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Current European flood-rich period exceptional compared with past 500~years

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2 **Current flood-rich period exceptional compared to past 500** 3 **years in Europe**

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11ABSTRACT

12There are concerns that recent climate change is altering the frequency and magnitudes of river
13floods in an unprecedented way¹. Historical studies have identified flood-rich periods in the past half
14millennium in various regions of Europe². However, because of the low temporal resolution of
15existing data sets and the relatively low number of series across Europe, it has remained unclear
16whether Europe is currently in a flood-rich period from a long term perspective. We analyze how
17recent decades compare with the flood history of Europe, using a new database composed of more
18than 100 high-resolution (sub-annual) historical flood series based on documentary evidence
19covering all major regions of Europe. Here we show that the past three decades were among the
20most flood-rich periods in Europe in the last 500 years, and that this period differs from other flood-
21rich periods in terms of its extent, air temperatures and flood seasonality. We identified nine flood-
22rich periods and associated regions. Among the periods richest in floods are 1560-1580 (Western
23and Central Europe), 1760-1800 (most of Europe), 1840-1870 (Western and Southern Europe), and
241990-2016 (Western and Central Europe). In most parts of Europe previous flood-rich periods
25occurred during cooler than usual phases, however the current flood-rich period has been much
26warmer. In the past, the dominant flood seasons in flood-rich periods were similar to those during
27the intervening (interflood) periods, but flood seasonality is more pronounced in the recent period.
28For example, during previous flood and interflood periods, 41% and 42% of Central European floods
29occurred in summer respectively, compared to 55% of floods in the recent period. The uniqueness of
30the present-day flood-rich period calls for process-based flood risk assessment tools and flood risk
31management strategies that account for these changes.

32

33MAIN TEXT

34Historical flood context

35In recent decades numerous devastating floods have occurred in Europe with enormous economic
36damage³. Flood data over the past 50 years suggest that some parts of Europe are experiencing
37upward flood trends⁴, but it is unclear whether we are currently in a flood-rich period (more
38frequent and bigger floods than usual in extent and/or magnitude) and, if so, how unusual it is
39relative to other flood-rich periods during the past 500 years. An exceptional flood-rich period in
40recent decades would require more intensive and perhaps different adaptation measures than a less
41unusual period. To understand whether recent decades are indeed exceptional, one needs to
42identify flood-rich periods and their characteristics in past centuries and compare them with recent
43decades.

44The existence of flood-rich periods in the last 500 years has been demonstrated for a number of
45individual catchments in Europe based on historical documentary evidence^{5, 6, 7, 8} and mountain lake
46sediments⁹. One of the few available regional studies (19 documentary-based data series) identified
471540-1600, 1640-1700, 1730-1790 and 1790-1840 as flood-rich periods in Central Europe², which is
48roughly consistent with sedimentary evidence from a set of Alpine lakes¹⁰ and six floodplains¹¹ in
49Central Europe. Several authors have suggested that more frequent flooding in the Little Ice Age
50(1300-1870), and specifically the late Maunder Solar Minimum (1675-1725), can be related to lower
51air temperatures^{6, 2, 12, 8}, but a more universal relationship with air temperatures for other flood-rich
52periods has not been identified^{7, 13, 11}. Temperature anomalies can be considered a proxy for changes
53in the atmospheric circulation system and are therefore of relevance for assessing past and future
54flood frequency changes.

55Here we analyse the most comprehensive data set of 103 sub-annual flood series over the past 500
56years covering all regions of Europe (Extended Data Fig. 1) in order to examine the existence and
57characteristics of flood-rich periods.

58Reconstructing historical flood frequency

59The flood series are based upon the collation of published and unpublished series based on
60chronicles, annals, administrative and legal records, newspapers, and private and official
61correspondence (Extended Data Table 1). We almost exclusively used contemporary documentation
62(i.e. written shortly after the flood events) because of its higher reliability relative to non-
63contemporary documentation. The documentation included direct indicators, such as the level and
64spatial extent of flood waters relative to identifiable landmarks and, to a lesser extent, indirect
65indicators such as their environmental or socio-economic impact. For each piece of evidence, a
66critical, historical source evaluation was conducted, utilizing the local socio-economic and
67environmental history knowledge of the analysts, in order to minimise errors in dating,
68interpretation and other possible mistakes originating from social biases.

69For 103 river reaches across Europe the documentary evidence on individual floods was transformed
70into a three-scaled intensity index for the period 1500-2016. The total number of floods contained in
71the data set are 9576, of which 8954 have a season assigned. In order to account for differences in
72the representativeness of different series in space, we assigned to each series a representativeness
73index, which reflects the level of confidence that important floods have been captured. In order to
74account for temporal observational biases, we assigned each year of each series a rank on a bias
75index that reflects the completeness of the source material in a historical context. While there is
76inevitable subjectivity in assigning these indexes, decisions are nonetheless made on the basis of
77expert judgment of the sources and phenomena in question.

78The intensity indices of the series were spatially-temporally interpolated, accounting where possible
79for uncertainty and bias (see methods section), which resulted in a three dimensional matrix of flood

80intensities over Europe in the last 500 years with voxel size of 41km*48km*4yrs. This matrix was
81used to identify contiguous flood-rich periods in space and time by applying an algorithm that
82connects neighbouring voxels that exceed an intensity threshold. We ranked these flood-rich periods
83by the sum of the scaled space-time extent and the scaled mean flood intensity. Based on a 500-year
84Central European air temperature reconstruction¹⁴, which we consider to currently be the highest
85quality multi-centennial reconstruction in Europe and to be spatially representative (see method
86section), we compared the average air temperatures of these flood-rich periods with those of the
87interflood periods before and after. Additionally, we analysed the seasonality of flood occurrence in
88the flood-rich and interflood periods.

89

90Flood-rich periods in past 500 years

91Here we find that the past three decades were among the most flood-rich in Europe during the last
92500 years, and that this period differs from other flood-rich periods in terms of its extent, associated
93air temperatures and flood seasonality.

94The nine flood-rich periods identified are rather regularly distributed in time, but the latest 30 year
95period is separated from the past periods by a 90-year disaster gap in most of Europe with the
96occurrence of few floods (Fig. 1, Table 1, Fig. 2) in line with historical flood impact research¹⁵. The
97most highly ranked flood-rich periods, on the basis of their space-time extent and flood intensity,
98were 1560-1580 (period II in Western and Central Europe), 1760-1800 (period V in most of Europe),
991840-1870 (period VI in Western and Southern Europe), and 1990-2016 (period IX in Western and
100Central Europe) (Table 1, Video 1).

101Individually, the nine flood-rich periods cover only part of Europe with areas between 0.41 and 1.83
10210⁶ km² (Extended Data Table 2), out of a total land area of xx 10⁶ km² examined. There is a tendency
103for flood-rich periods to occur more often in Central and Western Europe than in other regions (Fig.
1041, Fig. 3).

105The most recent flood-rich period is 1990-2016, the second largest in spatial extent (1.77 10⁶ km²)
106and the third largest in spatio-temporal extent (18.7 10⁶ km².yrs), indicating that it not only covered
107a large part of Europe, but also a significant duration in time (Extended Data Table 2). 2016 is the
108end of the data and possibly not the end of this flood-rich period.

109The average air temperatures in most Central European flood-rich periods were around 0.3°C lower
110than those in the intervals between flood-rich periods (termed interflood periods) (Fig. 4). Flood-rich
111period II was particularly cold and is known for the great glacier advances in the Alps¹⁶. The
112confidence bounds of the temperatures in most flood-rich periods of the past vs the interflood
113periods in Fig. 4b are below the 1:1 line, indicating that the differences are statistically significant.
114The only exception was period IV (1630-1660), with average annual temperature similar to those of
115the interflood periods, resulting from warm summers, however autumns and winters when most of
116the floods occurred were notably colder than usual¹⁷. This is consistent with the other flood-rich
117periods that were colder overall than the interflood periods. In other parts of Europe, there is also a
118tendency for flood-rich periods I to VIII to be colder than the interflood periods, with differences of
119about 0.3°C and 0.2°C in Western and Southern Europe, respectively (Extended Data Fig. 4).

120While flood-rich periods in the past have thus mostly been associated with comparatively colder air
121temperatures, this is not the case for the most recent flood-rich period IX, which was on average
122about 1.4°C warmer than the previous interflood period in all regions.

123The time of year when floods most often occur differs between regions and periods (Fig. 5, Extended
124Data Table 1). In Central Europe, floods mainly occur in summer. In the Central European flood-rich
125and the interflood periods of the past, 41% and 42% of the floods occurred in summer, respectively.
126In contrast, during the recent flood period IX, 55% of the floods occurred in summer. The red

127confidence bounds in Fig. 5b do not overlap, indicating that the differences in summer flood
128frequencies between the recent flood period IX and the previous periods are significant and have
129not simply occurred by chance. In Southern Europe, the corresponding frequencies for floods in
130autumn (which is the dominant flood season) increased from 43% (flood rich) and 41% (interflood)
131to 54% (flood period IX), and in Western Europe, the corresponding frequencies for floods in winter
132(which is the dominant flood season) increased from 49% (flood rich) and 46% (interflood), to 55%
133(flood period IX) (Extended Data Fig. 5).

134

135Flood processes and implications

136While there is some overlap between flood-rich periods detected here and those found previously in
137Central Europe based on 19 series² (their periods 1540-1600, 1640-1700, 1730-1790 approximately
138match periods II, IV and V here), their last period 1790-1840 does not emerge as a flood-rich period
139here. Similarly, the Late Maunder low solar intensity period (1675-1725) sometimes associated with
140flood occurrence in Europe⁶ was not particularly flood rich on a European level. The extent of the
141recent flood-rich period IX is consistent with the increasing trends in flood discharges observed in
142Northwestern and Central Europe in recent decades⁴.

143Previous analyses did not find coherent flood-temperature relationships at a European scale^{6, 7, 8},
144which may partly reflect the low number of high-resolution series. At a local to regional scale (e.g.
145Bohemia, Eastern Spain) and in some periods (e.g. late Maunder Solar Minimum and 18th-19th
146century) flood-temperature associations were demonstrated^{6, 18}. Our new comprehensive flood data
147set provides clear evidence that such a relationship exists across Europe over the past 500 years.

148The most significant flood-rich period in our ranking, Period V (1760-1800), occurred during the
149decades preceding the French Revolution. Notably lower temperatures also prevailed during this
150period. Air pressure reconstructions¹⁹ suggest that there was frequent polar air intrusion into North
151America, the North Atlantic region and Western Europe associated with an expanded polar cell, and
152lower north-south air pressure gradients (negative Northern Atlantic Oscillation (NAO) index)
153pointing towards frequent blocking situations in Europe^{20, 21}. In the 1780s, the sea ice extent around
154Iceland was at its greatest during the last 500 years²². The 1783 Lakigigar volcanic eruption in Iceland
155may have further contributed to lowering the temperatures²³.

156Temperature is the most easily observed and most predictable parameter of a changing climate
157system. Whilst flood-producing precipitation is not necessarily driven by air temperature anomalies,
158both are controlled by large-scale atmospheric circulations and ocean interactions²⁴. In summer, the
159relationship between temperature and precipitation tends to be negative, as precipitation
160associated with cyclones implies more cloud cover and less solar radiation (Gagen et al. 2016)²⁵. In
161winter, in contrast, there is a tendency for cyclones to transport moist and relatively warm air
162masses from the Atlantic to Europe resulting in a positive relationship²⁶. Spatio-temporal variations
163of precipitation and flooding depend on the NAO because of the link between NAO and the position
164of Atlantic storm tracks^{27, 28, 24}. In winter, enhanced cyclone activity occurs in Northern Europe during
165positive NAO phases while in Southern Europe this is the case during negative NAO phases²⁹, as the
166position of Atlantic storm tracks migrate northward and southward, respectively. The decadal
167oscillations of the storm track position also lead to subcontinental temperature variations through
168the redistribution of cloud cover and precipitation as a result of internal climate variability^{25, 30}. **The**
169**exact mix of influences** driving the past flood-rich periods remains an open question that will require
170further work. Also, we used a Central European air temperature reconstruction here and future work
171should incorporate further regionally specific reconstructions once available for the past 500 years.

172Another factor contributing to higher floods in cold periods is soil moisture. Lower temperatures
173lead to less evaporation and hence higher soil moisture which, in turn, results in larger floods, for
174the same rainfall^{31, 32}. The June 2013 flood in Central Europe is an example of this. The preceding

175winter and spring were cold, soil moisture was much higher than usual and thus the flood was much
176larger than floods with dry antecedent soils³³. While the temperature-precipitation relationship in
177Europe depends on the season, annual rather than seasonal temperatures are analysed here so that
178not only flood event properties but also antecedent soil moisture and snow conditions are
179considered, which can be relevant for flood magnitudes over multiple-seasons.

180During the past 30 years, hydroclimatic conditions over Europe have shifted to their millennial
181boundaries with a dry anomaly in Southern-, and a wet anomaly in Central and Northern Europe³⁴.
182These changes appear to be caused by a persistent anomalous circulation regime of frequent low
183pressure systems over the East Atlantic and Western Europe³⁴. Observational data suggest this
184pattern to be associated with a warm sea surface temperature anomaly in the Northern Atlantic
185Ocean^{35, 34}, positive Atlantic Multidecadal Oscillation (AMO) and negative NAO, resulting in
186conditions that are likely to cause heavy precipitation through intense cyclone development and
187frequent blocking over Western and Central Europe^{36, 37, 38}. Although contemporary air temperatures
188are much higher, there are similarities to the atmospheric circulation regime that prevailed in Period
189V (1760-1800). However, climate model simulations suggest that present and future precipitation
190increases in Europe may be driven more by thermodynamics, i.e. the higher water-holding capacity
191of a warmer atmosphere, than by changes in circulation^{39, 30}; with increased evaporation and
192shallower snow packs also modulating floods⁴. **It is therefore not clear how long the current flood-**
193**rich period IX will continue into the future.**

194Systematic records have demonstrated that the timing of river floods in Europe has changed since
1951960⁴⁰. Fig. 5 and Extended Data Fig. 5 demonstrate, however, that a change towards more frequent
196summer floods in Central Europe, more frequent winter floods in Western and more frequent
197autumn floods in Southern Europe started earlier than this, around 1940. The finding of increasing
198flood occurrence in the dominant flood season in all regions of Europe since 1960 in this paper is
199consistent with trends in flood timing and associated flood generating processes, such as earlier
200snowmelt and fewer ice jam floods in Central Europe, and a seasonal shift of winter storms in the
201Atlantic region of Europe^{2, 4, 40, 41, 42}. In the Mediterranean, the enhanced evaporation and convective
202activity have increased the frequency of autumn floods^{4, 43, 44}.

203In a global context, the European analysis presented here is the first, large-scale, high-resolution
204identification of flood-rich periods over multiple centuries. In other continents, flood-rich periods
205have been identified more locally. For example, in the states of Tabasco and Chiapas, Mexico, floods
206clustered during 1650-1680 and 1920-1950⁴⁵, which indicates some overlap with northern Europe
207(Fig. 2). At the River Paraná in South-America the 1590s, 1620s, 1740s and 1770s were flood-rich⁴⁶,
208but they were mainly due to El-Niño events, so one would expect different causal mechanisms from
209Europe. In Asia, millennial-scale investigations suggest larger floods occurred between 1500 and
2101700 on the River Yangtze⁴⁷.

211Our research advances the global study of flood sensitivity to climate variability. Eventually, it may
212be possible to draw correlations between flood-rich periods across the globe that go beyond
213individual river basins and flood events. While flood management is currently strongly based on the
214analysis of systematic data in past decades, extending the time window to past centuries would
215vastly strengthen the analysis, as they may provide a more complete guide to possible future flood
216changes thereby allowing the creation of predictive tools that can enhance adaptation capacity at
217global and local scales. We have strongly shown the potential of documentary data to contribute to
218such work. The finding that the most recent 30 years are separated from past flood-rich periods by a
21990 year disaster gap in most of Europe may explain why both public and flood managers have been
220surprised by the recent floods⁴⁸. Flood risk assessment tools and flood risk management strategies
221need to account for the fact that we are currently in an exceptional flood-rich period in terms of
222timing of flood occurrence, magnitudes and spatial extent within Europe. Process-based models that
223capture the physical mechanisms in the atmosphere and rainfall-runoff transformation on the land
224surface, including the role of precipitation, soil moisture, snowmelt and seasonality in flood

225 generation in both recent and historical times, will be an essential component of flood-risk
226 assessment tools in a changing climate.

227

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344

345AUTHOR CONTRIBUTIONS

346G. Blöschl, A.K. and A.V. designed the study and wrote the first draft of the paper. G. Blöschl initiated 347the study and provided guidance for the analyses. A.K. collated the database with the help of most 348of the co-authors, and provided guidance for the analyses. A.V. performed all quantitative analyses 349of the flood data. M. Barriendos, O.B., R.B., D. Coeur, G.D., A.K., M.C.L., N.M., D.R., L.R., P.S., I.A., M. 350Bělinová, G. Benito, C.B., D. Camuffo, D. Cornel, R.D., L.E., S.E., J.C.G., R.G., D. Limanówka, A. P., H.P., 351F.S.R., C.R., J.S., L.S., L.P.S., W.H.J.T. and O. W. developed historical river flood series. J.H., K.H., M.H.,

352J.K., D. Lun, J.P. and P.V. advised on the data analysis. D. Cornel and J. W. rendered Fig. 1 and the
 353Supplementary Video. All authors interpreted results, and contributed to framing and revising the
 354paper.

355

356**Competing financial interests**

357The authors declare no competing financial interests.

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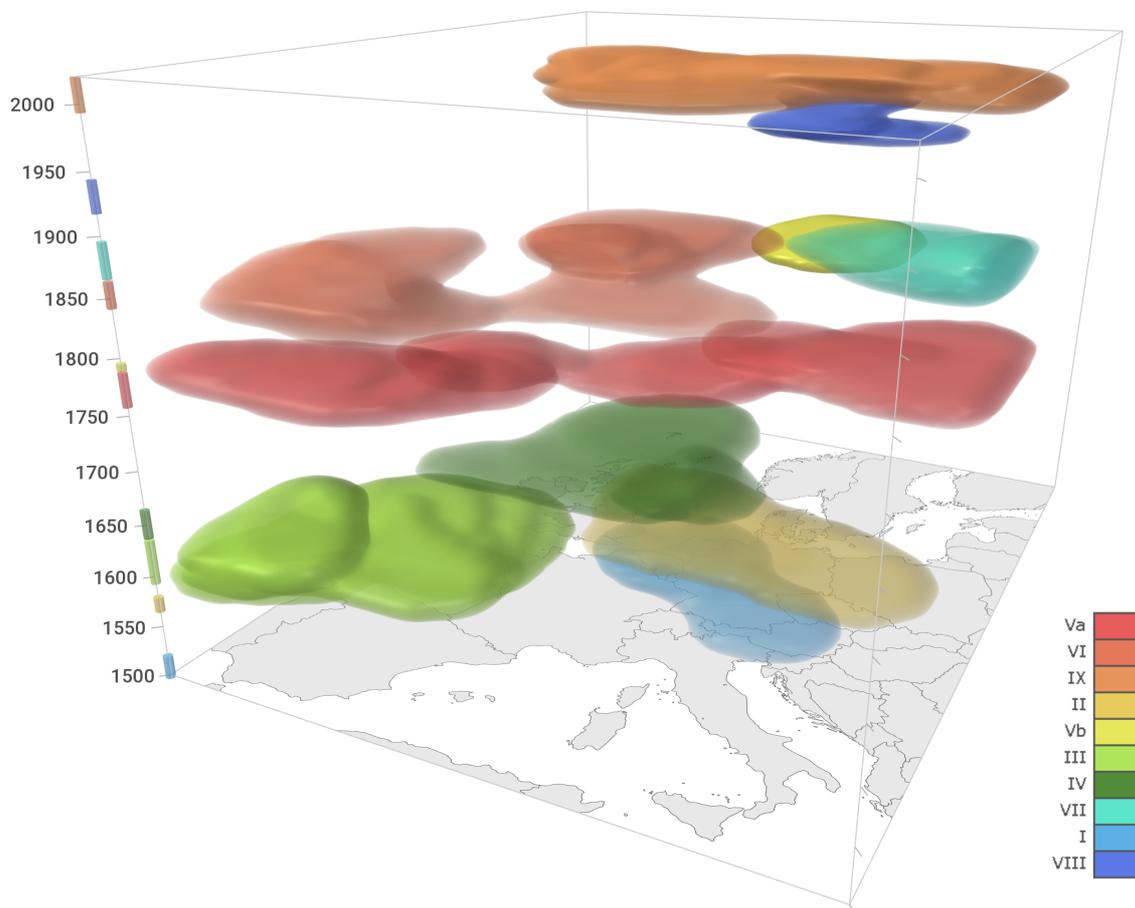
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365**Fig. 1 | Flood-rich periods in Europe in the past 500 years.** Periods are coloured by their rank, with red (period
 366Va) indicating the strongest and blue (period VIII) indicating the weakest period (Table 1). For a dynamic
 367visualisation see Supplementary Video.

368

369

370Table 1 Flood-rich periods in Europe since 1500. Regions are defined in the methods section. Rank 1 (period
 371Va) indicates the strongest and rank 10 indicates the weakest period (see Extended Data Fig. 2). Va and Vb
 372were given a combined name due to their overlap in time. * 2016 is the end of the data and possibly not the
 373end of period IX.

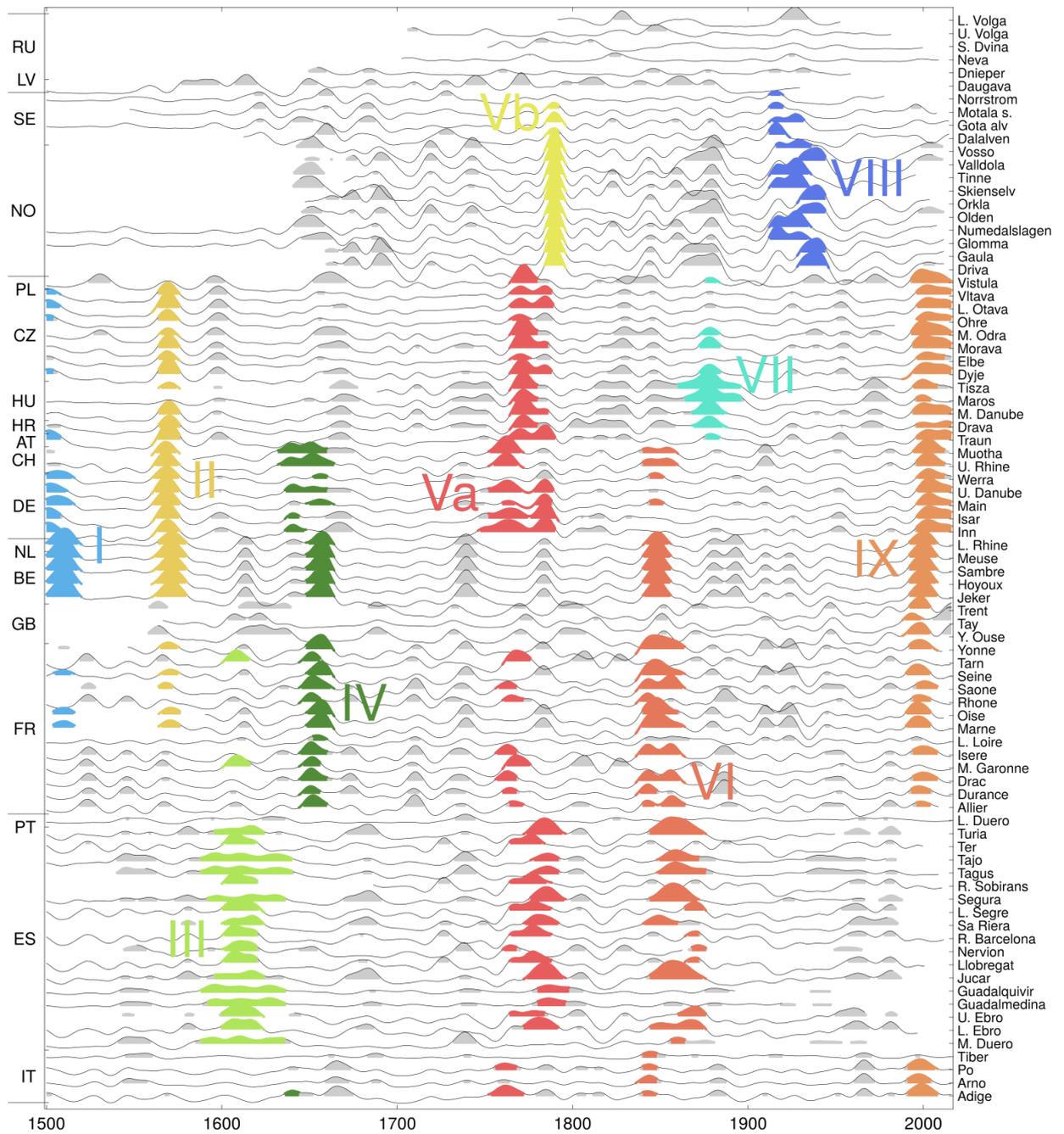
Periods	Full time period	Spatial extension (regions)	Rank
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I	1500-1520	Western Europe, Central Europe	9
II	1560-1580	Western Europe, Central Europe	4
III	1590-1640	Iberia, Southern France	6
IV	1630-1660	Western Europe, West-Central Europe, Northern Italy	7
V	1750-1800	Va Central Europe, Western Europe, Southern Europe Vb Scandinavia	1 5
VI	1840-1880	Western Europe, Southern Europe	2
VII	1860-1900	East Central Europe	8
VIII	1910-1940	Scandinavia	10
IX	1990-2016*	Western Europe, Central Europe, Italy	3

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378 **Fig. 2: Flood intensities interpolated in space and time (thin black lines) and flood-rich flood periods**
 379 **identified (coloured areas).** For numbers of flood-rich periods see Table 1 and Extended Data Table 2. Grey
 380 areas indicate years that exceed the flood intensity threshold and are not in one of the identified flood-rich
 381 periods. Countries (left vertical axis) are grouped by region (from top to bottom: Eastern, Northern, Central,
 382 Western and Southern Europe).

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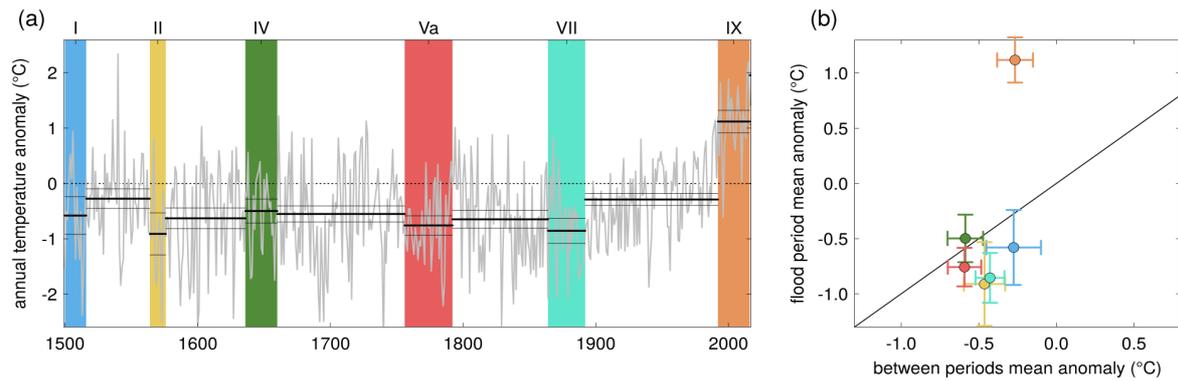


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388**Fig. 3: Flood-rich periods in Europe.** For numbers see Table 1 and Extended Data Table 2. Periods are coloured
389by their rank, with red (period Va) indicating the strongest and blue (period VIII) indicating the weakest period.
390Also see Extended Data Table 2 for the rank.

391

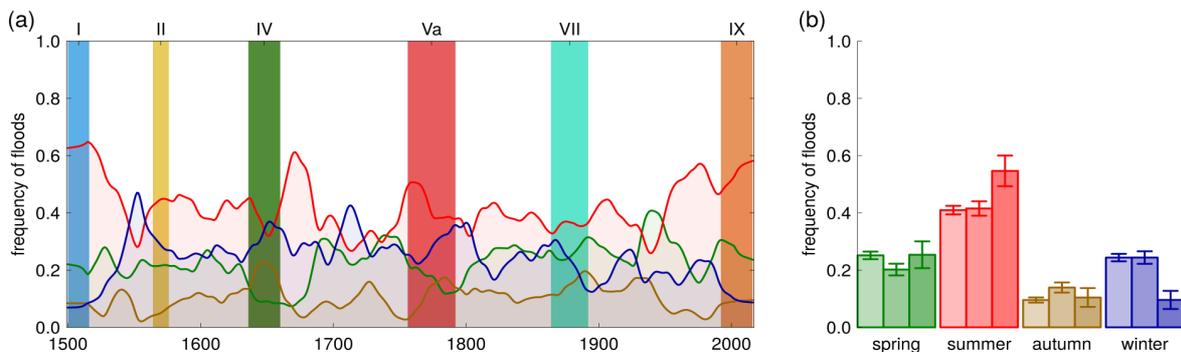
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394**Fig. 4 | Anomalies of annual air temperatures from their 1961-1990 mean within and outside flood-rich**
 395**periods in Central Europe.** (a) Time series of air temperature anomalies (grey line) and their averages and 90%
 396 confidence bounds (black lines), and flood-rich periods indicated by coloured bars. (b) Relationship between
 397 average temperature anomalies in flood-rich periods and those of the intervals in between. Error bars show
 398 90% confidence bounds. Colours correspond to those of the flood-rich periods in (a). Only the flood-rich
 399 periods that affected Central Europe are shown here. For other regions see Extended Data Fig. 4.

400



401

402**Fig. 5 | Seasonality of floods within and outside flood-rich periods in Central Europe.** (a) Time series of
 403 smoothed frequency of floods in four seasons (lines, green: spring, red: summer, brown: autumn, blue: winter)
 404 and flood-rich periods indicated by coloured bars. (b) Frequency of floods in four seasons. Left bars: interflood
 405 periods; middle bars: flood-rich periods of the past; right bars: flood-rich period IX (1990-2016). Error bars
 406 show 90% confidence bounds.

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410 Methods

411 Development of historical flood database

412 The development of the historical flood series from documentary evidence followed standard flood
 413 magnitude classification methods. The evidence consisted of historical documentation including
 414 narratives (e.g. chronicles), administrative sources, newspapers, and private and official
 415 correspondence (e.g. letters). We used almost exclusively (over 90%) contemporary documentation,
 416 written shortly after the flood events, rather than non-contemporary documentation, because of its
 417 higher reliability⁴⁹. The documentation always included direct indicators, such as the level and spatial
 418 extension of flood waters relative to identifiable landmarks and, in most cases, indirect indicators
 419 such as the environmental or socio-economic impact that provide complementary information. For
 420 each piece of evidence, a critical, historical source evaluation was conducted, utilizing the local

421 socio-economic and historical source knowledge of the analysts, in order to minimise errors in
422 dating, interpretation and other possible mistakes originating from social biases.

423 Individual series do not necessarily originate from exactly the same location. Series “HU01 Middle
424 Danube” (see Extended Data Table 1), for example, was compiled based on evidence from the
425 Danube reach between Bratislava and Mohács, a reach of about 400 km, as this reach can be
426 considered approximately homogeneous in terms of flood magnitude. Reaches were judged as
427 approximately homogeneous if the sources at different locations along that reach usually suggested
428 the same index value for the same event. In other cases, the information was more focused. For
429 example, series “ES19 Ter” is based on information from Girona only. Coordinates were assigned to
430 each series representing the centre of gravity of the source information. For the series “HU01 Middle
431 Danube”, for example, the coordinates were selected at Komárom, which is slightly upstream of the
432 middle of the reach.

433 The documentary evidence was then transformed into a numerical intensity index. We applied the
434 most widely used three-scaled index method, differentiating flood events into intensities i_f of
435 notable (no. 1), great (no. 2) and extraordinary (no. 3) magnitudes^{50, 51, 52}. A flood was considered
436 notable (no. 1) if the flood waters exceed the river banks, but not significantly; great (no. 2) **if it they**
437 considerably exceed the river banks, often over an extended period of time with local
438 hydromorphological changes; and extraordinary (no. 3) if the flood waters are much higher and
439 spatially more extended than usual floods, often unexpected and with major disruption of daily life.
440 Historical documents would typically refer to these three categories as flood, great flood and very
441 great flood (or extraordinary flood or deluge), respectively⁵¹. Since the intensity index was mainly
442 based on direct indicators, it is intended to reflect flood magnitudes, rather than flood damage. The
443 index also accounted for the construction of flood protection measures such as levees¹⁸. For
444 example, at Szeged in Hungary (HU03 Tisza series) a major levee system was constructed in the early
445 1880s. In the period before, a flood would be considered a notable (no. 1) flood if the lower
446 floodplain around the town, the pastures and some cultivated fields were inundated. In the period
447 after, a flood would be considered a notable (no. 1) flood if water significantly exceeded the quay
448 (low lying road along the shoreline) even though the pastures and the cultivated fields in the lower
449 floodplain were not inundated because they were protected⁵¹. Similar differentiations were made
450 for no. 2 and no. 3 floods. Land-use change effects were assumed to be small, as 80% of the
451 catchments were larger than 700 km² and land use changes tend only to be important for small
452 catchments⁵³. This is because changes in the infiltration capacity of soils mainly affect flood
453 generation resulting from thunderstorms in small catchments^{53, 54, 55}. Additionally, for all series we
454 identified (i) years with no floods, (ii) years with probably no floods, (iii) years with either no floods
455 or missing data (i.e. no information) and (iv) years outside the period covered by the series.

456 In order to account for differences in the representativeness of different series in space, we assigned
457 to each series a representativeness index u (1: low representativeness, 2: average
458 representativeness, 3: high representativeness), that reflects the level of confidence that important
459 floods have been captured, based on a holistic assessment of the completeness of the source
460 material in a regional context. For example, SE02 Motala strom series was considered highly
461 representative ($u=3$) because there is high confidence that all the important floods have been
462 captured even though total number of reported floods may be lower than in other stations. In this
463 case we have high confidence because of the nature of source type (consistent local chronicles and
464 diaries)¹². There is also a tendency for series of larger rivers to have higher representativeness than
465 series of smaller rivers because of the higher population density and the more frequent presence of
466 cities.

467 In order to account for temporal observational biases, we assigned to each year of each series a bias
468 index, on a scale from 1 to 4, that reflects the completeness of the source material in a historical
469 context. Index values from 1 to 4 indicate, respectively, no data, periods with possibly missing data,

470average, and periods with overly dense data compared to the average of that series. For example,
471AT01 Traun for the period 1500-1600 benefitted from the availability of weekly bridge master
472accounts, which make the data much more complete than later when such accounts were not
473available⁵⁶. For most series, however, the more recent years are more complete.

474A total of 103 river flood series were compiled. Out of these, 70 start in 1500. 82, 99 and 103 series
475start in or earlier than 1600, 1700 and 1800, respectively (Extended Data Figs. 1-3). The total number
476of floods contained in the data set are 9576 of which 8954 have a season assigned. The seasons are
477spring (March - May), summer (June - August), autumn (September - November) and winter
478(December - February). There are 5696 no. 1 floods (notable), 2616 no. 2 floods (great) and 1264 no.
4793 floods (extraordinary).

480Interpolation

481In interpolating flood intensity in space and time only class 2 and 3 floods are used, since they are
482considered to be less affected by observation bias. This is because class 2 and 3 floods tend to result
483in higher disruption of the daily life than class 1 floods, which increases the societal relevance and
484thus the likelihood of being documented. When a series contained more than one event per year,

485the intensities of the individual events i_f were aggregated to one annual intensity i_a by $i_a = \sqrt{\sum i_f^2}$
486where the summation is over the events of that year. To reduce some of the spatial correlations,
487only 83 out of the 103 series were used for interpolation, excluding series with similar intensities to
488neighbouring series either because they are nested catchments or derived from homogeneous flood
489regions (denoted 'supplementary' in Extended Data Fig. 1). Some spatial correlation may remain
490which may bias the results of the interpolation.

491In order to reduce observation bias, 0 intensities ($i_a=0$) were added randomly in some of the years
492when no class 2 or 3 flood was recorded with probability $p_0(t) = 1 - (1 - p_f(t))^\alpha$ where the annual
493flood probability $p_f(t)$ was estimated from the occurrence of no. 2 and 3 floods within a 100-year
494time window around the target year t . The exponent α was set to 10, based on test simulations. The
495consistency of the bias reduction method with the bias index (Extended Data Fig. 2) was checked
496visually by assessing how many zero values were added in periods characterised by different bias
497indices. In periods with possible missing data and in periods with overly dense data the method
498added a smaller and larger number of zeroes than average, respectively, suggesting that the bias
499reduction method is consistent with the bias index. The validity of the bias reduction method was
500checked by examining whether monotonic trends appeared over the entire 500 year period in the
501interpolated flood intensities. While, without bias correction, most major events would be identified
502in the second half of the 500 yr period, with bias correction, the events were more uniformly
503distributed in time and there were no monotonic trends in line with the historical expert
504assessment. The bias index was used to test the bias reduction method rather than to modify the
505flood intensity in each year and station individually, in order to enhance the repeatability and spatial
506consistency of the analysis.

507The intensities i_a were interpolated using the Thin Plate Spline regression algorithm of the *fastTps*
508function in the R package *fields*. The coordinates of the series were transformed into kilometres by
509an Azimuthal Equidistant projection centred at 51°N and 7°E. The interpolation is in space and time,
510so some equivalence of space and time is needed reflecting a typical relationship between the
511extent and duration of flood-rich periods in Europe. Based on space-time empirical variograms⁵⁷ of
512the intensities i_a and visual examination we chose a ratio of 50 km per year.

513The *fastTps* function assigns a weight to each data point that reflects the inverse of its uncertainty.
514These weights were calculated based on the representativeness index u of each series and the
515annual flood intensity i_a , as $w=k(u/2)^2$ where k is 0.2, 1.0 and 1.5 for $i_a < 1.5$, $1.5 < i_a < 2.5$ and $i_a > 2.5$,
516respectively. The small weights of the 0 intensities were chosen to reflect their larger uncertainty.

517The possible drawback of this procedure is an element of subjectivity of the parameters, but the
518results were more plausible from a historical expert perspective, than when ignoring the differences
519in representativeness of the series. The smoothing and tapering range parameters of *fastTps* were
520set to 10 and 20 years (or 1000 km), respectively, based on an expert assessment of test simulations.
521A linear drift component was selected.

522To increase the robustness of the procedure and assess the sensitivity of the results to adding 0
523intensities, the space-time interpolation was repeated 50 times with 50 different realisations of 0
524intensities. The resulting mean i_i of the interpolated intensities represents a three dimensional
525matrix of flood intensities i_i over Europe in the last 500 years with voxel size of about 41 km*48
526km*4 yrs. This matrix was used for identifying contiguous flood periods in space and time using an
527algorithm that connects neighbouring voxels that exceed an intensity threshold⁵⁸. We set the
528threshold i_i^* to the 95% quantile of the interpolated i_i over the matrix ($i_i^*=1.375$), which means that
529these contiguous periods collectively cover 5% of the space-time domain. A comparison of the flood-
530rich periods obtained for different realisations of 0 intensities showed some differences, but the
531main pattern remained. For example, the top ranked periods always remained at the top with similar
532spatial and temporal extents.

533We calculated the core duration of the flood-rich periods as the time differences between the
534centres of voxels, and we calculated the areas and volumes as the number of voxels included times
535their individual area and volume, respectively. As the interest of this study was in the large flood-rich
536periods, we only kept periods with volumes larger than 78711 km² yrs (corresponding to 10 voxels)
537for further analysis. This resulted in a total of 74 flood-rich periods for which the projected area
538(km²), the space-time extent or volume (km² yrs), a scaled space-time extent (0 for the smallest of
539the 74 events, 1 for the largest), and the scaled mean intensity of the period were calculated. The
540periods were ranked by the sum of the scaled space-time extent and scaled mean intensity. The top
541periods thus identified were 1756-1792 followed by 1840-1872 and 1992-2016. Changing the
542ranking function slightly changed the ordering of the periods, but the largest periods always
543remained at the top. The top ten periods were given Roman numerals in chronological order
544(Extended Data Table 2). Two periods (Va and Vb) were given a combined name due to their overlap
545in time. The results are moderately sensitive to the ratio parameter. For example, changing it from
54650 to 100 and 25 km/yr, changes the extent of period IX from 1.8 to 2.3 and $1.2 \cdot 10^6$ km², the
547duration from 25 to 17 and 25 years, and the volume from 19 to 23 and $14 \cdot 10^6$ km² yrs, respectively.
548The positions in time and space of the centres of the periods change little in most cases, and the
549current top 8 events remain in the list of top 10 events. The results show little sensitivity to the
550choice of the smoothing and tapering range parameters of the spline interpolation.

551

552Air temperatures

553We used a 500-year Central European temperature reconstruction¹⁴ to evaluate the air
554temperatures of the flood-rich periods, which we consider to currently be the highest quality
555reconstruction in Europe, as the annual correlations with other, more local, historical series in
556Europe are relatively high. The correlation coefficients with the series in Barcelona, Central England
557and Stockholm are 0.67, 0.73 and 0.64, respectively^{59, 60, 61} which indicates spatial representativeness
558over much of Europe. The data are temperature deviations (anomalies) from the mean 1961-1990
559and have been derived from documentary sources such as chronicles, weather diaries, accounts,
560letters, newspapers and legal sources. Potential biases and limitations may derive from data
561coverage and calibration relationships varying in time. We chose annual rather than seasonal
562temperatures for the analysis because we intended to not only capture flood event properties, but
563also antecedent soil moisture and snow conditions which can be relevant for flood magnitudes over
564more than one season. Annual and seasonal temperature averages over decades are correlated with
565r=0.75, 0.75 and 0.82 for summer, autumn and winter, respectively.

566 The average air temperatures of each flood-rich period were estimated separately for five regions in
 567 Europe, Eastern Europe (Russia, Latvia), Northern Europe (Sweden, Norway), Central Europe
 568 (Poland, Czechia, Hungary, Austria, Switzerland, Germany), Western Europe (Netherlands, Belgium,
 569 Great Britain, France), Southern Europe (Portugal, Spain, Italy) (Extended Data Fig. 1). Based on the
 570 spatial locations of the flood-rich periods, Eastern Europe showed some signal during period V (due
 571 to class 3 floods in 1760, 1761, 1770, 1771, 1777, 1779 and 1784 and 8 class 2 floods) and period VII
 572 (due to a class 3 flood in 1877 and 13 class 2 floods), however this was too weak to be included
 573 (possibly a result of lower data density). In Northern Europe, flood-rich periods Vb and VIII occurred,
 574 in Central Europe I, II, IV, Va, VII, IX, in Western Europe I, II, IV, Va, VI, IX, and in Southern Europe III,
 575 Va, VI, IX. Additionally, average temperatures were estimated for periods between these flood-rich
 576 periods (termed interflood periods here). The 90% confidence bounds of these averages m_T were
 577 estimated by $m_T \pm 1.645\sqrt{v_T / n}$ where v_T is the variance of the annual temperatures and n is the
 578 number of years in the period. Fig. 4b and Extended Data Fig. 4bd compare the average
 579 temperatures of the flood-rich periods with those of the interflood periods before and after (for
 580 period I only after, for period IX only before).

581 Seasonality analysis

582 The flood-rich periods were also analysed with respect to their average flood seasonality for the
 583 same five regions. In contrast to the interpolation of the intensities, for the seasonality all 103 series
 584 and all floods (including no. 1 floods) were included in order to develop a more robust estimate of
 585 seasonality, which tends to vary significantly between events⁶². Including the no. 1 classified floods
 586 reduced uncertainty in the flood seasonality resulting from missing data. The analysis was performed
 587 considering all flood events, i.e., in some cases more than one flood per year per site. As we were
 588 more interested in the seasonality of the large floods, while maintaining the robustness by including
 589 small events, we estimated the frequency of floods within each season as a weighted mean of the
 590 frequencies of each of the flood intensities, giving no. 1, 2, and 3 floods weights of 1, 2, and 3,
 591 respectively.

592 The lines in Fig. 5a and Extended Data Fig. 5ac show the frequency of floods in each season over the
 593 past 500 years applying a 30-year averaging window for Central, Southern and Western Europe. In
 594 Northern and Eastern Europe, the number of floods was too low to make reliable inferences on
 595 changes in seasonal flood frequencies. Fig. 5b and Extended Data Fig. 5bd show the averages of the
 596 frequencies over all interflood periods, the past flood-rich periods (excluding the recent one), and
 597 the recent flood-rich period IX. The 90% confidence bounds of the averages p_s were estimated by

598 $p_s \pm 1.645\sqrt{p_s(1 - p_s) / n}$, where n is the number of years with floods whose season is known.

599

600 Data Availability

601 The flood index data that were used in this paper and an extended list of references are available at
 602 <https://github.com/tuwhydro/500yrfloods>. The air temperature data are available at
 603 <https://www.ncdc.noaa.gov/paleo-search/study/9970>

604

605 Code availability

606 The data analysis was performed in R using the supporting package *fields* for the Thin Plate Spline
 607 interpolation (function *fastTps*). The code used can be downloaded from
 608 <https://github.com/tuwhydro/500yrfloods>.

609

610 Methods References

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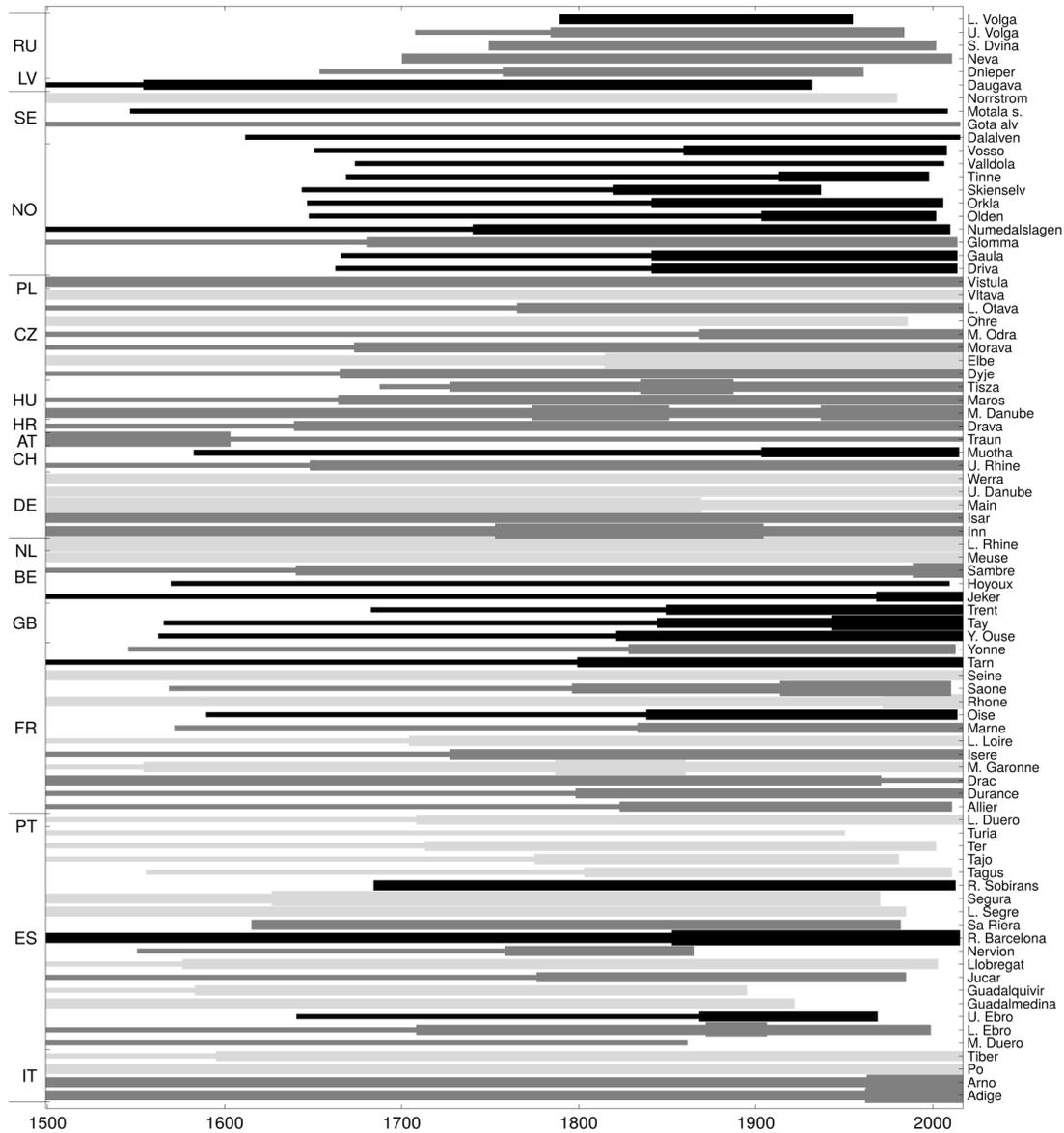
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653Extended Data Table 1: Flood series, data contributors and countries, involved in the present study. Italics
654indicate the series only used for the seasonality analysis (denoted 'supplementary' in Extended Data Fig. 1).
655The code of the series (first column) consists of the country code and a running number.

Code of series	Country	Series provider/publication	River flood series	Catchment areas (1000 km ²)
RU01, RU03-RU05	Russia (1)	Andrei Panin	Dnieper, Severnaya Dvina, Upper Volga, Lower Volga	504, 357, 236, 1380
RU02	Russia (2)	Published ⁶³	Neva	281
LV01	Latvia	Andrei Panin	Daugava	88
SE01-SE04	Sweden	Dag Retsö	Dalalven, Gota alv, Motala strom, Norrstrom	29, 50, 15, 23
NO01-NO10	Norway	Lars Roald	Driva, Gaula, Glomma, Numedalslagen, Olden, Orkla, Skienselv, Tinne, Valdola, Vosso	2.5, 3.7, 41, 56, 0.6, 3.1, 11, 0.2, 1.1, 1.5
PL01-PL02	Poland	Radoslav Doctor	<i>Upper Odra, Vistula</i>	106, 51
CZ01-CZ05, CZ08	Czech Republic (1)	Rudolf Brázdil	Dyje, Elbe, Morava, Middle Odra, Ohře, Vltava	11, 51, 21, 7.2, 113, 4.6, 28
CZ06-CZ07	Czech Republic (2)	Libor Elleder	Lower Otava, <i>Upper Otava</i>	2.9, 0.5
HU01-HU03	Hungary	Andrea Kiss	Middle Danube, Maros, Tisza	210, 27, 157
HR01	Croatia	Hrvoje Petrić	Drava	40
AT01	Austria (1)	Christian Rohr	Traun	4.1
AT02	Austria (2)	Partly published; compiled and indexed: Andrea Kiss	Wien	0.2
CH02, CH04, CH06-CH11	Switzerland (1)	Petra Schmocker-Fackel	<i>Alpenrhein, Emme, Muotha, Schächen, Sihl, Sitter, Thur, Umäsch</i>	6.2, 0.4, 0.3, 0.1, 0.3, 0.3, 1.7, 0.07
CH01	Switzerland (2)	Oliver Wetter	Upper Rhine	30
CH03, CH05	Switzerland (3)	Lothar Schulte	<i>Aare, Lutschine</i>	0.03, 0.4
DE05-DE06	Germany (1)	Rüdiger Glaser, Johannes Schönbeim	Main, Upper Danube	27, 7.5
DE01-DE04, DE07	Germany (2)	Oliver Böhm	Inn, <i>Iller, Isar, Lech, Salzach</i>	12, 1.0, 4.1, 3.9, 6.6
DE08	Germany (3)	Published ⁶⁴	Werra	5.5
NL01	Netherlands	Willem H.J. Toonen	Lower Rhine	185
BE01-BE04	Belgium	Gaston Demaree	Jeker, <i>Hoyoux, Sambre, Meuse</i>	0.5, 0.3, 2.7, 36
GB01-GB03	United Kingdom	Neil Macdonald	Yorkshire Ouse, Tay, Trent	3.3, 4.6, 7.5
FR01-FR02, FR04-FR05, FR07-FR015	France (1)	Denis Coeur	Allier, Durance, Middle Garonne, Upper Garonne, <i>Middle Loire</i> , Lower Loire, Marne, Oise, Rhône, Saone, Seine, Tarn, Yonne	14, 14, 52, 14, 39, 117, 13, 17, 96, 30, 44, 9.7, 11
FR03, FR06	France (2)	Published ⁶⁵	Drac, Isere	3.6, 9.5
PT01	Portugal	Inês Amorim, João Carlos Garcia, Luís Pedro Silva	Lower Duero	98
ES01-ES16, ES18-ES20	Spain (1)	Mariano Barriendos	Middle Duero, Lower Ebro, Upper Ebro, Guadalmedina, Guadalquivir, Jucar, Llobregat, Nervion, <i>Pisuerga</i> , Rieres Pla de Barcelona, Sa Riera Mallorca, <i>Upper Segre, Middle Segre</i> , Lower Segre, Segura, R. Sobirans, Tajo, Ter, Turia	40, 79, 15, 0.2, 57, 22, 4.9, 1.9, 15, 0.1, 0.1, 1.2, 1.7, 20, 20, 0.03, 82, 1.8, 6.4
ES17	Spain (2)	Gerardo Benito	Tagus	9.3
IT01-IT04	Italy	Silvia Enzi, Dario Camuffo, Chiara Bertolin	Adige, Arno, Po, Tiber	12, 8.2, 74, 17

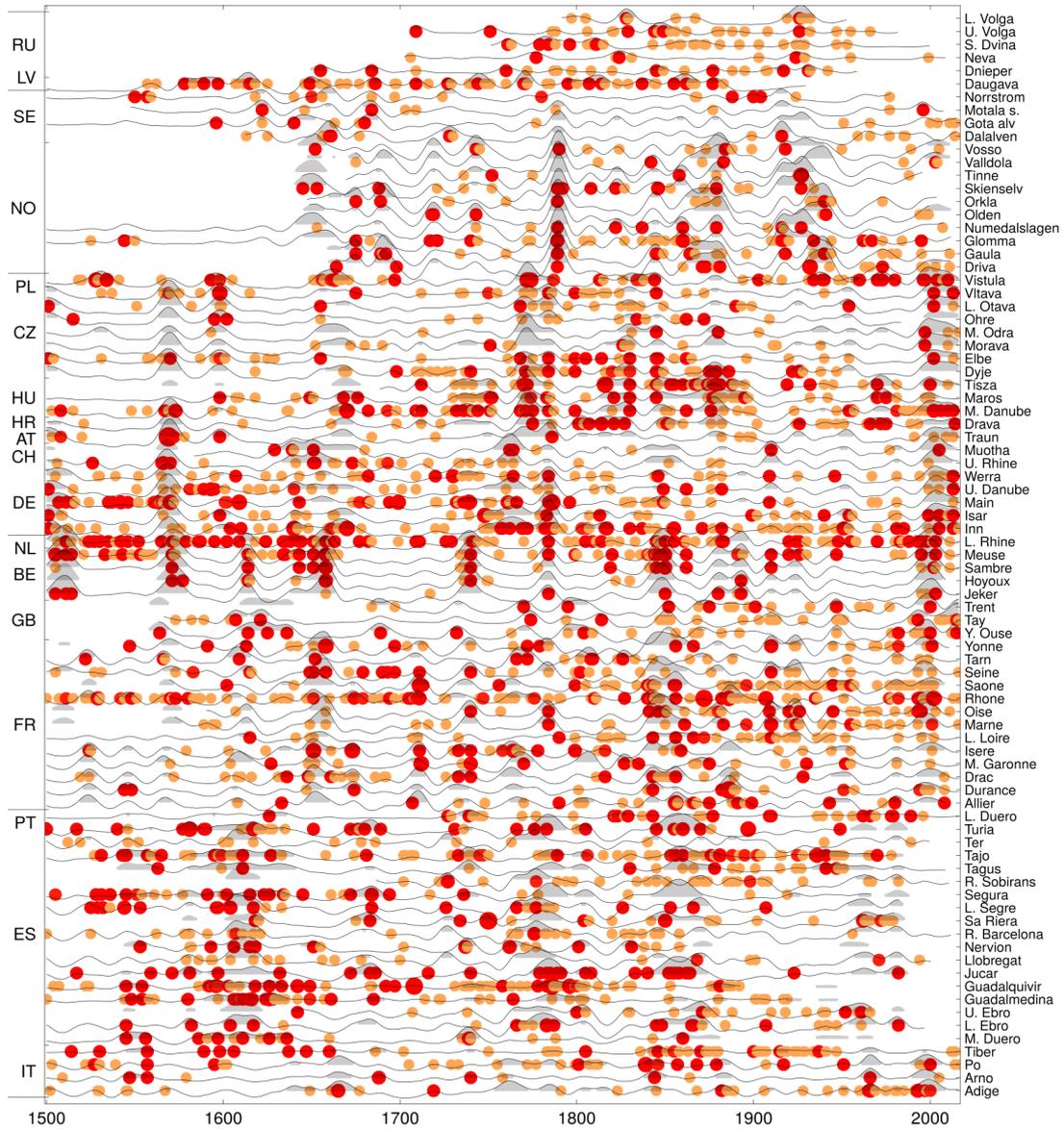
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659 **Extended Data Fig. 2: Duration, representativeness index and bias index of the flood data series.** The grey
 660 scale refers to the representativeness index that reflects the degree of data representativeness in a regional
 661 context (light grey: low representativeness (u=1); dark grey: average representativeness (u=2); black: high
 662 representativeness (u=3). The line width refers to the bias index that reflects the completeness of the source
 663 material in a historical context (no line: no data; thin line: period with possibly missing data; average line:
 664 average; thick line: period with overly dense data.



665

666Extended Data Fig. 3: Raw data of flood intensities. Great (no. 2) and extraordinary (no. 3) floods are marked
 667by orange and red dots, respectively. Thin lines show the interpolated flood intensities. Flood-rich periods are
 668shown as light grey areas.

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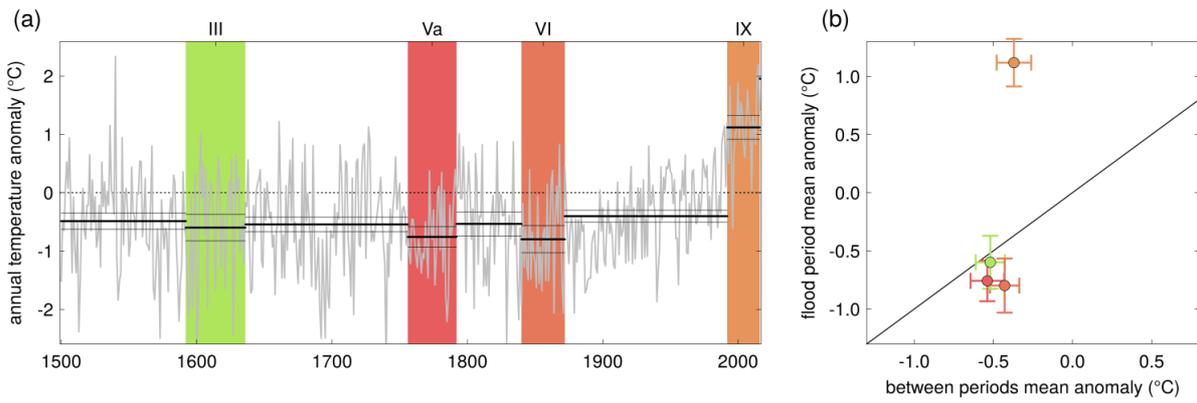
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671 **Extended Data Table 2: Flood-rich periods in Europe in the past 500 years.** Full time periods obtained by
672 generalising the core time periods, core time periods resulting from the analysis, durations of the core periods,
673 regions, maximum area, volume (i.e. space-time domain covered by period), scaled volume, scaled mean
674 intensity of the interpolated flood intensity, and rank. Scaling is from 0 to 1 for the 74 periods identified.

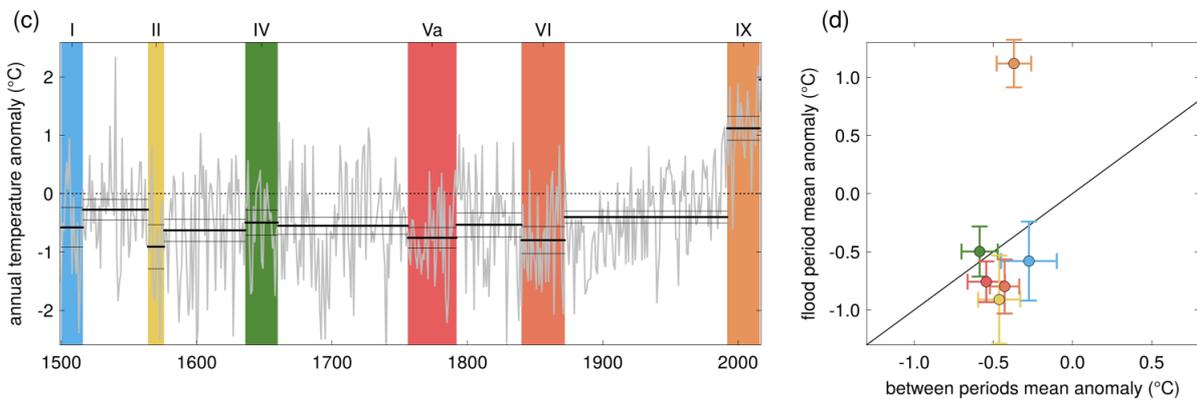
Period	Full time period	Core time period	Core duration (yrs)	Regions	Max area (10 ⁶ km ²)	Volume (10 ⁶ km ² yrs)	Scaled volume	Scaled mean intensity	Rank
I	1500-1520	1500-1516	17	Western Europe, Central Europe	0.569	5.97	0.282	0.622	9
II	1560-1580	1564-1576	13	Western Europe, Central Europe	0.923	8.76	0.416	0.826	4
III	1590-1640	1592-1636	45	Iberia, Southern France	1.025	18.08	0.864	0.269	6
IV	1630-1660	1636-1660	25	Western Europe, West-Central Europe, Northern Italy	0.891	9.71	0.462	0.602	7
Va	1750-1800	1756-1792	37	Central Europe, Western Europe	1.830	20.92	1.000	0.627	1
Vb	1750-1800	1788-1792	5	Scandinavia	0.496	3.75	0.176	1.000	5
VI	1840-1880	1840-1872	33	Western Europe, Southern Europe	1.621	19.86	0.949	0.637	2
VII	1860-1900	1864-1892	29	East Central Europe	0.411	5.62	0.266	0.657	8
VIII	1910-1940	1916-1940	25	Scandinavia	0.573	5.71	0.270	0.627	10
IX	1990-2016	1992-2016	25	Western Europe, Central Europe, Italy	1.771	18.69	0.893	0.607	3

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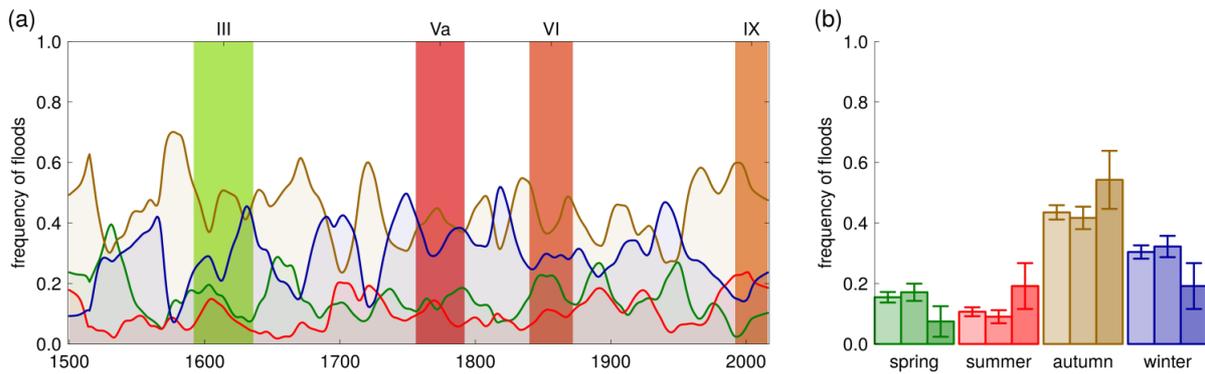
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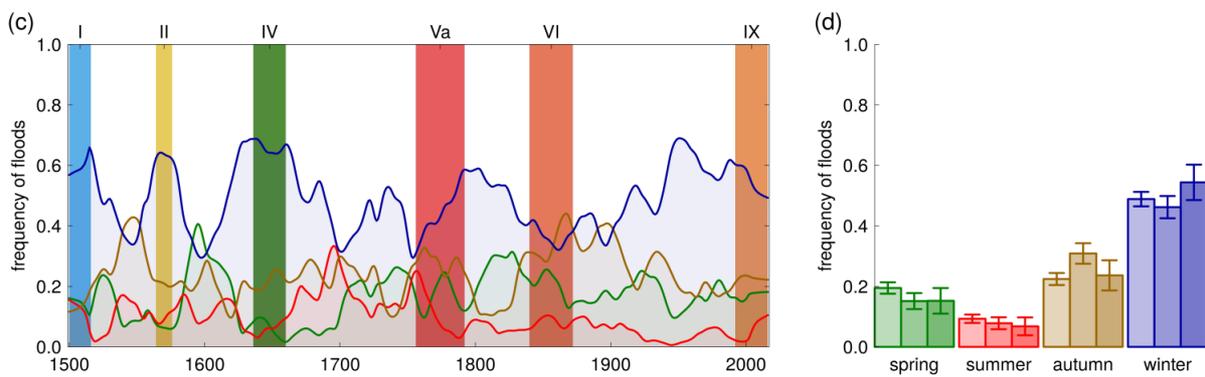
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679 **Extended Data Fig. 4: Anomalies of annual air temperatures from their 1961-1990 mean within and outside**
680 **flood-rich periods in Southern Europe (top) and Western Europe (bottom).** (a, c) Time series of air
681 temperature anomalies (grey line) and their averages and 90% confidence bounds (black lines), and flood-rich
682 periods indicated by colour bars. (b, d) Relationship between mean temperature anomalies in flood-rich
683 periods and those of the intervals in between. Error bars show 90% confidence bounds. Colours correspond to
684 those of the flood-rich periods in (a, c).

685



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688 **Extended Data Fig. 5: Seasonality of floods within and outside flood-rich periods in Southern Europe (top)**
689 **and Western Europe (bottom).** (a, c) Time series of smoothed frequency of floods in four seasons (lines, green:
690 spring, red: summer, brown: autumn, blue: winter) and flood-rich periods indicated by colour bars. (b, d)
691 Frequency of floods in four seasons. Left bars: interflood periods; middle bars: flood-rich periods of the past;
692 right bars: flood-rich period IX (1990-2016). Error bars show 90% confidence bounds.

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695 **Supplementary information**

696 **Video 1:** Dynamic visualisation of the flood-rich periods in Europe in the past 500 years and their relationship
697 to air temperature.

698