	217
25 years	533	439	253
50 years	625	485	279
100 years	717	530	305
200 years	808	576	332
500 years	928	636	366

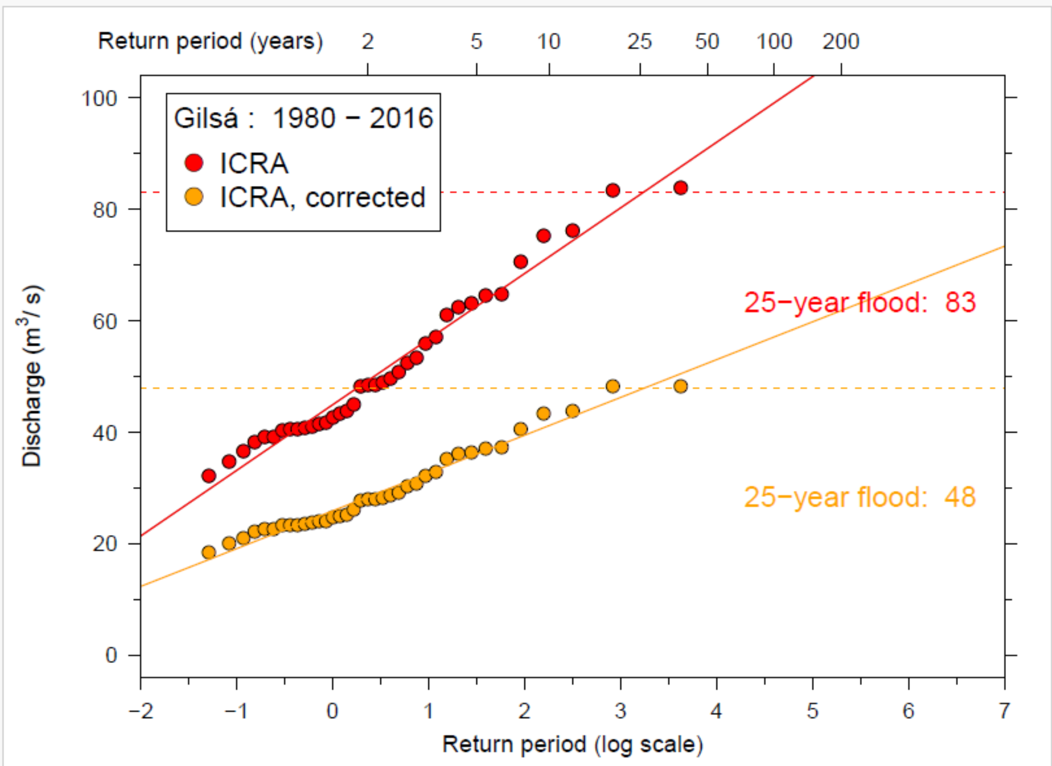
Appendix II. Flood estimates for the ungauged catchments

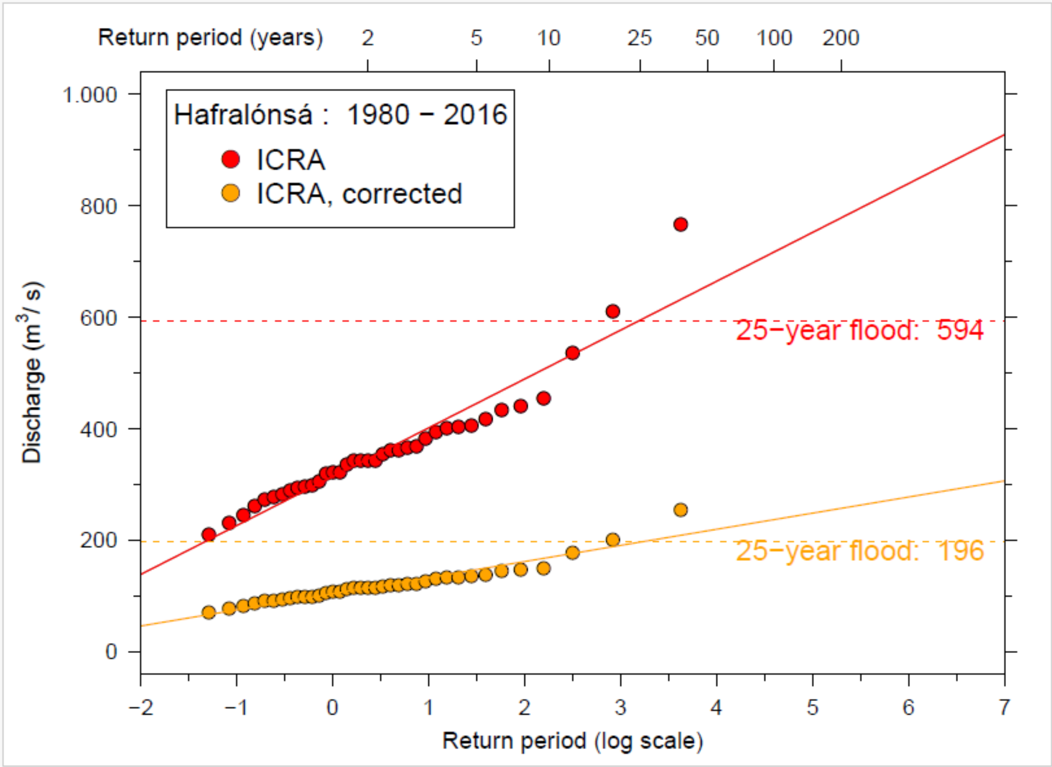
Return level plot for all the ungauged rivers, based on simulations of daily discharge before (red) and after correction (orange). Dashed-lines show the 25-year return level for the different datasets.

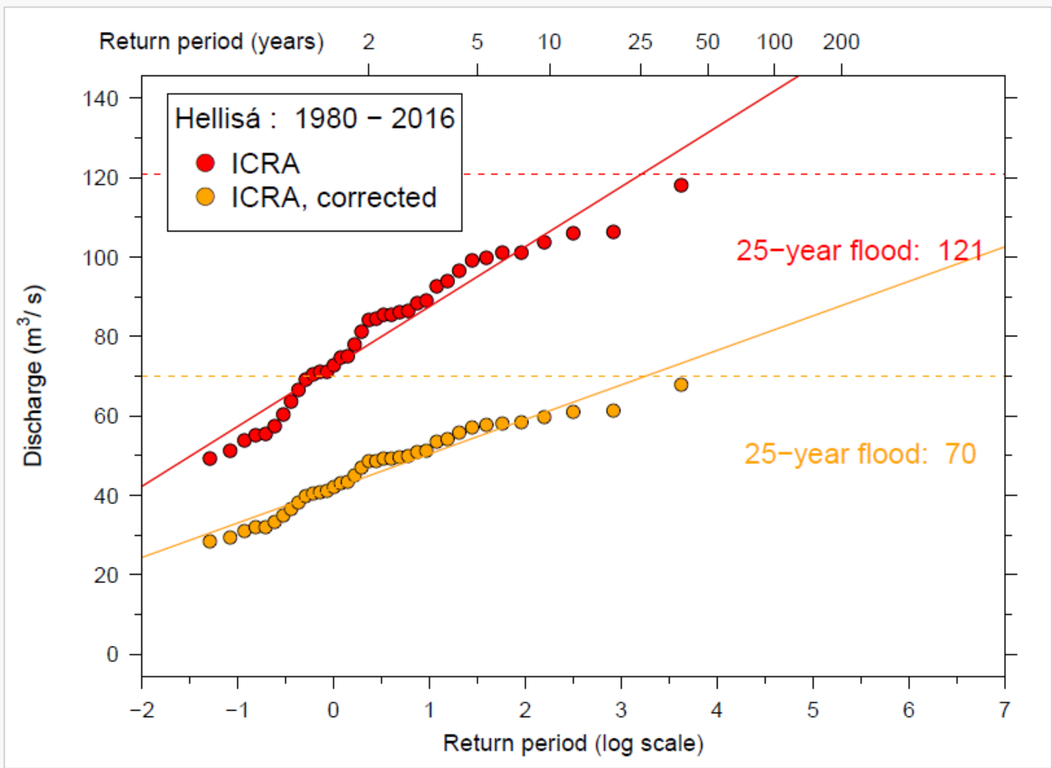


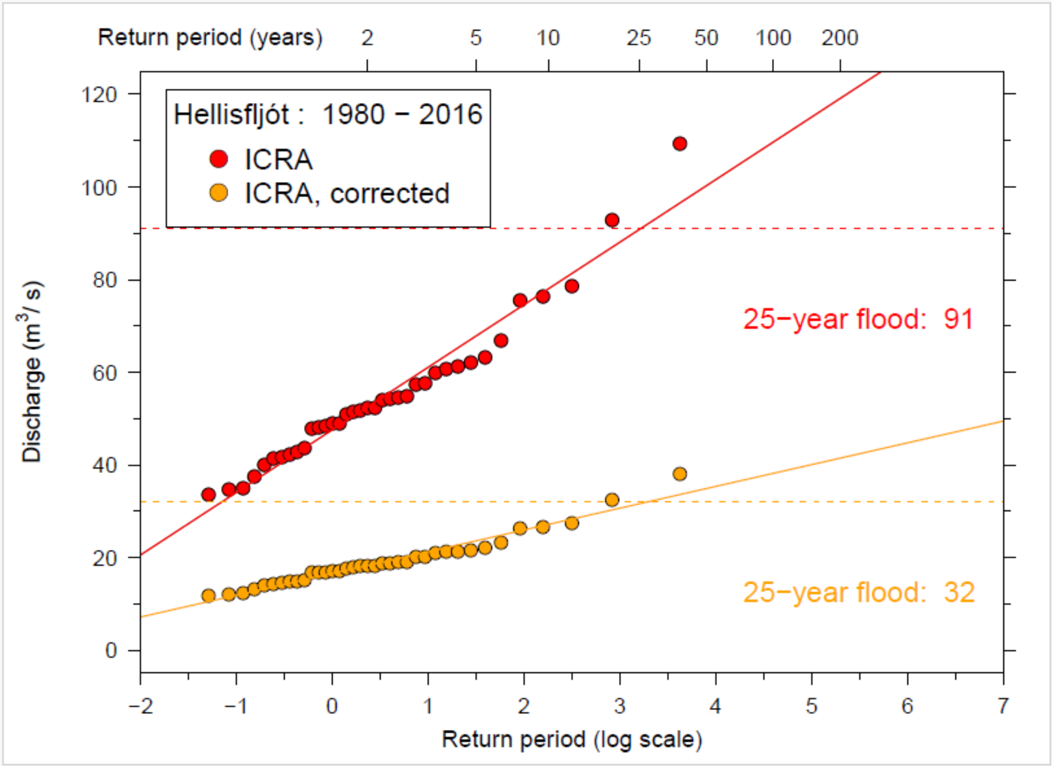


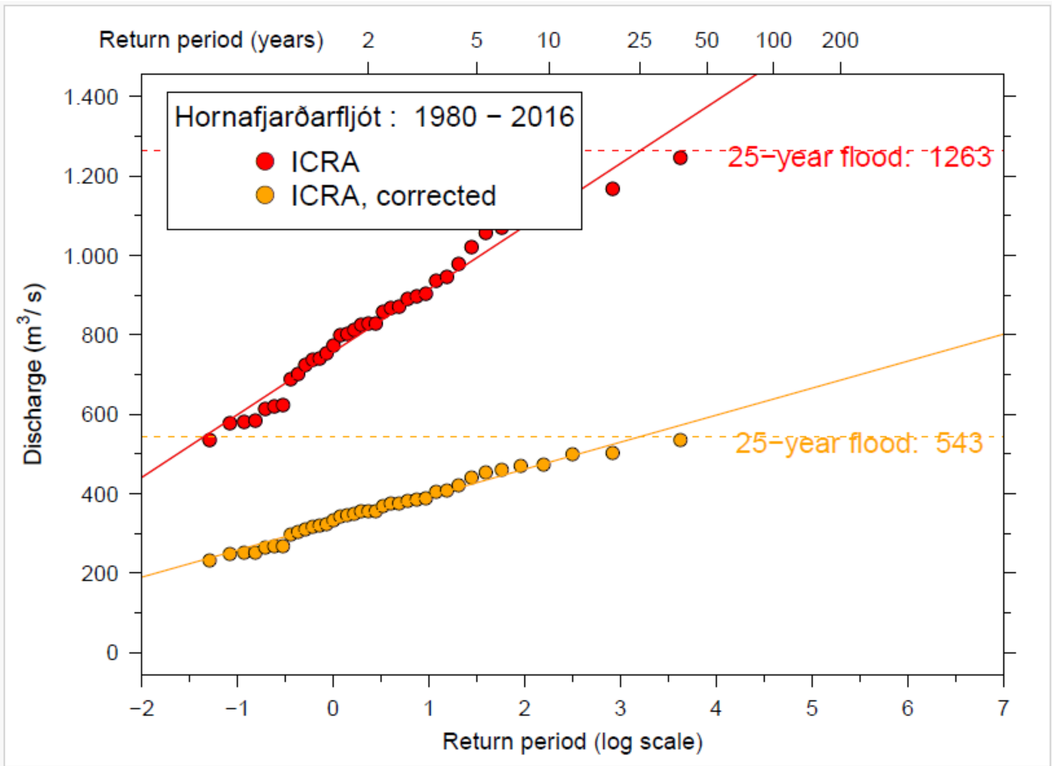

Return period (years)
2
5
10
25
50
100
200
Flókadalsá : 1980 − 2016
ICRA
ICRA, corrected
Discharge (m³/ s)
140
120
100
80
60
40
20
0
25−year flood: 101
25−year flood: 58
−2
−1
0
1
2
3
4
5
6
7
Return period (log scale)

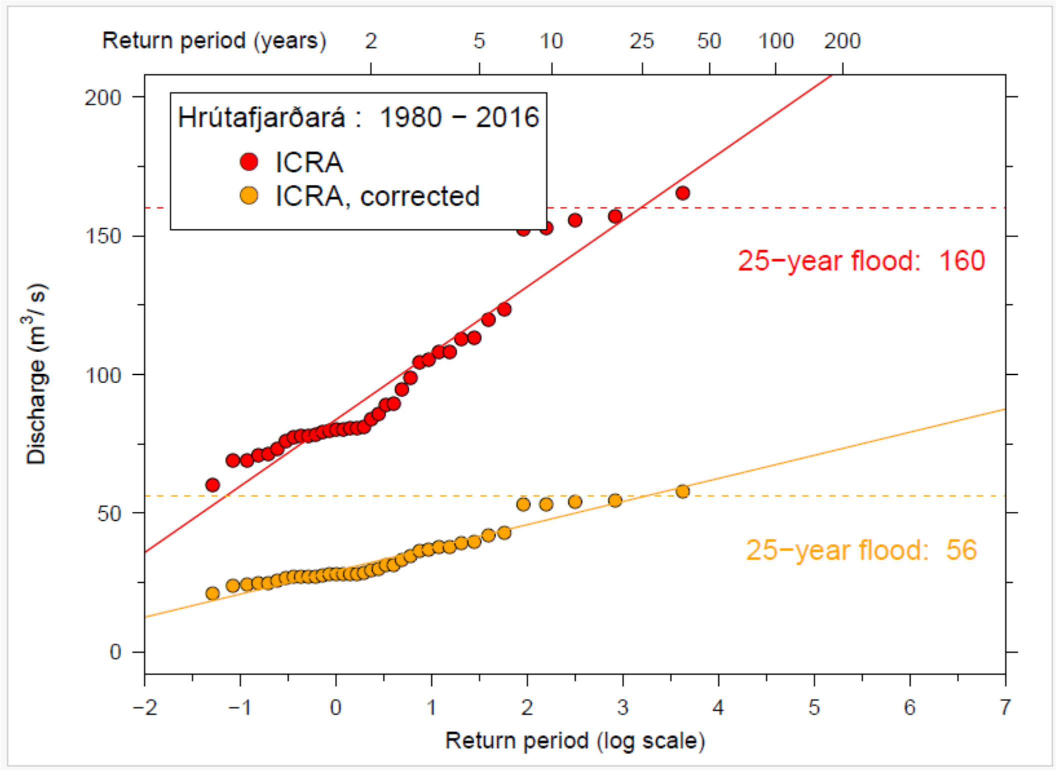

Return period (years)
2
5
10
25
50
100
200
Gilsá : 1980 − 2016
ICRA
ICRA, corrected
Discharge (m³/ s)
100
80
60
40
20
0
25−year flood: 83
25−year flood: 48
−2
−1
0
1
2
3
4
5
6
7
Return period (log scale)

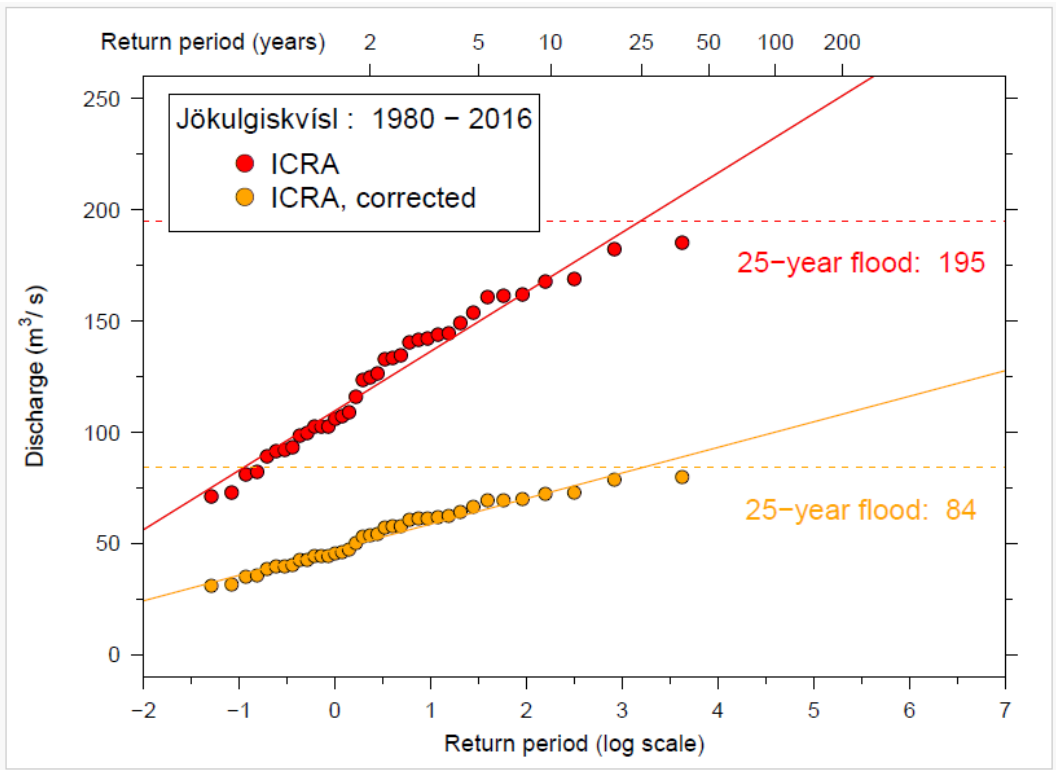

Return period (years)
2
5
10
25
50
100
200
1.000
800
600
400
200
0
Discharge (m3/ s)
Hafralónsá : 1980 − 2016
ICRA
ICRA, corrected
25−year flood: 594
25−year flood: 196
−2
−1
0
1
2
3
4
5
6
7
Return period (log scale)

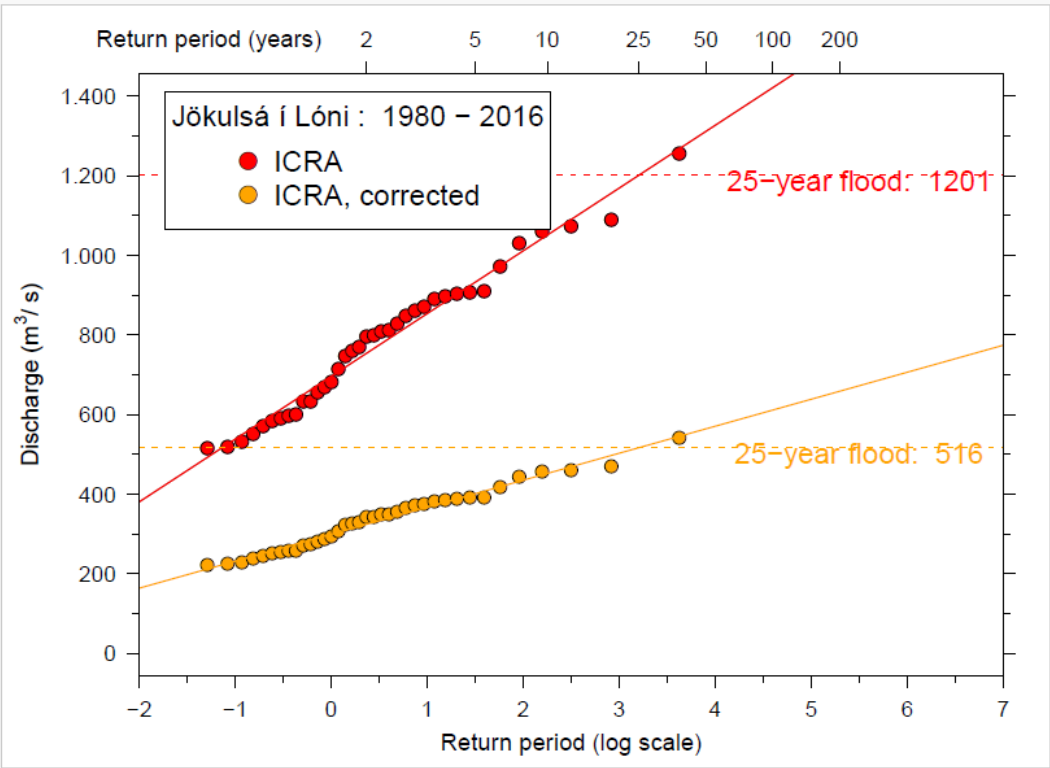

Return period (years)
2
5
10
25
50
100
200
140
120
100
80
60
40
20
0
Discharge (m3/ s)
Hellisá : 1980 − 2016
ICRA
ICRA, corrected
25−year flood: 121
25−year flood: 70
−2
−1
0
1
2
3
4
5
6
7
Return period (log scale)

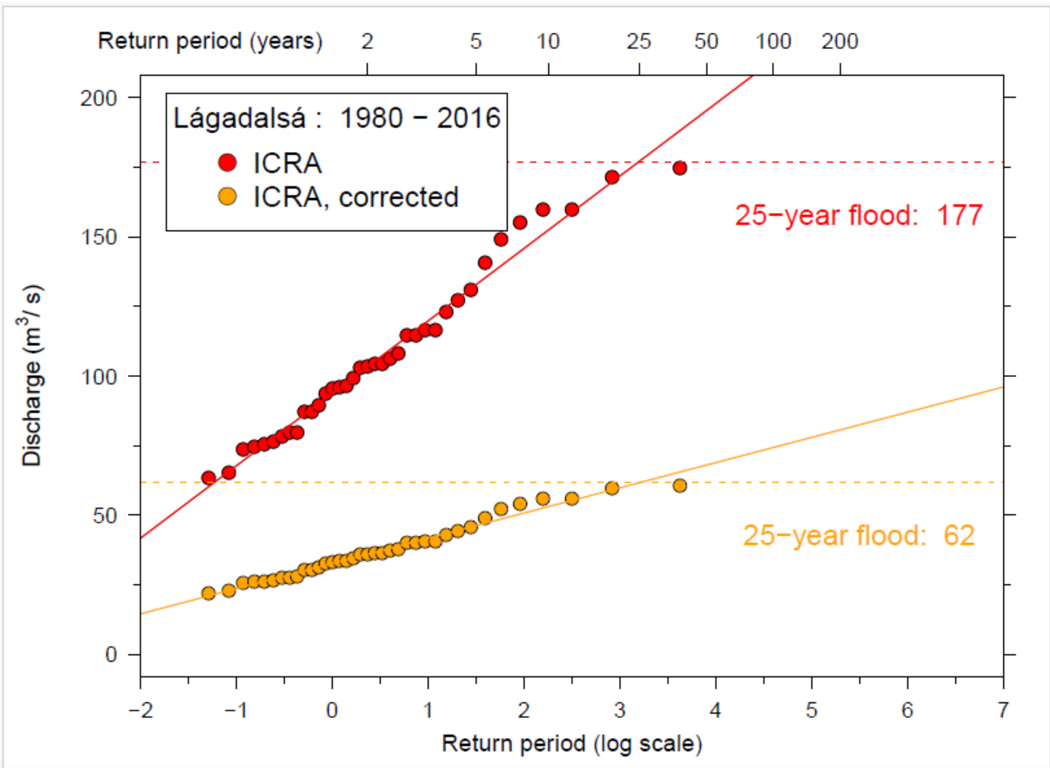

Return period (years)
2
5
10
25
50
100
200
120
100
80
60
40
20
0
Discharge (m³/ s)
Hellisfljót : 1980 − 2016
ICRA
ICRA, corrected
25−year flood: 91
25−year flood: 32
−2
−1
0
1
2
3
4
5
6
7
Return period (log scale)

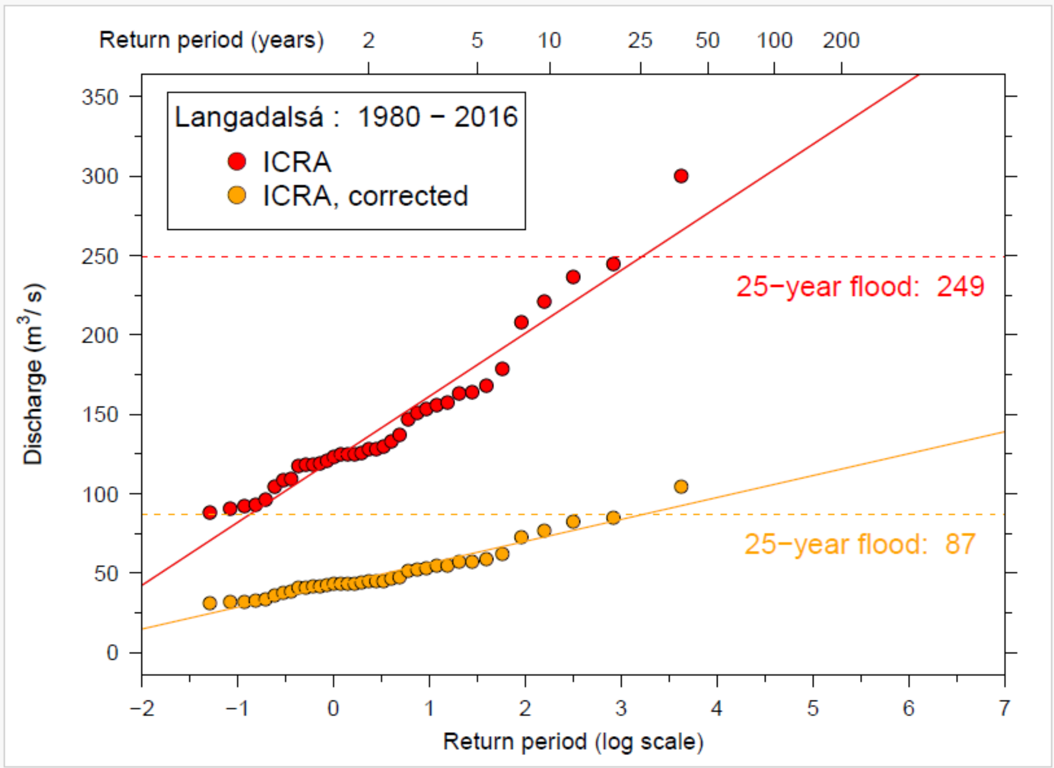

Return period (years)
2
5
10
25
50
100
200
1.400
1.200
1.000
800
600
400
200
0
Discharge (m³/ s)
Hornafjarðarfljót : 1980 − 2016
ICRA
ICRA, corrected
25−year flood: 1263
25−year flood: 543
−2
−1
0
1
2
3
4
5
6
7
Return period (log scale)


Return period (years)
2
5
10
25
50
100
200
Hrútafjarðará : 1980 − 2016
ICRA
ICRA, corrected
25−year flood: 160
25−year flood: 56
Discharge (m³/ s)
0
50
100
150
200
−2
−1
0
1
2
3
4
5
6
7
Return period (log scale)

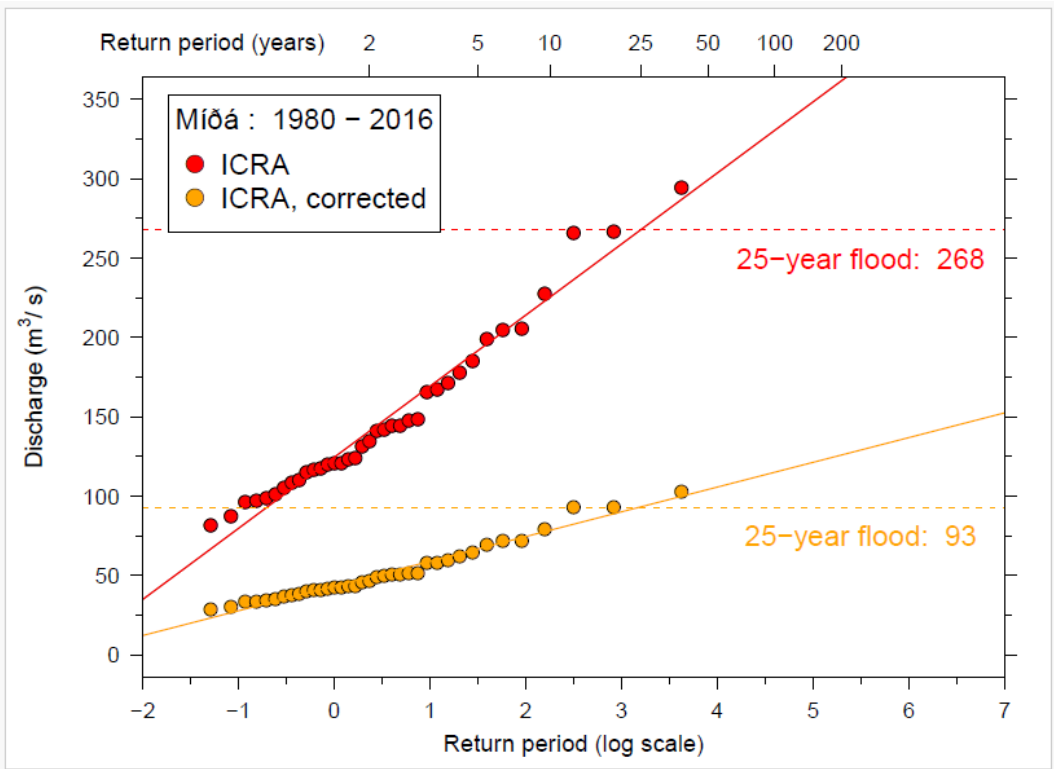

Return period (years)
2
5
10
25
50
100
200
Jökulgiskvísl : 1980 − 2016
ICRA
ICRA, corrected
25−year flood: 195
25−year flood: 84
Discharge (m³/ s)
0
50
100
150
200
250
−2
−1
0
1
2
3
4
5
6
7
Return period (log scale)


Return period (years)
2
5
10
25
50
100
200
1.400
1.200
1.000
800
600
400
200
0
Discharge (m³/ s)
Jökulsá í Lóni : 1980 − 2016
ICRA
ICRA, corrected
25−year flood: 1201
25−year flood: 516
−2
−1
0
1
2
3
4
5
6
7
Return period (log scale)

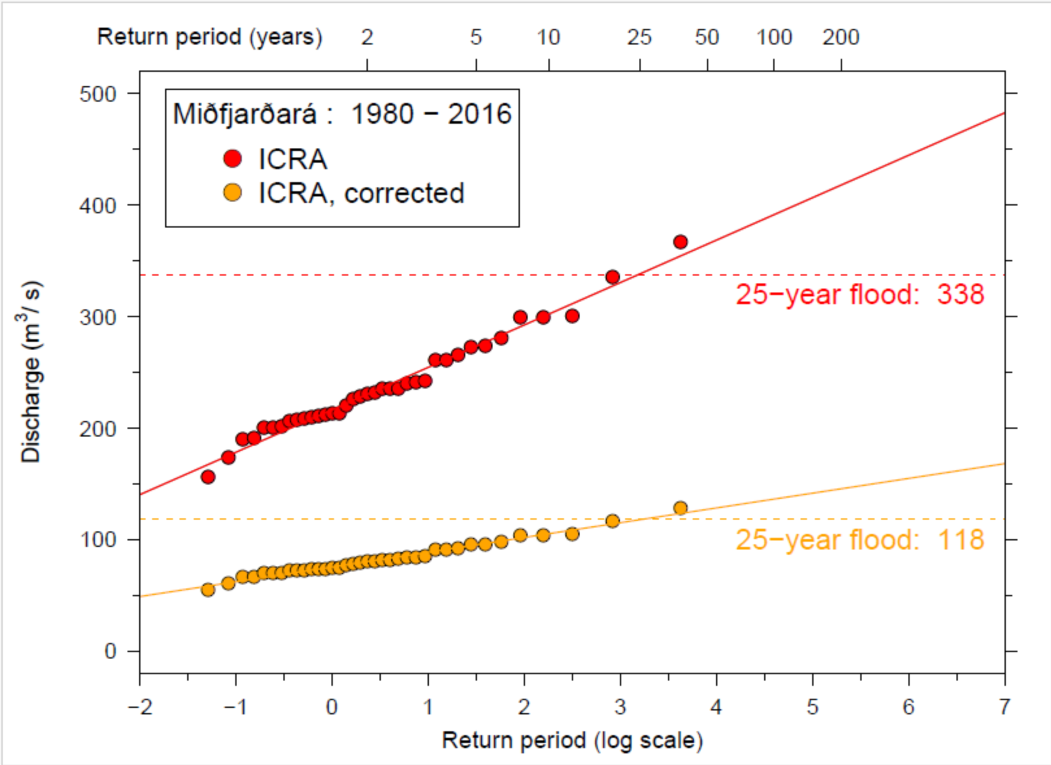

Return period (years)
2
5
10
25
50
100
200
200
150
100
50
0
Discharge (m³/ s)
Lágadalsá : 1980 − 2016
ICRA
ICRA, corrected
25−year flood: 177
25−year flood: 62
−2
−1
0
1
2
3
4
5
6
7
Return period (log scale)

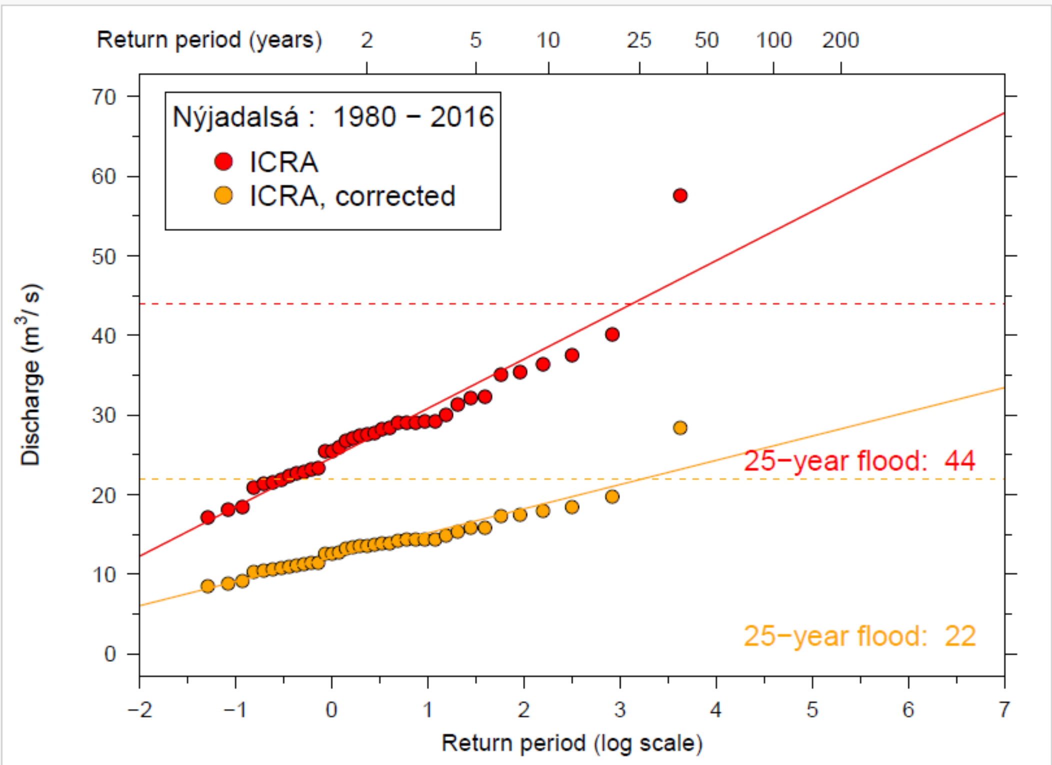


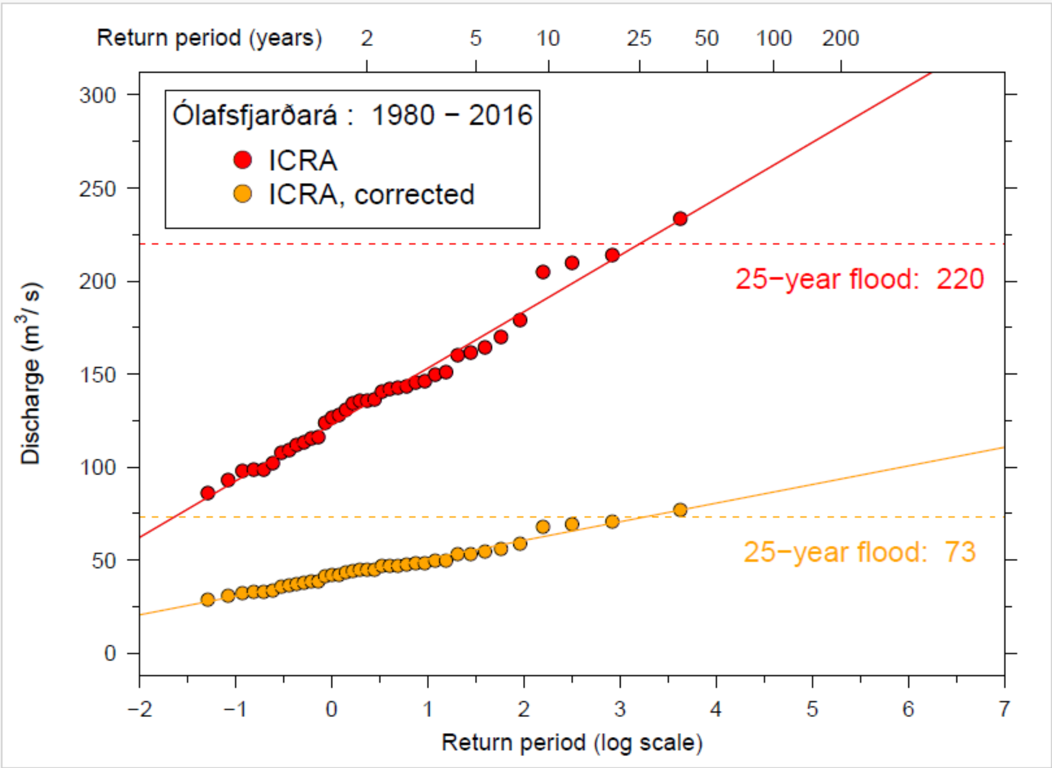
Return period (years)
2
5
10
25
50
100
200
Langadalsá : 1980 − 2016
ICRA
ICRA, corrected
25−year flood: 249
25−year flood: 87
Discharge (m³/ s)
350
300
250
200
150
100
50
0
−2
−1
0
1
2
3
4
5
6
7
Return period (log scale)



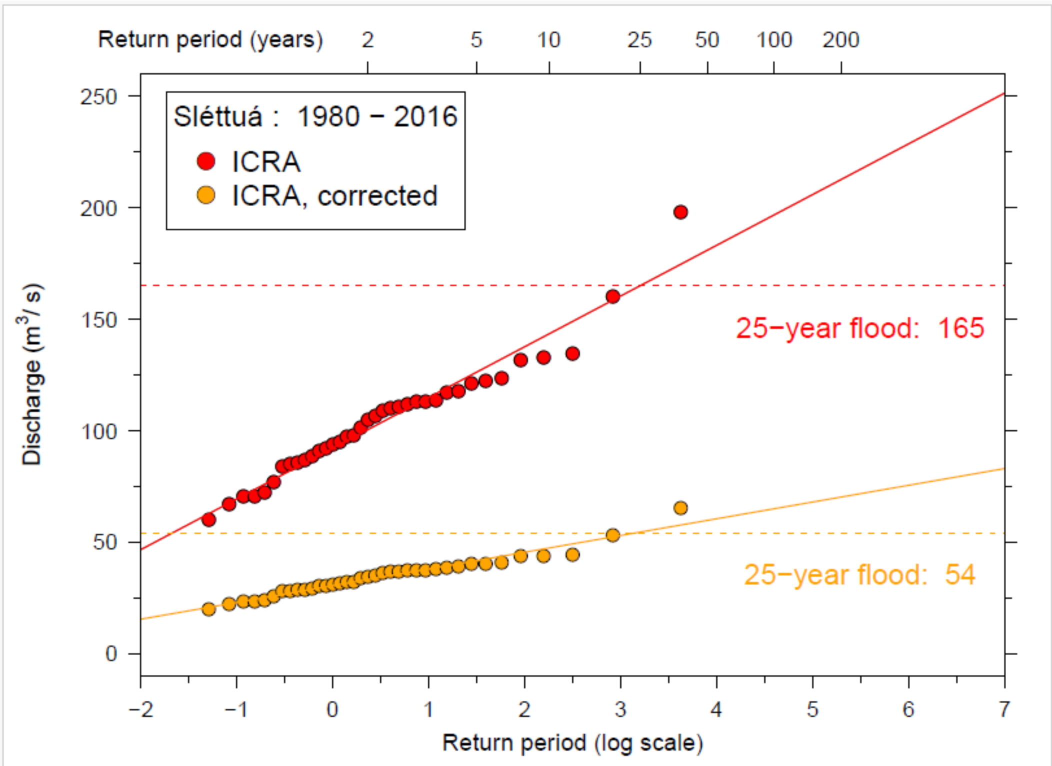
Return period (years)
2
5
10
25
50
100
200
Míðá : 1980 − 2016
ICRA
ICRA, corrected
25−year flood: 268
25−year flood: 93
Discharge (m³/ s)
350
300
250
200
150
100
50
0
−2
−1
0
1
2
3
4
5
6
7
Return period (log scale)


Return period (years)
2
5
10
25
50
100
200
Miðfjarðará : 1980 − 2016
ICRA
ICRA, corrected
25−year flood: 338
25−year flood: 118
Discharge (m3/ s)
Return period (log scale)

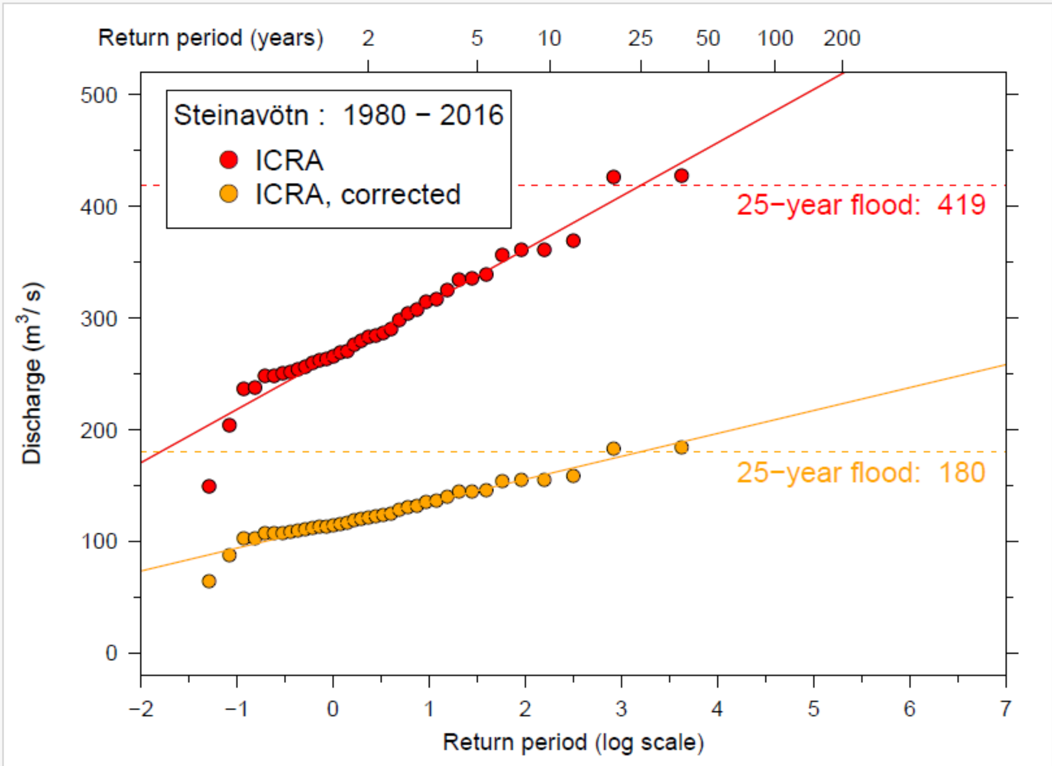

Return period (years)
2
5
10
25
50
100
200
Nýjadalsá : 1980 − 2016
ICRA
ICRA, corrected
25−year flood: 44
25−year flood: 22
Discharge (m3/ s)
Return period (log scale)

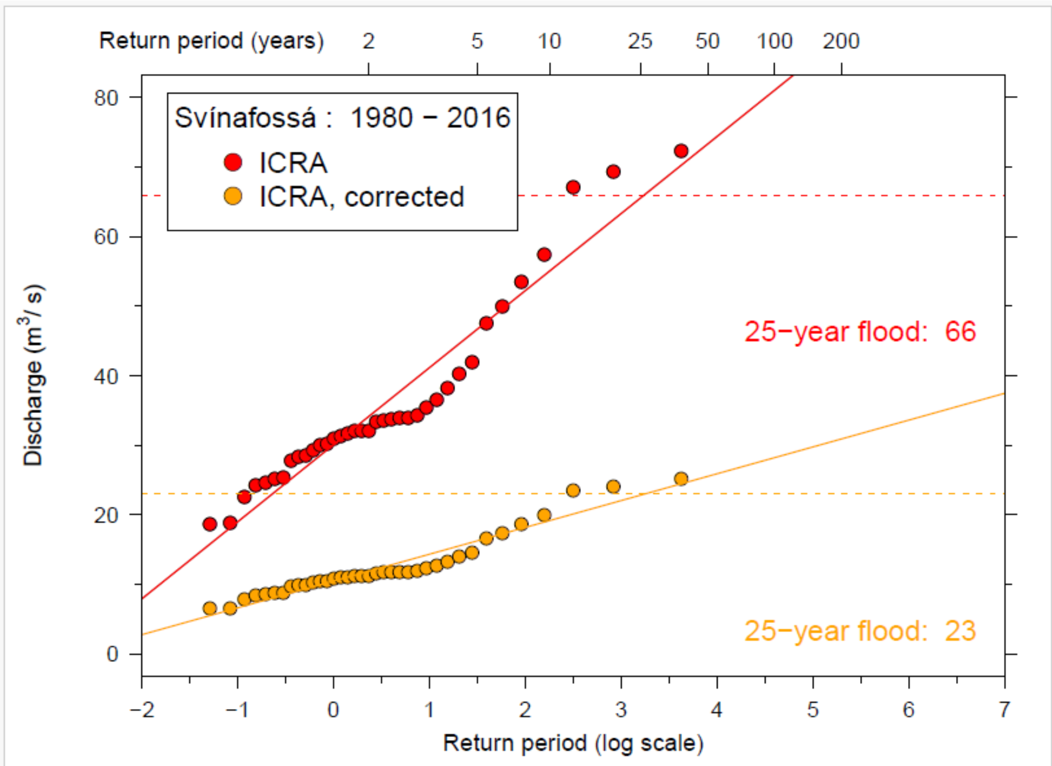


Return period (years)
2
5
10
25
50
100
200
Ólafsfjarðará : 1980 – 2016
ICRA
ICRA, corrected
25–year flood: 220
25–year flood: 73
Discharge (m³/ s)
300
250
200
150
100
50
0
–2
–1
0
1
2
3
4
5
6
7
Return period (log scale)



Return period (years)
2
5
10
25
50
100
200
Sléttuá : 1980 – 2016
ICRA
ICRA, corrected
25–year flood: 165
25–year flood: 54
Discharge (m³/ s)
250
200
150
100
50
0
–2
–1
0
1
2
3
4
5
6
7
Return period (log scale)


Return period (years)
2
5
10
25
50
100
200
Steinavötn : 1980 − 2016
ICRA
ICRA, corrected
25−year flood: 419
25−year flood: 180
Discharge (m³/ s)
0
100
200
300
400
500
−2
−1
0
1
2
3
4
5
6
7
Return period (log scale)


Return period (years)
2
5
10
25
50
100
200
Svínafossá : 1980 − 2016
ICRA
ICRA, corrected
25−year flood: 66
25−year flood: 23
Discharge (m³/ s)
0
20
40
60
80
−2
−1
0
1
2
3
4
5
6
7
Return period (log scale)

Return levels (m3 s-1) for all ungauged rivers. Results are based on the simulated discharge from the ICRA runoff before (top table) and after (bottom table) correction.

ICRA discharge – before correction

	10-year	25-year	50-year	100-year	200-year	500-year
Berufjarðará	71	83	91	100	108	120
Fjarðará	241	271	296	319	342	372
Flókadalsá	88	101	110	120	129	142
Gilsá	71	83	91	99	107	118
Hafralónsá	511	594	656	717	779	859
Hellisá	106	121	131	142	152	166
Hellisfljót	78	91	100	110	119	132
Hornafjarðarfljót	1113	1263	1375	1485	1595	1740
Hrútafjarðará	138	160	177	194	211	233
Jökulgilskvísl	170	195	214	233	251	276
Jökulsá í Lóni	1051	1201	1312	1422	1532	1677
Lágadalsá	152	177	195	214	232	256
Langadalsá	211	249	277	304	332	368
Miðá	225	268	299	331	362	403
Miðfjarðará	302	338	365	392	418	453
Nýjadalsá	39	44	49	53	57	63
Ólafsfjarðará	191	220	241	262	284	311
Sléttuá	143	165	181	197	213	234
Steinavötn	374	419	452	486	519	563
Svínafossá	55	66	73	81	89	99

ICRA discharge – after correction

	10-year	25-year	50-year	100-year	200-year	500-year
Berufjarðará	24	27	30	33	36	39
Fjarðará	79	90	98	105	113	123
Flókadalsá	51	58	64	69	75	82
Gilsá	41	48	52	57	62	68
Hafralónsá	169	196	217	237	257	284
Hellisá	61	70	76	82	88	96
Hellisfljót	27	32	35	38	41	46
Hornafjarðarfljót	479	543	591	639	686	748
Hrútafjarðará	48	56	62	68	73	81
Jökulgilskvísl	73	84	92	100	108	119
Jökulsá í Lóni	452	516	564	611	659	721
Lágadalsá	53	62	68	74	81	89
Langadalsá	73	87	96	106	116	128
Miðá	78	93	104	115	126	140
Miðfjarðará	105	118	127	136	146	158
Nýjadalsá	19	22	24	26	28	31
Ólafsfjarðará	63	73	80	87	94	103
Sléttuá	47	54	60	65	70	77
Steinavötn	161	180	195	209	223	242
Svínafossá	19	23	26	28	31	34