

Title: Climatic control of Mississippi River flood hazard amplified by river engineering

Authors: Samuel E. Munoz^{1,2,3*}, Liviu Giosan¹, Matthew D. Therrell⁴, Jonathan W.F. Remo⁵, Zhixiong Shen^{6,7}, Richard M. Sullivan^{1,8}, Charlotte Wiman¹, Michelle O'Donnell¹, Jeffrey P. Donnelly¹

Summary paragraph:

Over the last century, many of the world's major rivers have been modified for the purposes of flood mitigation, power generation, and commercial navigation¹. Engineering modifications to the Mississippi River system have altered the river's sediment budget and channel morphology², but the influence of these modifications on flood hazard is debated³⁻⁵. Detecting and attributing changes in river discharge is challenging because instrumental streamflow records are often too short to evaluate the range of natural hydrological variability prior to the establishment of flood mitigation infrastructure. Here we show that multi-decadal trends of flood hazard on the lower Mississippi River are strongly modulated by dynamical modes of climate variability, particularly the El Niño-Southern Oscillation (ENSO) and the Atlantic Multidecadal Oscillation (AMO), but that artificial channelization has greatly amplified flood magnitudes over the last century. Our results, based on a multi-proxy reconstruction of flood frequency and magnitude spanning the last five hundred years, reveal that the magnitude of the 100-year flood has increased by 20% over the period of record, with ~75% of this increase attributed to river engineering. We conclude that the interaction of human alterations to the Mississippi River system with dynamical modes of climate variability has elevated the current flood hazard to levels that are unprecedented within the last five centuries.

Main text:

Flooding of the lower Mississippi River in the spring of 2011 was among the largest discharge events since systematic measurements began in the late 19th century, and caused \$3.2 billion in agricultural losses and damages to infrastructure⁶. This and other recent flood events on the Mississippi River – including those in 2016 and 2017 – have repeatedly, though controversially, been attributed to an aggressive campaign of river engineering designed and implemented over the last 150 years³⁻⁵. Federally mandated efforts to reduce the impacts of flooding began in the late 19th century and initially relied almost exclusively on the use of artificial levees, but this strategy was revised in the wake of a particularly devastating flood in the spring of 1927 that overwhelmed the levee system⁷. The current flood management system – the Mississippi River & Tributaries Project (MR&T) – includes a series of spillways that can be opened to relieve pressure on an enlarged levee system, as well as an artificially shortened and straightened main channel that is held in place by concrete revetments and isolated from most of its natural floodplain^{2,6,7}. While these modifications are credited with protecting communities and croplands within the floodplain from inundation, artificial channelization has altered the relationship between discharge and river stage^{3,4} and accelerated the rate of land loss in the Mississippi River delta⁸ necessitating additional investments in flood mitigation infrastructure and coastal restoration⁹.

Although fluvial processes are sensitive to flood mitigation infrastructure, climate variability can also shape the dynamics of continental drainage networks – particularly over decadal to centennial timescales that are difficult to detect using short observational records^{10,11}. Precipitation and soil water storage over the Mississippi River basin are influenced by climate variability driven by sea-surface temperature anomalies in the both Pacific and Atlantic Oceans^{12,13}. Yet, establishing the natural controls on discharge extremes of the lower Mississippi has proven challenging because relatively short-lived gauging station measurements record a limited range of variability, particularly prior to the implementation of major investments in river engineering. As a result, analyses of the climate controls on historical streamflow records disagree over the role that dynamical modes of climate variability play in modulating the lower Mississippi's discharge^{12,14,15}. To plan flood mitigation and other infrastructure projects, it is critical to understand the climate controls on the discharge of the lower Mississippi River, but the short length of the instrumental record fundamentally limits our ability to evaluate the range of natural hydrological variability using observational data alone.

Recent advances in palaeoflood hydrology hold the potential to extend the instrumental record back in time to diagnose the controls on the discharge of large alluvial rivers like the lower Mississippi. Traditional approaches in palaeoflood hydrology, which include the use of slackwater deposits as flood event indices¹⁶, are of limited use on the low-relief landscapes that characterize the Mississippi River alluvial plain. One new approach uses the sedimentary archives held in floodplain lakes, which act as sediment traps during overbank floods, to develop continuous, quantitative, and event-scale records of past flood frequency and magnitude^{17,18}. Parallel work in dendrochronology demonstrates that when trees are inundated by floodwaters they exhibit anatomical anomalies in that year's growth ring such that they provide a precise chronology of flood events that occurred during the growing season¹⁹. Together, these methodological advances provide an opportunity to evaluate inter-annual to multi-decadal scale trends in flood frequency and magnitude on a large alluvial river such as the lower Mississippi prior to and during the era of river engineering.

Here we analyze records of individual overbank flood events derived from sedimentary and tree-ring archives from the lower Mississippi River's floodplain (Fig. 1). We collected sediment cores from the infilling thalwegs of three oxbow lakes, Lake Mary (MRY), False River Lake (FLR), and Lake Saint John (STJ) that formed by neck cut-offs of the lower Mississippi River in AD 1776, AD 1722, and ca. AD 1500, respectively²⁰ (Extended Data Figs. 1–3). On these sedimentary archives, we identified individual flood events using grain-size analysis, bulk geochemistry via X-ray fluorescence scanning (XRF), and radiography, developed age-depth models constrained by multiple independent chronological controls (Extended Data Figs. 4–6), and estimated flood magnitudes using a linear model that relates the coarse grain-size component to the discharge of historical flood events¹⁸ (Extended Data Fig. 7; see *Methods* for details). We also include tree-ring records from the floodplain of the lower Mississippi collected and described by ref. 21; each tree-ring series was examined for anatomical evidence of flood injury to produce a record of overbank flood events that extends back to the late 17th century²¹. A composite flood frequency time series describing the number of flood events in a moving 31-year window derived from sedimentary and tree-ring archives (Fig. 2b) is highly correlated with instrumental flood frequency ($r = 0.90$, $t = 19.12$, $v_{\text{eff}} = 3.77$, $p < 0.001$) for the interval of overlap, while reconstructed flood magnitudes (Fig. 2c) track trends observed in gauging station measurements (see *Supplementary Information* for additional validation), indicating that the palaeoflood archives provide robust reconstructions of hydrological extremes on the lower Mississippi River beyond the period of instrumental record.

Our multi-proxy palaeoflood dataset extends the record of extremes in the discharge of the lower Mississippi River back to the early 16th century, and demonstrates that both the frequency and magnitude of flooding has increased over the last 150 years as land use and river engineering efforts have intensified (Fig. 2). Flood frequencies and magnitudes exhibit multi-decadal oscillations that increase in amplitude around the beginning of the 20th century such that the highest rates of overbank flooding and the largest discharge events of the last 500 years have occurred within the last century. The amplification of flood magnitudes that has occurred over the last 150 years corresponds in time with the intensification of anthropogenic modifications to the lower Mississippi River and its basin, particularly the artificial channelization of the river with levees, revetments, and cut-offs in the late 19th and early 20th centuries^{2,7}. Yet, the continued presence of multi-decadal oscillations in flood frequency and magnitude throughout the entire period of record indicates that anthropogenic modifications to the Mississippi River system are acting in concert with other factors to alter flood hazard through time.

To evaluate the role of climate variability on flood hazard, we examined the relationships between flood frequency, ENSO, and AMO, to find that sea-surface temperature anomalies in both the Pacific and Atlantic Oceans exert a strong influence on the occurrence of lower Mississippi River floods (Fig. 3). Over the last five centuries, correlations between composite flood frequency and the frequency of El Niño events ($r = 0.73$) and the AMO index ($r = -0.39$) derived from instrumental and palaeoclimate datasets are significant ($p < 0.001$; see *Methods* for details). The strength and direction of these relationships supports the hypothesis that discharge extremes on the lower Mississippi River arise through the interaction of ENSO,

which influences antecedent soil moisture, with the AMO that controls the flux of moisture from the Gulf of Mexico inland^{12,15}. Extreme precipitation events over the Mississippi River basin are associated with a stronger and more westerly position of the North Atlantic Subtropical High that is characteristic of the negative phase of the AMO^{12,13}, and these heavy precipitation events are more likely to generate discharge extremes if they fall on the saturated soils that tend to be left in the wake of El Niño events¹⁵.

Despite the strong influence of climatic variability on lower Mississippi River flood occurrence, the amplification of flood magnitudes we observe over the last 150 years is primarily the result of human modifications to the river and its basin (Fig. 4). The magnitude of the 100-year flood (Q_{100} ; a flood with a 1% chance of exceedance in any year) estimated from gauging station measurements (AD 1897–2015) is $20 \pm 7\%$ larger when compared to Q_{100} for the period prior to major human impacts to the river and its basin (AD 1500–1800) estimated from the palaeoflood data (see *Methods* for details). To identify the influence of human activities on this observed increase in Q_{100} , we use a linear model that relates peak discharge to the AMO index over the period prior to major human impacts to the river, AD 1500–1800 ($R^2 = 0.35$, $v = 18$, $p < 0.01$), and use this model to predict flood magnitudes over the entire period of record. This ‘climate-only’ regression predicts that, in the absence of human modifications to the land surface, Q_{100} would have increased by only $5 \pm 6\%$ over the same period, accounting for only ~25% of the observed increase in Q_{100} and implying that the remaining ~75% of this elevated flood hazard is the result of human modifications to the river and its basin. The timing and nature of the amplification of flood magnitudes at the onset of the 20th century strongly implies that it reflects the transformation of a freely meandering alluvial river to an artificially confined channel because the confinement of flood flows to a levee-defined floodway can speed up the downstream propagation of a flood wave and increase peak discharge for a given flood²². The establishment of widespread agricultural activity in the Mississippi River basin occurred in the 19th century, prior to the divergence of the observed and ‘climate-only’ flood magnitudes, indicating a secondary and possibly lagged influence of agricultural expansion²³ on flood magnitudes relative to that of river engineering. In short, this analysis identifies artificial channelization of the lower Mississippi River, and its effects on the river’s gradient, channel area, and flow velocity^{2,7}, as having significantly increased the discharge of a given flood event relative to pre-engineering conditions.

Our main finding – that river engineering has elevated flood hazard on the lower Mississippi to levels that are unprecedented within the last five centuries – adds to a growing list of externalized costs associated with conventional flood mitigation and navigation projects, including a reduction in a river’s ability to convey flood flows^{3,4}, the acceleration of coastal land loss⁸ and hypoxia²⁴. Despite the societal benefits these major infrastructure projects convey⁶, the costs associated with maintaining current levels of flood protection and navigability will continue to grow at the expense of communities and industries situated in the river’s floodplain and its delta. For those interested in improving seasonal and longer-term forecasts of flood hazard, or management strategies that reconnect the river with its floodplain, the Mississippi River’s discharge of freshwater – and by extension the flux of sediment, nutrients, and pollutants – to its outlet should be viewed as highly sensitive to both anthropogenic modifications to the basin and variability of the global climate system.

References:

1. Meybeck, M. Global analysis of river systems: from Earth system controls to Anthropocene syndromes. *Philos. T. R. Soc. B* **358**, 1935–1955 (2003).
2. Smith, L. M., Winkley, B. R. The response of the Lower Mississippi River to river engineering. *Eng. Geol.* **45**, 433–455 (1996).
3. Criss, R. E., Shock, E. L. Flood enhancement through flood control. *Geology* **29**, 875–878 (2001).
4. Pinter, N., Jemberie, A. A., Remo, J. W., Heine, R. A., Ickes, B. S. Flood trends and river engineering on the Mississippi River system. *Geophys. Res. Lett.* **35**, doi:10.1029/2008GL035987 (2008).
5. Watson, C. C., Biedenharn, D. S., Thorne, C. R. Analysis of the impacts of dikes on flood stages in the Middle Mississippi River. *J. Hydraul. Eng.* **139**, 1071–1078 (2013).

6. Camillo, C.A. *Divine providence: The 2011 flood in the Mississippi River and Tributaries Project*. Mississippi River Commission (2012).
7. Remo, J.W.F. Managing the Mississippi River in a non-stationary world: Past practices and future challenges. *Fishery Resources, Environment, and Conservation in the Mississippi and Yangtze (Changjiang) River Basins* (American Fisheries Society, 2016).
8. Blum, M. D., Roberts, H. H. Drowning of the Mississippi Delta due to insufficient sediment supply and global sea-level rise. *Nature Geosci.* **2**, 488–491 (2009).
9. Louisiana Coastal Protection and Restoration Authority. *Louisiana's Comprehensive Master Plan for a Sustainable Coast* (Coastal Protection and Restoration Authority of Louisiana, 2017).
10. Aalto, R., Maurice-Bourgoin, L., Dunne, T., Montgomery, D. R., Nittrouer, C. A., Guyot, J. L. Episodic sediment accumulation on Amazonian flood plains influenced by El Niño/Southern Oscillation. *Nature* **425**, 493–497 (2003).
11. Darby, S.E. et al. Fluvial sediment supply to a mega-delta reduced by shifting tropical-cyclone activity. *Nature* **539**, 276–279 (2016).
12. Enfield, D. B., Mestas-Núñez, A. M., Trimble, P. J. The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental US. *Geophys. Res. Let.* **28**, 2077–2080 (2001).
13. Hu, Q., Feng, S., Oglesby, R. J. Variations in North American summer precipitation driven by the Atlantic Multidecadal Oscillation. *J. Climate* **24**, 5555–5570 (2011).
14. Rogers, J. C., Coleman, J. S. Interactions between the Atlantic Multidecadal Oscillation, El Niño/La Niña, and the PNA in winter Mississippi valley stream flow. *Geophys. Res. Let.* **30** doi:10.1029/2003GL017216 (2003).
15. Munoz, S. E., Dee, S. G. El Niño increases the risk of lower Mississippi River flooding. *Scientific Reports* **7**, DOI:10.1038/s41598-017-01919-6 (2017).
16. Baker, V. R. Paleoflood hydrology and extraordinary flood events. *J. Hydrology* **96**, 79–99 (1987).
17. Munoz, S. E. et al. Cahokia's emergence and decline coincided with shifts of flood frequency on the Mississippi River. *Proc. Natl. Acad. Sci. USA* **112**, 6319–6324 (2015).
18. Toonen, W. H. J., Winkels, T. G., Cohen, K. M., Prins, M. A., & Middelkoop, H. Lower Rhine historical flood magnitudes of the last 450 years reproduced from grain-size measurements of flood deposits using End Member Modelling. *Catena* **130**, 69–81 (2015).
19. St. George, S., Nielsen, E. Signatures of high-magnitude 19th-century floods in *Quercus macrocarpa* tree rings along the Red River, Manitoba, Canada. *Geology* **28**, 899–902 (2000).
20. Fisk, H. N. *Geological Investigation of the Alluvial Valley of the Lower Mississippi River*. (Mississippi River Commission, 1945)
21. Therrell, M. D., Bialecki, M. B. A multi-century tree-ring record of spring flooding on the Mississippi River. *J. Hydrology* **529**, 490–498 (2015).
22. Jacobson, R.B., Lindner, G., Bitner, C. The role of floodplain restoration in mitigating flood risk, lower Missouri River, USA. *Geomorphic Approaches to Integrated Floodplain Management of Lowland Fluvial Systems in North America and Europe* (Springer, 2015).
23. Trimble, S.W. Decreased rates of alluvial sediment storage in the Coon Creek Basin, Wisconsin, 1975-93. *Science* **285**(5431), 1244–1246 (1999).
24. Rabalais, N. N., Diaz, R. J., Levin, L. A., Turner, R. E., Gilbert, D., & Zhang, J. (2010). Dynamics and distribution of natural and human-caused hypoxia. *Biogeosciences*, **7**(2), 585-619

Supplementary Information line

Acknowledgements:

We thank S. Colman, S.G. Dee, K. Lotterhos, S.P. Muñoz, W.H.J. Toonen, G.C. Trussell, and T. Webb III for discussion and comments, M. Besser, D. Carter, J. Elsenbeck, K. Esser, A. LaBella, and J. Nienhuis, for field and/or laboratory assistance. Seed funding for this project was provided to L.G. and J.P.D by the

Coastal Ocean Institute of WHOI. Support for S.E.M. was provided by the Postdoctoral Scholar Program of the Woods Hole Oceanographic Institution (WHOI). Additional support to S.E.M. and L.G. was provided by the Ocean and Climate Change Institution of WHOI. Support for M.D.T. and J.W.F.R. was provided by the U.S. National Science Foundation Geography and Spatial Science Program (award number BSC1359801). This is contribution #362 from the Marine Science Center at Northeastern University.

Author Contributions:

L.G. and J.P.D. initiated the project. S.E.M., L.G., M.D.T., J.W.F.R., Z.S., and J.P.D. conceived the ideas, designed the study and, interpreted the results. M.D.T. provided dendrochronological data. J.W.F.R. provided historical discharge and geospatial data. Z.S. performed OSL dating. S.E.M., L.G., R.M.S., C.W., and M.O. collected sedimentary archives and/or performed laboratory analyses. S.E.M. wrote the manuscript with contributions from all authors.

Author Information:

¹Department of Geology & Geophysics, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543, USA

²Marine Science Center, Department of Marine & Environmental Sciences, Northeastern University, Nahant, Massachusetts 01908, USA

³Department of Civil & Environmental Engineering, Northeastern University, Boston, Massachusetts 02115, USA

⁴Department of Geography, University of Alabama, Tuscaloosa, Alabama 35401, USA

⁵Department of Geography and Environmental Resources, Southern Illinois University, Carbondale, Illinois 62901, USA

⁶Department of Marine Sciences, Coastal Carolina University, Conway, South Carolina 29526

⁷Department of Geography and Planning, University of Liverpool, Liverpool L69 7ZT, UK

⁸Department of Oceanography, Texas A&M University, College Station, Texas 77840, USA

*Corresponding author: s.munoz@northeastern.edu

Competing financial interests: The authors declare no competing financial interests.

Figure legends:

Figure 1. The lower Mississippi River and the Mississippi River basin in North America. River engineering modifications (artificial cutoffs and levees) that contribute to channelization, the locations of palaeoflood records (False River Lake, FLR; Lake Mary, MRY; Lake Saint John, STJ; and Big Oak Tree, BOT), and river gauging stations on the lower Mississippi used in this study (Memphis, Helena, Arkansas City, Vicksburg, and Baton Rouge) are shown. Shaded relief shows relative topographic highs (dark shades) and lows (light shades) using the National Elevation Dataset⁴⁰.

Figure 2. Instrumental and reconstructed flood frequencies and magnitudes of the lower Mississippi River. (a) Human impacts to the lower Mississippi River (MR&T refers to the Mississippi River and Tributaries Project, a major river engineering initiative); timing and intensity of agricultural land use⁴¹ and river engineering; (b) Flood frequencies (i.e., number of flood events in a 31-year moving window) derived from palaeoflood records, including mean and bootstrapped 2 σ confidence intervals of all palaeoflood archives, and the instrumental frequency of all floods attaining major flood stage (i.e., > 1.5 m above flood stage) at the Mississippi River gauging station at Baton Rouge (station number 07374000); (c) Flood magnitudes derived from the sedimentary palaeoflood records with 1 σ uncertainties, and instrumental flood magnitudes for the Mississippi River gauging station at Vicksburg (station number 07289000).

Figure 3. Lower Mississippi River flood frequency and its relation to dominant modes of climate variability. (a) Atlantic Multidecadal Oscillation (AMO) derived from instrumental³² and palaeoclimate³⁶ datasets; (b) Frequency of El Niño events (i.e., the warm phase of the El Niño-Southern Oscillation) in a 31-year moving window derived from instrumental³² and palaeoclimate³³⁻³⁶ datasets (mean with 2σ bootstrapped confidence interval); (c) Frequency of lower Mississippi River floods derived from palaeoflood data (mean with bootstrapped 2σ confidence interval); (d) Correlation field of monthly precipitation⁴² with the AMO³² (AD 1901-2014) smoothed with a common 121-month filter; (e) Correlation field of monthly Palmer Drought Severity Index⁴³ with the Niño 3.4 index³² (AD 1948-2011). Correlation fields are interpolated to a common $2^\circ \times 2^\circ$ grid, and individual points with significant correlations at the $p < 0.05$ level are marked with a hollow circle.

Figure 4. Attribution of the observed increase in flood magnitudes over the last five centuries. (a) Composite peak discharges from palaeoflood archives and the instrumental record from Vicksburg, with trends in the largest flood of the century in a moving window observed (red line) and under ‘climate-only’ conditions estimated with a statistical model (blue line; see text for details) with 1σ confidence intervals. Instrumental peak discharge estimates are reported without uncertainty, so are plotted without confidence intervals. (b) Comparison of the 100-year flood (Q_{100} ; a flood with a 1% chance of exceedance in any year) observed during the baseline period (AD 1500–1800) prior to major human modifications to the Mississippi River and its basin (gray boxplot) with that estimated using a statistical model under ‘climate-only’ conditions (blue boxplot) and observed (red boxplot) during the modern period of instrumental record (AD 1897–2015). Boxplots show mean (center line) and 1σ confidence intervals (box top and bottom) for Q_{100} estimates.

Methods:

Instrumental streamflow data: We obtained daily stage data for Mississippi River gauges at Vicksburg (station number 07289000) and Baton Rouge (07374000) from the United States Army Corps of Engineers (USACE) and the United States Geological Survey (USGS). Discharges for the Vicksburg, Memphis (07032000), Helena (07047970), Arkansas City (07146500), and Baton Rouge gauges were compiled from multiple sources. For the early instrumental record (pre-1927), peak discharges and measured discharges were compiled from historical documents^{25,26}. In the few cases in which annual peak discharge were not recorded during this period, we used the measured discharges to create rating curves from which to determine the peak discharge for the annual peak stage. Discharge data after AD 1927 were acquired either from the USACE or from the USGS. The discharge record at Vicksburg is the longest and most continuous of the available discharge records, and its peak annual discharge is highly correlated ($r > 0.86$, $p < 0.01$) with that of other lower Mississippi River gauging stations in the study area (see *Supplementary Information*), and was thus used to reconstruct flood magnitudes from the sedimentary archives.

Sedimentary archives: We collected sediment cores from the infilling thalwegs of Lake Mary, Mississippi (MRY), False River Lake, Louisiana (FLR), and Lake Saint John, Louisiana (STJ) using a rod driven vibracore system in July 2012 and March 2016 (Extended Data Figs. 1-3). For each core, we collected a replicate drive using a 7.5 cm diameter polycarbonate piston corer to ensure recovery of an intact sediment/water interface. The targeted lakes were selected because the lateral position of the active channel near the lake’s arm has remained relatively stable since the time of cut-off to the mid-20th century²⁰. We cannot eliminate the possibility that minor lateral and/or vertical channel migration has occurred near these lakes since the time of cut-off, but reduce the influence of this potential bias on our analysis by (i) using a low-pass filter on the grain-size data (see below) and (ii) validating the resulting flood frequency and magnitude datasets against the instrumental record (see *Supplementary Information*). At FLR and STJ, mainline levees of the MR&T have inhibited the deposition of fluvial sediment in the lake during overbank floods after ca. AD 1950 and 1937, respectively; MRY is not protected by artificial levees and it continues to be inundated during overbank floods. Oxbow lakes can continue to exchange water and sediment with the main channel when the river is below flood stage²⁷ to create high rates of fine grained ‘background sedimentation’ that differs in texture and composition from the coarser material that is mobilized during

high magnitude flood events. Cores were collected along an arm of the oxbow lakes at locations proximal to the ‘plug’ that separates the active channel from the lake to maximize the contrast between background and flood event sediments. Core locations at each site were targeted based on bathymetric surveys prior to core collection.

Cores were transported back to the Woods Hole Oceanographic Institution (WHOI) where they were split, described, and photographed. Archived core halves were subjected to high-resolution XRF (4,000 μm resolution) and radiography (200 μm resolution) in an ITRAX core scanner housed at WHOI. For grain-size analysis, sediment sub-samples at continuous 1 cm intervals were dispersed in water using a vortex mixer prior to 5 sec. sonication and analysis in a Beckman Coulter LS 13 320 laser diffraction particle size analyzer; randomly selected replicate samples showed a <1% volume difference in any detector. Complex, multi-modal grain-size distributions were modeled as mixtures of discrete, simple distributions and decomposed using end-member calculations into four representative populations, or end-members (EMs), that were considered geologically meaningful, using the EMMAgeo package run in RStudio. The score of each sample on the coarsest end-members (EM1), representing deposition of bedload during overbank floods¹⁸, was normalized with a low-pass (41 cm) moving minimum filter to remove long-term trends in sediment composition caused by local geomorphic processes. We then identified potential flood deposits as normalized EM1 scores that exceeded a high-pass (11 cm) moving mean with a 0.1 threshold, and verified identified peaks against the XRF and radiography (Extended Data Figs. 4-6).

To estimate flood magnitudes from the sediment records, we used the method of ref. 18 and developed linear models that describe the normalized EM1 scores as a function of historical flood event discharge at the Mississippi River gauging station at Vicksburg, such that flood deposits were assigned to a historical flood events approximating ‘major flood stage’ as defined by the USGS at a nearby gauging station, in stratigraphic order, and within its 2σ age estimate (Extended Data Fig. 7). The requirement for flood deposits to be assigned to a historical flood in stratigraphic order eliminated ambiguity in cases where more than one historical flood fell within a deposit’s 2σ age estimate. There were no cases where a flood deposit could not be assigned to a historical flood within the period instrumental observations (AD 1897–2015), but there were three cases at FLR (AD 1944, 1929, and 1920) and two cases at STJ (AD 1920 and 1913) where a major historic flood did not leave an identifiable flood deposit. These ‘missing’ flood deposits are rare and occur during periods of high flood frequency, and may reflect reduced sediment availability²⁸ during these events. The sedimentary record reconstructs peak annual discharge at the Vicksburg gauge, not at individual site locations.

We developed age-depth models using Bacon v.2.2²⁹, a Bayesian age-depth modeling program, informed by multiple independent dating techniques (see *Supplementary Information*), including: (1) ^{137}Cs and $^{210}\text{Pb}_{\text{ex}}$ activity on desiccated and powdered bulk sediment samples in a Canberra GL2020RS low-energy Germanium gamma well detector, and used the constant rate of supply model³⁰ to estimate the age of a sampled depth; (2) Radiocarbon (^{14}C) dating via accelerator mass spectrometry (AMS) of a terrestrial plant macrofossil at the National Ocean Sciences Accelerator Mass Spectrometers (NOSAMS) facility at WHOI calibrated using the IntCal13 curve embedded in Bacon; (3) Optically-stimulated luminescence (OSL) dating with the fast component of silt-sized quartz³¹ using a Risø DA-15 B/C luminescence reader at the University of Liverpool, UK; (4) Core tops as the date of collection and, when appropriate, the age of lake formation²⁰ as the core bottom. Sedimentation rate priors were increased to near instantaneous rates through thick (> 20 cm) flood deposits¹⁷.

Tree-ring records: Tree-ring samples from 33 living and two dead oak (*Quercus lyrata* and *Q. macrocarpa*) trees were collected by from Big Oak Tree State Park (BOT) in southeast Missouri²¹. One-to-four increment core samples were extracted from each tree at or below breast height (~1.4 m) using a 5-mm diameter Swedish increment borer. Cross-sections from dead trees were collected as close to the base of the tree as possible. All samples were absolutely cross-dated using the skeleton-plot method of dendrochronology. Tree-ring widths were measured on a stage micrometer to a nominal resolution of 0.001 mm. We crosschecked the accuracy of our visual dating using the computer program COFECHA. We visually

determined flood-ring years by examining each tree-ring series for any evidence of flood injury consistent with the anomalous anatomical features caused by flooding as described by previous flood-ring studies¹⁹. Additional characteristics we used in our identification included “jumbled” or “additional ranks” of early wood vessels or zones of “extended earlywood” and disorganized flame parenchyma as well as “offset” early wood ranks¹⁹. We used the same criteria as ref. 21 to identify flood events (i.e., a year in which >10% of sampled trees exhibited signs of flood injury) as this threshold encompasses all historic floods that attained major flood stage and occurred during the growing season²¹.

Historical climate and palaeoclimate data: Historical (late 19th century to present) indices of ENSO and AMO³² were extended back to the 16th century with annual palaeoclimate reconstructions of ENSO³³⁻³⁶ and AMO³⁷. To compare the ENSO series, we identified El Niño events in the historical Nino 3.4 index as periods of 5 consecutive overlapping 3-month windows at or above +0.5°C, and as years with anomalies >+0.5°C in the palaeoclimate series. We then derived El Niño event frequencies using a 31-year moving window on each record, and computed the mean of the historical and all palaeoclimate El Niño frequencies and bootstrapped 2σ confidence intervals using the *boot* function in RStudio. For the composite AMO series, we used the detrended historical AMO index³² back to AD 1871, and then transition to a palaeoclimate AMO reconstruction³⁷ to AD 1572. We sampled this composite AMO index at the median age probability of the 20 palaeofloods that occurred between AD 1500–1800, and used these data to develop a linear model (using the *lm* function in RStudio) that relates peak discharge from the AMO index; the El Niño frequency timeseries was not a significant predictor of flood magnitudes, presumably because Pacific sea-surface temperatures do not control the inland flux of Gulf of Mexico moisture that triggers high magnitude discharge events¹⁵, so only the AMO index was used to statistically estimate flood magnitudes under ‘climate-only’ conditions. The AMO is detrended to remove recent warming of North Atlantic sea surface temperatures, so the ‘climate-only’ estimates of Q_{100} do not consider the potential effects of recent greenhouse warming on flood magnitudes – although we note that the inverse relationship between AMO and Mississippi River flood magnitudes implies that warming of North Atlantic sea-surface temperatures would act to suppress flood magnitudes. When evaluating the significance of Pearson correlations between climate and hydrological time-series that exhibited high degrees of serial autocorrelation, we estimated the effective degrees of freedom (v_{eff}) with the following relation³⁸.

$$v_{\text{eff}} = N(1 - \varphi_x \cdot \varphi_y) / (1 + \varphi_x \cdot \varphi_y) \quad (1)$$

where N is the number of independent samples, and φ_x and φ_y are the lag-1 autocorrelation coefficients of time series x and y respectively.

Flood hazard attribution: The magnitude of the 100-year flood (Q_{100}) was estimated both empirically and via statistical modeling. The sedimentary palaeoflood archives record major flood events over periods greater than 100 years, and are suitable for estimating recurrence intervals empirically using the relation:

$$t_r = (n + 1) / m \quad (2)$$

where t_r is the recurrence interval (the inverse of t_r is the probability that the event magnitude will be exceeded in any one year), n is the number of years in the window being considered, and m is the number of recorded occurrences of the event being considered. This same approach was used to estimate Q_{100} in the statistically modeled ‘climate-only’ peak annual discharges derived from palaeoclimate and historical climate records. The instrumental record at the Vicksburg gauge provides a measurement for peak annual discharge in every year, but is relatively short, so the modern Q_{100} was estimated statistically by fitting a log Pearson type III distribution to the dataset following standard protocols outlined by the United States Interagency Advisory Committee of Water Data³⁹ for instrumental hydrological datasets. We compared the observed Q_{100} baseline (AD 1500–1800) to the observed and ‘climate-only’ Q_{100} estimates for the modern period (AD 1897–2015), and attributed the proportion of the observed change that was not explained by the ‘climate-only’ estimates to human alterations to the river channel and basin. The modern Q_{100} estimated empirically from sedimentary records and the modern Q_{100} estimated by fitting a Generalized Extreme Value (GEV) distribution to the instrumental data both fall within the 1σ confidence intervals of the modern

Q_{100} estimated by fitting a log Pearson type III to the instrumental record (see *Supplementary Information*), indicating that our findings are robust to different estimations of flood hazard.

Data availability statement: The datasets generated by this study are available as Supplementary Data.

Code availability: The R code used to produce the figures in this paper is available from the corresponding author on reasonable request.

Methods References:

25. Mississippi River Commission. *Results of the Discharge Observations Mississippi River and its Tributaries and Outlets, 1838-1923* (Mississippi River Commission, 1925).
26. Mississippi River Commission. *Results of the Discharge Observations Mississippi River and its Tributaries and Outlets, 1924-1930* (Mississippi River Commission, 1931).
27. Hudson, P.F., Sounny-Slitine, M.A., LaFevor, M. A new longitudinal approach to assess hydrologic connectivity: Embanked floodplain inundation along the lower Mississippi River. *Hydrol. Process.* **27**(15), 2187-2196 (2013).
28. Heitmueller, F.T., Hudson, P.F., Kesel, R.H. Overbank sedimentation from historic AD 2100 flood along the lower Mississippi River, USA. *Geology* **45**(2), 107-110 (2017).
29. Blaauw, M., Christen, J. A. Flexible paleoclimate age-depth models using an autoregressive gamma process. *Bayesian Anal.* **6**, 457-474 (2011).
30. Appleby, P. G., Oldfield, F. (1978). The calculation of lead-210 dates assuming a constant rate of supply of unsupported ^{210}Pb to the sediment. *Catena* **5**, 1-8 (1978).
31. Shen, Z., Lang, A. Quartz fast component optically stimulated luminescence: Towards routine extraction for dating applications: *Radiat. Meas.* **89**, 27-34 (2016).
32. Rayner, N. A. *et al.* Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *J. Geophys. Res-Atmos.* **108**, doi:10.1029/2002JD002670 (2003).
33. Gergis, J. L., Fowler, A. M. A history of ENSO events since AD 1525: implications for future climate change. *Climatic Change* **92**, 343-387 (2009).
34. Li, J. *et al.* Interdecadal modulation of El Niño amplitude during the past millennium. *Nat. Clim. Change* **1**, 114-118 (2011).
35. McGregor, S., Timmermann, A., Timm, O. A unified proxy for ENSO and PDO variability since 1650. *Clim. Past* **6**, 1-17 (2010).
36. Braganza, K., Gergis, J. L., Power, S. B., Risbey, J. S., Fowler, A. M. A multiproxy index of the El Niño-Southern Oscillation, AD 1525-1982. *J. Geophys. Res-Atmos.* **114**, doi:10.1029/2008JD010896 (2009).
37. Gray, S. T., Graumlich, L. J., Betancourt, J. L., Pederson, G. T. (2004). A tree-ring based reconstruction of the Atlantic Multidecadal Oscillation since 1567 AD. *Geophys. Res. Lett.* **31** 10.1029/2004GL019932 (2004).
38. Dawdy, D., Matlas, N. *Statistical and Probability Analysis of Hydrologic Data, Part III: Analysis of variance, covariance and time series.* (McGraw-Hill, 1964).
39. Interagency Advisory Committee on Water Data. *Guidelines for Determining Flood-Flow Frequency: Bulletin 17B of the Hydrology Subcommittee* (United States Geological Survey, 1982).
40. Gesch, D. *et al.* The National Elevation Dataset. *Photogramm. Eng. Rem. S.* **68**, 5-32 (2002).

41. Klein Goldewijk, K., Beusen, A., Doelman, J., Stehfest, E. New anthropogenic land use estimates for the Holocene; HYDE 3.2. *Earth Syst. Sci. Data Discuss.*, doi: 10.5194/essd-2016-58 (2016).
42. Schneider, U. *et al.* Evaluating the hydrological cycle over land using the newly-corrected precipitation climatology from the Global Precipitation Climatology Centre (GPCC). *Atmosphere* **8**(3), 52–69 (2017).
43. Vose, R.S. *et al.* Improved historical temperature and precipitation time series for U.S. climate divisions. *J. Appl. Meteorol. Clim.* **53**, 1232–1251 (2014).

Extended data figure captions:

Extended data Figure 1. Location of Lake Mary, Mississippi (MRY) and sediment core (MRY2) used in this study. Lake Mary is an oxbow lake that formed via neck cutoff of the lower Mississippi River in AD 1776²⁰, and is situated inside the modern floodway such that it continues to be inundated during overbank floods. Bathymetric contours (white) given in meters. Shaded relief shows relative topographic lows (dark shades) and highs (light shades) using the National Elevation Dataset⁴⁰.

Extended data Figure 2. Location of False River Lake, Louisiana (FLR) and sediment core (FLR1) used in this study. False River Lake is an oxbow lake that formed via neck cutoff of the lower Mississippi River in AD 1722²⁰, and is situated outside the modern floodway. Bathymetric contours (white) given in meters. Shaded relief shows relative topographic lows (dark shades) and highs (light shades) using the National Elevation Dataset⁴⁰.

Extended data Figure 3. Location of Lake Saint John, Louisiana (STJ) and sediment core (STJ1) used in this study. Lake Saint John is an oxbow lake that formed via neck cutoff of the lower Mississippi River ca. AD 1500²⁰, and is situated outside the modern floodway. Bathymetric contours (white) given in meters. Shaded relief shows relative topographic lows (dark shades) and highs (light shades) using the National Elevation Dataset⁴⁰.

Extended data Figure 4. Radiography, bulk geochemistry, grain-size, and chronology of core MRY2 (Lake Mary, Mississippi). The age-depth model at right shows the median age probability (black line) and 1 σ confidence intervals (grey shading), with 2 σ confidence intervals on individual chronological controls.

Extended data Figure 5. Radiography, bulk geochemistry, grain-size, and chronology of core FLR1 (False River Lake, Louisiana). The age-depth model at right shows the median age probability (black line) and 1 σ confidence intervals (grey shading), with 2 σ confidence intervals on individual chronological controls.

Extended data Figure 6. Radiography, bulk geochemistry, grain-size, and chronology of core STJ1 (Lake Saint John, Louisiana). The age-depth model at right shows the median age probability (black line) and 1 σ confidence intervals (grey shading), with 2 σ confidence intervals on individual chronological controls.

Extended data Figure 7. Relationships between peak annual discharge and normalized EM score (a measure of grain-size) for historical floods in sedimentary archives. Scatterplots and linear regressions with 1 σ prediction intervals relating normalized EM score to peak annual discharge of historical flood events for (a) Lake Mary (MRY), (b) False River Lake (FLR), and Lake Saint John (STJ). Peak annual discharge estimates are from the Mississippi River gauging station at Vicksburg. Calibration periods vary due to site specific factors discussed in the *Methods* and *Supplementary Information*.