

Megafloods in Europe can be anticipated from observations in hydrologically similar catchments

Miriam Bertola, Günter Blöschl, Milon Bohac, Marco Borga, Attilio Castellarin, Giovanni B Chirico, Pierluigi Claps, Eleonora Dallan, Irina Danilovich, Daniele Ganora, et al.

▶ To cite this version:

Miriam Bertola, Günter Blöschl, Milon Bohac, Marco Borga, Attilio Castellarin, et al.. Megafloods in Europe can be anticipated from observations in hydrologically similar catchments. Nature Geoscience, 2023, 16, pp.982-988. 10.1038/s41561-023-01300-5 . hal-04344730

HAL Id: hal-04344730 https://hal.inrae.fr/hal-04344730

Submitted on 14 Dec 2023 $\,$

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers. L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés. 1 2

Megafloods in Europe can be anticipated from observations in hydrologically similar catchments

5

6 Author list

7 Miriam Bertola^{1*}, Günter Blöschl¹, Milon Bohac², Marco Borga³, Attilio Castellarin⁴,

- 8 Giovanni B. Chirico⁵, Pierluigi Claps⁶, Eleonora Dallan³, Irina Danilovich⁷, Daniele
- 9 Ganora⁶, Liudmyla Gorbachova⁸, Ondrej Ledvinka^{2,9}, Maria Mavrova-Guirguinova¹⁰,
- 10 Alberto Montanari⁴, Valeriya Ovcharuk¹¹, Alberto Viglione⁶, Elena Volpi¹², Berit
- 11 Arheimer¹³, Giuseppe Tito Aronica¹⁴, Ognjen Bonacci¹⁵, Ivan Čanjevac¹⁶, Andras
- 12 Csik¹⁷, Natalia Frolova¹⁸, Boglarka Gnandt¹⁷, Zoltan Gribovszki¹⁹, Ali Gül²⁰, Knut
- 13 Günther²¹, Björn Guse^{21,22}, Jamie Hannaford^{23,24}, Shaun Harrigan²⁵, Maria Kireeva¹⁸,
- ¹⁴ Silvia Kohnová²⁶, Jürgen Komma¹, Jurate Kriauciuniene²⁷, Brian Kronvang²⁸,
- 15 Deborah Lawrence²⁹, Stefan Lüdtke²¹, Luis Mediero³⁰, Bruno Merz^{21,31}, Peter
- 16 Molnar³², Conor Murphy²⁴, Dijana Oskoruš^{33,34}, Marzena Osuch³⁵, Juraj Parajka¹,
- 17 Laurent Pfister³⁶, Ivan Radevski³⁷, Eric Sauquet³⁸, Kai Schröter³⁹, Mojca Šraj⁴⁰, Jan
- 18 Szolgay²⁶, Stephen Turner²³, Peter Valent¹, Noora Veijalainen⁴¹, Philip J. Ward^{42,43},
- 19 Patrick Willems⁴⁴, Nenad Zivkovic⁴⁵.
- 20

21 Affiliations

- ¹Institute of Hydraulic Engineering and Water Resources Management, Technische Universität Wien, Vienna,
 Austria.
- 24 ²Czech Hydrometeorological Institute, Prague, Czechia.
- 25 ³Department of Land, Environment, Agriculture and Forestry, University of Padova, Padua, Italy
- ²⁶ ⁴Department of Civil, Chemical, Environmental and Materials Engineering (DICAM), Università di Bologna,
- 27 Bologna, Italy.
- 28 ⁵Department of Agricultural Sciences, University of Naples Federico II, Naples, Italy.
- ⁶Department of Environment, Land and Infrastructure Engineering (DIATI), Politecnico di Torino, Turin, Italy.
- 30 ⁷Climate Research Laboratory, Institute for Nature Management, The National Academy of Science of Belarus,
- 31 Minsk, Belarus.
- 32 ⁸Department of Hydrological Research, Ukrainian Hydrometeorological Institute, Kyiv, Ukraine.
- ³³⁹Department of Physical Geography and Geoecology, Faculty of Science, Charles University, Prague, Czechia.
- ³⁴ ¹⁰University of Architecture, Civil Engineering and Geodesy, Sofia, Bulgaria.
- 35 ¹¹Hydrometeorological Institute, Odessa State Environmental University, Odessa, Ukraine.
- 36 ¹²Department of Engineering, University Roma Tre, Rome, Italy.
- 37 ¹³Swedish Meteorological and Hydrological Institute, Norrköping, Sweden.
- 38 ¹⁴Department of Engineering, University of Messina, Messina, Italy.
- ³⁹ ¹⁵Faculty of Civil Engineering, Architecture and Geodesy, Split University, Split, Croatia.
- 40 ¹⁶Department of Geography, Faculty of Science, University of Zagreb, Zagreb, Croatia.
- 41 ¹⁷General Directorate of Water Management, Budapest, Hungary.
- 42 ¹⁸Department of Land Hydrology, Lomonosov Moscow State University, Moscow, Russia.

- 43 ¹⁹University of Sopron, Faculty of Forestry, Institute of Geomatics and Civil Engineering, Sopron, Hungary.
- 44 ²⁰Department of Civil Engineering, Faculty of Engineering, Dokuz Eylul University, Izmir, Turkey.
- 45 ²¹Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Section Hydrology, Potsdam,
- 46 Germany.
- 47 ²²Department of Hydrology and Water Resources Management, Institute for Natural Resource Conservation, Kiel
- 48 University, Kiel, Germany
- 49 ²³Centre for Ecology and Hydrology, Wallingford, UK.
- 50 ²⁴Irish Climate Analysis and Research Units (ICARUS), Department of Geography, Maynooth University,
- 51 Maynooth, Ireland.
- ⁵² ²⁵Forecast Department, European Centre for Medium-Range Weather Forecasts (ECMWF), Reading, UK.
- 53 ²⁶Department of Land and Water Resources Management, Faculty of Civil Engineering, Slovak University of
- 54 Technology in Bratislava, Bratislava, Slovakia.
- 55 ²⁷Lithuanian Energy Institute, Kaunas, Lithuania
- ²⁸Department of Ecoscience, Danish Centre for Environment and Energy, Aarhus University, Aarhus, Denmark.
- 57 ²⁹Norwegian Water Resources and Energy Directorate, Oslo, Norway.
- 58 ³⁰Department of Civil Engineering: Hydraulic, Energy and Environment, Universidad Politécnica de Madrid,
- 59 Madrid, Spain.
- 60 ³¹Institute of Environmental Sciences and Geography, University Potsdam, Potsdam, Germany
- 61 ³²Institute of Environmental Engineering, ETH Zurich, Zurich, Switzerland.
- 62 ³³Department of Hydrotechnics, Faculty of Geotechnical Engineering, University of Zagreb, Varaždin, Croatia.
- 63 ³⁴Croatian Meteorological and Hydrological Service, Zagreb, Croatia.
- ⁶⁴ ³⁵Department of Hydrology and Hydrodynamics, Institute of Geophysics Polish Academy of Sciences, Warsaw,
- 65 Poland.
- ⁶⁶ ³⁶Luxembourg Institute of Science and Technology (LIST), Esch-sur-Alzette, Luxembourg.
- 67 ³⁷Institute of Geography, Faculty of Natural Sciences and Mathematics, Ss. Cyril and Methodius University,
- 68 Skopje, North Macedonia.
- 69 ³⁸Irstea, UR RiverLy, Lyon-Villeurbanne, France.
- ³⁹Leichtweiss Institute for Hydraulic Engineering and Water Resources, Technische Universität Braunschweig,
- 71 Braunschweig, Germany.
- ⁴⁰Faculty of Civil and Geodetic Engineering, University of Ljubljana, Ljubljana, Slovenia.
- 73 ⁴¹Finnish Environment Institute, Helsinki, Finland.
- ⁴²Institute for Environmental Studies (IVM), Vrije Universiteit Amsterdam, The Netherlands.
- ⁴³Deltares, Delft, The Netherlands.
- 76 ⁴⁴Department of Civil Engineering, KU Leuven, Leuven, Belgium.
- ⁴⁵Faculty of Geography, University of Belgrade, Belgrade, Serbia.
- 78 *Corresponding author. E-mail: bertola@hydro.tuwien.ac.at
- 79
- 80

81 Abstract

82 Megafloods that far exceed previously observed records often take citizens and 83 experts by surprise, resulting in extremely severe damage and loss of life. Existing 84 methods based on local and regional information rarely go beyond national borders 85 and cannot predict these floods well because of limited data on megafloods, and 86 because flood generation processes of extremes differ from those of smaller, more frequently observed events. Here we analyse river discharge observations from over 87 88 8000 gauging stations across Europe and show that recent megafloods could have 89 been anticipated from those previously observed in other places of Europe. Almost all 90 observed megafloods (95.5%) fall within the envelope values estimated from previous 91 floods at other similar places on the continent, implying that local surprises are not 92 surprising at the continental scale. This holds also for older events, indicating that 93 megafloods have not changed much in time relative to their spatial variability. The 94 underlying concept of the study is that catchments with similar flood generation 95 processes produce similar outliers. It is thus essential to transcend national 96 boundaries and learn from other places across the continent to avoid surprises and 97 save lives.

98

99 Main Text

100 Megafloods that are much larger than floods experienced previously in a given catchment or region, can take citizens and local flood managers by surprise, resulting 101 102 in catastrophic damage and loss of life. For example, the discharge of the July 2021 103 flood at the Rhine tributaries in Germany, and rivers in the Netherlands, Belgium and 104 Luxembourg, was up to four times larger than any event on record in the region¹, 105 causing almost 200 fatalities and damage in excess of \$40 billion. In this and other 106 cases, the lack of previous local experience of events of this magnitude resulted in 107 insufficient flood defence measures, preparedness and real-time response^{1,2}.

108 Because of their rare occurrence, megafloods are difficult to predict. The standard 109 method of estimating the magnitude of potential large floods consists of fitting a 110 probability distribution to long series of flood observations, and extrapolating the 111 distribution to small probabilities³. However, long series that include several exceptional events are rarely available. Some estimation methods use flood 112 observations from neighbouring catchments⁴, to make up for the brevity of streamflow 113 114 records which, however, rarely increases the chances of capturing megafloods. Even when such events are observed, accurate discharge estimates are difficult to obtain 115 as the flood wave may partially bypass the gauge and difficulties with extrapolating the 116 117 rating curve. Moreover, the processes that generate extreme floods tend to differ from 118 those that generate smaller and more frequent events⁵, making extrapolation 119 notoriously inaccurate. One way of capturing changing flood processes with 120 magnitude is through rainfall-runoff models, but they require long series of precipitation and are also subject to uncertainty^{6,7,8}. Large floods in historic or prehistoric times 121

(paleofloods) can also be used, although the information available is often not
 commensurate with the requirements of flood management^{9,10,11}.

124 An alternative for enhancing the accuracy of megaflood estimates is the transfer of 125 flood information from hydrologically similar catchments where large events may have 126 occurred⁴. In Europe the occurrence of megafloods is well documented at the national 127 scale. The August 2002 flood in Germany, Austria and Bohemia was the largest in the 128 last half century based on economic losses; the November 1994 Piedmont flood was 129 the second costliest event in Europe between 1970 and 2020¹². Both events were 130 caused by rainfall greater than one-third of the annual total, delivered in only 72 hours^{13,14}. However, flood information transfer rarely goes beyond national borders, 131 and no previous study has examined megafloods in a systematic way across an entire 132 133 continent, with the objective of learning from other places about the potential of future 134 flood surprises. Some examples comparing the world's maximum measured floods 135 also exist¹⁵, but they do not compare hydrologically similar catchments, which makes flood estimation less useful for practical proposes. 136

137

138 Anticipating megafloods

139 Here we analyse the most comprehensive dataset of annual maximum discharges in Europe available to date and show that recent megafloods could have been 140 anticipated from observations in other parts of Europe, which would not be possible 141 142 using national data only. We also show that the predictability of megafloods does not change in time when sub-periods are analysed. We base our analysis on annual 143 maximum river discharge observations from 8023 gauging stations for the period 144 1810–2021. The average length of the series is 51.4 years and the catchment areas 145 146 range between 1 km² and 800,000 km². Catchments across Europe are grouped into 147 five hydroclimatic regions (Fig. 1) as a first step of identifying hydrologically similar catchments¹⁶. For each region, we estimate a regional envelope curve of flood 148 149 discharges that represents the relationship between flood discharge and catchment 150 area that is not exceeded by any observed flood in the region (see Methods; Extended 151 Data Table 2). To examine possible changes in time, we also compare envelope 152 curves obtained using observations from two 30-year sub-periods, i.e., 1961-1990 and 153 1991-2020.

154 We focus on 498 catchments ("target" catchments) where 510 recent (i.e. after 1999) megafloods that are surprising based on local data are identified (see Methods). To 155 156 evaluate the possibility of anticipating megafloods in target catchments using 157 information from other places in Europe, we perform a hindcast experiment of predicting their peak discharge with regional envelope curves, using flood 158 159 observations from similar catchments up to the year before their occurrence. For each target catchment, a group of similar catchments ("donor" catchments) is identified in 160 161 the corresponding hydroclimatic region based on the similarity of catchment area and 162 the mean and coefficient of variation of the truncated flood series (up to the year before 163 the megaflood). From this group of donor catchments we construct an envelope curve

- 164 which we compare with the megaflood that occurred later in the target catchments.
- 165 We repeat this analysis for all 510 detected megafloods in the target catchments.
- 166

167 European envelope curves of flood discharges

Our data show that recent megafloods have occurred in all regions of Europe, although they are more frequent in the Atlantic and Continental regions (Fig.1; Extended Data Table 3), where respectively 8.7% and 7.2% of the catchments exhibit recent megafloods. In the Boreal region, the respective value is only 1.3%. The smaller value is related to the smaller interannual variability of floods in the Boreal region¹⁷.

- In the Atlantic region, the megafloods (coloured points in Fig. 1b-f) are on average 3.4 times larger than the local mean annual maximum discharges (squares), while in the Continental and Mediterranean regions they are 5.3 and 5.2 times larger (Extended Data Table 3). The larger ratio in the Mediterranean is likely related to the more nonlinear rainfall-runoff process and more variable precipitation in arid than in humid climates^{5,18}. However this analysis is not able to conclude whether megafloods are becoming more frequent or not.
- 180 The envelope curves defined by the largest floods also differ between hydroclimatic regions in terms of their intercept and slope (thick continuous lines in Fig. 1b-f; 181 Extended Data Table 2). For a catchment size of 1000 km², the envelope specific 182 discharge in the Mediterranean region is 5.26 m³s⁻¹km⁻² while in the Boreal region it is 183 1.37 m³s⁻¹km⁻². This is because the flood-inducing rainstorms in the Mediterranean 184 185 are associated with much larger intensities than the flood-inducing snowmelt typical of Northern Europe. The slopes of the envelope curves are steepest in the Mediterranean 186 area (-0.57) and flattest (-0.07) in the Boreal region (Fig. 1). This is because the 187 188 Mediterranean rainstorms tend to be more localised than the snowmelt in the North of Europe. The envelope curves for the most recent sub-period (thin dotted lines) tend to 189 190 be slightly lower than those for the first sub-period (thin dashed lines), except for the 191 Mediterranean and the Atlantic region. The median regression curves (thin continuous lines) are slightly flatter than the respective envelopes, as larger catchments tend to 192 193 have more regular flood regimes than small ones. Figs. 1g-j illustrate examples of flood 194 series in pairs of catchments with and without megafloods.

195 To illustrate the potential of anticipating megafloods from other places in Europe, Fig. 196 2 shows three examples. The 2002 flood in the Kamp catchment in Austria (Fig. 2a) 197 peaked at 459 m³s⁻¹ which is equivalent to a specific discharge of 0.74 m³s⁻¹km⁻² (black triangle) given the catchment area of 622 km². The envelope curve (blue line), defined 198 199 by the hydrologically similar catchments within the hydroclimatic region, gives a specific discharge of 1.68 m³s⁻¹km⁻². This means that, in light of European floods, the 200 Kamp was not at all surprising while for the locals it was¹⁹. The regional envelope 201 202 discharge illustrated in Fig. 2 is defined based on previously observed floods in various 203 European countries, including Bulgaria and Poland (blue circles in Fig. 2d).

The 2009 flood in the Cumbrian Derwent catchment in the UK (Fig. 2b) peaked at 0.84 m³s⁻¹km⁻² and was 58% larger than the second largest event on record which occurred in 2005. The corresponding envelope specific discharge is 1.64 m³s⁻¹km⁻². Much larger extremes were observed in similar catchments in Norway (Fig. 2e). The 2009 megaflood in the Derwent was itself exceeded in 2015, however this later event still lies below the envelope curve and was not as surprising as the 2009 event (11% larger)².

The 2021 flood in the Ahr catchment in Germany (Fig. 2c) peaked at 0.80 m³s⁻¹km⁻², 211 similar to the Kamp flood, with an envelope estimate of 1.57 m³s⁻¹km⁻². For the Ahr 212 213 catchment, the similar catchments making up the donor group are, in descending order 214 of flood magnitude: the Timis in Romania, the Freiberger Mulde in Germany, the 215 Maritsa in Bulgaria, the Lijg in Serbia, the Lausitzer Neisse in Germany, the Corrèze 216 and Le Lot in France, the Nysa Kłodzka in Poland and the Birs in Switzerland (Fig. 3). 217 Although each of these catchments has a specific hydrological behaviour, overall they can be considered hydrologically similar to the Ahr in terms of average climate and 218 219 flood statistical properties. All of these ten catchments experienced record-breaking 220 floods that were surprising based on previously observed events at that location, and 221 these occurred in the period before 2021 (Fig. 3).

222 The analysis of Fig. 2 is repeated for all 510 recent megafloods in the target 223 catchments in Europe (Fig. 4). In 95.5% of the target catchments, the discharge of the envelope is larger than that of the observed megaflood, suggesting that, from a 224 225 European perspective, almost none of the events can be considered a regional 226 surprise. In 9.6% of the cases, the observed megafloods are within 75% and 150% of 227 the envelope (red points in Fig. 4a), i.e. the order of magnitude is similar. The target 228 catchments are distributed all over Europe with a higher concentration in the West 229 (Fig. 4b), reflecting positive trends in flood magnitudes in Western Europe^{20,21} and, to 230 some degree, the higher station density.

The prediction is also conducted for 151 and 188 catchments with 151 and 190 recent (i.e. in the last 10 years of each sub-period) megafloods in the first and second subperiod, respectively. The distribution of the ratio between observed and predicted discharge (inset of Fig. 4a) indicates that there are no substantial changes in the predictability of megafloods in time. The discharge of the envelope is larger than that of the observed megaflood in 92% and 93.7% of the respective target catchments.

237 To evaluate the suitability of the donor selection, we compare the timing within the 238 year of the target megafloods with that of the ten largest floods in the donor catchments (Fig. 4c). Flood timing is a proxy of flood generation processes²². Fig. 4c shows that 239 the timing of the target megafloods (black lines) generally agrees with that of the 240 241 donors (brown lines), both in terms of the average timing (angle from the centre of the circle) and the consistency of timing between events (distance to the centre). The 242 243 agreement points towards the plausibility of the donor selection and prediction. A 244 tendency for the observed timings to be more bimodal than the predictions is likely 245 related to the smaller number of events.

246

247 Implications of expanding the perspective

Whereas previous studies have assessed the potential for megafloods mainly based on local or regional data, this study expands the observation area to the continental scale. We use megafloods that have occurred in hydrologically similar catchments elsewhere on the continent as a surrogate for the megafloods that could happen in the catchment of interest in the future.

The degree to which this transfer of information is possible depends on the suitable 253 254 choice of donor catchments based on the notion of hydrological similarity²³. The underlying concept is that catchments with similar flood generation processes, 255 256 including rainfall, infiltration and flow paths, produce similar outliers, as these processes determine the transition from smaller to larger events^{5,24,25}. Here we use 257 catchment area and the mean and coefficient of variation of the truncated flood series 258 259 within the same hydroclimatic region as a proxy of similarity in flood generation 260 processes. While other similarity measures exist¹⁶, our donor catchment selection is deemed plausible because of the similarity of the timing within the year of the events, 261 262 given that timing is a fingerprint of the interplay between climatic and catchment processes²². Additional spot testing of catchment pairs (such as the Ahr catchment in 263 Germany paired with the Timis catchment in Romania) based on prior knowledge from 264 the literature^{1,25} confirms the similarity. To assess robustness of the method we 265 conduct a sensitivity analysis on the parameters of the similarity criteria and the choice 266 of hydroclimatic regions (Extended Data Fig. 1-8). The results show that changing 267 268 parameters and/or regions may modify individual donor catchments, but the envelope curve that arises from the set of donor catchments is affected much less (see method 269 270 section for details).

271 The cross-validation experiment conducted here, starting from observed megafloods, withholding them and only using data from floods that have occurred previously, 272 273 mimics the case of anticipating megafloods that have not yet occurred. We show that 274 it is indeed feasible to estimate the order of magnitude of possible future megafloods. 275 Almost all observed megafloods (95.5%) are smaller than the envelope values 276 estimated, i.e. the local surprises are not surprising at the continental scale. Similar 277 results are found for different sub-periods, indicating that megafloods have not changed much in time relative to their spatial variability within Europe. These findings 278 279 are in line with recent studies in the US showing little evidence for temporal trends of 280 large floods²⁶.

The proposed envelope curve approach complements alternative methods such as regional statistical approaches that spatially interpolate observed discharges⁴ or process-based rainfall-runoff modelling²⁷. These methods provide best estimates of expected floods, while the envelope method reflects a possible worst case – which itself is an important aspect of flood risk planning. 286 The focus on a possible worst case implies that the envelope values are generally too 287 large to serve as design values for most types of flood defence infrastructure from a cost-benefit perspective. Rather, they describe a possibility space²⁸ that is prudent to 288 consider as civil protection scenarios, required to organise local preparedness, and 289 290 for testing the safety of very large dams. They can be used to derive extreme flood 291 hazard scenarios, either failure scenarios (what can go wrong?) or future development 292 scenarios (what could the future look like?) that could strengthen existing methods such as the Probable Maximum Flood (PMF) concept²⁹. There is an increasing need 293 294 for considering the extremes of the extremes, as there is a tendency in society for 295 smaller acceptable risks²⁹, so flood risk management should account for the potential 296 of surprises and their devastating consequences. This requires a shift in thinking²⁹ and the application of envelope curves, storylines^{2,30} and compound event analyses³¹. 297 Making individuals and societies more robust against surprises therefore goes beyond 298 299 the design of spillways and flood management plans.

In summary, to anticipate megafloods we must learn from other places in order to reduce the surprise factor of their occurrence, increase flood risk awareness and enhance preparedness of flood risk management. To this end, it is essential to move beyond national flood risk assessment and share information on megafloods across countries and continents.

305

306 Acknowledgements

307 We acknowledge all flood data providers listed in Extended Data Table 1. G. Blöschl and M. Bertola 308 were supported by the FWF projects 'SPATE' (I 3174, I 4776) and W1219-N22. B. Merz and B. 309 Guse were supported by the DFG 'SPATE' project (FOR 2416). A.Viglione, P.Claps, D. Ganora, 310 M. Borga and E. Dallan were supported by the European Union Next-GenerationEU 'RETURN' 311 Extended Partnership (National Recovery and Resilience Plan - NRRP, Mission 4, Component 312 2, Investment 1.3 – D.D. 1243 2/8/2022, PE0000005). S. Kohnová and J. Szolgay were supported 313 by the Slovak Research and Development Agency (number APVV-20-0374) and the VEGA Grant 314 Agency (number 1/0782/21). J. Hannaford and S.Turner were supported by the ROBIN (Reference 315 Observatory of Basins for INternational hydrological climate change detection) initiative, with 316 funding from the Natural Environment Research Council (grant number NE/W004038/1). The 317 authors acknowledge the involvement in the data screening process of M. Haas.

318

319 Author Contributions Statement

320 G. Blöschl and M. Bertola initiated the study and wrote the first draft of the paper. M. Bertola, G. 321 Blöschl, M. Borga, A.C., P.C., E.D., D.G., A.M., A.V. and E.V. designed the study. M. Bertola 322 collated the updated version of the database with the help of most of the co-authors and conducted 323 the analyses. G. Blöschl, M. Bertola, interpreted the results in the context of underlying geophysical 324 mechanisms. G. Boglarka, M. Boháč, A.C., S.K., O.L., S.L. M.M.-G., K.G., Z.G., B.G., J.K., B.M., 325 P.M., J.P., L.P., I.R., K.S., J.S., P.V., P. Ward, P. Willems., and N.Ž. interpreted the results in 326 central Europe. G.T.A., O.B., M. Borga, A.C., I.Č., G.B.C., P.C., E.D., D.G., A.G., A.M., L.M., D.O., 327 M.Š., A.V. and E.V. interpreted the results in southern Europe. B.A., B.K., D.L., and N.V. 328 interpreted the results in northern Europe. J.H., S.H., C.M., S.T., and E.S. interpreted the results 329 in western Europe. I.D., N.F., L.G., M.K., J.K., M.O. and V.O. interpreted the results in eastern 330 Europe. All authors contributed to framing and revising the paper.

- 331
- 332

333 Competing Interests Statement

- 334 The authors declare no competing interests.
- 335

Figure Captions



337

Fig. 1: Megafloods in Europe. (a) Five hydroclimatic regions: Boreal (purple), 338 339 Continental (blue), Mediterranean (orange), Alpine (green) and Atlantic (red). (b-f) 340 Maximum observed specific flood discharges (points) and mean of annual specific flood discharges (squares) over the entire observation period at each stream gauge 341 342 as a function of catchment area. Regional envelope curves (thick lines) and median 343 regional annual specific flood discharges (thin lines) for the full record period are 344 shown for each hydroclimatic region. Envelope curves for two 30-year sub-periods are also shown (dashed lines for 1961-1990, dotted lines for 1991-2020). Parameters of 345 the envelope curves are listed in Extended Data Table 2. Coloured symbols indicate 346 the mean and maximum flood discharges in the 498 catchments with recent 347 348 megafloods, grey points those of the remaining catchments. (g-j) Examples of series 349 of annual flood discharges with (g and i) and without (h and j) megafloods; their corresponding mean (squares) and maximum values (points) are highlighted in black 350 in (c) and (f). The locations of corresponding stream gauges are indicated in (a) by 351 352 circles.

353





355 Fig. 2: Envelope curves for three catchments with recent megafloods in Europe. 356 (a,d) Kamp (622 km² catchment area) with 2002 flood; (b,e) Cumbrian Derwent (363 km²) with 2009 flood, and (c,f) Ahr (746 km²) with 2021 flood, indicated with triangles. 357 (a-c) Maximum specific discharges observed before the year of occurrence of the 358 megaflood for 824 (a), 196 (b) and 590 (c) similar donor catchments (points) selected 359 360 within the corresponding hydroclimatic region. Coloured points indicate ten largest 361 events (in terms of distance to the envelope curve), with shades being darker for events that are closer to the envelope. Line shows resulting envelope curve with the 362 363 slope estimated from the hydroclimatic regions (Fig. 1b-f). (d-f) Location of the target (triangle) and donor (points) catchments. Note that the envelope curves of Fig. 1 refer 364 365 to the entire hydroclimatic region, while here they refer to the donor group within a region. 366

367



368

369 Fig. 3: Annual flood series for the Ahr and ten donor catchments with extreme

370 **floods.** (a) Ahr at Altenahr, Germany, with 2021 megaflood (the target event) indicated

371 as a triangle. (b-k) Series for the ten donor catchments indicates as coloured dots in372 Fig. 2c,f).

373



374

375 Fig. 4: Predicted versus observed megafloods. (a) Predicted specific envelope discharge for 498 target catchments versus observed specific discharge of the 376 377 megafloods in the same catchments. Predicted envelope discharges are estimated using discharge observations from a pool of donor catchments up to the year before 378 379 the target megaflood. The number of target megafloods is shown in the inset for the entire period ("all") and the two sub-periods 1961-1990 ("P1") and 1991-2020 ("P2"). 380 Colours indicate the ratio of observed and predicted discharge. (b) Location of target 381 382 catchments. Megafloods occur all over Europe and are less surprising than commonly assumed. (c) Circular distribution of the timing of the megafloods observed in the 383

- target catchments (black lines), and mean timing of the 10 largest floods in the donor
- catchments (coloured points) and their distribution (brown lines). The distance of the
 points to the centre is inversely proportional to the standard deviation of the flood
 timing.
- - -
- 388 389

390 **References**

- Apel, H., Vorogushyn, S., & Merz, B. Brief communication–Impact Forecasting Could
 Substantially Improve the Emergency Management of Deadly Floods: Case Study July 2021
 floods in Germany. Natural Hazards and Earth System Sciences Discussions, 1-10 (2022).
- Kreibich, H., Van Loon, A.F., Schröter, K. et al. The challenge of unprecedented floods and droughts in risk management. Nature 608, 80–86 (2022).
- Be Niel, J., Demarée, G., Willems, P. Weather typing based flood frequency analysis validated for
 exceptional historical events of past 500 years along the Meuse river, Water Resources
 Research, 53(10), 8459-8474 (2017).
- Robson, A. J. and Reed, D. W. Flood Estimation Handbook (FEH), chap. Statistical procedures
 for flood frequency estimation, p. Vol. 3, Institute of Hydrology, Wallingford, UK (1999).
- 401 5. Rogger, M., Pirkl, H., Viglione, A., Komma, J., Kohl, B., Kirnbauer, R., Merz, R., & Blöschl, G.
 402 (2012). Step changes in the flood frequency curve: Process controls. Water Resources Research,
 403 48(5), 1–15.
- 404
 6. Bergstrand M., Asp S. and Lindström G. Nationwide hydrological statistics for Sweden with high
 405
 resolution using the hydrological model S-HYPE. Hydrology Research, 45.3, 349-356 (2014).
- 406
 407
 407
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
 408
- 8. Bouaziz, L. et al. Behind the scenes of streamflow model performance, Hydrol. Earth Syst. Sci.,
 25, 1069–1095 (2021).
- 411
 9. Kjeldsen, T.R. et al. Documentary evidence of past floods in Europe and their utility in flood
 412 frequency estimation. Journal of Hydrology, 517, 963–973 (2014).
- 413
 10. Blöschl, G., Kiss, A., Viglione et al. Current European flood-rich period exceptional compared with
 414 past 500 years. Nature, 583(7817), 560–566 (2020).
- 415 11. U.S. Geological Survey Scientific Investigations Report 2020–5065, 89 p. (2020).
- 416
 417
 417
 417
 417
 417
 417
 417
 417
 417
 417
 417
 417
 417
 417
 417
 417
 417
 417
 417
 417
 417
 417
 417
 417
 417
 417
 417
 417
 417
 417
 417
 417
 417
 417
 417
 417
 417
 417
 417
 417
 417
 417
 417
 417
 417
 417
 417
 417
 417
 417
 417
 418
 418
 418
 418
 418
 418
 418
 418
 418
 418
 418
 418
 418
 418
 418
 418
 418
 418
 418
 418
 418
 418
 418
 418
 418
 418
 418
 418
 418
 418
 418
 418
 418
 418
 418
 418
 418
 418
 418
 418
 418
 418
 418
 418
 418
 418
 418
 418
 418
 418
 418
 418
 418
 418
 418
 418
 418
 418
 418
 418
 418
 418
 418
 418
 418
 418
 418
 418
- 418
 418
 419
 419
 420
 420
 43. Blöschl, G., Nester, T., Komma, J., Parajka, J., & Perdigão, R. A. P. The June 2013 flood in the Upper Danube Basin, and comparisons with the 2002, 1954 and 1899 floods. Hydrology and Earth System Sciences, 17(12), 5197–5212 (2013).
- 421 14. Lionetti, M. The Italian floods of 4–6 November 1994. *Weather*, *51*(1), 18-27 (1996).
- 422 15. Herschy, R. W. (2002). The world's maximum observed floods. Flow Measurement and
 423 Instrumentation, 13(5–6), 231–235. https://doi.org/10.1016/S0955-5986(02)00054-7
- 424 16. Kuentz, A., Arheimer, B., Hundecha, Y., and Wagener, T. Understanding hydrologic variability
 425 across Europe through catchment classification, Hydrol. Earth Syst. Sci., 21, 2863-2879 (2017)

- 426 17. Lun, D., Viglione, A., Bertola, M., Komma, J., Parajka, J., Valent, P., & Blöschl, G. Characteristics
 427 and process controls of statistical flood moments in Europe a data-based analysis. Hydrology
 428 and Earth System Sciences, 25(10), 5535–5560 (2021).
- 429 18. Blöschl, G. Flood generation: process patterns from the raindrop to the ocean, Hydrol. Earth Syst.
 430 Sci., 26, 2469–2480 (2022)
- 431
 431
 432
 432
 433
 434
 434
 434
 435
 435
 436
 436
 436
 437
 438
 438
 438
 439
 439
 430
 430
 430
 431
 431
 431
 431
 432
 432
 432
 433
 434
 434
 434
 435
 435
 436
 436
 437
 437
 438
 438
 438
 438
 439
 439
 430
 430
 431
 431
 431
 431
 431
 432
 432
 432
 433
 434
 434
 434
 435
 434
 435
 434
 435
 434
 435
 434
 435
 434
 435
 434
 435
 434
 435
 434
 435
 434
 435
 434
 435
 434
 435
 434
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
 435
- 433 20. Blöschl, G., Hall, J., Viglione, A. et al. Changing climate both increases and decreases European
 434 river floods. Nature, 573(7772), 108–111 (2019).
- 435 21. Bertola, M., Viglione, A., Lun, D., Hall, J., & Blöschl, G. Flood trends in Europe: are changes in
 436 small and big floods different? Hydrology and Earth System Sciences, 24(4), 1805–1822 (2020).
- 437 22. Blöschl, G., Hall, J., Parajka, J., Perdigão, R. A., Merz, B., Arheimer, B., ... & Živkoviæ, N.
 438 Changing climate shifts timing of European floods. Science, 357(6351), 588-590 (2017).
- 439 23. Blöschl, G., Sivapalan, M., Wagener, T., Viglione, A., Savenije, H.H. Runoff Prediction in
 440 Ungauged Basins Synthesis across Processes, Places and Scales. Cambridge University Press
 441 (2013).
- 442 24. Kemter, M., Merz, B., Marwan, N., Vorogushyn, S., & Blöschl, G. Joint Trends in Flood
 443 Magnitudes and Spatial Extents Across Europe. Geophysical Research Letters, 47(7), 1–8
 444 (2020).
- 445 25. Popescu, I., Jonoski, A., Van Andel, S. J., Onyari, E., & Moya Quiroga, V. G. Integrated modelling
 446 for flood risk mitigation in Romania: case study of the Timis–Bega river basin. International journal
 447 of river basin management, 8(3-4), 269-280 (2010).
- 26. Collins, M. J., Hodgkins, G. A., Archfield, S. A., & Hirsch, R. M. (2022). The occurrence of large
 floods in the United States in the modern hydroclimate regime: Seasonality, trends, and largescale climate associations. Water Resources Research, 58,
- 451 e2021WR030480. https://doi.org/10.1029/2021WR030480
- 452 27. Donnelly, C, Andersson, J.C.M. and Arheimer, B. Using flow signatures and catchment similarities
 453 to evaluate a multi-basin model (E-HYPE) across Europe. Hydr. Sciences Journal 61(2):255-273
 454 (2016)
- 455 28. Sivapalan, M., & Blöschl, G. Time scale interactions and the coevolution of humans and water.
 456 Water Resources Research, 51(9), 6988–7022 (2015).
- 457 29. Merz, B., Vorogushyn, S., Lall, U., Viglione, A., & Blöschl, G. Charting unknown waters-On the
 458 role of surprise in flood risk assessment and management. Water Resources Research, 51(8),
 459 6399–6416 (2015).
- 30. Shepherd, T. G. Storyline approach to the construction of regional climate change information.
 Proceedings of the Royal Society A, 475(2225), 20190013 (2019).
- 462 31. Thieken, A. H., Samprogna Mohor, G., Kreibich, H., and Müller, M.: Compound inland flood
 463 events: different pathways, different impacts and different coping options, Nat. Hazards Earth
 464 Syst. Sci., 22, 165–185 (2022).
- 465

466 Methods

467

468 Datasets

The hydrological data used in this study were obtained from a pan-European Flood 469 470 Database³² with subsequent updates. The current version contains data from 8,023 471 hydrometric gauging stations from 68 European data sources for the period 1810-472 2021 (Extended Data Table 1). The dataset consists of the highest discharge (daily 473 mean or instantaneous discharge) in each calendar year for each station. The stations are located within the domain bounded by 22.25° W-63.25° E and 34.25° N-71.25° N 474 475 (Extended Data Fig. 1), and catchment areas range between 1 km² and 800,000 km². 476 The dataset was screened for data errors. The screening involved visual examination of the flood records, analysis of flood seasonality and examination of the guage 477 478 location and catchment area in Google Maps. All available stations, including those 479 affected by reservoir construction, were considered for the analysis because reservoir 480 effects were deemed to have little significance for envelope curves for large 481 hydroclimatic regions. Similarly, all available years with data were considered notwithstanding differences in the record lengths, because the focus was on the 482 483 maxima observations of each series. The minimum series length is 10 years, and the 484 average length is 51.4 years.

485 The gauging stations were grouped into five regions (Fig. 1a; Extended Data Fig.1) 486 that reflect similar hydroclimatic conditions by generalising the European Biogeographical regions³³ with a view on flood processes. The Steppic and Pannonian 487 regions were merged with the Continental region, the Arctic region with the Boreal 488 region, and the Anatolian and Black Sea regions with the Mediterranean region. 489 490 Additionally, part of northern Italy was considered as part of the Mediterranean region 491 and Iceland as part of the Atlantic region. For comparison, an alternative subdivision of Europe into five regions¹⁷ was considered in a sensitivity analysis (Extended Data 492 493 Fig. 4a). In order to examine possible changes, the observation period was subdivided 494 into two 30-year sub-periods, P1 (1961-1990) and P2 (1991-2020).

495

496 **Regional envelope curves**

We quantified the largest flood events in each region by scaling the peak discharges
by catchment area via envelope curves that represent the upper limit of the dataset
(Fig. 1):

500

$$log(q) = a + b \cdot log(A) \tag{1}$$

where q (m³s⁻¹km⁻²) is the specific discharge, i.e. the discharge per unit catchment area *A*. The parameter *b* was estimated by quantile regression with quantile *z*=0.999 using the rq function of the R quantreg package^{34,35}. The quantile regression enables a more robust estimate than the tangents on the maxima, because it uses the complete dataset rather than the maxima only. The intercept *a* was determined such that it

- satisfies the envelope condition, i.e. the envelope curve is the upper bound of all observed flood discharges in a region (Extended Data Table 2). For comparison, a guantile regression with z=0.5 is also shown in Fig. 1 (thin line).
- 509

510 Megafloods

- 511 For the selection of recent megafloods (Fig. 4) the following criteria were adopted:
- (i) the discharge value is a high outlier in the corresponding series of annual maximum
- 513 flood discharges, according to the definition³⁶:
- 514

$$q_{mf} > Q_3 + k * (Q_3 - Q_1)$$
 (2)

where Q_1 and Q_3 are the first and third quartile (i.e. respectively 25% and 75% of the observations lies below this values) and *k*=3;

- (ii) the discharge value is record-breaking and locally surprising, i.e., its return period T_{mf} is at least 3 times larger than the return period of the second largest event up to
- that year T_{sl} . The return period was obtained by fitting a GEV distribution to each flood
- 520 series up to the year of the megaflood using the L-moments (R extRemes package).
- (iii) it occurred after the year 1999 (when the full observation period is analysed) and
 the corresponding series has at least 20 years of data previous to the event.
- 523 The selection resulted in a set of 510 megafloods from 498 target catchments, whose 524 observed specific discharge and location of corresponding gauges are shown in Fig. 525 4a and 4b. When detecting megafloods in the two 30-year sub-periods, only 526 observations within each sub-period are considered and the criterion (iii) is modified 527 such that events in the last 10 years of the respective sub-period are selected (i.e. 528 after 1979 for P1 and after 2009 for P2).
- 529 We tested the robustness of the results to the criterion (i) for the selection of high 530 outliers, using the definition for skewed data³⁷:
- 531 $\begin{cases} q_{mf} > Q_3 + 1.5e^{3MC}IQR & if MC > 0\\ q_{mf} > Q_3 + 1.5e^{4MC}IQR & if MC < 0 \end{cases}$ (3)
- 532 Where MC is the medcouple³⁸, a robust measure of skewness, defined as:
- 533 $MC(X_n) = \operatorname{med}_{x_i \le m_n \le x_j} h(x_i, x_j)$ (4)

534 with m_n is the sample median of X_n and

535
$$h(x_i, x_j) = \frac{(x_j - m_n) - (m_n - x_i)}{x_j - x_i}$$
(5)

536 The alternative selection resulted in a set of 677 megafloods (Supplementary Fig. S1),

whose observed specific discharge and location of corresponding gauges are shownin Supplementary Fig. S2.

- 539 We also tested the sensitivity of the results to criterion (ii) for the selection of record-540 breaking and surprising events, by varying the threshold T_{mf}/T_{sl} between 1 and 4. The 541 results of the sensitivity analysis are shown in Supplementary Fig. S3 and indicate
- 542 that, when the definition of megafloods is extended to less surprising events (i.e. T_{mt}/T_{sl}
- $_{J+2}$ mat, when the definition of megalloods is extended to less surprising events (i.e. I_{mf}/I_{sl}
- 543 <3), the fraction of megaflooods larger than the envelope is unchanged. The only</p>
- 544 exception is the Boreal region, where fewer events are selected.
- 545

546 **Donor catchments**

For each catchment in which a megaflood had occurred (target catchment), a pool of similar catchments (donor catchments) was identified in the same region. The similarity between the catchments was quantified in terms of weighted normalised Euclidean distance *D* in a three-dimensional space with the following dimensions: the logarithm of catchment area *A*, the logarithm of the mean of the annual maximum specific discharges q_m normalised to a catchment area of 100km², and the coefficient of variation *CV* of the annual maximum discharges:

554
$$D = \sqrt{\alpha \left(\frac{\log A_i - \log A_j}{sd(\log A)}\right)^2 + \beta \left(\frac{\log q_{m,i} - \log q_{m,j}}{sd(\log q_m)}\right)^2 + \gamma \left(\frac{CV_i - CV_j}{sd(CV)}\right)^2} \quad (6)$$

where *i* refers to the target catchment, *j* to a potential donor catchment and *sd* is the 555 standard deviation of all catchments in the donor group. Greek letters indicate weights. 556 557 q_m and CV were calculated on flood data prior to the year of occurrence of the target event to obtain a cross-validation experiment that resembles a case of anticipating 558 559 megafloods a priori. In estimating q_m and CV we excluded outliers (for both the target and the donor catchments) according to the criterion of Eq. (2), because megafloods 560 561 should not influence the comparison, and only smaller, frequently occurring floods 562 were used, which is the only information usually available in the case of a prediction. 563 In selecting the number of catchments in the pooling group, there is a tradeoff between a larger group that has a higher chance of containing very large floods, and a smaller 564 565 group that is hydrologically more homogeneous. For Fig. 1, 2, 3 we used $\alpha = \beta = \gamma = 1$ (corresponding to the assumption of the three dimensions having the same 566 importance) and included catchments with $D < D_{max}$ with $D_{max} = 1$, guided by a sensitivity 567 568 analysis (see below and Extended Data Fig. 2).

569

570 Megaflood prediction

We repeated the selection of the donor group for each target catchment and estimated the envelope curve, using the slope *b* of the corresponding hydroclimatic region and the intercept determined as the minimum that satisfies the envelope condition of the group only. The procedure only uses observations from donor catchments up to the year before the megaflood in the target catchment (Fig. 2a-c). We finally obtained an estimate of the discharge of a potential megaflood in the target catchment (predicted 577 megaflood) from the envelope curve and compared it to the discharge of the observed578 megaflood (Fig. 4a).

579 In order to evaluate the plausibility of the donor selection we analysed the timing of 580 the megafloods observed in the target and donor catchments using previously 581 established methods²² (Fig. 4c). We compared the distribution of the timing of the 582 observed megafloods to the average timing of the 10 largest floods in the donor group.

- 583 The circular distributions in Fig. 4c were obtained using the R circular package.
- 584

585 In order to evaluate the robustness of the method we conducted a number of sensitivity 586 analyses. We varied D_{max} between 0.5 and 1.5 and showed that an increase in D_{max} translates into an increasing number of target megafloods that are below the envelope 587 588 (Extended Data Fig. 2). The larger fraction in the Boreal region is because of fewer 589 donors available compared to the other regions. We also tested the sensitivity of α , β 590 and γ , examining four weight combinations: equal weights ($\alpha = \beta = \gamma = 1$) and doubling 591 one of the weights (α =2 and $\beta = \gamma = 1$; $\alpha = \gamma = 1$ and $\beta = 2$; $\alpha = \beta = 1$ and $\gamma = 2$), which 592 corresponds to the hypothesis of one dimension being more important than the others in the donor selection. There is very little effect on the number of target megafloods 593 594 below the envelope (Extended Data Fig. 3). While a different set of parameters may 595 modify some of the donor catchments, the resulting envelope curve changes very little. 596 Finally we tested the effect of replacing the regional subdivision of Fig. 1 by an alternative subdivision¹⁷. The analysis shows that the alternative regions may modify 597 598 the choice of individual donor catchments but, again, the overall conclusions do not 599 change (Extended Data Fig. 4-7).

600

601 Data availability

602 The flood discharge data from the data holders/sources listed in Extended Data

- Table 1 that were used in this paper are available at
- 604 https://github.com/tuwhydro/megafloods.
- 605

606 Code availability

The data analysis was performed in R using the supporting packages circular,
lubridate, plotrix, quantreg, raster, RColorBrewer, rgdal, rworldmap and scales. The
code used can be downloaded from https://github.com/tuwhydro/megafloods.

610

611 Methods-only references

612
 32. Hall, J. et al. A European Flood Database: facilitating comprehensive flood research beyond
 613 administrative boundaries. Proc. Int. Assoc. Hydrol. Sci. 370, 89–95 (2015)

- 614 33. Roekaerts, M.: The biogeographical regions map of Europe, in: Basic principles of its creation
 615 and overview of its development, European Environment Agency, Copenhagen, available at:
 616 https://www.eea.europa.eu/data-and-maps/ data/biogeographical-regions-europe-3 (2002).
- 617 34. Koenker, R. W. Quantile Regression, Cambridge U. Press (2005).
- 618 35. Amponsah, W., Marra, F., Marchi, L., Roux, H., Braud, I., Borga, M. Objective Analysis of
 619 Envelope Curves for Peak Floods of European and Mediterranean Flash Floods. In: Leal
 620 Filho, W., Nagy, G., Borga, M., Chávez Muñoz, P., Magnuszewski, A. (eds) Climate Change,
 621 Hazards and Adaptation Options. Climate Change Management. Springer, Cham (2020).
- 622 36. Tukey JW. Exploratory Data Analysis. Reading (Addison-Wesley): MA, 1977.
- 623
 623
 624
 37. Hubert, M., & Vandervieren, E. (2008). An adjusted boxplot for skewed distributions. Computational statistics & data analysis, 52(12), 5186-5201.
- 625
 626
 38. Brys G, Hubert M, Struyf A. A robust measure of skewness. J. Comput. Graph. Stat. 2004;
 13: 996–1017.