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Key Points:

- The *flood synchrony scale*—the distance over which multiple rivers flood near synchronously—varies strongly across Europe
- Flood synchrony scales have grown by ~50% over the period 1960–2010
- Years with spatially extensive floods tend to follow one another

Supporting Information:

- Supporting Information S1
- Movie S1

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Growing Spatial Scales of Synchronous River Flooding in Europe

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Abstract River flooding is a common hazard, causing billions of dollars in annual losses. Flood impacts are shaped by the spatial scale over which different rivers flood simultaneously, but this dimension of flood risk remains largely unknown. Using annual flood data from several thousand European rivers, we demonstrate that the *flood synchrony scale*—the distance over which multiple rivers flood near synchronously—far exceeds the size of individual drainage basins and varies regionally by more than an order of magnitude. These data also show that flood synchrony scales have grown by about 50% over the period 1960–2010. Detrended flood synchrony values are serially correlated, implying that years with spatially extensive floods tend to follow one another. These findings reveal that flood risks are correlated well beyond the individual drainage basins for which flood hazards are typically assessed and managed.

Plain Language Summary When rivers flood, surrounding rivers often flood at the same time. This synchronization of floods amplifies their impacts. We show that the distance over which multiple rivers flood near synchronously varies strongly across Europe, and these distances have grown by about 50% over the period 1960–2010. Risk finance, flood forecasting, and interpretations of flood trends can be improved by accounting for how flood risks extend beyond the borders of individual drainage basins.

1. Introduction

When rivers flood, surrounding rivers often flood at the same time. In Europe, the interplay of weather and landscape conditions has led to cases where many rivers flood simultaneously over large regions, sometimes spanning multiple countries (Becker & Grünwald, 2003; Blöschl et al., 2013; De Luca et al., 2017; Kundzewicz et al., 2013; Merz et al., 2018; Stadtherr et al., 2016; Uhlemann et al., 2010). Such spatially extensive floods can be highly damaging (Blöschl et al., 2013; Kundzewicz et al., 2013; Stadtherr et al., 2016), because the synchronization of floods beyond individual drainage basins amplifies their societal impacts and magnifies their financial risks (Jongman et al., 2014). The spatial extent of flooding has been reported for a limited number of flood events and regions (e.g., Blöschl et al., 2013; De Luca et al., 2017; Kundzewicz et al., 2013; Merz et al., 2018; Stadtherr et al., 2016; Uhlemann et al., 2010) but has not been systematically investigated at the continental scale and thus remains largely unquantified.

Here we analyze the spatial extent of flood events across Europe, using dates of annual maximum floods in the European Flood Database (Blöschl et al., 2017; Hall et al., 2014, 2015) for each calendar year from 1960 to 2010. Spanning over 4,000 river basins, this database has uniquely dense spatial coverage, but it only records the dates of annual maximum floods and not their magnitudes, making a continental-scale analysis of flood magnitudes infeasible. Nonetheless, it allows us to quantify the scale of synchronous flooding across Europe, evaluate how this flood synchrony scale has varied over time, and test its coherence with topographic and climatic patterns.

2. Methods

2.1. Synchrony Scales

To characterize the spatial extent of floods, we introduce the *flood synchrony scale*, defined as the maximum radius around an individual river gauge within which at least half of the other river gauges also record

Figure 1. Two annual maximum floods on 6 July 1997, with two contrasting flood synchrony scales. (a) The Jaworzyna River in Poland (51°53′30″N, 16°86′70″E) had its annual flood on 6 July and many nearby rivers also flooded within ± 7 days surrounding that date, resulting in a flood synchrony scale of 352 km. The Artibai River in Spain (42°09′47″N, 2°54′18″W) flooded on the same date. While its closest neighboring river did not flood, two nearby rivers flooded within ± 7 days, resulting in a flood synchrony scale of 70 km. (b) The flood synchrony scale is defined as the maximum radius at which at least half of the surrounding river gauges also record flooding within ± 7 days.

flooding almost simultaneously. To estimate the flood synchrony scale, we first determine the fraction of gauges that flood near simultaneously as a function of distance from the reference gauge

$$f(l) = \frac{1}{n(l)} \sum_{i=1}^{n(l)} f_i \quad (1)$$

where n is the number of gauges that are within distance l (L) of the central gauge and f_i indicates whether the annual flood at gauge i occurs within ($f_i = 1$) or outside ($f_i = 0$) a time interval $t_{\max}$ (T) from the date of flooding at the central gauge. We use $t_{\max} = 7$ days to capture responses to single forcing events (e.g., a rainstorm) but allow for somewhat lagged responses, because weather systems move at finite speeds and rivers have different times of concentration. The flood synchrony scale is defined as the largest radius l around the central gauge for which $f(l) \geq 0.5$ (Figure 1). Mean flood synchrony scales for individual stations (Figure 2) are calculated by averaging their annual flood synchrony scales across a series of years. *Precipitation synchrony scales* are determined by the same procedures, applied to gridded precipitation data.

2.2. Data

We apply this approach to the European Flood Database (Blöschl et al., 2017; Hall et al., 2014, 2015), consisting of dates of annual maximum streamflows or water levels (daily or instantaneous values) for each calendar year from 1960 to 2010. There are 4,037 catchments within our study domain (35° to 70°N, 12°W to 45°E) with an average distance of 14.9 km between nearest-neighbor stations. Basins range in size from ~ 5 to $\sim 100,000$ km², but these values are undisclosed, and several basins have unknown sizes. The number of stations that report annual flood data ranges from 2,486 in the year 1960 to 3,733 in 1983 and then declines again to 2,679 in 2010 (Figure S1 in the supporting information). Daily gridded precipitation data for the same time period were obtained from the E-OBS data set (version 15.0; Haylock et al., 2008) with a spatial resolution of 0.25°.

2.3. Trend Analyses

We quantify temporal trends in flood synchrony scales using ordinary least squares regression. Station-scale trends in the flood synchrony scale are calculated for the 3,730 stations that have at least 20 years of annual flood peak data (Figure 3b). Continental-scale trends are calculated by normalizing the annual flood synchrony scales for each individual station by that station's mean and then averaging the normalized flood synchrony scales across all available stations for each individual year (Figure 3a). This procedure minimizes the influence of missing data on the continental-scale trends. Robust linear regressions, fitted using iteratively reweighted least squares with MATLAB's default bisquare weighting function, yield similar results to the ordinary least squares trends.

Figure 2. Flood synchrony scales across Europe over the period 1960–2010. Site-averaged flood synchrony scales vary regionally by over an order of magnitude. Floods are spatially correlated over large distances in most of western and northeastern Europe, whereas flooding in a band stretching from northern Spain toward the Alps, into central Europe, and the Carpathians is much more localized.

3. Results and Discussion

The spatial patterns of annual floods across Europe vary greatly over the period 1960 to 2010 (Movie S1). Sometimes, a river floods with very few or none of its surrounding rivers reaching their annual maximum flows simultaneously. For example, on 6 July 1997 the Artibai River in northern Spain experienced its annual flood (Figure 1a), and two nearby rivers flooded around the same time (± 7 days, i.e., 30 June to 12 July), resulting in a flood synchrony scale of 70 km (Figure 1b). The next closest flood was recorded 150 km away, a radius at which only 7.5% of the rivers flooded near simultaneously with the Artibai River. During the same time interval, however, the Jaworzyna River in Poland and hundreds of surrounding rivers all had their annual floods, with a flood synchrony scale of 352 km (Figure 1). This event, the Central European Flood of 1997, caused more than 100 fatalities and several billion dollars in damage (Kundzewicz et al., 2013).

Analysis of the entire European Flood Database shows that the flood synchrony scale averages 148 km across Europe as a whole but varies regionally (Figure 2). In a band stretching from northern Spain toward the Alps, into central Europe and the Carpathians, flood synchrony scales are generally less than 100 km, indicating that annual maximum floods are relatively localized around these mountainous regions. Floods are usually correlated over larger distances in the rest of western Europe, and flood synchrony scales frequently exceed 250 km across large swaths of northeastern Europe. The average flood synchrony scale represents a surface area of almost 70,000 km², which is over an order of magnitude larger than the typical size of drainage basins in the database.

Although several basins are nested, relationships between upstream and downstream gauges have minimal effects on our flood synchrony scale estimates (Figure S2). Across Europe, flood synchrony scales are $\sim 1/3$ smaller when a time threshold of 3 days, rather than 7 days, is

Figure 3. European flood synchrony scales have been growing overall, but trends differ regionally. Annual flood synchrony scales, averaged across all available stations (a), have grown by roughly 50% over the period 1960–2010 (trend is significant at $p < 0.01$; dotted lines indicate $p = 0.05$ confidence bounds). Detrended flood synchrony values are also serially correlated, indicating that years with above-average flood synchrony tend to follow one another (see inset to panel (a); blue line indicates significance threshold for $p = 0.05$). Trends for individual river basins (b) indicate regional differences on how flood synchrony scales have evolved in recent decades.

used to define near-synchronous flooding (Figure S3), but their patterns remain similar to those obtained using a 7-day threshold.

The flood synchrony scales shown in Figures 2 and S3 are site averages over many years of data. Almost all rivers can have highly localized flooding in individual years, even in regions where floods are often spatially synchronized over large distances (Figure S4a). Conversely, individual rare events can cause widespread flooding anywhere in Europe (Figure S4b), although the scales of these extreme events tend to follow the spatial pattern of the long-term average flood synchrony scales (Figure 2).

Averaged across Europe, the flood synchrony scale has grown by roughly 1.1 percent per year (± 0.55 , 95% confidence interval) on average over the period 1960–2010 (Figure 3a). This means that flood synchrony scales have grown by approximately 50% over these five decades and thus that flooding has become more spatially synchronized. However, trends in flood synchrony scales differ regionally (Figure 3b). Flood synchrony scales have grown across most of Europe, most notably in parts of the British-Irish Isles and large parts of Germany, Belgium, the Netherlands, Austria, Italy, Sweden and the Balkans, but have declined in eastern Poland, Romania, and parts of Russia.

There are substantial year-to-year variations around the long-term European trend (Figure 3a), and these variations are serially correlated, indicating that years with above-average flood synchrony often follow one another. Flooding at individual stations is known to exhibit serial correlation (Douglas et al., 2000; Mallakpour et al., 2017), with flood-rich and flood-poor periods; our results show that at a larger scale, years with widespread flooding are also clustered in time. This serial correlation in flood synchrony suggests a possible link to drivers that vary over multiannual time scales, such as long-term climatic oscillations. However, although flood risks in Europe are known to be affected by the El Niño–Southern Oscillation and the North Atlantic Oscillation (Emerton et al., 2017; Nobre et al., 2017; Ward et al., 2014), neither has a measurable correlation with the average European flood synchrony scale (Figure S5). This disconnect may arise from regional differences on how El Niño–Southern Oscillation and the North Atlantic Oscillation affect flood risks in Europe (Emerton et al., 2017; Nobre et al., 2017; Ward et al., 2014).

Mean flood synchrony scales show virtually no spatial correlation with the synchrony scales of annual maximum daily precipitation (Figure S6), even though precipitation is an important driver of flooding. This disconnect between the spatial scaling of hydrological and meteorological extremes is consistent with previous studies (Berghuijs et al., 2016; Blöschl et al., 2017; Stephens et al., 2015) that find that many annual floods do not result from maximum annual precipitation but instead (for example) from snowmelt or subextreme precipitation during times of high soil moisture. In places where most flooding is caused by precipitation, the spatial extent of synchronous precipitation provides an approximate upper bound on the spatial extent of synchronous flooding. In northeastern Europe, snowmelt is a principal driver of flooding (Blöschl et al., 2017; Hall et al., 2014) and can be synchronous over large areas, but even here the synchrony scales of annual floods do not exceed those of annual peak precipitation (Figure S6). Topography, on the other hand, appears to substantially influence the flood synchrony scale. Mean flood synchrony scales are inversely correlated ($p < 0.001$) with station elevation and terrain ruggedness (Amatulli et al., 2018), indicating that flooding tends to be more spatially coherent at lower altitudes and in flatter landscapes (Figure S7).

Our flood synchrony scale is designed to infer flood characteristics for a data set with good spatial coverage on river flooding but that provides only the dates of annual flood events (Blöschl et al., 2017). Data on flood magnitudes would provide further insight into flood synchrony, but these data are not available across Europe. Flood magnitude data would allow multivariate statistics (Jongman et al., 2014; Keef et al., 2013; Zscheischler et al., 2018; Salvadori and De Michele, 2004) to quantitatively account for interbasin dependencies in flow magnitudes when assessing flood risks. Such efforts could also be supported by regional and continental scale flood models, but such models still have large uncertainties (Trigg et al., 2016; Ward et al., 2015), and their ability to reproduce synchrony patterns of flooding has not yet been evaluated. Predicting how flood synchrony will evolve in the future requires an improved understanding of the mechanisms controlling large-scale floods (Milly et al., 2008). These controlling mechanisms must extend beyond precipitation patterns (Touma et al., 2018) alone (as evidenced by the disconnect between the synchrony scales of rainfall and flooding) and include the spatial coherence on how landscapes respond to incoming precipitation.

4. Summary and Conclusions

When rivers flood, surrounding rivers often flood at the same time. Using annual flood data from several thousand European rivers, our analysis shows that the flood synchrony scale (Figure 1)—the distance over which multiple rivers flood near synchronously—far exceeds the size of individual drainage basins and varies regionally by more than an order of magnitude (Figure 2). Over the period 1960–2010 flood synchrony scales have grown by about 50% (Figure 3a), and years with spatially extensive floods tend to follow one another (Figure 3b). The synchrony of interbasin flooding is a largely overlooked dimension of flood behavior, because flood risks are typically assessed and managed at the scale of individual basins. Risk finance, flood forecasting, and interpretations of flood trends can be improved by accounting for how flood risks extend beyond the borders of individual drainage basins.

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References

- Amatulli, G., Domisch, S., Tuanmu, M. N., Parmentier, B., Ranipeta, A., Malczyk, J., & Jetz, W. (2018). A suite of global, cross-scale topographic variables for environmental and biodiversity modeling. *Scientific Data*, 5, 180040. <https://doi.org/10.1038/sdata.2018.40>
- Becker, A., & Grünewald, U. (2003). Flood risk in central Europe. *Science*, 300(5622), 1099. <https://doi.org/10.1126/science.1083624>
- Berghuijs, W. R., Woods, R. A., Hutton, C. J., & Sivapalan, M. (2016). Dominant flood generating mechanisms across the United States. *Geophysical Research Letters*, 43, 4382–4390. <https://doi.org/10.1002/2016GL068070>
- Blöschl, G., Hall, J., Parajka, J., Perdigão, R. A. P., Merz, B., Arheimer, B., et al. (2017). Changing climate shifts timing of European floods. *Science*, 357(6351), 588–590. <https://doi.org/10.1126/science.aan2506>
- Blöschl, G., Nester, T., Komma, J., Parajka, J., & Perdigão, R. A. P. (2013). 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. <https://doi.org/10.5194/hess-17-5197-2013>
- De Luca, P., Hillier, J. K., Wilby, R. L., Quinn, N. W., & Harrigan, S. (2017). Extreme multi-basin flooding linked with extra-tropical cyclones. *Environmental Research Letters*, 12(11), 114009. <https://doi.org/10.1088/1748-9326/aa868e>
- Douglas, E. M., Vogel, R. M., & Kroll, C. N. (2000). Trends in floods and low flows in the United States: Impact of spatial correlation. *Journal of Hydrology*, 240(1–2), 90–105. [https://doi.org/10.1016/S0022-1694\(00\)00336-X](https://doi.org/10.1016/S0022-1694(00)00336-X)
- Emerton, R., Cloke, H. L., Stephens, E. M., Zsoter, E., Woolnough, S. J., & Pappenberger, F. (2017). Complex picture for likelihood of ENSO-driven flood hazard. *Nature Communications*, 8, 14796. <https://doi.org/10.1038/ncomms14796>
- Hall, J., Arheimer, B., Aronica, G. T., Bilibashi, A., Boháč, M., Bonacci, O., et al. (2015). A European flood database: Facilitating comprehensive flood research beyond administrative boundaries. *Proceedings of IAHS*, 370, 89–95. <https://doi.org/10.5194/piahs-370-89-2015>
- Hall, J., Arheimer, B., Borga, M., Brázdil, R., Claps, P., Kiss, A., et al. (2014). Understanding flood regime changes in Europe: A state-of-the-art assessment. *Hydrology and Earth System Sciences*, 18(7), 2735–2772. <https://doi.org/10.5194/hess-18-2735-2014>
- Haylock, M. R., Hofstra, N., Klein Tank, A. M. G., Klok, E. J., Jones, P. D., & New, M. (2008). A European daily high-resolution gridded data set of surface temperature and precipitation for 1950–2006. *Journal of Geophysical Research*, 113, D20119. <https://doi.org/10.1029/2008JD010201>
- Jongman, B., Hochrainer-Stigler, S., Feyen, L., Aerts, J. C. J. H., Mechler, R., Botzen, W. J. W., et al. (2014). Increasing stress on disaster-risk finance due to large floods. *Nature Climate Change*, 4(4), 264–268. <https://doi.org/10.1038/nclimate2124>
- Keef, C., Tawn, J. A., & Lamb, R. (2013). Estimating the probability of widespread flood events. *Environmetrics*, 24(1), 13–21. <https://doi.org/10.1002/env.2190>
- Kundzewicz, Z. W., Pińskwar, I., & Brakenridge, G. R. (2013). Large floods in Europe, 1985–2009. *Hydrological Sciences Journal*, 58(1), 1–7. <https://doi.org/10.1080/02626667.2012.745082>
- Mallakpour, I., Villarini, G., Jones, M. P., & Smith, J. A. (2017). On the use of Cox regression to examine the temporal clustering of flooding and heavy precipitation across the central United States. *Global and Planetary Change*, 155, 98–108. <https://doi.org/10.1016/j.gloplacha.2017.07.001>
- Merz, B., Dung, N. V., Apel, H., Gerlitz, L., Schröter, K., Steirou, E., & Vorogushyn, S. (2018). Spatial coherence of flood-rich and flood-poor periods across Germany. *Journal of Hydrology*, 559, 813–826. <https://doi.org/10.1016/j.jhydrol.2018.02.082>
- Milly, P. C. D., Betancourt, J., Falkenmark, M., Hirsch, R. M., Kundzewicz, Z. W., Lettenmaier, D. P., & Stouffer, R. J. (2008). Stationarity is dead: Whither water management? *Science*, 319(5863), 573–574. <https://doi.org/10.1126/science.1151915>
- Nobre, G. G., Jongman, B., Aerts, J. C. J. H., & Ward, P. J. (2017). The role of climate variability in extreme floods in Europe. *Environmental Research Letters*, 12(8), 084012. <https://doi.org/10.1088/1748-9326/aa7c22>
- Salvadori, G., & De Michele, C. (2004). Frequency analysis via copulas: Theoretical aspects and applications to hydrological events. *Water Resources Research*, 40, W12511. <https://doi.org/10.1029/2004WR003133>
- Stadtherr, L., Coumou, D., Petoukhov, V., Petri, S., & Rahmstorf, S. (2016). Record Balkan floods of 2014 linked to planetary wave resonance. *Science Advances*, 2(4), e1501428. <https://doi.org/10.1126/sciadv.1501428>
- Stephens, E., Day, J. J., Pappenberger, F., & Cloke, H. (2015). Precipitation and floodiness. *Geophysical Research Letters*, 42, 10,316–10,323. <https://doi.org/10.1002/2015GL066779>
- Touma, D., Michalak, A. M., Swain, D. L., & Diffenbaugh, N. S. (2018). Characterizing the spatial scales of extreme daily precipitation in the United States. *Journal of Climate*, 31(19), 8023–8037. <https://doi.org/10.1175/JCLI-D-18-0019.1>
- Trigg, M. A., Birch, C. E., Neal, J. C., Bates, P. D., Smith, A., Sampson, C. C., et al. (2016). The credibility challenge for global fluvial flood risk analysis. *Environmental Research Letters*, 11(9), 094014. <https://doi.org/10.1088/1748-9326/11/9/094014>
- Uhlmann, S., Thieken, A. H., & Merz, B. (2010). A consistent set of trans-basin floods in Germany between 1952–2002. *Hydrology and Earth System Sciences*, 14(7), 1277–1295. <https://doi.org/10.5194/hess-14-1277-2010>
- Ward, P. J., Jongman, B., Kumm, M., Dettinger, M. D., Sperna Weiland, F. C., & Winsemius, H. C. (2014). Strong influence of El Niño Southern Oscillation on flood risk around the world. *Proceedings of the National Academy of Sciences*, 111(44), 15,659–15,664. <https://doi.org/10.1073/pnas.1409822111>

- Ward, P. J., Jongman, B., Salamon, P., Simpson, A., Bates, P., de Groeve, T., et al. (2015). Usefulness and limitations of global flood risk models. *Nature Climate Change*, 5(8), 712–715. <https://doi.org/10.1038/nclimate2742>
- Zscheischler, J., Westra, S., van den Hurk, B. J. J. M., Seneviratne, S. I., Ward, P. J., Pitman, A., et al. (2018). Future climate risk from compound events. *Nature Climate Change*, 8(6), 469–477. <https://doi.org/10.1038/s41558-018-0156-3>