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Supplement of

Novel extensions to the Fisher copula to model flood spatial dependence over North America

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Supplementary information: Novel extensions to the Fisher copula to model flood spatial dependence over North America

Table S1: Catchment attribute description (130 attributes)

	Covariates	***Description***
1	catch_lat	Unit catchment centroid latitude
2	catch_lon	Unit catchment centroid longitude
3	centroid_lat	Latitude of centroid of upstream area
4	centroid_lon	Longitude of centroid of upstream area
5	SLPmean	River slope mean
6	River_slope	River slope
7	log_drainage_area	log10 of upstream drainage area
8	log_drainage_length	log10 of sum of upstream drainage length
9	log_river_length	log10 of length of drainage from station to Network outlet
10	log_dam_area	log10 of sum of upstream area protected by dams based on GOODDS dataset
11	RD	River Depth
	Source: MERIT DEM: Multi-Error-Removed Improved-Terrain DEM (u-tokyo.ac.jp)	
12	Dmean	Mean DEM value
13	Dmin	Minimum DEM value
14	Dmax	Maximum DEM value
15	FDR0	Fractional coverage of flow direction classes – Flat area
16	FDR1	Fractional coverage of flow direction classes – East (90°)
17	FDR2	Fractional coverage of flow direction classes – Southeast (135°)
18	FDR4	Fractional coverage of flow direction classes – South (180°)
19	FDR8	Fractional coverage of flow direction classes – Southwest (225°)
20	FDR16	Fractional coverage of flow direction classes – West (270°)
21	FDR32	Fractional coverage of flow direction classes – Northwest (315°)
22	FDR64	Fractional coverage of flow direction classes – North (0°)
23	FDR128	Fractional coverage of flow direction classes – Northeast (45°)
	Source: Land-Atmosphere Interaction Research Group at Sun Yat-sen University (bnu.edu.cn) – 30s resolution	
24	BS45	Mean base saturation at 45mm
25	BS91	Mean base saturation at 91mm
26	BS166	Mean base saturation at 166mm
27	BS289	Mean base saturation at 289mm
28	BS493	Mean base saturation at 493mm
29	BS829	Mean base saturation at 829mm
30	BS1383	Mean base saturation at 1383mm
31	BS2296	Mean base saturation at 2296mm
32	BD45	Mean bulk density at 45mm
33	BD91	Mean bulk density at 91mm
34	BD166	Mean bulk density at 166mm
35	BD289	Mean bulk density at 289mm
36	BD493	Mean bulk density at 493mm
37	BD829	Mean bulk density at 829mm
38	BD1383	Mean bulk density at 1383mm
39	BD2296	Mean bulk density at 2296mm
40	CLAY45	Mean clay fraction at 45mm

41	CLAY91	Mean clay fraction at 91mm
42	CLAY166	Mean clay fraction at 166mm
43	CLAY289	Mean clay fraction at 289mm
44	CLAY493	Mean clay fraction at 493mm
45	CLAY829	Mean clay fraction at 829mm
46	CLAY1383	Mean clay fraction at 1383mm
47	CLAY2296	Mean clay fraction at 2296mm
48	GRAV45	Mean gravel fraction at 45mm
49	GRAV91	Mean gravel fraction at 91mm
50	GRAV166	Mean gravel fraction at 166mm
51	GRAV289	Mean gravel fraction at 289mm
52	GRAV493	Mean gravel fraction at 493mm
53	GRAV829	Mean gravel fraction at 829mm
54	GRAV1383	Mean gravel fraction at 1383mm
55	GRAV2296	Mean gravel fraction at 2296mm
56	SAND45	Mean sand fraction at 45mm
57	SAND91	Mean sand fraction at 91mm
58	SAND166	Mean sand fraction at 166mm
59	SAND289	Mean sand fraction at 289mm
60	SAND493	Mean sand fraction at 493mm
61	SAND829	Mean sand fraction at 829mm
62	SAND1383	Mean sand fraction at 1383mm
63	SAND2296	Mean sand fraction at 2296mm
64	SILT45	Mean silt fraction at 45mm
65	SILT91	Mean silt fraction at 91mm
66	SILT166	Mean silt fraction at 166mm
67	SILT289	Mean silt fraction at 289mm
68	SILT493	Mean silt fraction at 493mm
69	SILT829	Mean silt fraction at 829mm
70	SILT1383	Mean silt fraction at 1383mm
71	SILT2296	Mean silt fraction at 2296mm
72	AWC_5	Available Water Capacity in mm/m 50 mm/m
73	AWC_4	Available Water Capacity in mm/m 75 mm/m
74	AWC_1	Available Water Capacity in mm/m 150 mm/m
75	AWC_3	Available Water Capacity in mm/m 100 mm/m
76	AWC_2	Available Water Capacity in mm/m 125 mm/m
77	AWC_6	Available Water Capacity in mm/m 15 mm/m
78	DRAINAGE_1	Surface soil drainage classes
79	DRAINAGE_2	Surface soil drainage classes
80	DRAINAGE_3	Surface soil drainage classes
81	DRAINAGE_4	Surface soil drainage classes
82	DRAINAGE_5	Surface soil drainage classes
83	DRAINAGE_6	Surface soil drainage classes
84	OC45	Mean Organic Carbon fraction at 45mm
85	OC91	Mean Organic Carbon fraction at 91mm
86	OC166	Mean Organic Carbon fraction at 166mm
87	OC289	Mean Organic Carbon fraction at 289mm
88	OC493	Mean Organic Carbon fraction at 493mm
89	OC829	Mean Organic Carbon fraction at 829mm
90	OC1383	Mean Organic Carbon fraction at 1383mm

91	OC2296	Mean Organic Carbon fraction at 2296mm
92	TEXTURE_1	Surface soil texture classes
93	TEXTURE_2	Surface soil texture classes
94	TEXTURE_3	Surface soil texture classes
95	TEXTURE_4	Surface soil texture classes
	Source: Copernicus, Product User Manual Land Cover 100m V2.0 (copernicus.eu)	
96	LULC1	Permanent water bodies
97	LULC2	open/closed forest
98	LULC3	Herbaceous vegetation, Moss and lichen
99	LULC4	Herbaceous wetland
100	LULC5	Cultivated and managed vegetation/agriculture (cropland)
101	LULC6	Shrubs
102	LULC7	Urban / built up
103	LULC8	Bare / sparse vegetation
104	LULC9	Snow and Ice
105	LULC10	Open/Closed forest, evergreen needle leaf
106	LULC11	Open/Closed forest, evergreen, broad leaf
107	LULC12	Open/Closed forest, deciduous needle leaf
108	LULC13	Opem/Closed forest, deciduous broad leaf
	Source: Historical climate data — WorldClim 1 documentation – 30s resolution	
109	Srad	Upstream mean solar radiation from 1970 to 2000
110	Vapr	Upstream mean vapor pressure from 1970 to 2000
111	Wind	Upstream mean windspeed from 1970 to 2000
112	mean.BIOC_1	Annual Mean Temperature
113	mean.BIOC_2	Mean Diurnal Range (Mean of monthly (max temp - min temp))
114	mean.BIOC_3	Isothermality (BIO2/BIO7) (×100)
115	mean.BIOC_4	Temperature Seasonality (standard deviation ×100)
116	mean.BIOC_5	Max Temperature of Warmest Month
117	mean.BIOC_6	Min Temperature of Coldest Month
118	mean.BIOC_7	Temperature Annual Range (BIO5-BIO6)
119	mean.BIOC_8	Mean Temperature of Wettest Quarter
120	mean.BIOC_9	Mean Temperature of Driest Quarter
121	mean.BIOC_10	Mean Temperature of Warmest Quarter
122	mean.BIOC_11	Mean Temperature of Coldest Quarter
123	mean.BIOC_12	Annual Precipitation
124	mean.BIOC_13	Precipitation of Wettest Month
125	mean.BIOC_14	Precipitation of Driest Month
126	mean.BIOC_15	Precipitation Seasonality (Coefficient of Variation)
127	mean.BIOC_16	Precipitation of Wettest Quarter
128	mean.BIOC_17	Precipitation of Driest Quarter
129	mean.BIOC_18	Precipitation of Warmest Quarter
130	mean.BIOC_19	Precipitation of Coldest Quarter

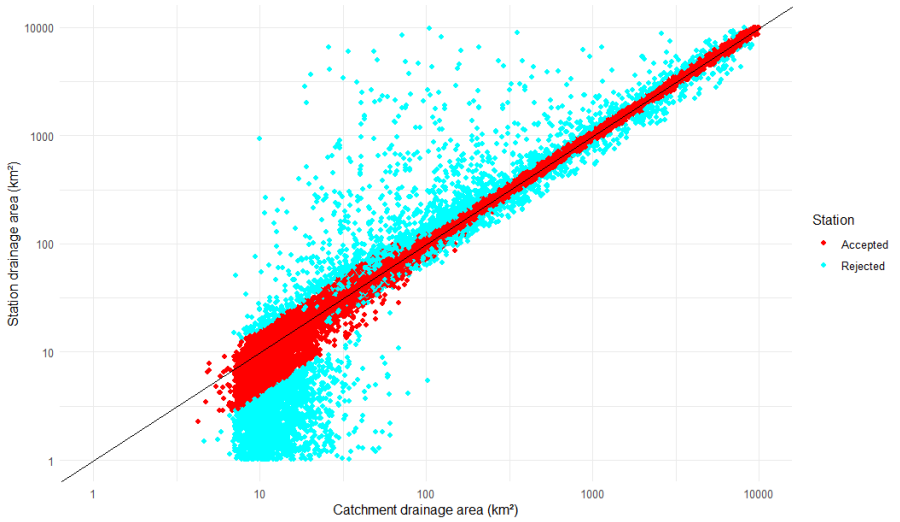

Figure S1: Catchment cumulative upstream drainage area and station drainage area comparison, calculated for a total of 43941 stations. Among these stations, 37336 met the specified criterion (maximum of either 15% of the upstream catchment drainage area or 60% of the catchment unit area) and were accepted, while 6605 stations were rejected.

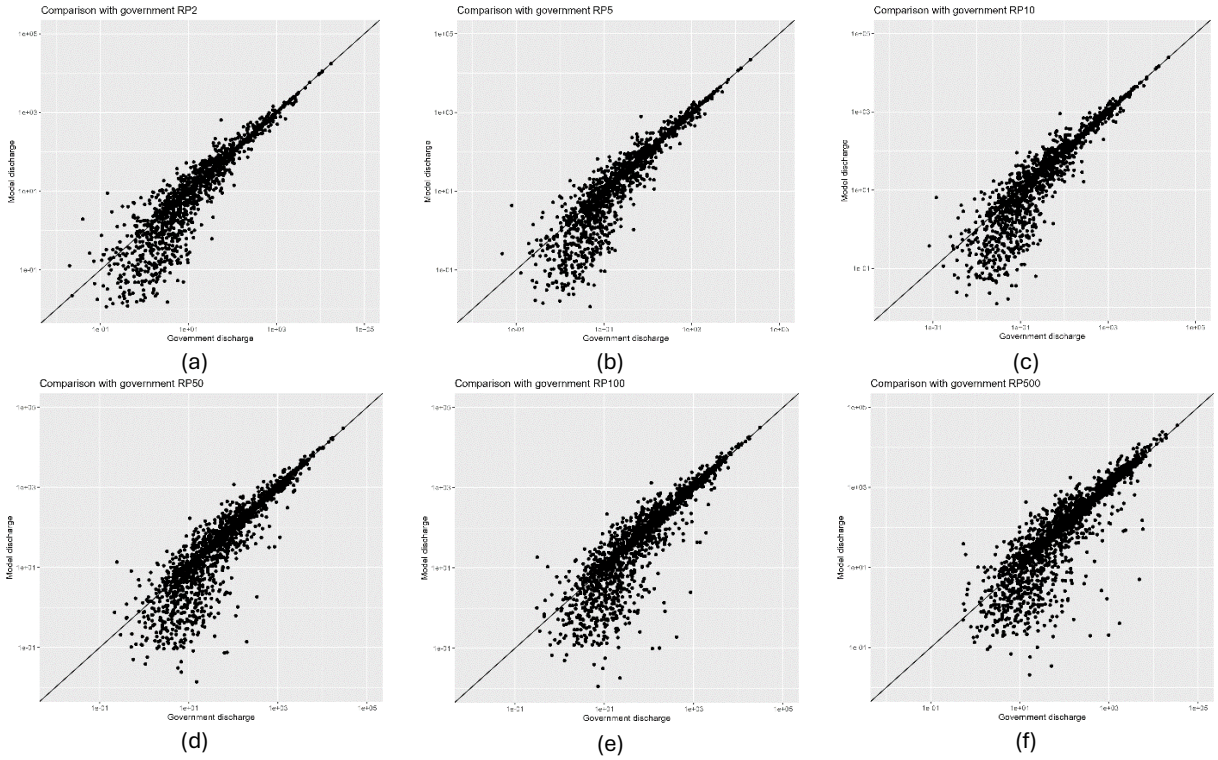

Figure S2: Comparison of the discharge return levels calculated with the marginal model (section 4.3.2, manuscript) (y-axis) and the return levels from government sources[1,2] (x-axis), for return periods 2, 5, 10, 50, 100, 500 years (a-f respectively) and for region 9 (British Columbia).

(1) U.S. Geological Survey: National Water Information System data, https://waterdata.usgs.gov/nwis, 2016

(2) Atlas hydroclimatique, https://www.donneesquebec.ca/recherche/dataset/atlas-hydroclimatique-2022, 2022.

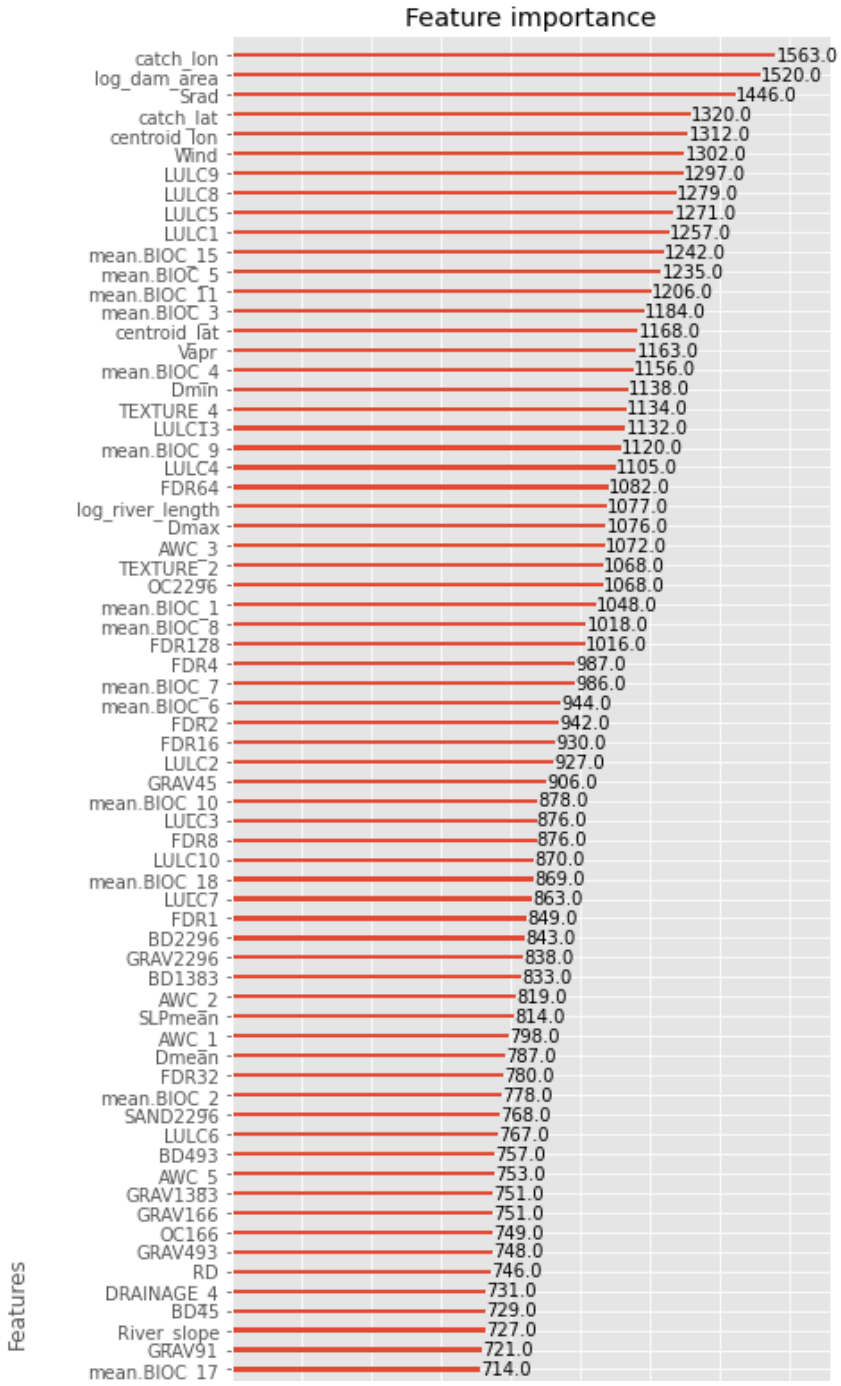

Figure S3: Feature importance for the XGBoost tau interpolation model applied to region 9, with importance decreasing from top to bottom.

Spatial flood analysis for regions 7 (St Lawrence), 8 (Prairie), 10 (East coast) and 11 (Midwest)

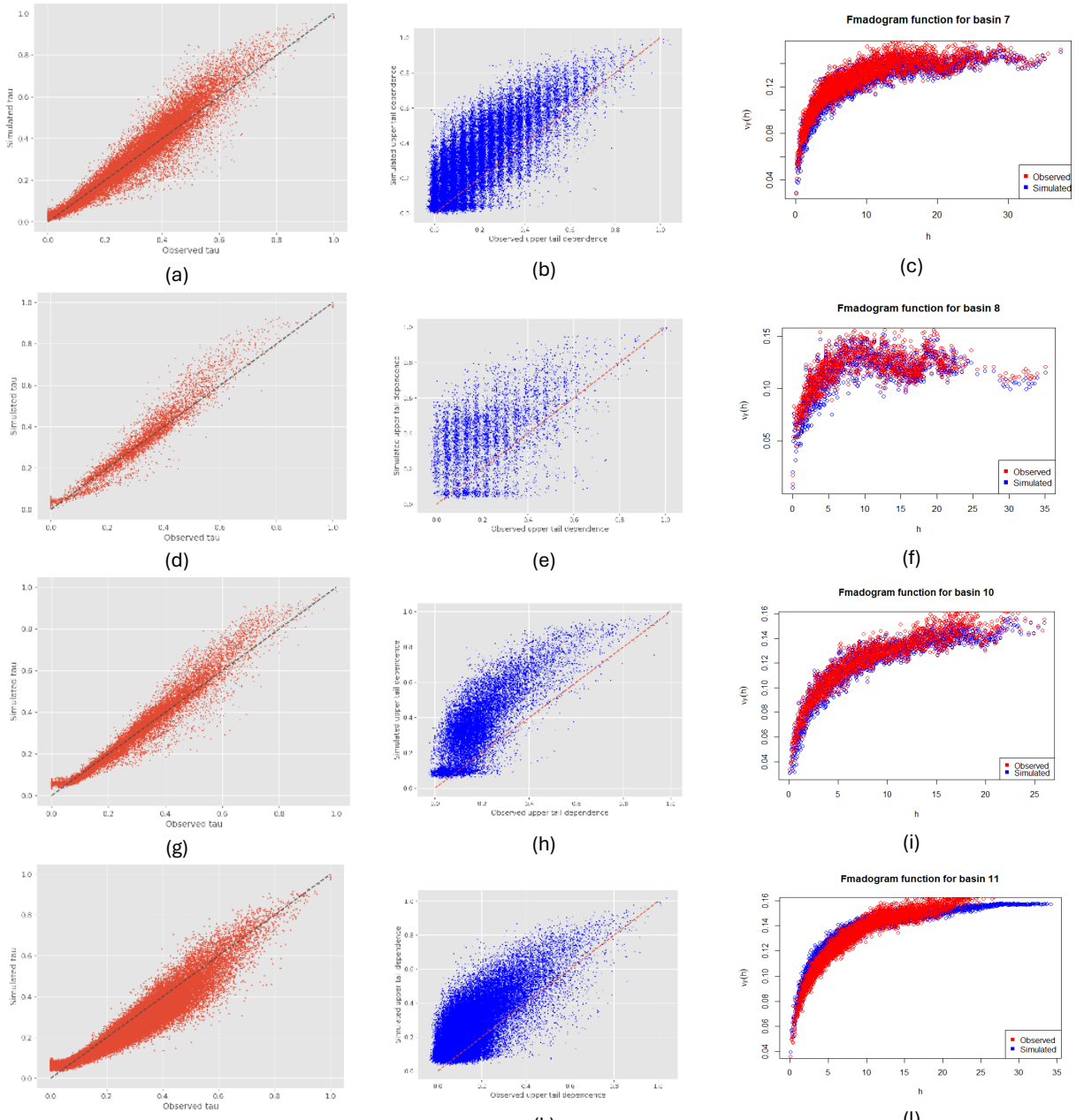

Figure S4: Validation of the Fisher copula model by comparing pairwise Kendall's taus, upper tail dependence and F-madogram for region 7 (a-c), 8 (d-f), 10 (g-i) and 11 (j-l).

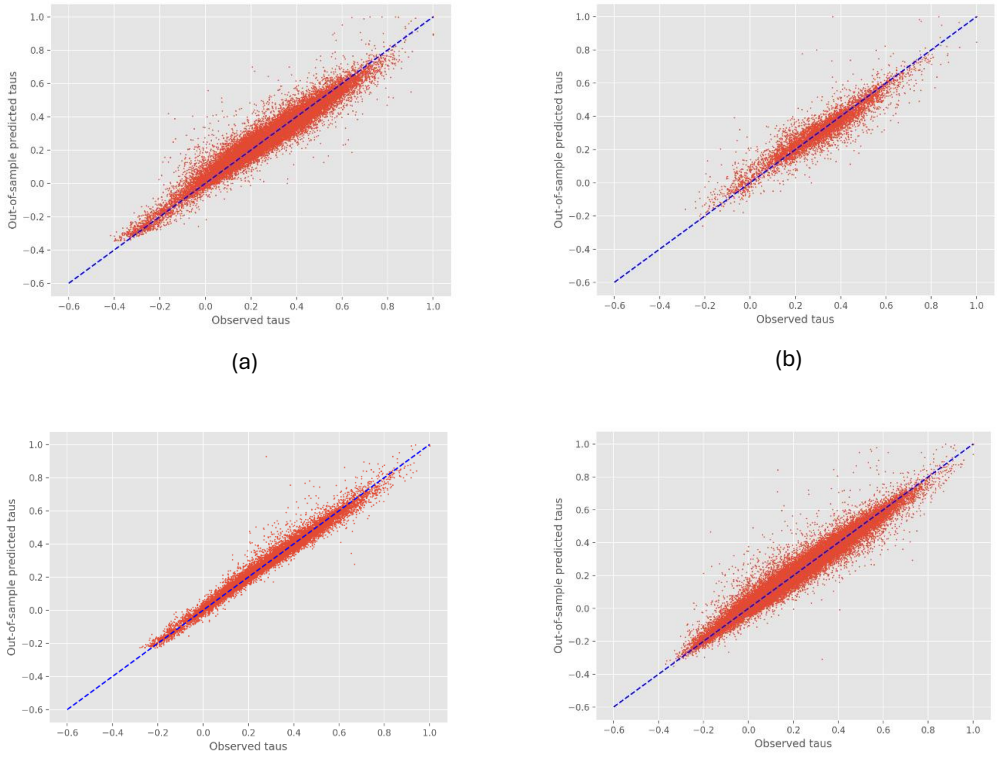

Figure S5: XGBoost tau interpolation model cross-validation results for regions 7, 8, 10 and 11 respectively (a-d). Out-of-sample Kendall's tau predictions are compared with the true values using 10-fold cross validation.

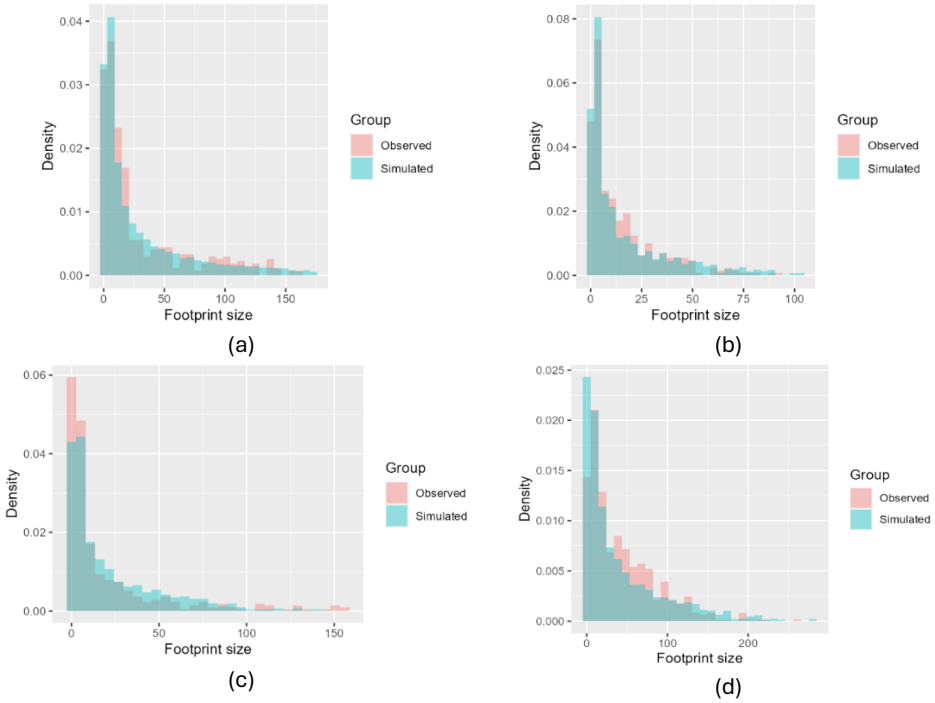

Figure S6: Histogram of event footprint sizes, defined as the number of gauges with a flow greater than the 0.9th quantile flow, for observed and simulated events, for region 7 (a), 8 (b), 10 (c) and 11 (d)

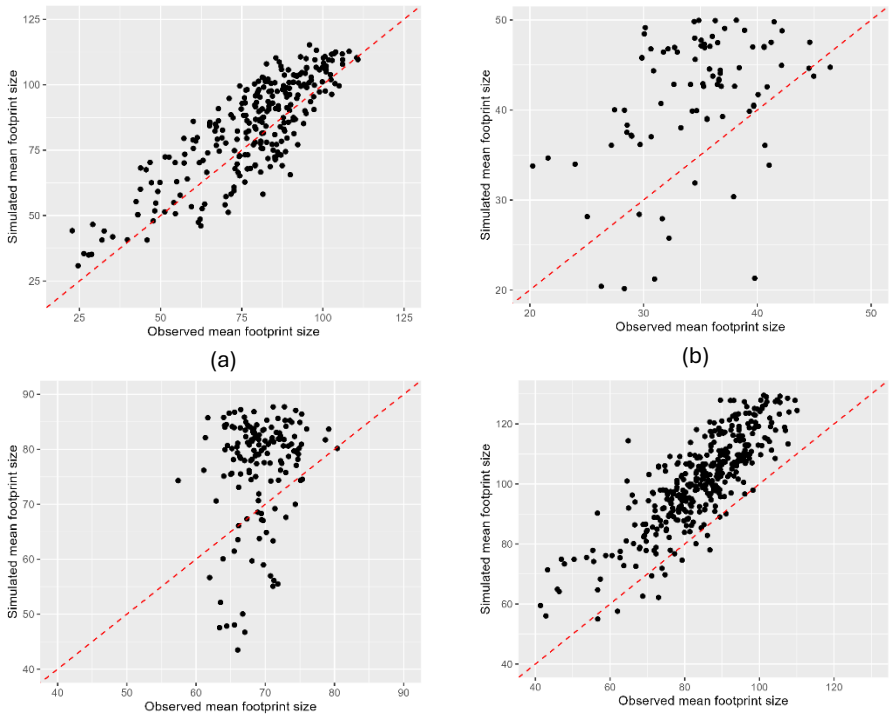

Figure S7: Mean event footprint size for the observed and simulated events at each gauged station, for region 7 (a), 8 (b), 10 (c) and 11 (d). The means are calculated over all events impacting each gauge with a flow greater than the 0.9th quantile flow.

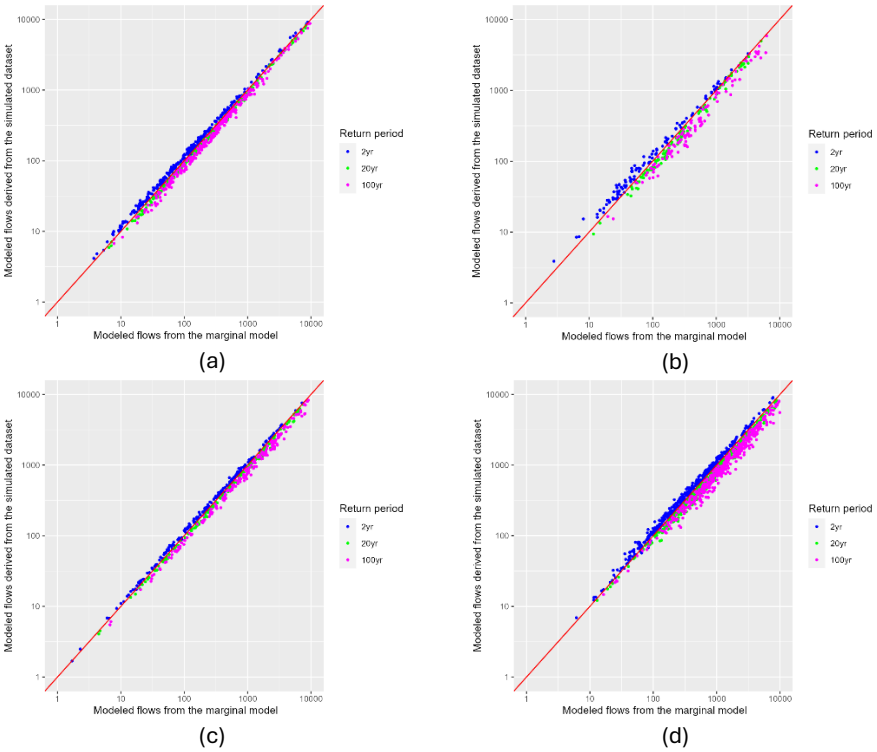

Figure S8: Discharge levels with return period 2 (blue), 20 (green) and 100 years (magenta) for all gauged stations, estimated from the synthetic event set and compared with the same quantities from the marginal model in section 4.3.2, for regions 7 (a), 8 (b), 10 (c) and 11 (d).

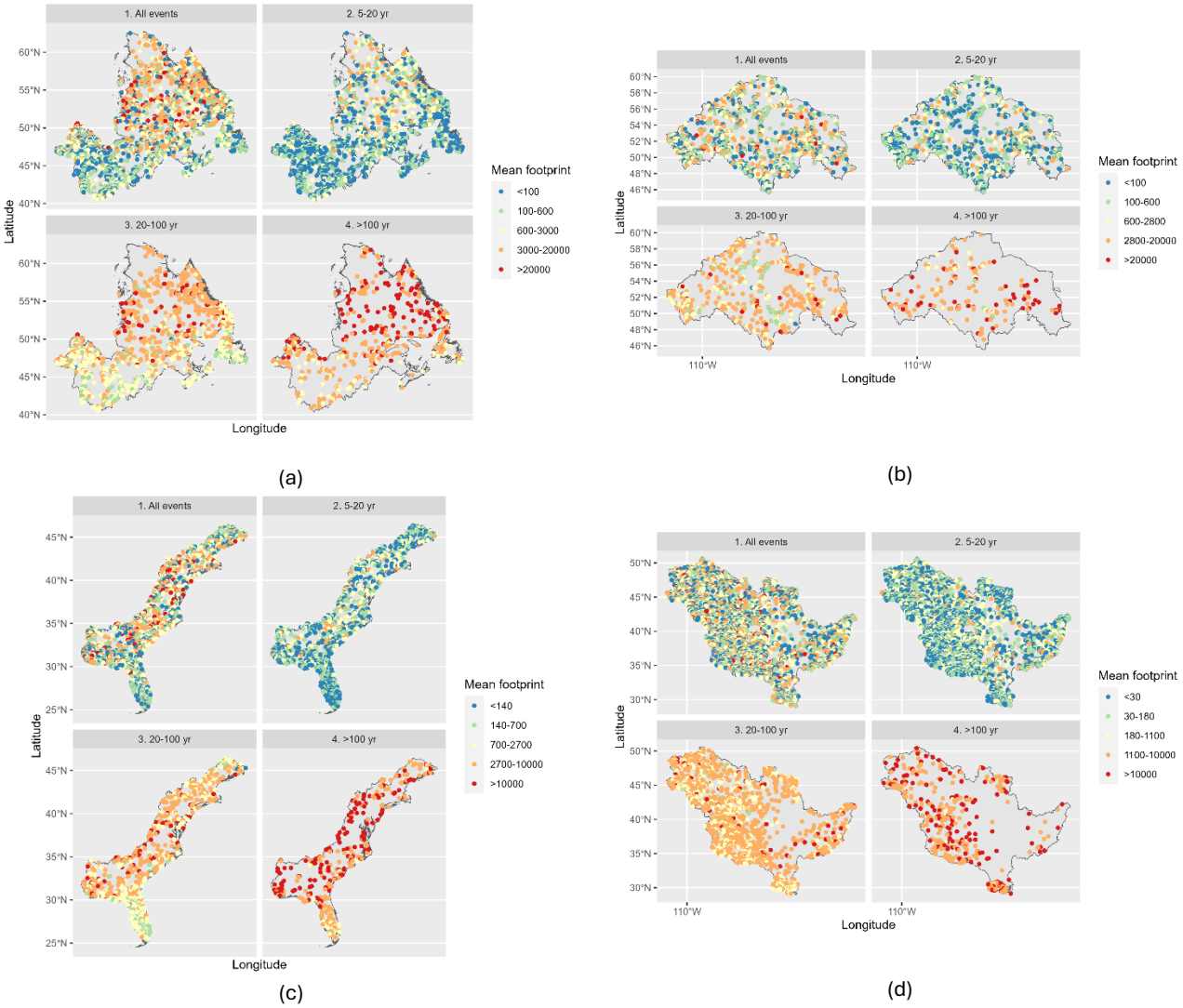

Figure S9: Mean event footprint size for catchments experiencing events with peak magnitude within one of four categories (> 5 (all events), 5-20, 20-100 and >100 year magnitudes), for region 7 (a), 8 (b), 10 (c) and 11 (d).

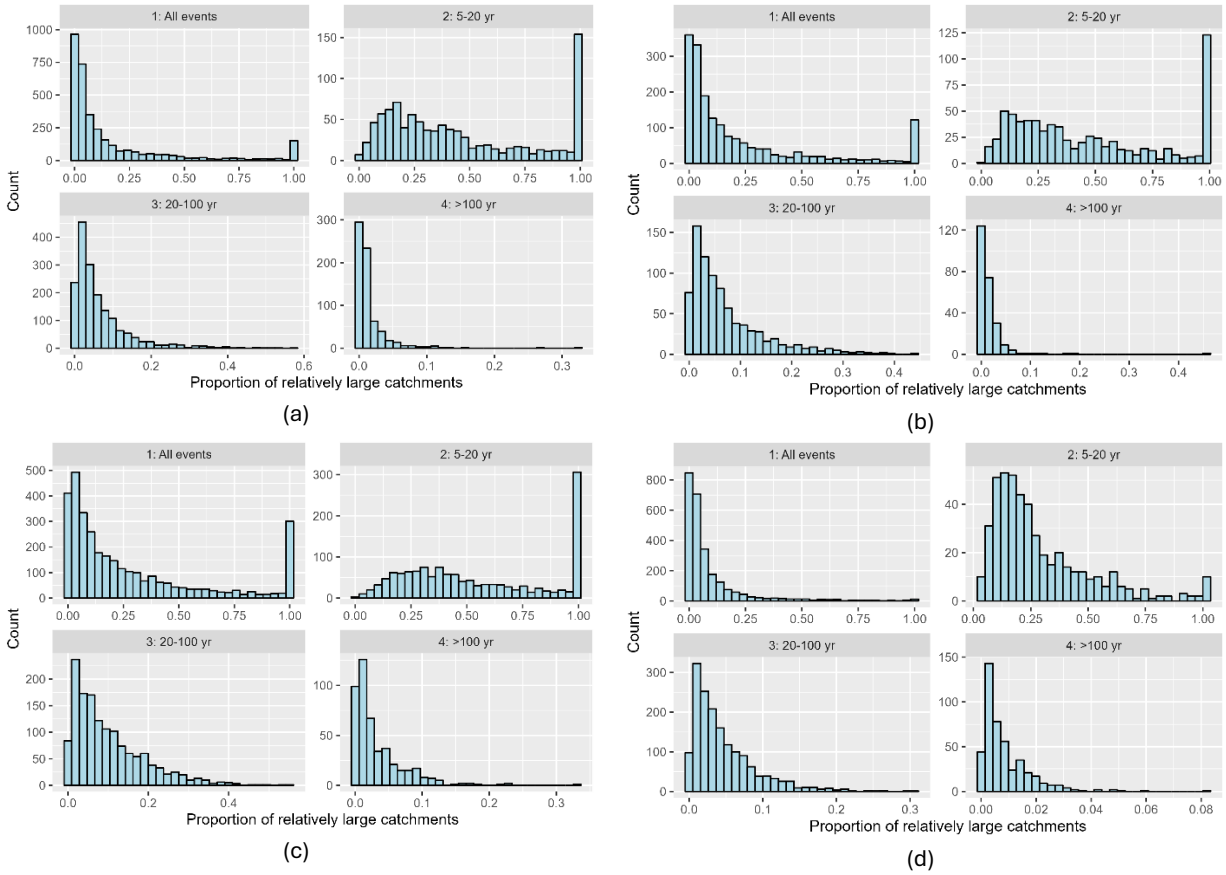

Figure S10: Histograms of the proportion of catchments in a given event with flow return period at least half the maximum event flow return period. The events are divided into four categories of magnitude: greater than 5, 5 to 20, 20 to 100 and greater than 100-year return period ranges. This is shown for region 7 (a), 8 (b), 10 (c) and 11 (d).