ReFH2 Science Report

Calibration and Evaluation of the ReFH2.3-FEH22 Design Event Model

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For and on behalf of Wallingford HydroSolutions Ltd.

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Contents

1 Introduction

The Flood Estimation Handbook (FEH) rainfall-runoff method has continuously been improved, with the latest updates implemented in the ReFH2 software. The original ReFH1 method was published in 2005 by Kjeldsen et al.[1] as a replacement for the FSR/FEH rainfall-runoff method[2]. ReFH1 was developed for use in estimates only up to 150 years using the (now legacy) FEH99 rainfall DDF (depth duration frequency) model and was found to perform poorly for high permeability catchments. Despite the known issues, there was no public funding available to further develop the methods and tools at that time. The fully published ReFH1 method has been continuously improved by WHS to address gaps in the method. ReFH2 was first released in 2015, with the latest demonstrably improved 'water balance' ReFH2.3 model released in 2019[3].

The 2019 ReFH2.3 model used the FEH13 rainfall DDF model[4] for generating design rainfall events (ReFH2.3-FEH13). UKCEH developed the FEH22 rainfall DDF model in 2022. The FEH22 model benefits from a much greater quantity of input data, both spatially and temporally, than the FEH13 model. FEH22 is therefore expected to offer improvements in modelled design depths, particularly in areas which previously had low density of rainfall gauges used, for example in Northwest Scotland. Details on the FEH22 model are provided in Vesuviano, 2022[5], Vesuviano & Stewart, 2021[6], and Vesuviano et al., 2021[7].

This science report presents the recalibration of the 'water balance' ReFH2.3 model using the FEH22 rainfall DDF model (ReFH2.3-FEH22). No changes have been made to the ReFH2.3 model structure. The ReFH2.3 model is calibrated via the estimation of C_{ini} to the observed 2 year peak flow, often referred to as the median flood or QMED, based on the gauged AMAX data in the NRFA Peak Flow v11 dataset[8]. This is a relatively low return period and is known generally to a high certainty. The largest differences between the FEH13 and FEH22 DDF rainfall models tend to be for shorter storm durations and longer return period events. As ReFH2 is calibrated for catchment recommended storm durations and the 2 year return period events, significant differences between the ReFH2.3-FEH13 and ReFH2.3-FEH22 calibrations were not expected. Differences at the longer return periods are attributed to differences (improvements) in the DDF rainfall model.

Section 2 first details the NRFA Peak Flow dataset gauges used in the ReFH2.3-FEH22 calibration. Section 3 then presents the calibration method and the measures of fit used to compare model performance. The model results for the ReFH2.3-FEH22 calibration, as well as the ReFH2.3-FEH13 calibration and ungauged FEH statistical method, are presented in Section 4 for a wide range of return periods (2, 100, 200, 1000 and 10,000 years). The FEH statistical method was first developed as part of the FEH Handbook[9] and was revisited in 2008 by Kjeldsen[10], with several subsequent updates (for example, inclusion of urbanisation and local data adjustments to QMED). Section 4 also includes ReFH2.3-FEH22 calibration results by particular catchment types and regionally by country, as well as a direct comparison between the FEH22 and FEH13 rainfall and peak flows.

[1] Kjeldsen, T. R., Stewart, E. J., Packman, J. C., Folwell, S. S & Bayliss, A. C., 2005. Revitalisation of the FSR/FEH rainfall-runoff method. Defra R&D Technical Report FD1913/TR.

[2] Houghton-Carr, H., 1999. Restatement and application of the Flood Studies Report rainfall-runoff method. Flood Estimation Handbook Volume 4.

[3] Wallingford HydroSolutions 2019. ReFH2 Science Report: Closing a Water Balance. Available via https://refhdocs.hydrosolutions.co.uk/References/

[4] Stewart, E. J., Jones, D. A., Svensson, C., Morris, D. D., Dempsey, P.,Dent. J. E., Collier, C. G., Anderson, C. W. 2013. Reservoir Safety – Long return period rainfall. Joint Defra/EA R&D Technical Report WS 194/2/39/T (two volumes).

[5] Vesuviano G. 2022. The FEH22 rainfall depth-duration-frequency (DDF) model. UK Centre for Ecology & Hydrology, Wallingford. Available via https://fehwebdocs.hydrosolutions.co.uk/docs/DDF-Science/FEH22/.

[6] Vesuviano G, Stewart E. 2021. Recalibration of FEH13 model for Cumbria. UK Centre for Ecology & Hydrology, Wallingford. NORA 529809

[7] Vesuviano G, Stewart E, Spencer P, Miller J D. 2021. The effect of depth-duration-frequency model recalibration on rainfall return period estimates. Journal of Flood Risk Management 14(2), e12703. 10.1111/jfr3.12703

[8] NRFA Peak Flow Dataset. Available via https://nrfa.ceh.ac.uk/peak-flow-dataset

[9] Robson, A., Reed, D. 1999. Statistical procedures for flood frequency estimation. Flood Estimation Handbook Volume 3.

[10] Kjeldsen, T.R., Jones, D. A., and Bayliss, A. C. 2008. Improving the FEH statistical procedures for flood frequency estimation, Joint Defra / Environment Agency Flood and Coastal Erosion Risk Management R&D Programme, Science Report: SC050050.

2 Dataset

The NRFA Peak Flow Version 11 dataset, released in September 2022, contains the following data for 939 gauging stations:

- Catchment descriptors (such as Area, SAAR)
- AMAX data – annual maxima
- POT data – peaks over threshold data

The following criteria were used to identify the gauges for use within the ReFH2.3-FEH22 calibration:

- Classified as being either suitable for the estimation of QMED or Pooling (depending on the return period that is being estimated);
- with more than 14 years of data (recommended for the calculation of QMED[11]);
- 'rural' (URBEXT2000<0.15 identifying catchments in which the urban impact on peak flows is indiscernible); and
- as the impact of flood attenuation by reservoirs and lakes is not included within the ReFH model structure, catchments with FARL<0.9 were also removed from the dataset.

This criteria is consistent with the criteria used for ReFH2.3-FEH13 calibration dataset[12].

26 additional gauges were removed for the ReFH2.3-FEH22 calibration for one or more of the following reasons:

- The topographic area was cited by the NRFA as being very different from the contributing catchment. It would not be possible to obtain a satisfactory water balance within these catchments for this reason.
- The ratio of the estimated QMED to the QMED based on AMAX was out by a factor of 3 within both the statistical ungauged method and the rainfall-runoff method, and in addition the mean flow estimation within the Qube[13] water resources software was out by a factor of 1.3. This is an additional indication that a satisfactory water balance would not be possible in these catchments.
- The ReFH model was unable to close the water balance during the calibration except through extreme Cini or BR parameter estimates.
- Gauges on the main River Spey. SEPA recommended these were removed as these are heavily influenced by external activities.

25 gauges were previously removed for ReFH2.3-FEH13 calibration for the above reasons, of which 22 were in the list of potential gauges to be used in the ReFH2.3-FEH22 calibration. 4 additional gauges were removed.

The ReFH2.3-FEH22 calibration dataset therefore consisted of 710 gauges for QMED (2 year return period) and 439 gauges for longer return periods. Table 1 summarises the criteria used for the calibration dataset, and the location of these gauges are presented in Figure 1 and Figure 2 for Great Britain and Northern Ireland. For comparison, the 2019 ReFH2.3-FEH13 calibration used 655 gauges for QMED and 431 gauges for longer return periods.

[11] Robson A & Reed D, 1999. Statistical procedures for flood frequency estimation, Flood Estimation Handbook Volume 3.
[12] Wallingford HydroSolutions 2019. ReFH2 Science Report: Closing a Water Balance. Available via https://refhdocs.hydrosolutions.co.uk/References/
[13] https://www.hydrosolutions.co.uk/software/qube/

Table 1. Criteria for selection of calibration and assessment dataset.

Purpose	NRFA PF Dataset	'Suitable for QMED' and/or 'Suitable for Pooling'	Length of record	URBEXT2000	FARL	Additional Stations Removed?
Gauges used for calibration of ReFH2.3-FEH22.	V11	Y	>=14	<=0.15	>=0.9	Y
Gauges in the assessment dataset for comparison of the peak flow estimates using ReFH2.3-FEH22, ReFH2.3-FEH13, the ungauged statistical method and the FEH statistical Enhanced Single Site (ESS) method.	V11	Y	>=14	<=0.15	>=0.9	Y

Figure 1. Great Britain gauges in the ReFH2.3-FEH22 calibration dataset for QMED (left) and longer return periods (right).

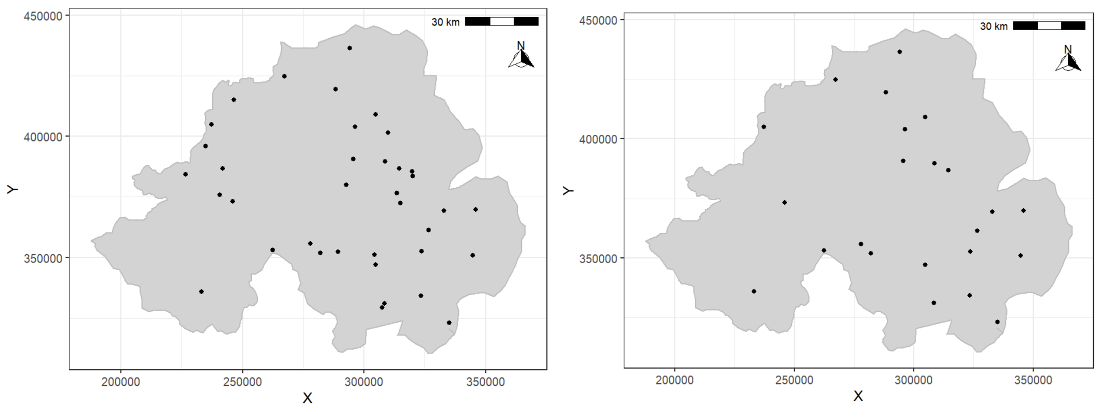

Figure 2. Northern Ireland gauges in the ReFH2.3-FEH22 calibration dataset for QMED (left) and longer return periods (right).

3 Method

3.1 Calibration Method

The method for calibration for ReFH2.3-FEH22 is consistent with the ReFH2.3-FEH13 calibration, presented in the 'Closing a Water Balance' ReFH2 Science Report[14]. The following process was applied to each catchment:

- The 2 year return period design storm was estimated using the FEH22 DDF model for the recommended duration for that catchment.
- The value of C_{ini}/C_{max} (range 0 - 1) required to calibrate the ReFH2.3 estimate of the QMED to the value of QMED estimated directly from gauged AMAX data was identified.

A relationship between the 'optimal' C_{ini}/C_{max} and the BFIHOST19 was then established, as presented in Equation 1 and Figure 3.

Equation 1.

$$ln\left[\frac{C_{ini}}{C_{max}}\right] = a\,.\,BFIHOST19 + b$$

The summer C_{ini} is estimated as a function of the winter C_{ini} using the procedure detailed in Environment Agency Project SC090031[15]. The form of the equation is presented in Equation 2.

Equation 2.

$$\frac{C_{iniS}}{C_{iniW}} = a\left(\frac{BFIHOST19}{SAAR}\right)^{0.5} + b$$

[14] Wallingford HydroSolutions. 2019. ReFH2 Science Report: Closing a Water Balance. Available via https://refhdocs.hydrosolutions.co.uk/References/

[15] Environment Agency. Estimating flood peaks and hydrographs for small catchments: Phase 2. Project: SC090031.

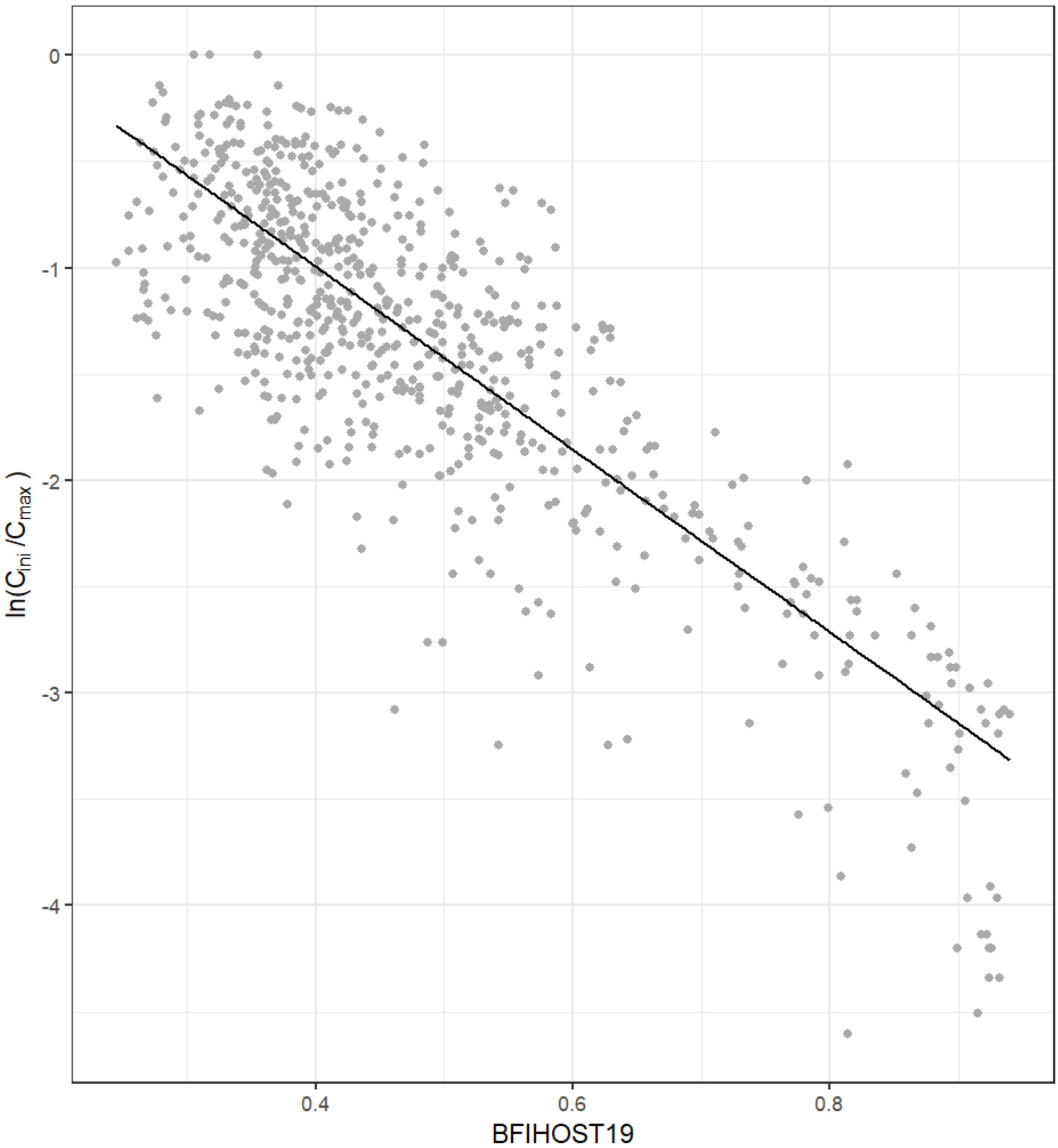

Figure 3. The relationship between the 'optimal' C_{ini}/C_{max} and the BFIHOST19.

3.2 Measures of fit

The gauging station assessment dataset is the same dataset that was used for the ReFH2.3-FEH22 calibration described in Section 2 and Table 1. Measures of fit have been calculated for the assessment gauging stations for the QMED (2 year return period) and longer return periods (100, 200, 1000 and 10,000 years) for the ReFH2.3-FEH22 calibration, as well as ReFH2.3-FEH13 and ungauged FEH statistical method. Details on the model run configurations used to derive the measures of fit for the modelled peak flow estimates are provide in Table 2 for ReFH2.3 and Table 3 for the statistical methods.

These three methods are compared against the best estimate of the observed peak flows. The observed QMED can be estimated directly from gauged AMAX data, thus has a relatively low uncertainty. In contrast, the peak flow for larger return periods is unknown, therefore the 'observed' peak flows are estimated using the FEH statistical Enhanced Single Site (ESS) method. These estimates have a much higher uncertainty but represent the best estimate as the analysis gives greatest weight to the at site AMAX series. At short return periods these might be regarded as 'observed', whilst at longer return periods these estimates are statistical method estimates, where the estimate is derived as the product of a pooled growth curve estimate with additional weight given to the at site data within the pooled growth curve combined with a local 'observed' estimate of QMED.

Table 3 provides the model run configurations for the statistical methods. For QMED, the measures of fit are calculated using gauges which are within the 'Suitable for QMED' group. For longer return periods (100, 200, 1000 and 10,000 years) a subset of this dataset was used, with gauges flagged as 'Suitable for Pooling' selected.

It should be noted that the ESS method uses the same pooling group method utilised for the ungauged peak flows, but simply includes the at-site gauged data with a higher weighting. The methods and assumptions are therefore similar for the statistical ungauged and ESS peak flow estimates and these are not independent of one another.

For the statistical methods, catchments under 40km^2 used the small catchment pooling group distance measures. Only gauges with an URBEXT2000 less than 0.03 were selected for use in the pooling group and the L-CV and L-Skew were deurbanised.

The rural peak flows have been estimated using the statistical ungauged (catchment descriptor and pooled) and ReFH2.3 models, which are compared against the observed peak flows for rural catchments.

Table 2. Model run configuration for ReFH2.3 peak flow estimates

Purpose	NRFA PF Dataset	DDF Rainfall Dataset	Method	Results reported (Urban / Rural)
ReFH2.3-FEH13 peak flow estimates	v11	FEH13	ReFH2.3 model structure with FEH13 calibration.	Rural
ReFH2.3-FEH22 peak flow estimates	v11	FEH22	ReFH2.3 model structure with FEH22 calibration.	Rural

Table 3. Model run configuration for statistical peak flow estimates

Purpose	Method		Criteria applied in statistical peak flow analysis						Results reported (Urban / Rural)
	QMED	Return periods > 2	NRFA PF Dataset	'Suitable for QMED' and/or 'Suitable for Pooling'	Length of record	URBEXT2000	FARL	Additional Stations Removed?	
ESS statistical peak flow estimates	Median of AMAX (observed, urban)	ESS Method. Pooling group with more than 500 years of records. Deurbanised L-moments in pooling group. Small catchments method used as appropriate.	v11	Y	>5	<=0.03	>=0.9*	N	Urban
Ungauged statistical peak flow estimates	Catchment descriptor rural equation	Pooling group with more than 500 years of records. Deurbanised L-moments in pooling group. Small catchments method used as appropriate.	v11	Y	>5	<=0.03	>=0.9*	N	Rural

* FARL criteria appropriate as the assessment dataset only has catchments >0.9.

The measures of fit used to compare model performance are the BIAS, FSE and RMSE. All are based on the ln values to remove the influence of scale. The BIAS provides an indication of whether, in general, the model over or underestimates the peak flows and is provided as the BIAS (used in the figures illustrating BIAS for individual gauges) and the BIAS % which provides the overall BIAS as a percentage for the assessment dataset. The FSE and RMSE provide an indication of the 'scatter' of model peak flow estimates compared with the 'observed' values. Note that at QMED the 'obs' values are the peak flows estimated using the AMAX data, which is a robust estimate of the QMED for long records. At longer return periods the 'obs' results are represented by the ESS modelled peak flow estimates, which while maximising use of at site data, are not strictly 'observed' values.

Equation 3 BIAS

$$BIAS \ = \ln(mod) - \ln\,(obs)$$

$$BIAS\,\% = \ exp\left(\frac{\sum BIAS}{n}\right) \times 100$$

Equation 4. FSE

$$FSE = \exp\left(\sqrt{\frac{\sum(\ln obs - \ln mod)^2}{n-1}}\right)$$

Equation 5. RMSE

$$RMSE = \sqrt{\frac{\sum(\ln mod - \ \ln obs)^2}{n}}$$

Where: *mod* are model predictions, *obs* are correspondent observed values and *n* is the number of data points.

4 ReFH2.3-FEH22 Results

The rural peak flows have been estimated for the QMED (2 year return period) and longer return periods (100, 200, 1000 and 10,000 years) for the ReFH2.3-FEH22 calibration, as well as the ReFH2.3-FEH13 calibration and ungauged FEH statistical method. These three methods are compared against the observed peak flows (taken to be the QMED from AMAX and ESS peak flow estimate) for rural catchments in Section 4.1. Table 1 provides the criteria used for the gauged assessment dataset, with the model run configurations for the methods provided in Table 2 and Table 3.

Sections 4.2 and 4.3 then present the ReFH2.3-FEH22 estimates of 2 and 100 year return period peak flows for different catchment types and for different regions (countries). A direct and spatial comparison of FEH13 and FEH22 derived ReFH2.3 peak flows is then presented in Section 4.4.

4.1 Comparison of ReFH2.3-FEH22, ReFH2.3-FEH13 and FEH Statistical Methods

Figure 4 to Figure 8 present a comparison of peak flows for the 2, 100, 200, 1000 and 10,000 year return periods each of the three methods against the observed peak flows. As described in Section 3.2, the observed QMED can be estimated directly from gauged AMAX data, whereas observed peak flows for larger return periods are estimated using the statistical ESS method, thus have higher uncertainty. Measures of fit statistics are presented in Table 4 to Table 6.

All three methods give very comparable estimates over all catchments meeting the selection criteria. Figure 4 shows the very close correspondence of the three estimates within these catchments for the 2 year return period. The measures of fit values are comparable to those presented for the ReFH2.3-FEH13 calibration[16]. The values differ slightly from the previously reported figures for the ReFH2.3-FEH13 calibration and the statistical ungauged method due to the slightly increased sample size of gauges and use of the latest version of the NRFA Peak Flow dataset.

The impact of sampling uncertainty (the number and type of gauges in the dataset) can be illustrated by the effect on the 2 year return period BIAS values. The BIAS in Table 4 using the 'Suitable for QMED' dataset (-1.44, -3.96, -1.45), would have been -0.08, -2.71 and 0.07, respectively, if the smaller 'Suitable for Pooling' dataset was used.

The main findings are that:

- All methods are generally unbiased below the 1000 year return period.
- The uncertainty measures generally increase for longer return periods, which is as expected given the uncertainties are greater for longer return periods.
- The uncertainties are similar for all three methods for short return periods. They generally increase from the statistical ungauged model, through to the ReFH2.3-FEH22 calibration and then the ReFH2.3-FEH13 calibration. This is as expected, given the rainfall-runoff methods are independent of the statistical ESS method.
- The uncertainties are similar for the ReFH2.3-FEH13 and ReFH2.3-FEH22 calibrations at low return periods but can start to diverge at longer return periods; attributed to the differences (improvements) in the FEH22 rainfall model.

[16] Wallingford HydroSolutions 2019. ReFH2 Science Report: Closing a Water Balance. Available via https://refhdocs.hydrosolutions.co.uk/References/

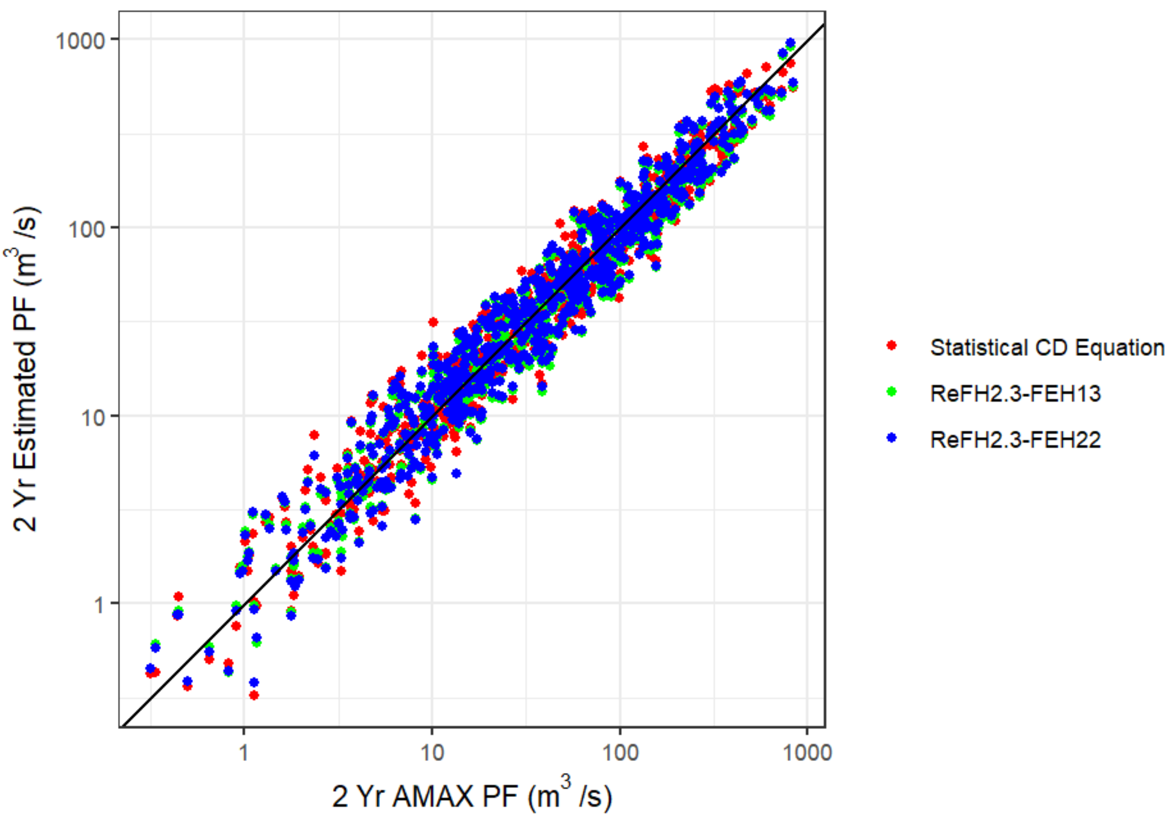

Figure 4. The 2 year peak flow estimates for the ReFH2.3 and statistical ungauged (catchment descriptor equation) methods compared with the observed peak flow (from gauged AMAX).

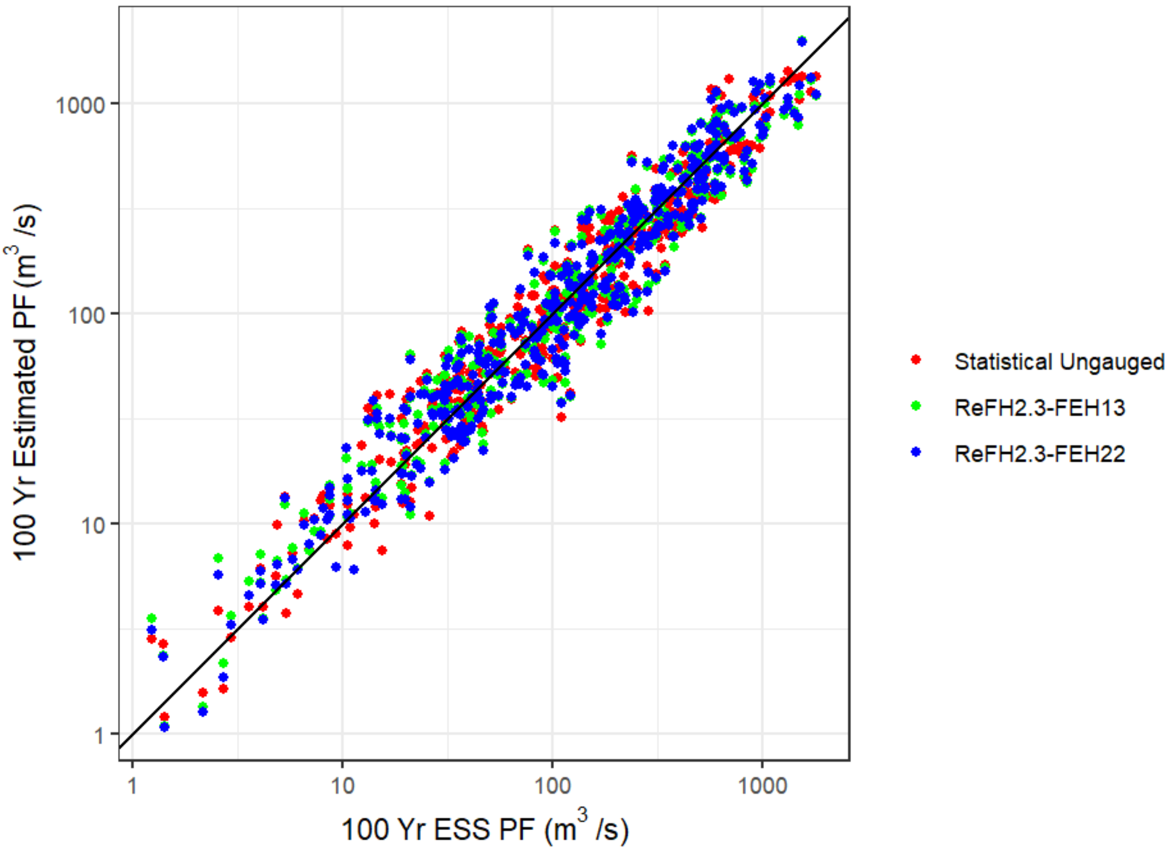

Figure 5. The 100 year peak flow estimate for the ReFH2.3 and statistical ungauged (pooled) methods compared with the ESS peak flows.

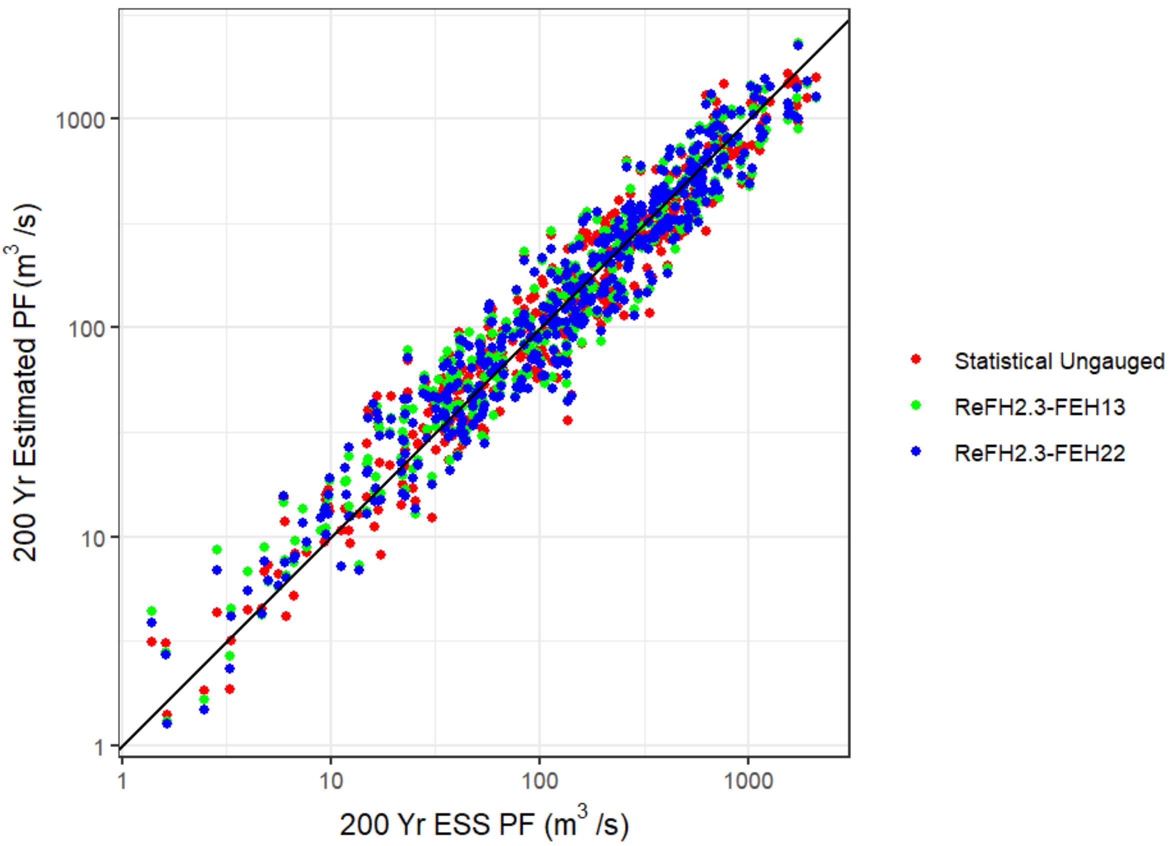

Figure 6. The 200 year peak flow estimate for the ReFH2.3 and statistical ungauged (pooled) methods compared with the ESS peak flows.

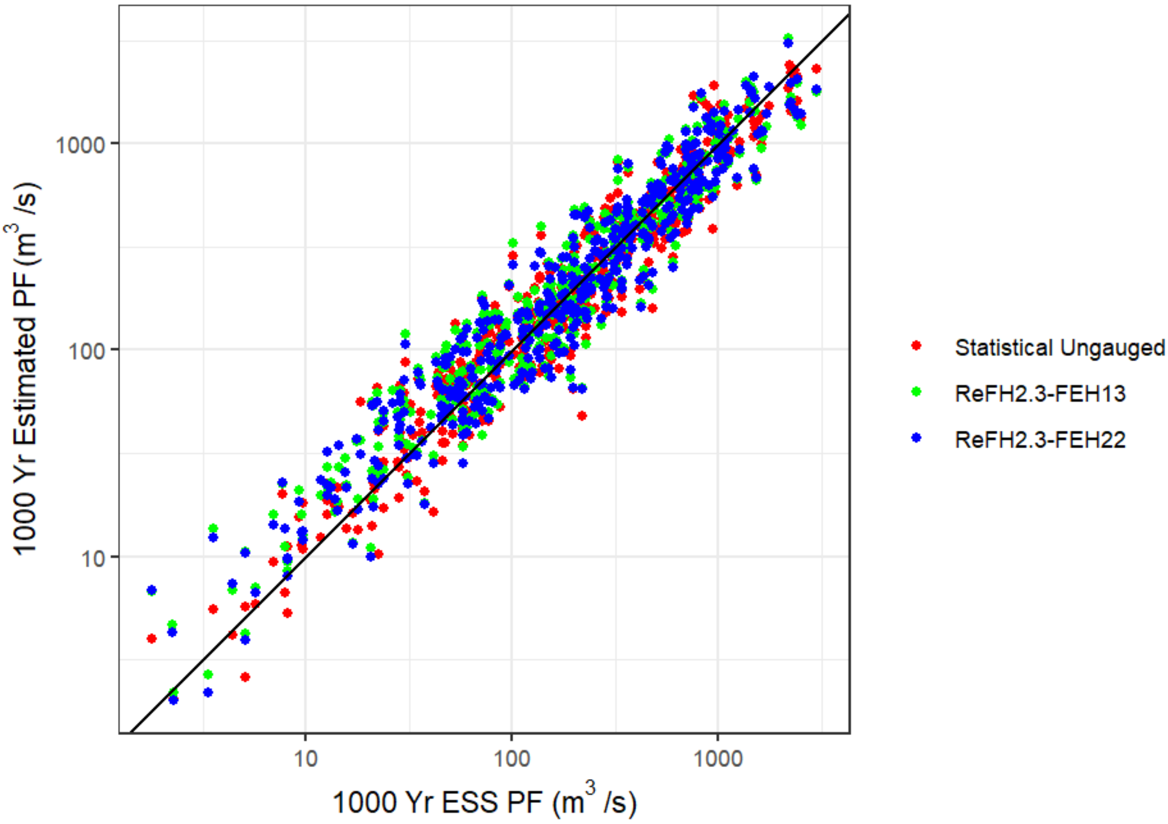

Figure 7. The 1000 year peak flow estimate for the ReFH2.3 and statistical ungauged (pooled) methods compared with the ESS peak flows.

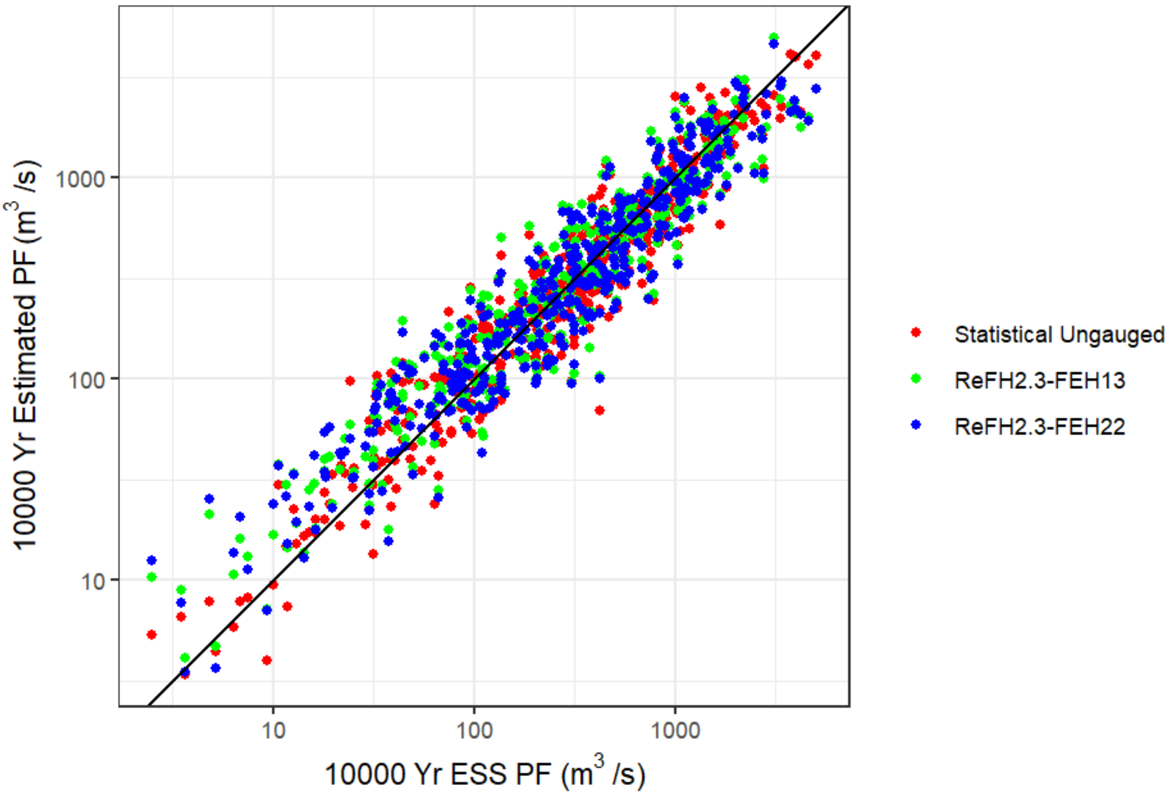

Figure 8. The 10,000 year peak flow estimate for the ReFH2.3 and statistical ungauged (pooled) methods compared with the ESS peak flows.

Table 4. BIAS for peak flows for the ReFH2.3 and statistical ungauged methods compared with the observed peak flow (2 year gauged AMAX and ESS for longer return periods). Note the BIAS is the bias of the ln values. N is 710 for the 2 year and 439 for longer return periods.

Return Period	Statistical Ungauged	ReFH2.3-FEH13	ReFH2.3-FEH22
2	-1.43	-3.88	-1.44
100	0.178	-0.688	-0.818
200	0.0974	2	0.595
1000	-0.177	7.51	4.8
10000	-0.735	7.01	3.67

Table 5. RMSE for peak flows for the ReFH2.3 and statistical ungauged methods compared with the observed peak flow (2 year gauged AMAX and ESS for longer return periods). N is 710 for the 2 year and 439 for longer return periods.

Return Period	Statistical Ungauged	ReFH2.3-FEH13	ReFH2.3-FEH22
2	0.348	0.36	0.358
100	0.371	0.384	0.374
200	0.377	0.396	0.384
1000	0.393	0.43	0.415
10000	0.422	0.484	0.475

Table 6. FSE for peak flows for the ReFH2.3 and statistical ungauged methods compared with the observed peak flow (2 year gauged AMAX and ESS for longer return periods). N is 710 for the 2 year and 439 for longer return periods.

Return Period	Statistical Ungauged	ReFH2.3-FEH13	ReFH2.3-FEH22
2	1.42	1.43	1.43
100	1.45	1.47	1.45
200	1.46	1.49	1.47
1000	1.48	1.54	1.51
10000	1.53	1.62	1.61

4.2 ReFH2.3-FEH22 Catchment Type Assessment

To determine whether there is BIAS for specific types of catchments, the results were assessed relative to the catchment area, rainfall (using SAAR, the standardised average annual rainfall in mm) and permeability (using BFIHOST19). Figure 9 and Figure 10 present the log residuals (BIAS) for the ReFH2.3-FEH22 method relative to catchment area (differentiated on permeability) and BFIHOST19 (differentiated on annual rainfall).

The locations and BFIHOST19 values for permeable (BFIHOST19 >0.65) catchments within the QMED assessment dataset are presented in Figure 11. Figure 12 and Figure 13 present the peak flows for permeable catchments for the 2 and 100 year return periods.

The main findings are that:

- The ReFH2.3-FEH22 calibration is generally unbiased across all catchments with reference to these catchment descriptors.
- Catchment area has little impact on BIAS (or other uncertainty measures, FSE or RMSE).
- Although unbiased across all catchments, the permeability and rainfall can impact the BIAS, and the related FSE and RMSE.

The complexity of groundwater-dominated catchments means that the BIAS is negative for all models at the 2 year return period but increases to being increasingly positive as the return period increases. The EA (2022)[17] recently reported on the challenges of flood estimation within groundwater dominated (permeable) catchments. The relatively high BIAS values within all models, particularly for high return periods, illustrates that more work is needed within permeable catchments to be able to understand the dominant processes and improve methods for flood estimation within permeable catchments. It is recommended, as per the recent EA report, that further work is completed in permeable catchments to better understand the processes and allow methods to be improved in these catchments.

[17] Faulkner, D., Murphy, K., Zaidman. M. 2022. Review of flood frequency estimation in groundwater-dominated catchments. Environment Agency. 2021s1484.

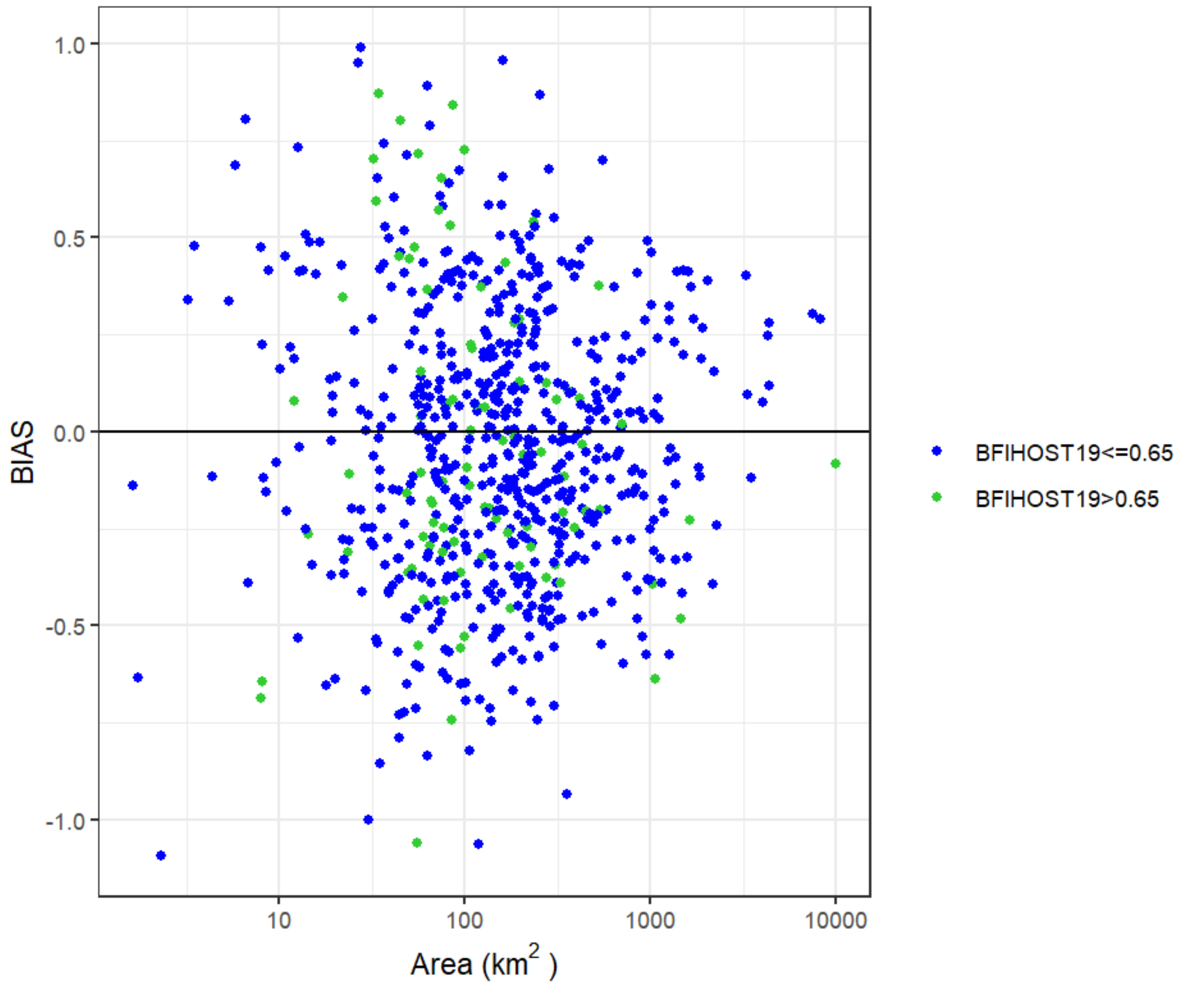

Figure 9. The ln residuals (BIAS) for the ReFH2.3-FEH22 2 year event against catchment area. Permeable (BFIHOST19 >0.65) and impermeable (BFIHOST19<=0.65) catchments are highlighted.

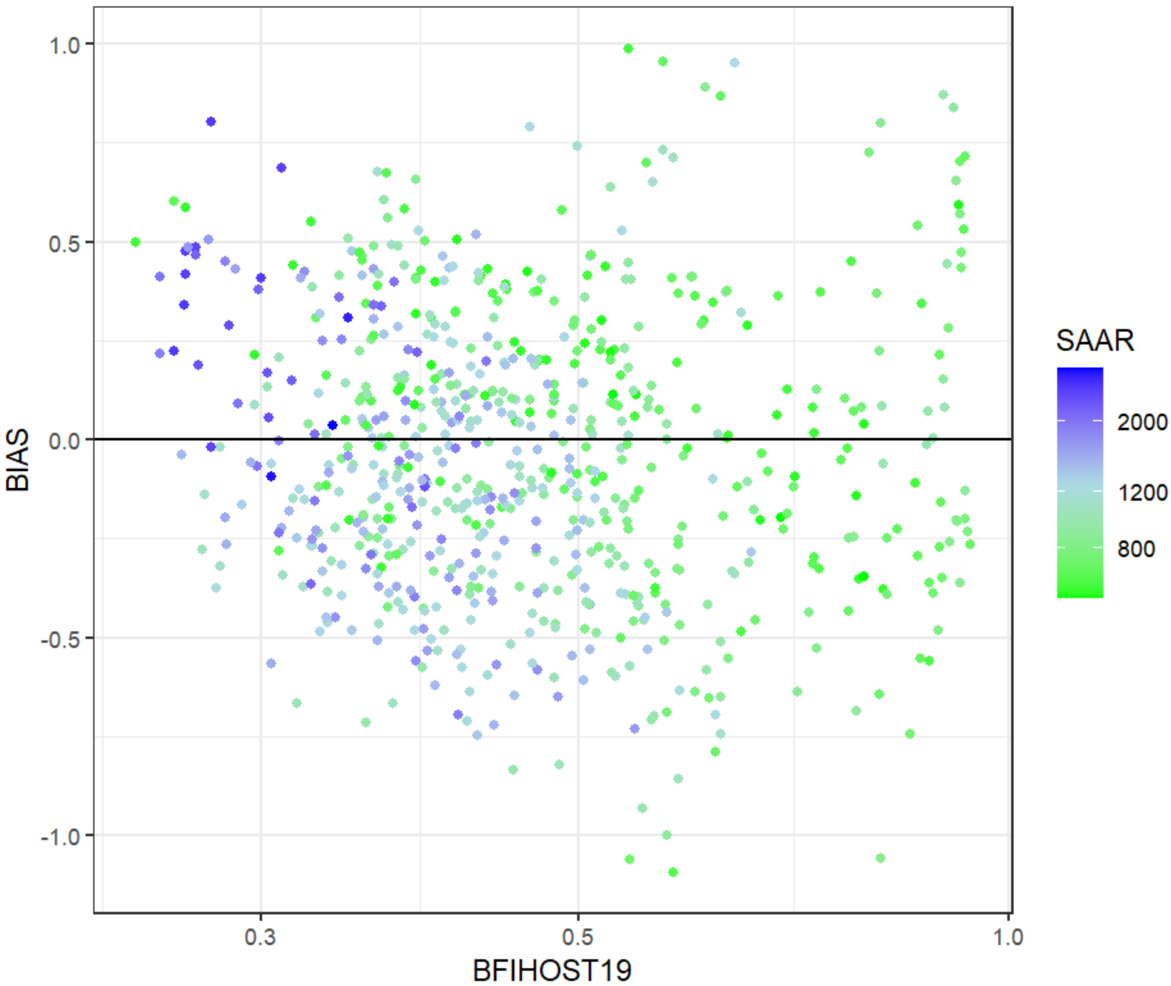

Figure 10. The ln residuals (BIAS) for the ReFH2.3-FEH22 2 year event against BFIHOST19 with the associated SAAR values.

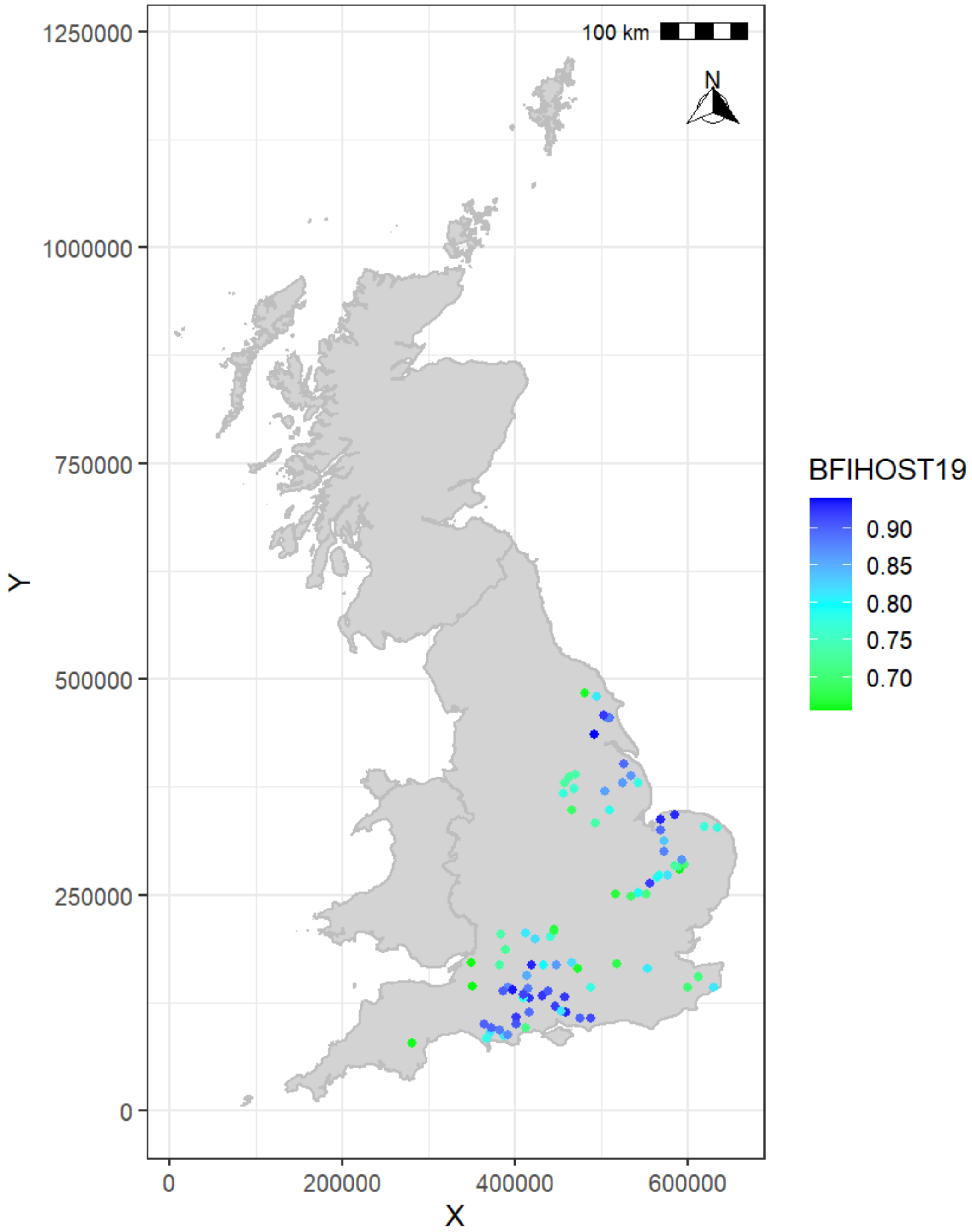

Figure 11. The locations of gauges with a BFIHOST19 greater than 0.65 in the UK in the QMED assessment dataset. Note there are no gauges within the NI assessment dataset that have a permeability greater than 0.65.

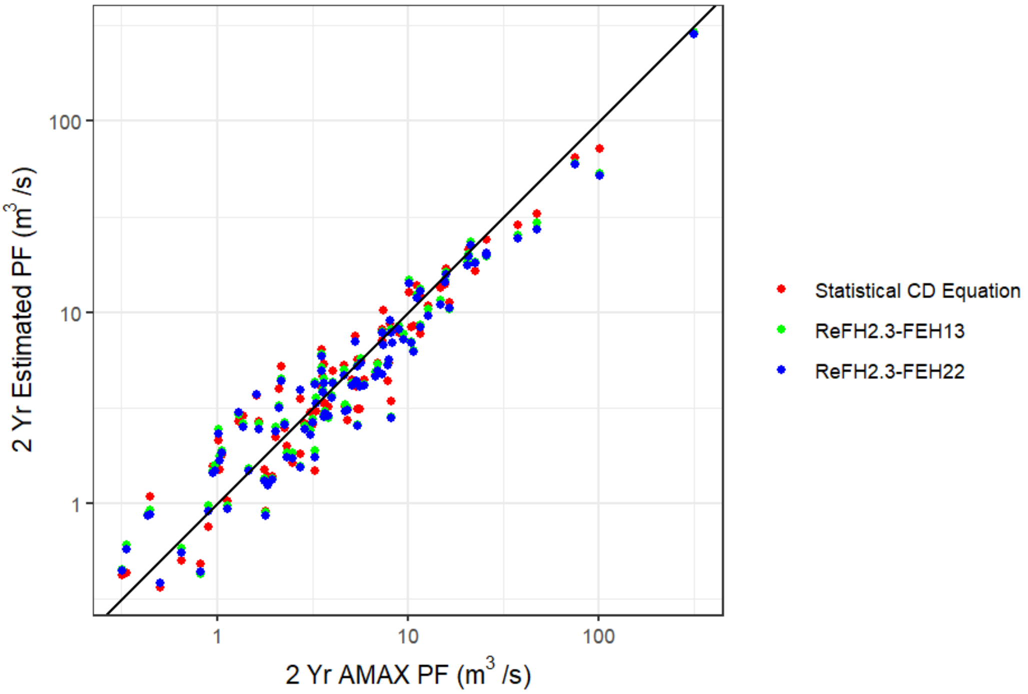

Figure 12. The 2 year peak flow estimates for the ReFH2.3 and statistical ungauged (catchment descriptor equation) methods compared with the observed peak flow (from gauged AMAX) for permeable (BFIHOST19 > 0.65) catchments.

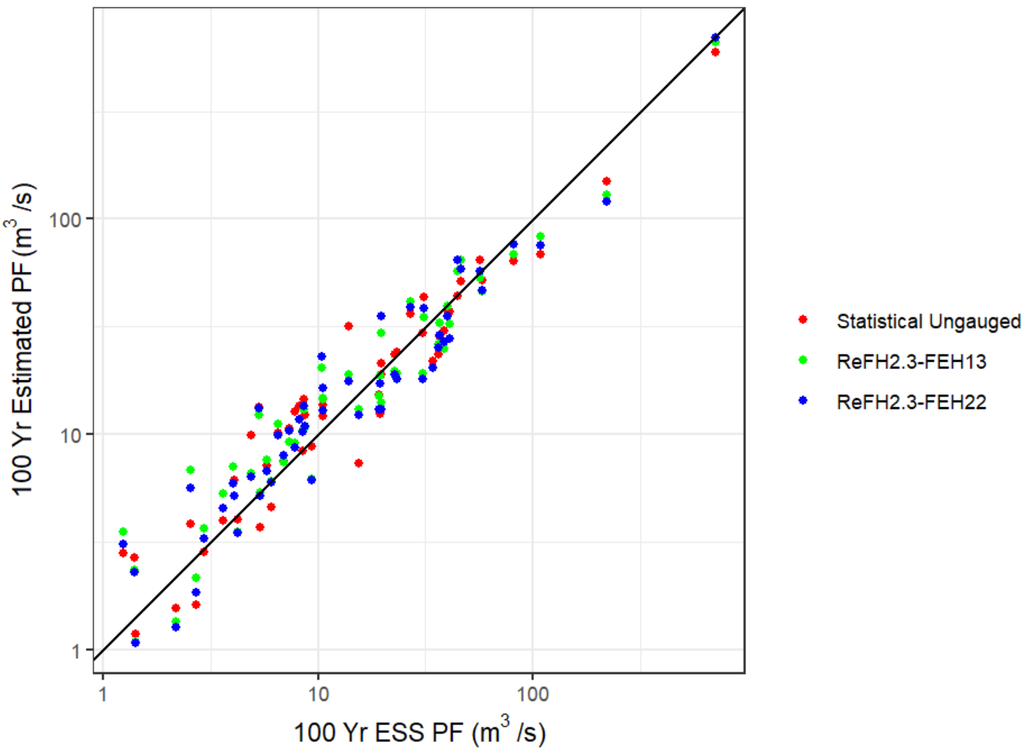

Figure 13. The 100 year peak flow estimate for the ReFH2.3 and statistical ungauged (pooled) methods compared with the ESS peak flows for permeable (BFIHOST19 > 0.65) catchments.

4.3 ReFH2.3-FEH22 Regional Assessment

The ReFH2.3-FEH22 peak flow estimates for the 2, 100 and 200 year return period are presented for each country in Figure 14, Figure 15 and Figure 16. The results for the statistical ungauged model are presented in Appendix 1.

These illustrate that there are differences between the performance of the models, and the variability of peak flows, for each country in the UK. The ReFH2.3-FEH22 results for the different countries are consistent with ReFH2.3-FEH13 (also see Section 4.4).

The main findings are that:

- The uncertainty within different countries can vary, but clear patterns are difficult to discern due to the small sampling size, particularly in Northern Ireland.
- It is recommended that further work is completed in the future on the spatial patterns, and how these may be linked to catchment types, and their flood generating processes within the UK.

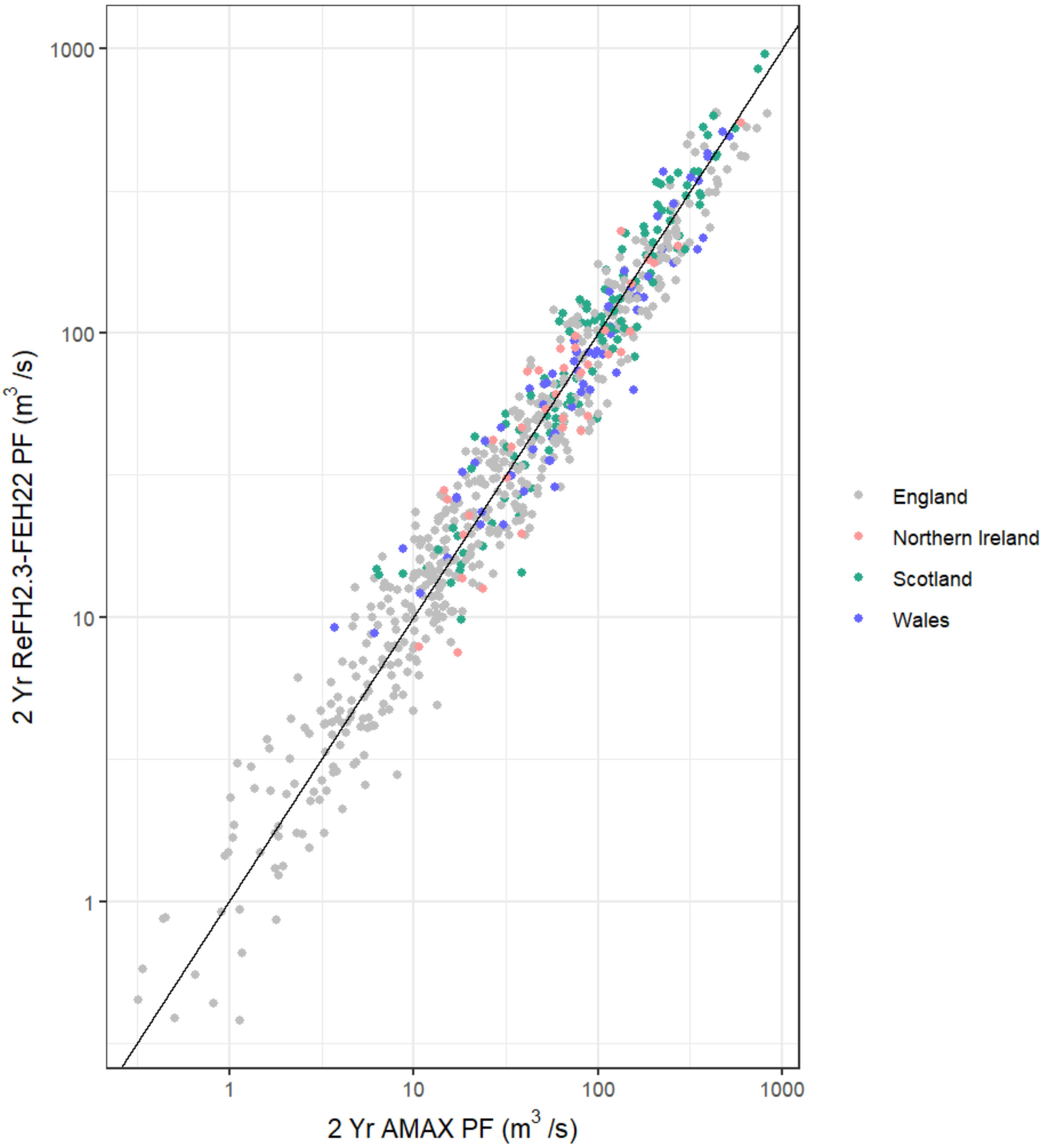

Figure 14. The 2 year peak flow estimates for the ReFH2.3-FEH22 calibration compared with the observed peak flow (from gauged AMAX) for each country.

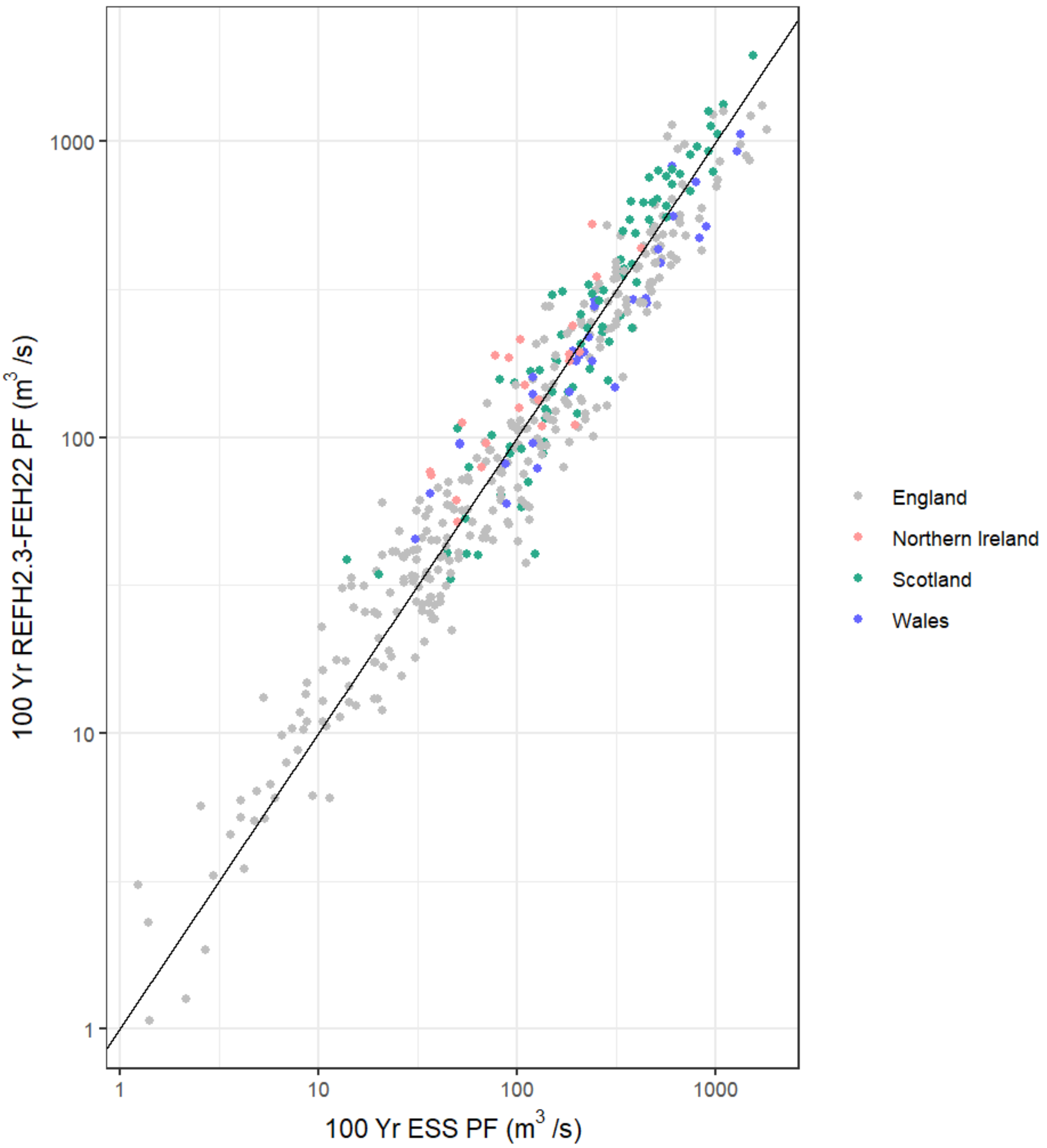

Figure 15. The 100 year peak flow for the ReFH2.3-FEH22 calibration compared with the ESS peak flows for each country.

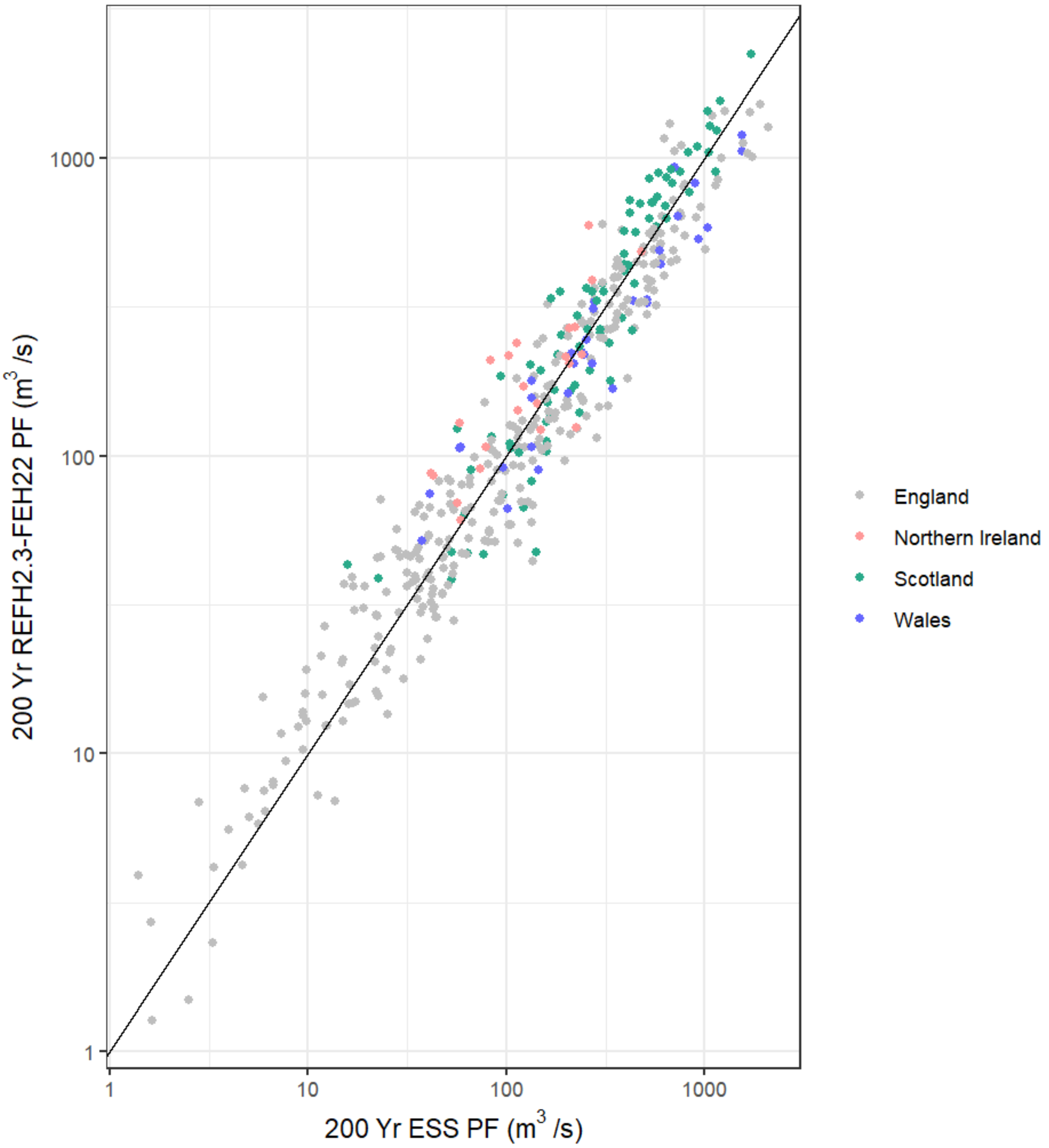

Figure 16. The 200 year peak flow for the ReFH2.3-FEH22 calibration compared with the ESS peak flows for each country.

4.4 Comparison of FEH13 and FEH22 derived Peak Flows

Figure 17 presents a direct comparision of the 100 and 1000 year return period peak flows estimated using the ReFH2.3-FEH13 and ReFH2.3-FEH22 calibrations. These show that although in general there is no significant bias, there can be significant differences for individual catchments, and that the differences become more marked at longer return periods.

Figure 18 to Figure 27 then present the FEH22/FEH13 rainfall ratios for a representative storm duration alongside the ReFH2.3-FEH13/ReFH2.3-FEH22 peak flow ratios for all Great Britain, England, Scotland, Wales and Northern Ireland. The 12 hour storm is used as this is close to the median recommended duration of the gauges which is 11 hours.

The main findings are that:

- The differences between the ReFH2.3-FEH13 and ReFH2.3-FEH22 calibration peak flows are largely related to the differences between the FEH13 and FEH22 rainfall models.
- In general, the ratio of the peak flows will be greater than the rainfall for surface water dominated catchments and can be lower for catchments which are heavily dominated by groundwater.
- The gauged dataset captures the general spatial variability of the differences between the FEH13 and FEH22 rainfall models, therefore it is envisaged that the measures of fit for the gauged dataset are representative of the effect on peak flow estimates across the UK.

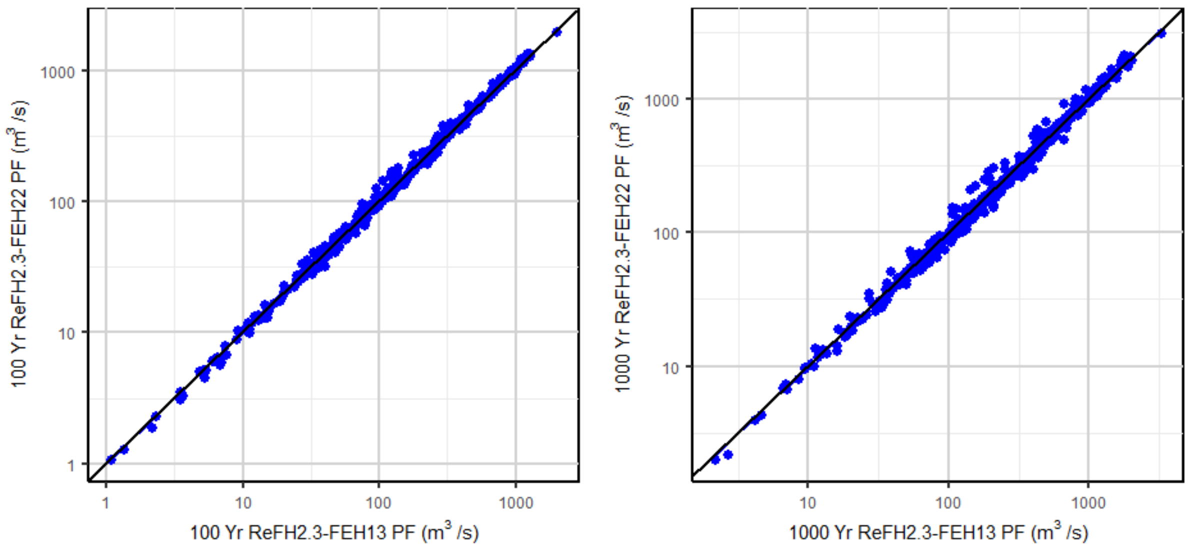

Figure 17. The ReFH2.3-FEH13 and ReFH2.3-FEH22 peak flows for the 100 and 1000 return period.

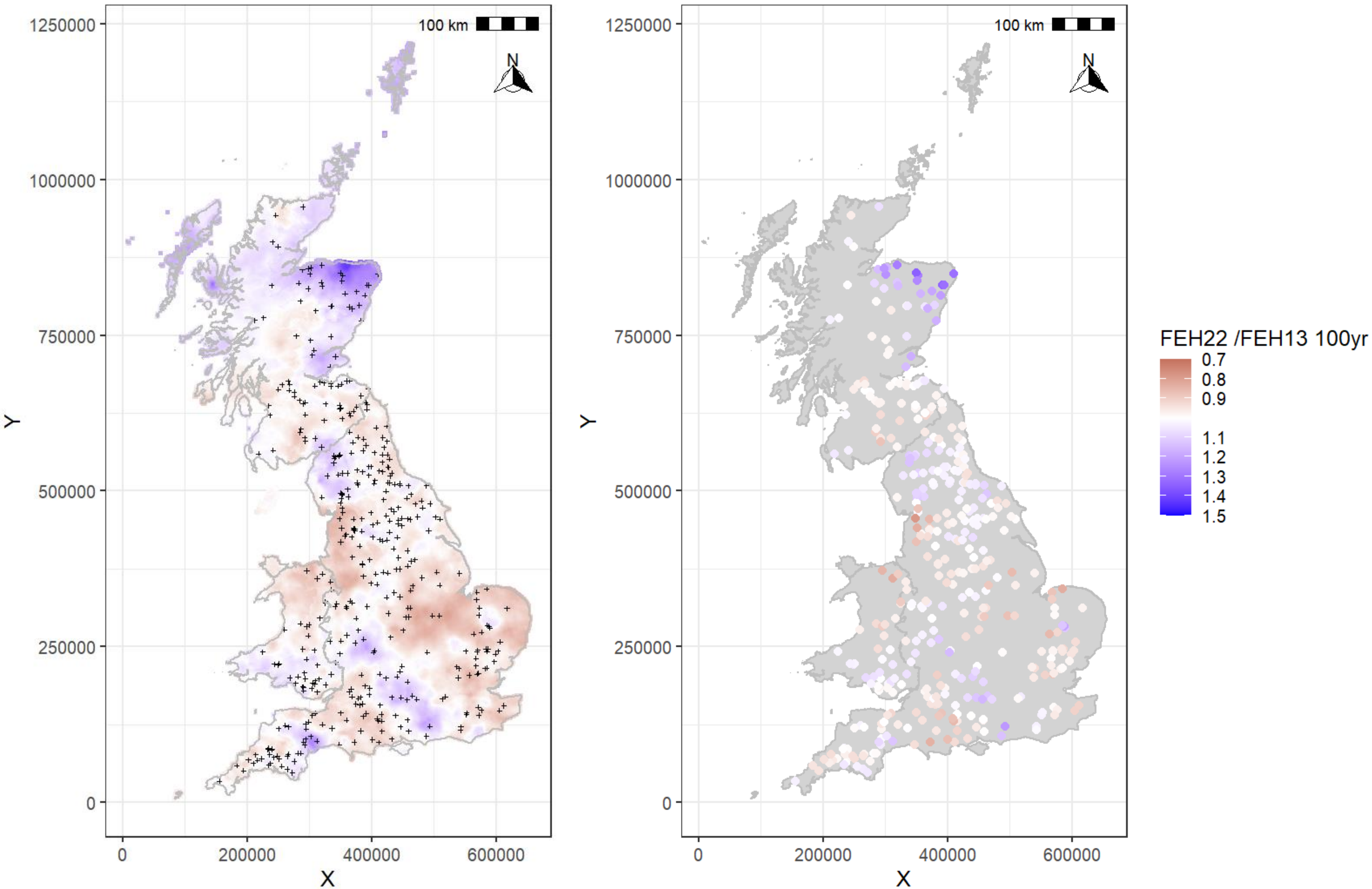

Figure 18. Great Britain. The 100 year 12 hour FEH22/FEH13 gridded rainfall ratio (left) and ReFH2.3 peak flow ratio (right).

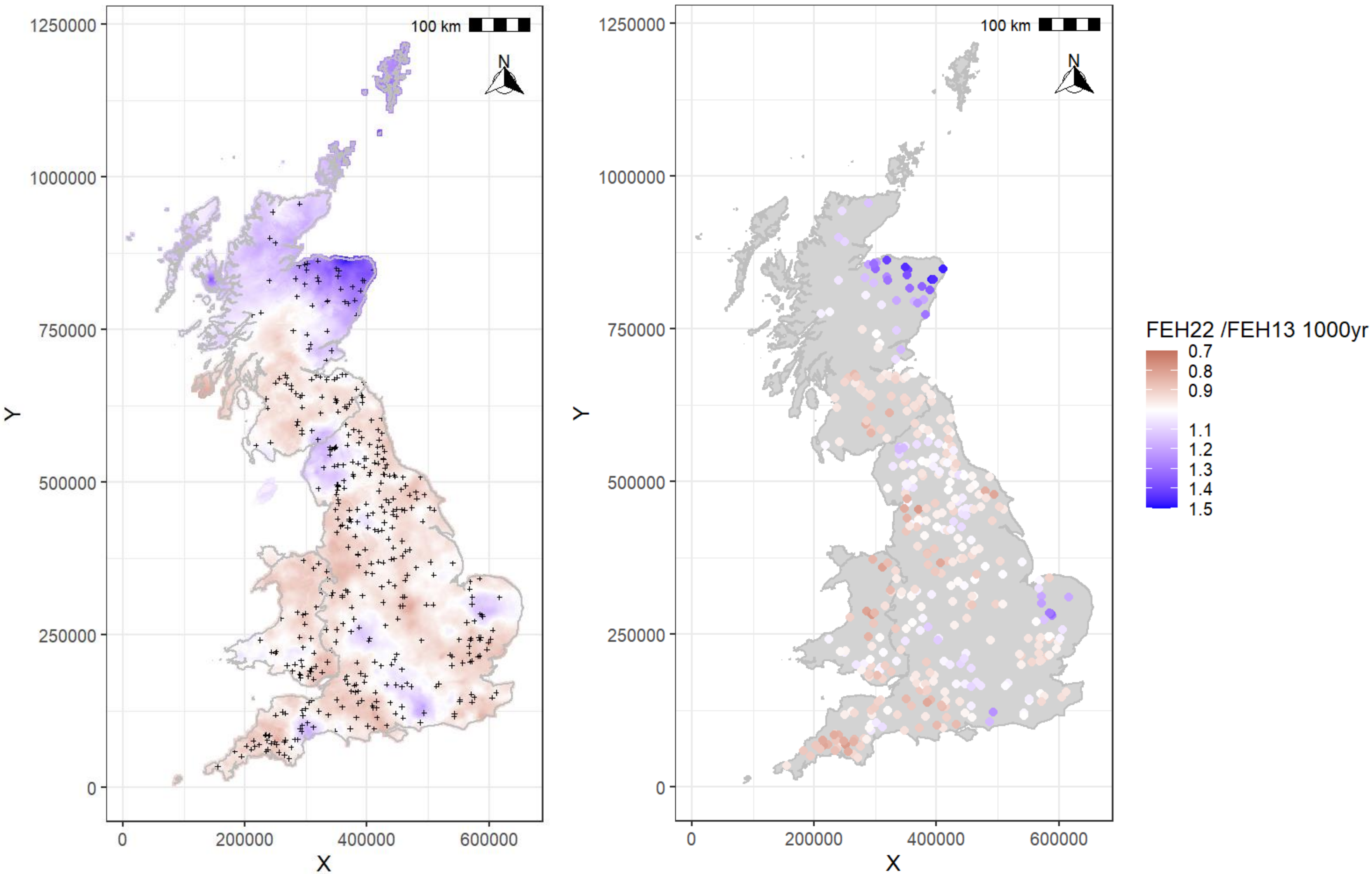

Figure 19. Great Britain. The 1000 year 12 hour FEH22/FEH13 gridded rainfall ratio (left) and ReFH2.3 peak flow ratio (right).

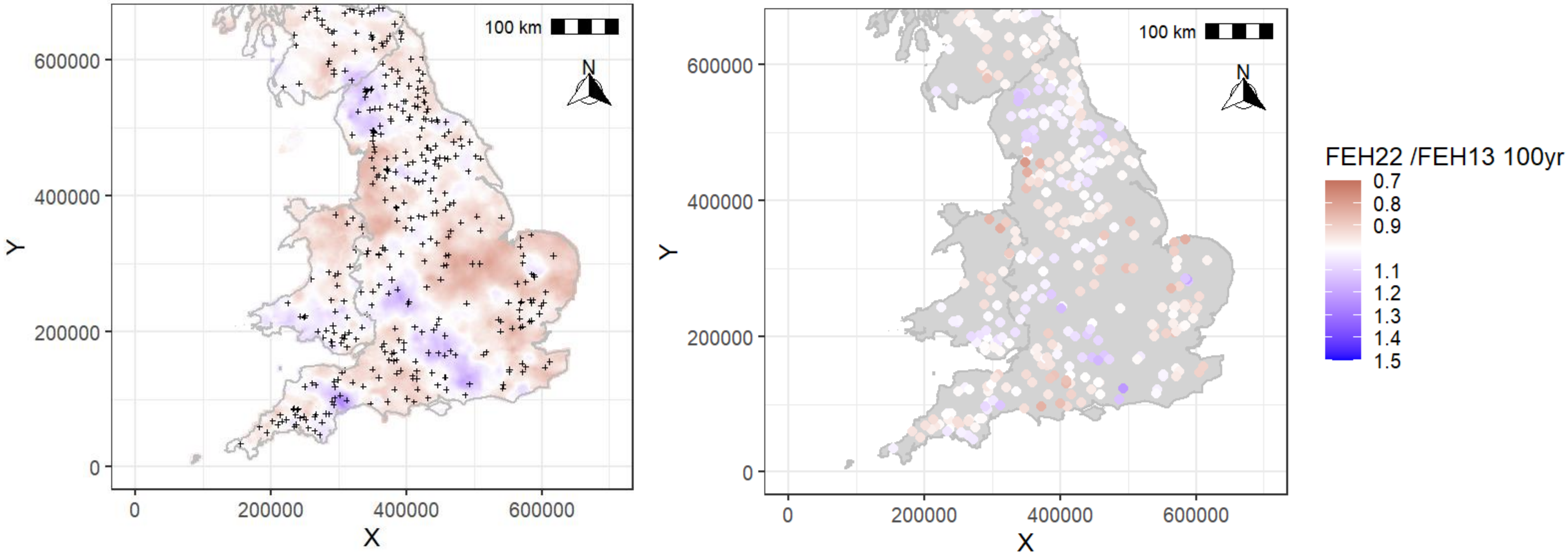

Figure 20. England. The 100 year 12 hour FEH22/FEH13 gridded rainfall ratio (left) and ReFH2.3 peak flow ratio (right).

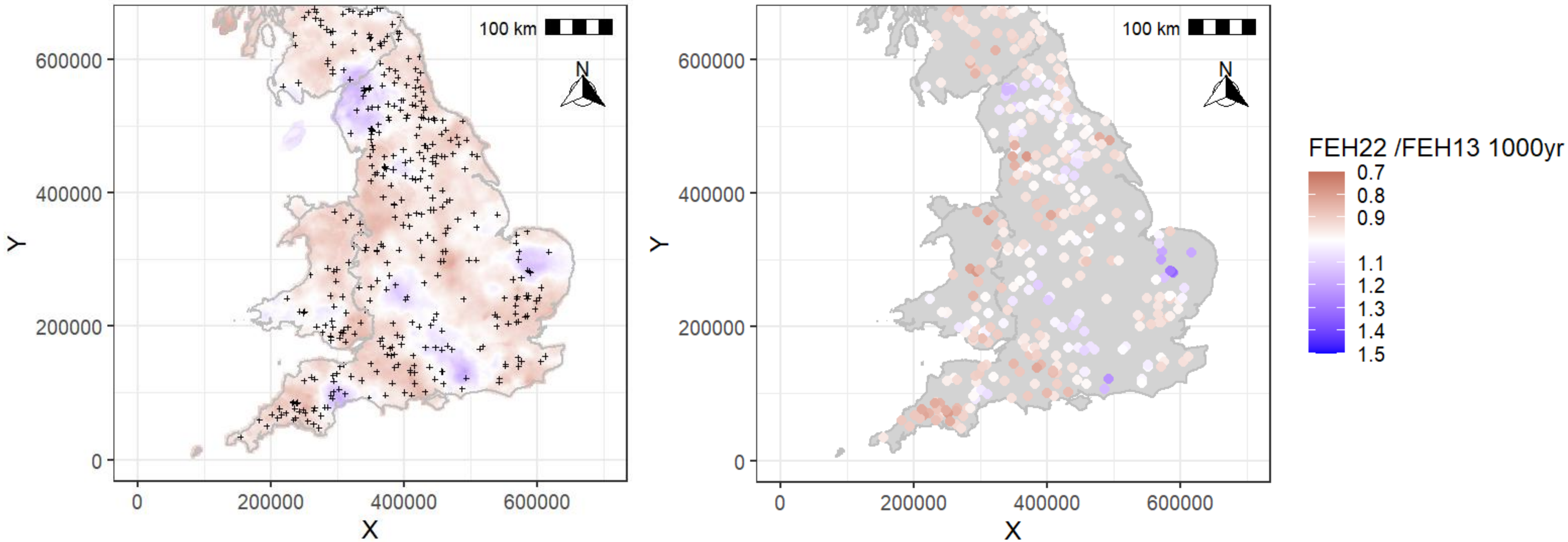

Figure 21. England. The 1000 year 12 hour FEH22/FEH13 gridded rainfall ratio (left) and ReFH2.3 peak flow ratio (right).

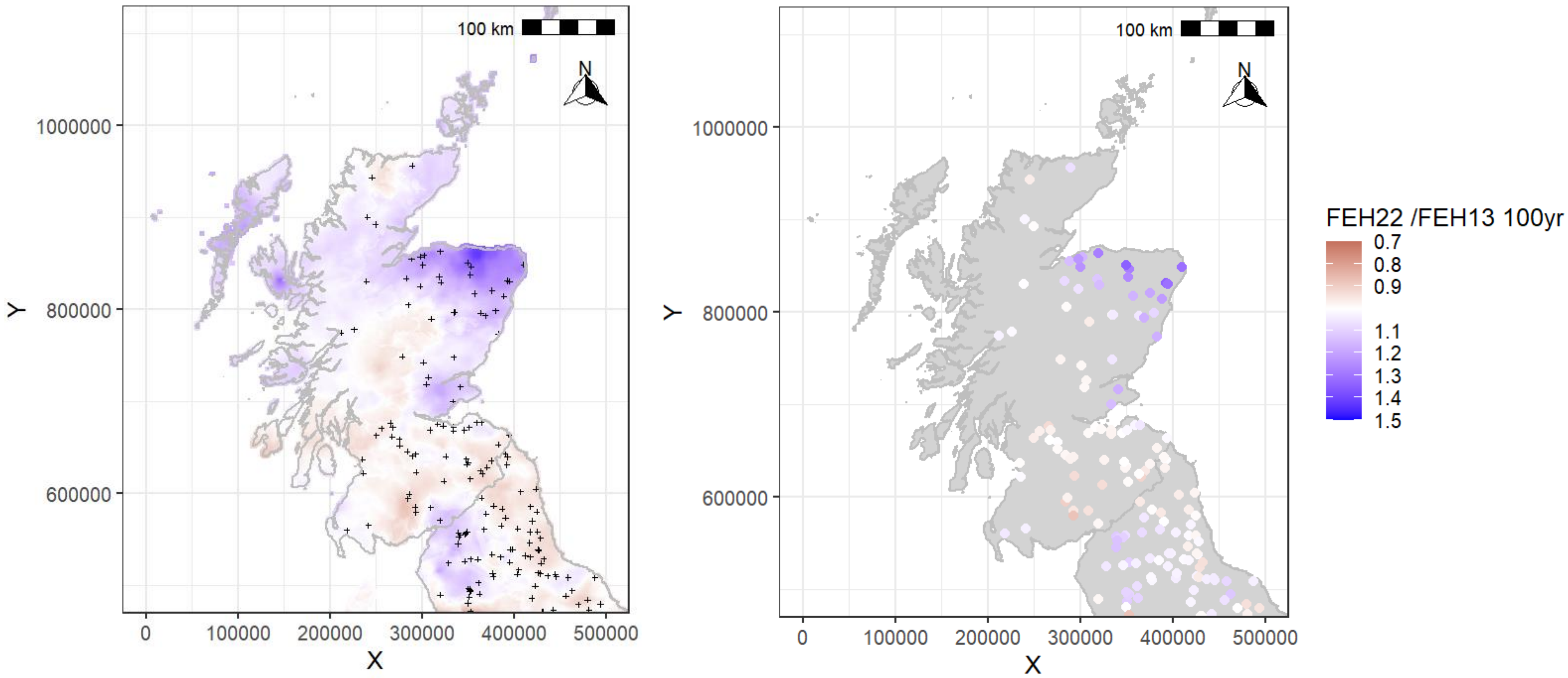

Figure 22. Scotland. The 100 year 12 hour FEH22/FEH13 gridded rainfall ratio (left) and ReFH2.3 peak flow ratio (right).

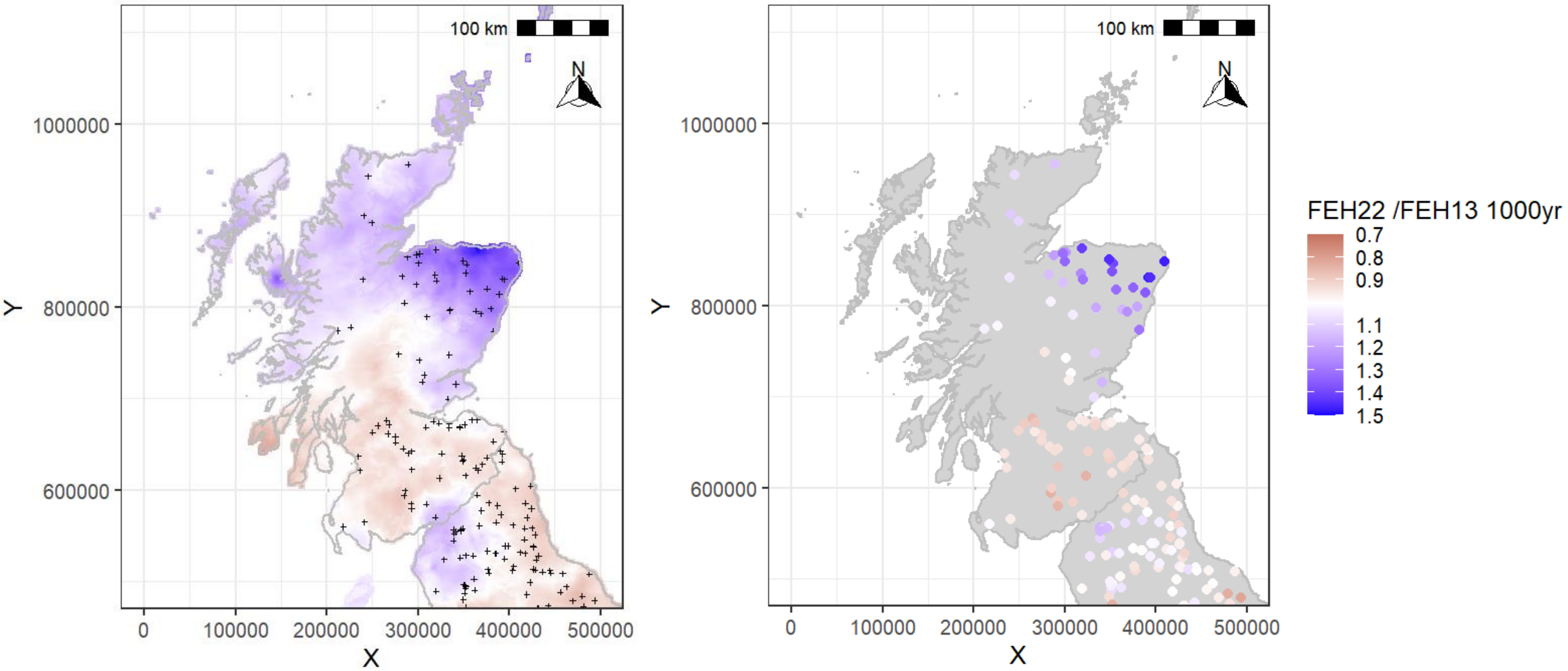

Figure 23. Scotland. The 1000 year 12 hour FEH22/FEH13 gridded rainfall ratio (left) and ReFH2.3 peak flow ratio (right).

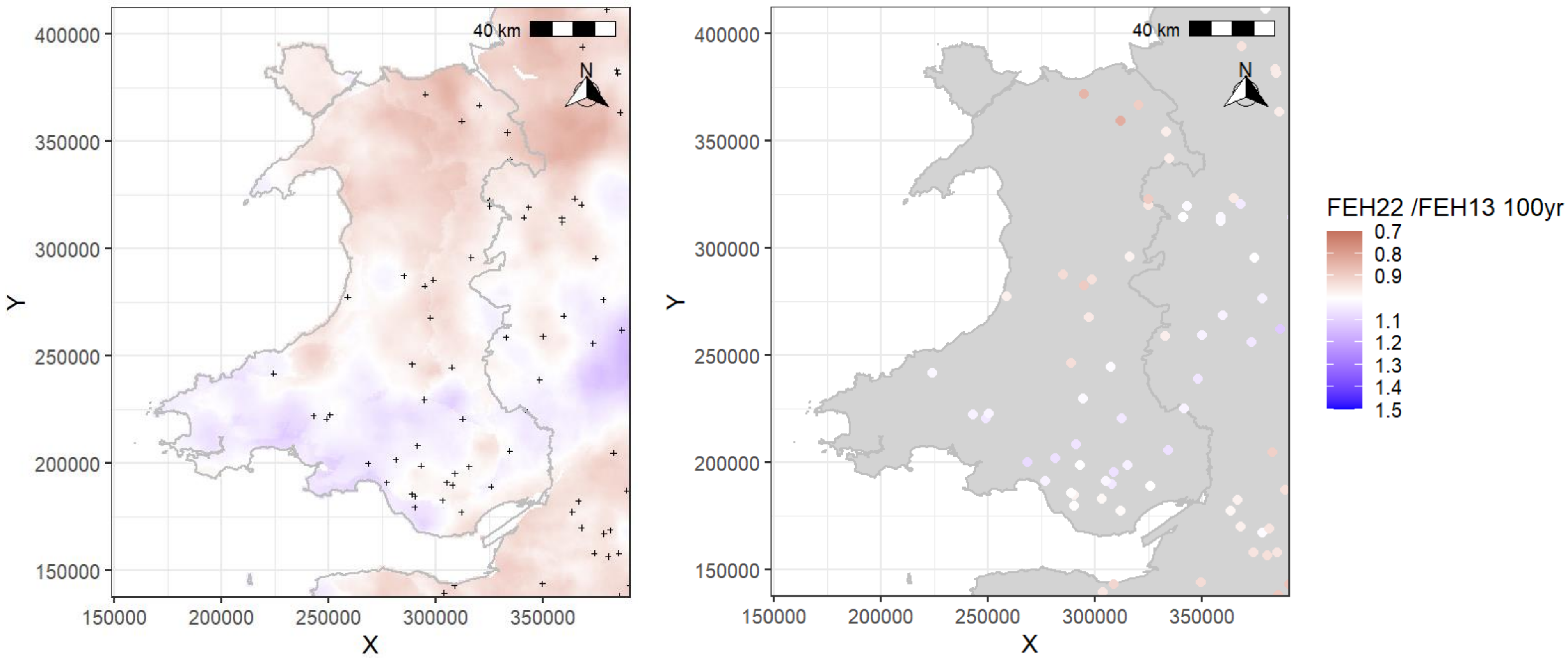

Figure 24. Wales. The 100 year 12 hour FEH22/FEH13 gridded rainfall ratio (left) and ReFH2.3 peak flow ratio (right).

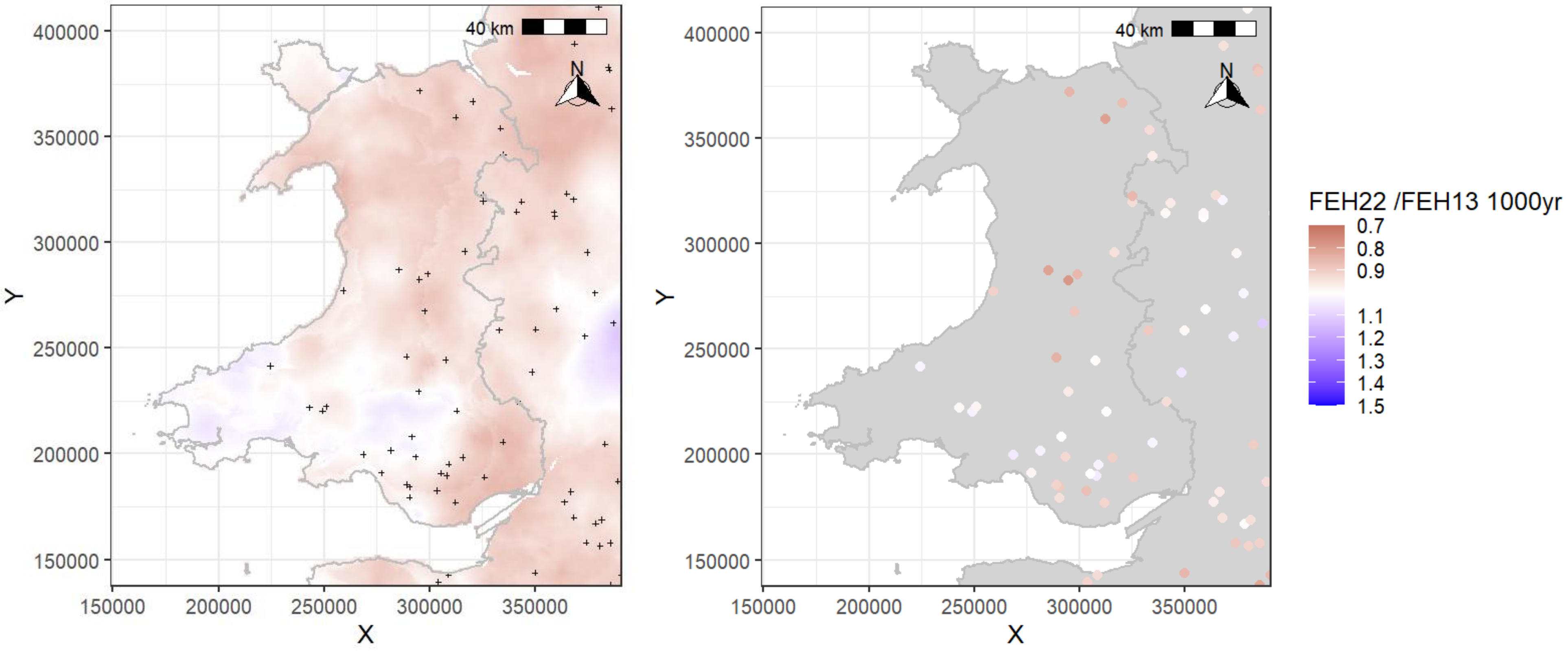

Figure 25. Wales. The 1000 year 12 hour FEH22/FEH13 gridded rainfall ratio (left) and ReFH2.3 peak flow ratio (right).

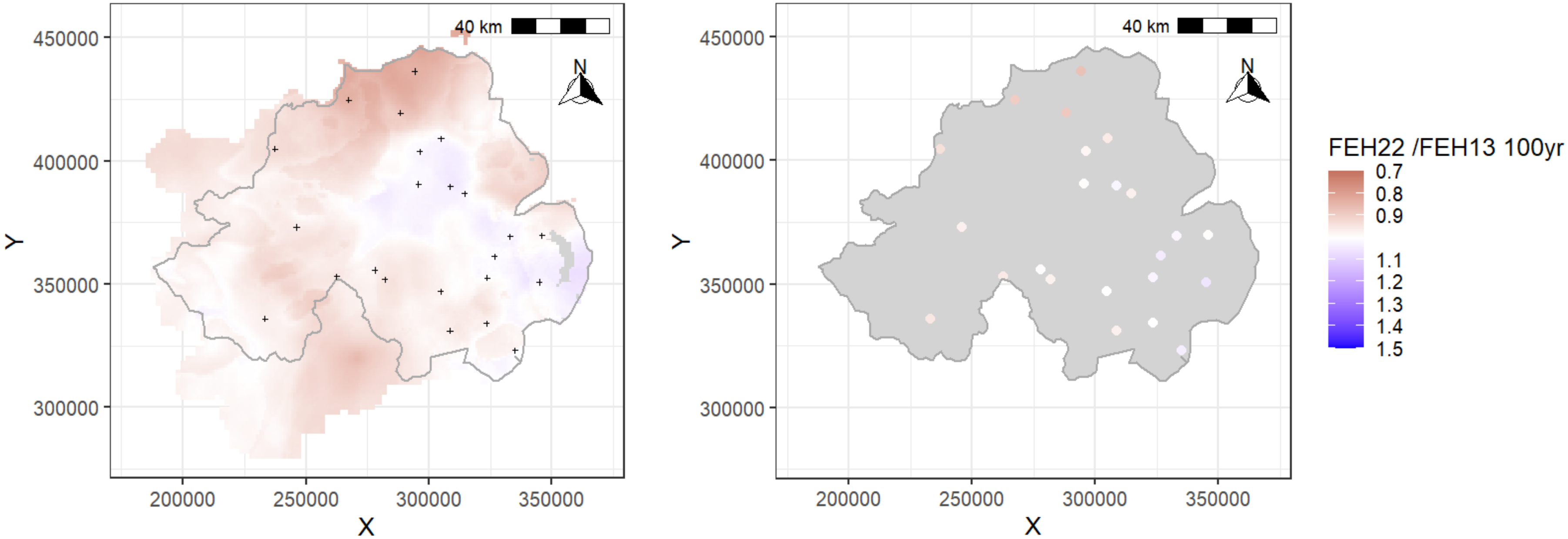

Figure 26 Northern Ireland. The 100 year 12 hour FEH22/FEH13 gridded rainfall ratio (left) and ReFH2.3 peak flow ratio (right).

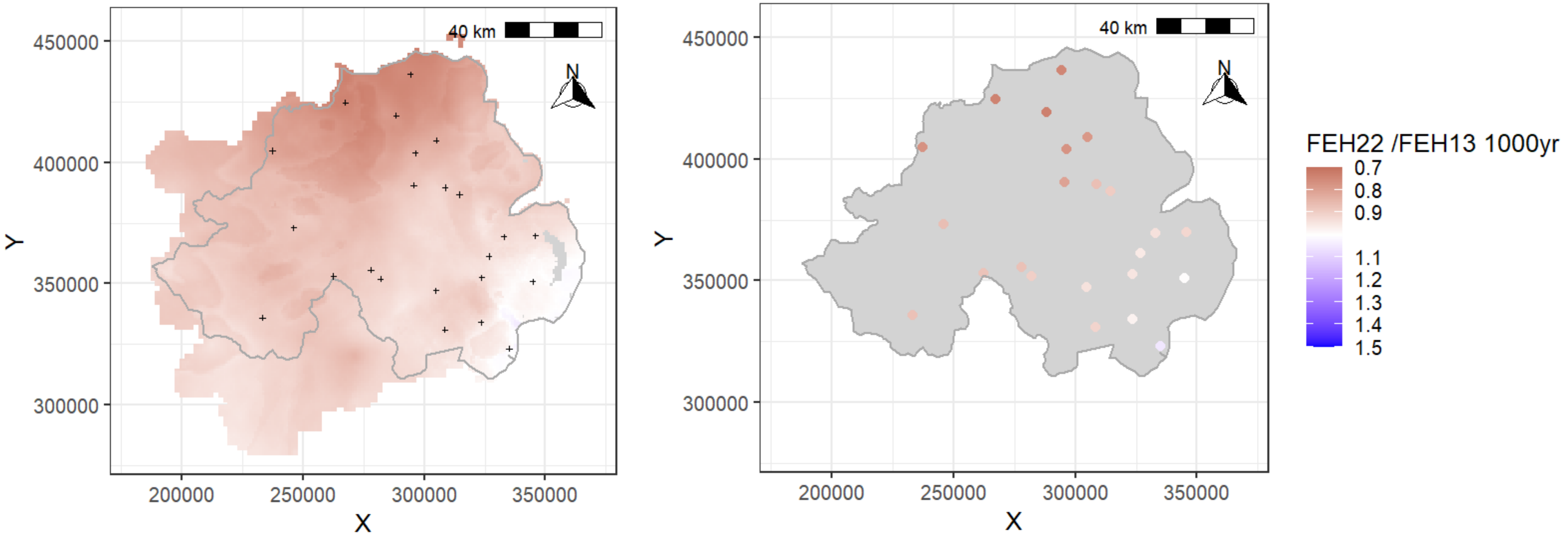

Figure 27. Northern Ireland. The 1000 year 12 hour FEH22/FEH13 gridded rainfall ratio (left) and ReFH2.3 peak flow ratio (right).

Appendix 1 FEH Ungauged Statistical Method Regional Assessment

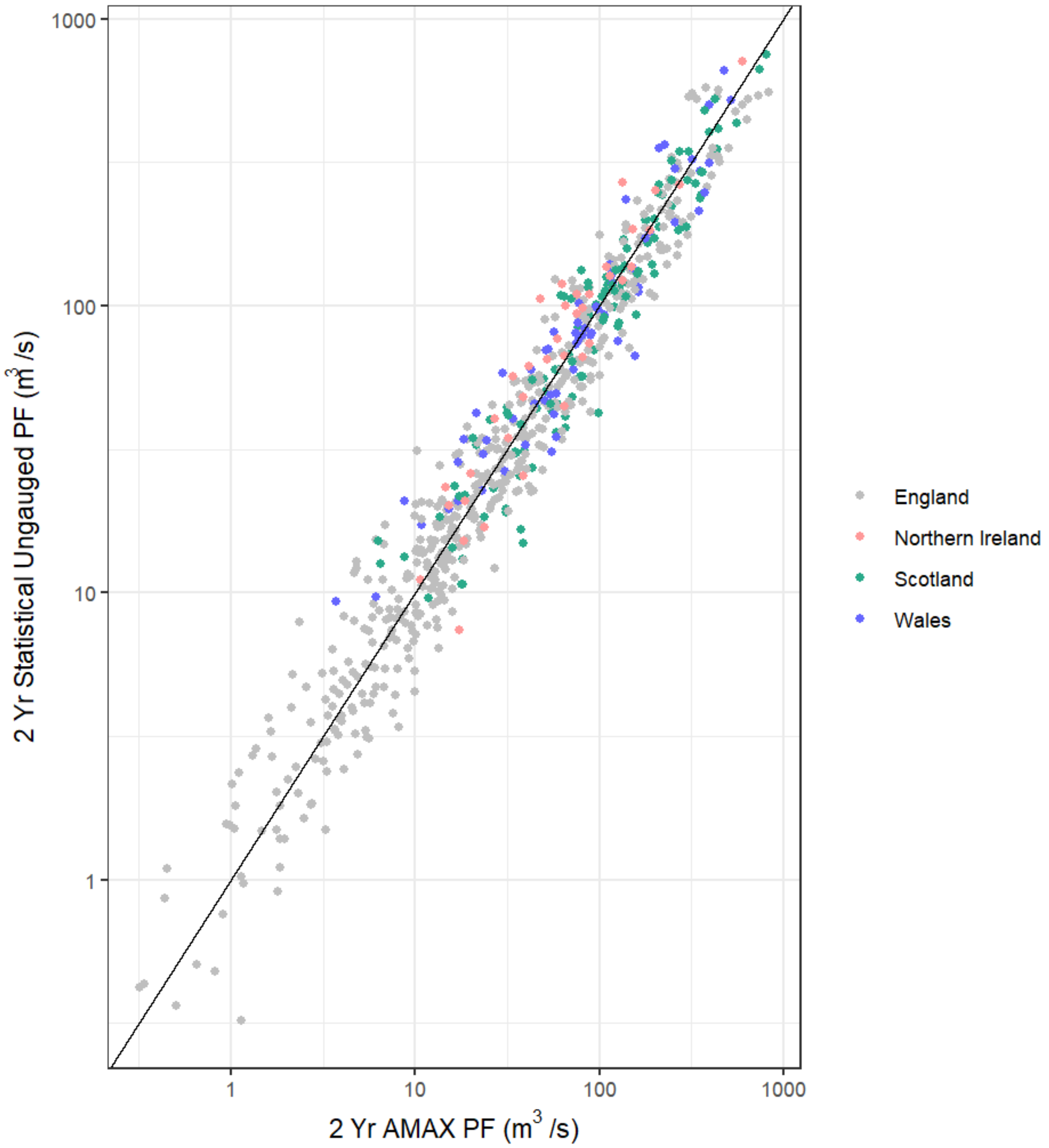

Figure 28. The 2 year peak flows for the statistical ungauged model compared with the observed peak flow (2 year gauged AMAX and 100 year ESS) for each country.

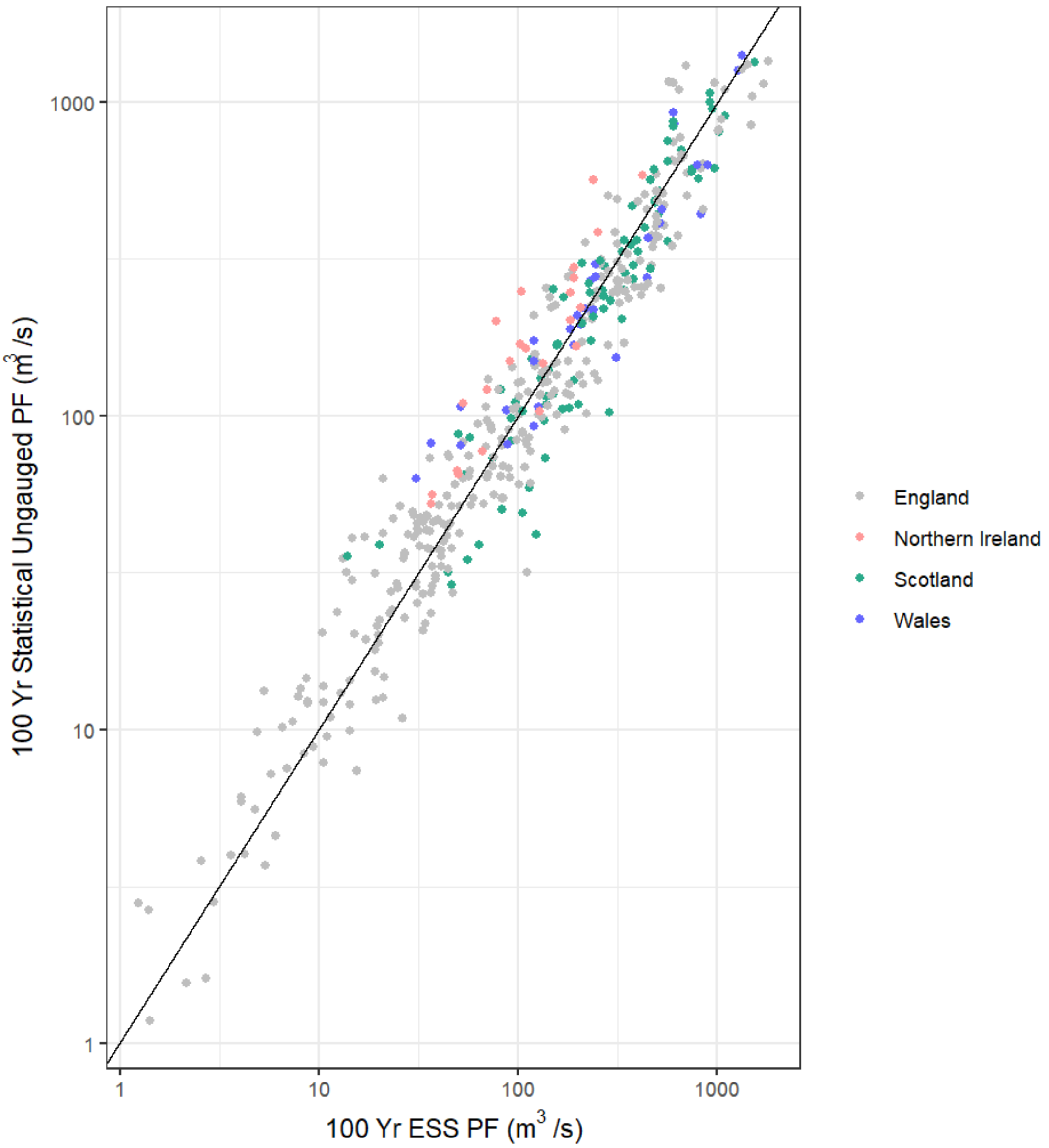

Figure 29. The 100 year peak flows for the statistical ungauged model compared with the observed peak flow (2 year gauged AMAX and 100 year ESS) for each country.

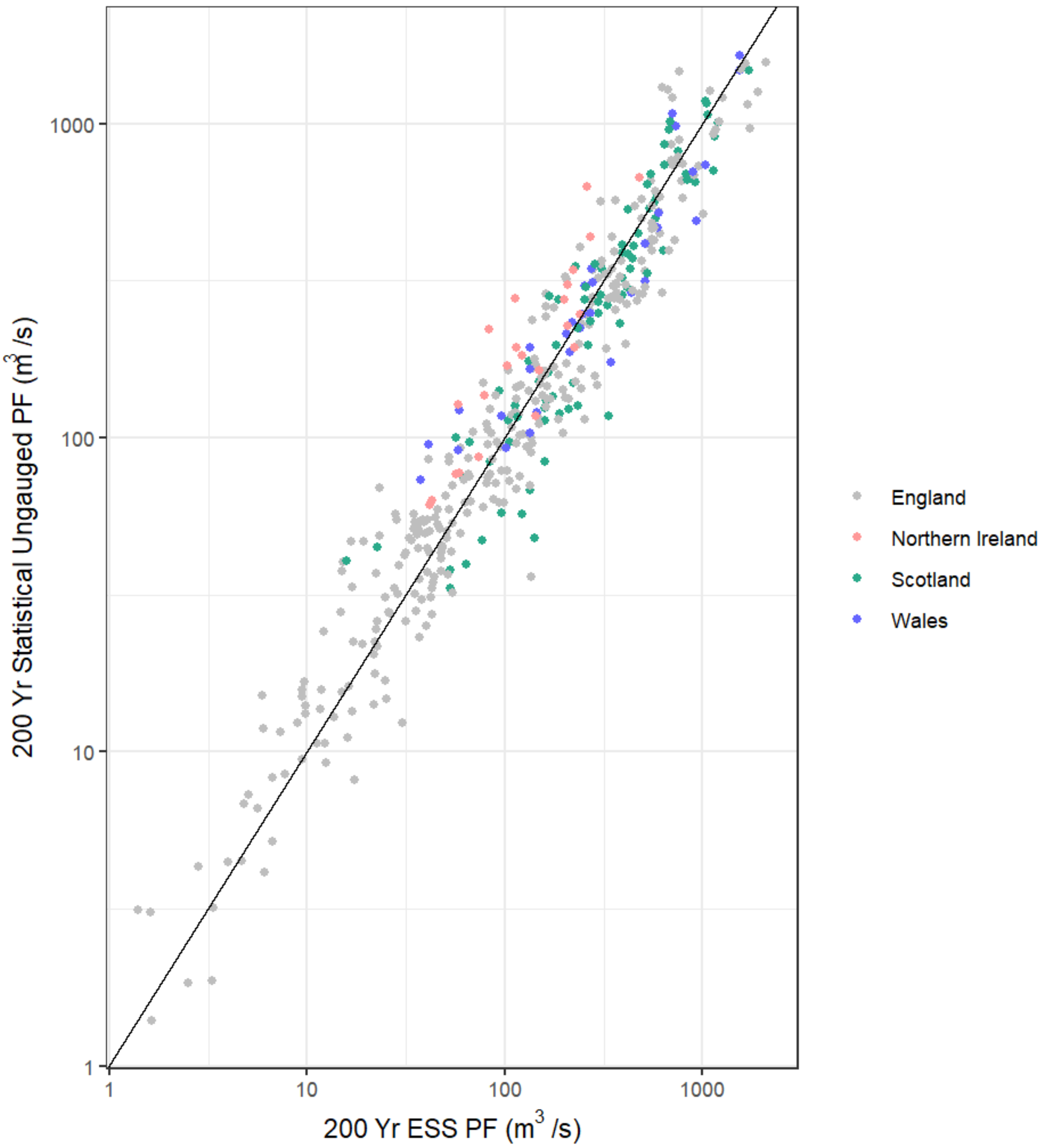

Figure 30. The 200 year peak flows for the statistical ungauged model compared with the observed peak flow (2 year gauged AMAX and 100 year ESS) for each country.