SUPPLEMENTARY MATERIAL

Enhanced flood hazard assessment beyond decadal climate cycles based on centennial historical data

Gerardo Benito[1], Olegario Castillo[2], Juan A. Ballesteros-Cánovas[3], Maria Machado[1], Mariano Barriendos[4]

[1]National Museum of Natural Sciences, MNCN-CSIC, C/ Serrano 115bis, 28006, Madrid, Spain
[2]Dpt. Ingeniería Industrial e Ingeniería Civil, Escuela Politécnica Superior de Algeciras, 11202 Algeciras, Spain
[3]Climatic Change Impacts and Risks in the Anthropocene (C-CIA), Institute for Environmental Sciences, University of Geneva, Geneva, Switzerland
[4]Dpt. D`Història Moderna, Universitat de Barcelona, 08001 Barcelona, Spain

Correspondence to: Gerardo Benito (benito@mncn.csic.es)

FIGURES:

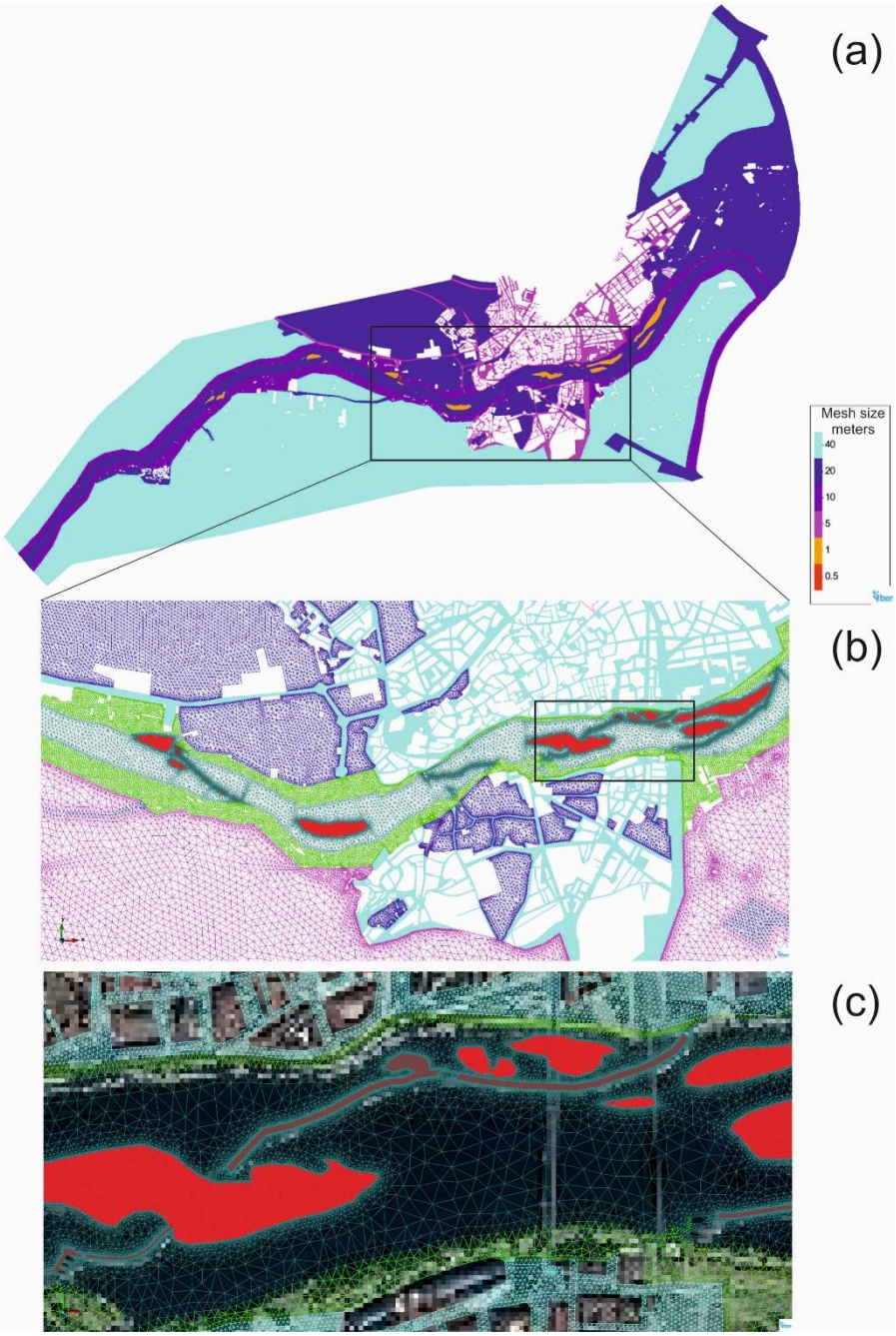

Figure S1: Numerical domain used on the two-dimensional hydraulic model (Iber) along the 13 km studied reach of the Duero River between the Carrascal gauge station and the confluence with the Valderaduey River. The elements of the mesh range from a size of 40-10 m on the floodplains, 5-1 m in the channel and 5 to 0.5 m in urban areas. a) General view of the studied reach and characteristic mesh sizes. b) Detail of the mesh size at the Zamora city area. c) Mesh size used between the Cabañales mills and the railroad bridge. Location of this area is marked by a rectangle in b. Aerial Orthophoto and LiDAR data from the Spanish National Geographic Institute, IGN; https://www.ign.es.

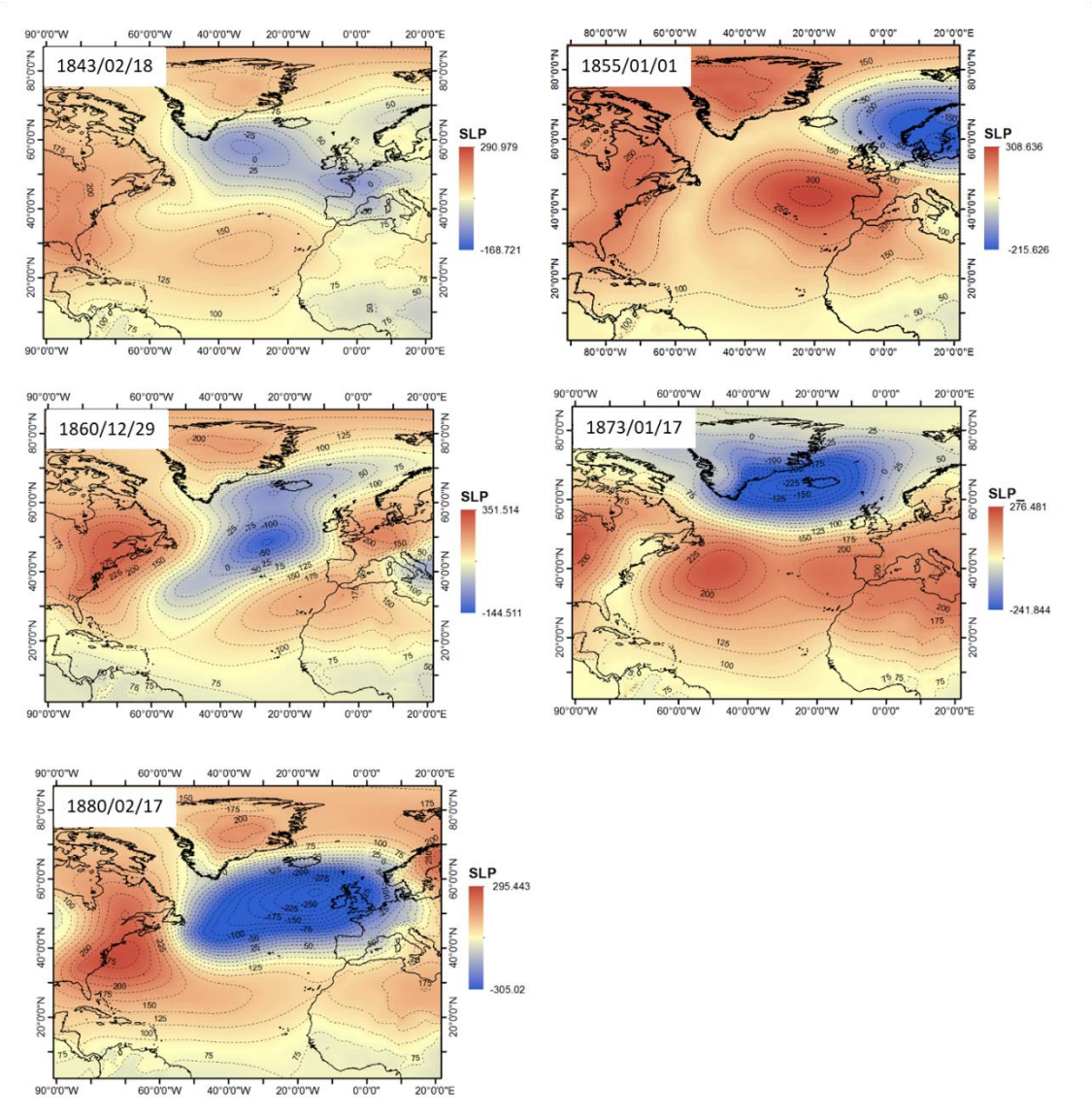

Figure S2: Chart displaying the composite (-5 days) SLP related to each flood previous 1881.

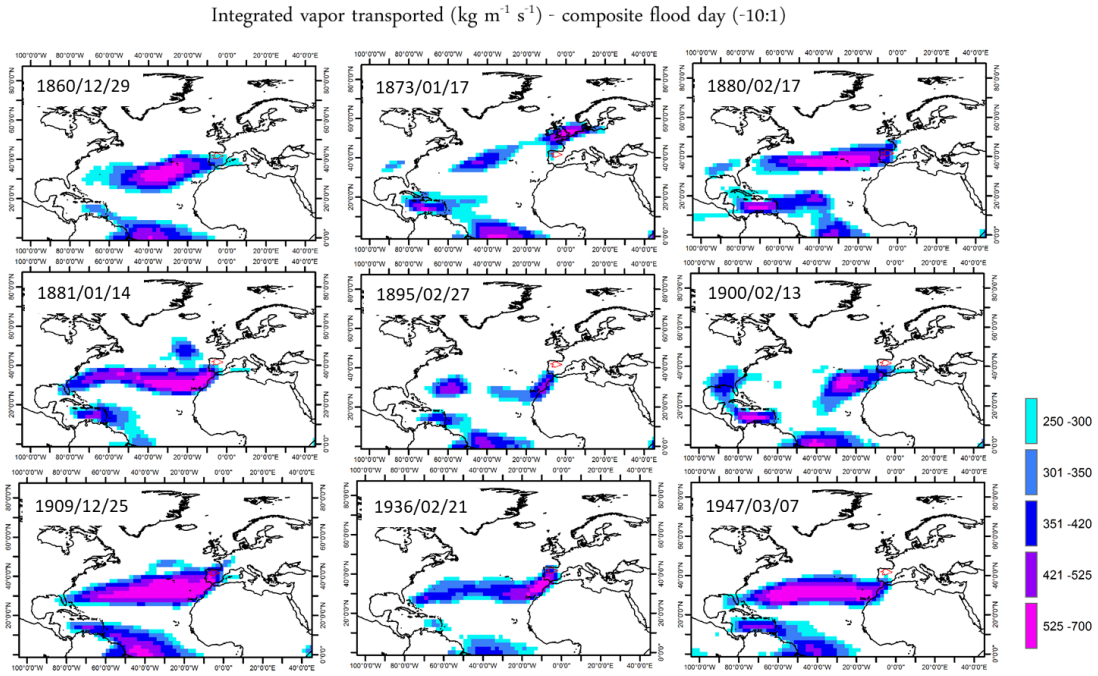

Figure S3: Mean integrated vapor transported for the 10 days prior each flood exceeding the perception thresholds. Data: 20CRV2c

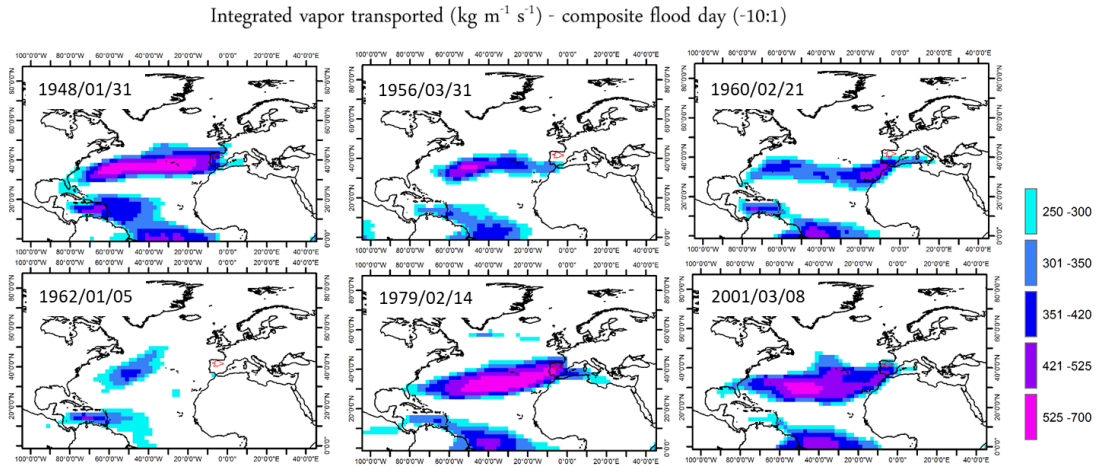

Figure S3 (cont.): Mean integrated vapor transported for the 10 days prior each flood exceeding the perception thresholds. Data: 20CRV2c

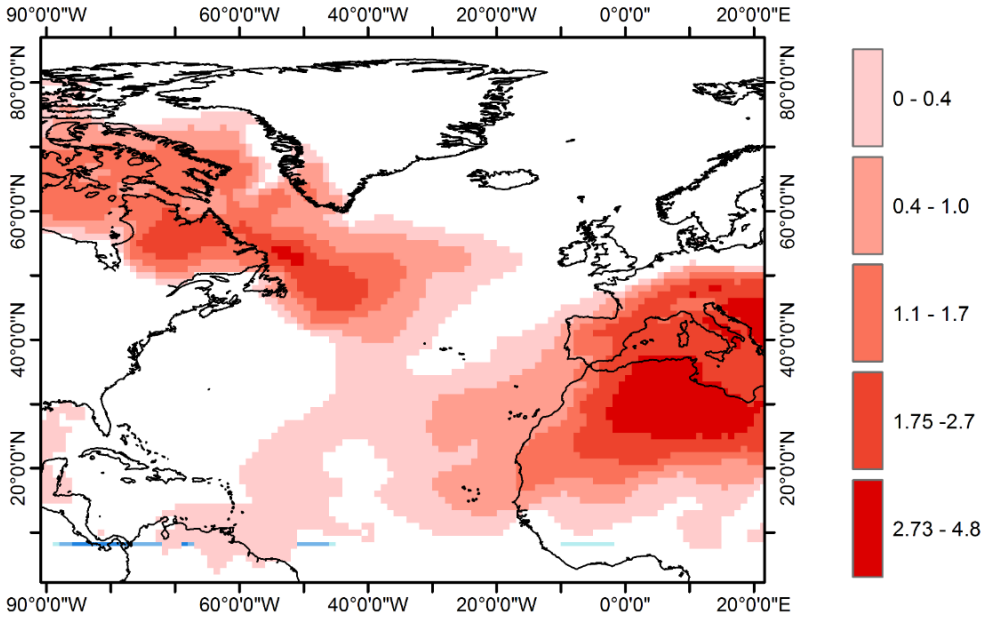

Figure S4: Temperature anomaly retrieved from 20CRV3.

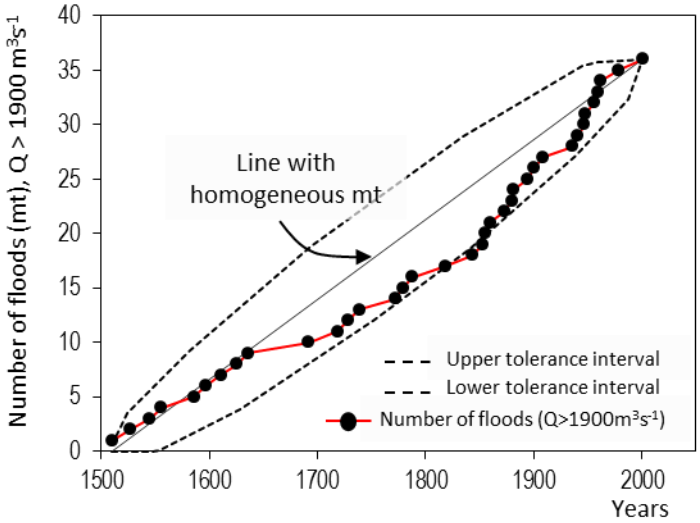

Figure S5. Stationary test on the time flood process of the Duero River over the period CE 1511–2018, for flood events equal or exceeding a discharge threshold of 1900 m3/s. The null hypothesis is to assume that the distribution of the number of exceedences can be described by a homogeneous Poisson process (i.e., independent and identically distributed random variables; Lang et al., 1999 and 2004). The test is passed when the accumulated flood line (red line with black dots) stays inside the 90% tolerance interval (95 and 5% quantiles; dashed lines), implying the compliance of the Poisson process hypothesis.

TABLES:

Num.	Site	X	Y	Z (ground)	Year	Flood water elevation meters asl	Discharge m^3/s	Comments	Reference
1	Dueñas de Cabañales (Dominicas Convent)	270708.923	4597455.379	626.628	1264	>626.7	>2300	Convent was flooded. Damages in the convent.	Revista Contemporánea, Año VI, Tomo XXV, 1880, Madrid. p. 36
					1597	>626.7	>2300	Convent was flooded	Puig y Larraz, G. 1883.
					1636	>626.8	>2300	Cabañales wall breached by flood waters	Revista Contemporánea, Año VI, Tomo XXV, 1880, Madrid. p. 36
					1739	627.45	2700	Limnimark. Exact discharge	
					1855	>626.7	>2300	Description of main hall flooded (atrio)	Zatarín Fernández, 1898
					1860	628.50	3400	Limnimark. Exact discharge	
					1962	~626.9	~2150	Water reach Carros plaza next to Medieval bridge	
2	San Frontis church	270084.358	4597209.135	626.246	1739	>626.4	>2100	San Frontis was flooded	Puig y Larraz, G. 1883.
					1860	627.95	3350	Limnimark. Exact discharge	Marquina, 1945
3	Aceña de Olivares (Olivares mills)	270106.401	4597660.211	624.116	1860	628.11	3450	Inscription. Elevation corrected by -0.15m from Marquina survey	Marquina, 1945
					1962	626.50	2200	Base of Church door	
4	San Claudio de Olivares church (north door)	270027.366	4597676.785	626.675	1258	628.70	3700	Inscription at rightside upper doorpost (Marquina, 1945)	Marquina, 1945
					1839	~626.0	~1800	Inscription at the pedestal of the cross in front of S. Claudio church	Revista Contemporánea, Año VI, Tomo XXV, 1880, Madrid. p. 39
					1860	628-628.4	3450-3600	Water stage reach pulpit level (Zatarín Fernandez, YEAR)	Zatarín Fernández, 1898
						627.10	2780	Base of church door. Maximum/minimum flood stage	
5	Former Convent of Santa Clara S. XIV (placed next Santiago de los Caballeros)	269691.17	4597767.78	626.3	1586	~627	2800	Santa Clara Convent, located until 14th c. next o St. Caballeros. Archive destruction	Dominguez, Juan Antonio, 1761. Crónica seráfica de la provincia de Santiago, Parte Tercera; Heras Hernández, 1973: 214
6	Santiago de los Caballeros (southern side)	269771.173	4597894.585	626.548	1586	>626.54	>2300	Santiago El Viejo was flooded	Zatarín Fernández, 1898
					1739	>626.6	>2500	Santiago El Viejo was flooded	Puig y Larraz, G. 1883.
7	San Francisco Convent	270491.51	4597645.21	626.48	1597	>626.7	>2400	The San Francisco wall destroyed by floodwaters	Revista Contemporánea, Año VI, Tomo XXV, 1880, Madrid. p. 37
8	Medieval stone Bridge	270621.023	4597822.561	631.397	1597	628.20	3200	Floodwater covered the middle lightening spillways arches	Revista Contemporánea, Año VI, Tomo XXV, 1880, Madrid. p. 38

	Medieval stone Bridge	270621.023	4597822.561	631.397	1909	625.657	1350	Stage at the upstream	Marquina, 1945
					1909	625.577	1350	Stage at the downstream	Marquina, 1945
9	Puerta del Pescado (Gate)	270454.892	4597900.747	627.00	1860	628.50	3400	Old landmark at 1.5 m from the gate base.	Revista Contemporánea, Año VI, Tomo XXV, 1880, Madrid. p. 40; Puig y Larraz, 1883.
10	Iglesia de Santa Lucia (door)	270677.756	4598036.145	628.985	1853	627.00	2200	Lower part of the plaza	Zatarín Fernández, 1898
					1855	626.80	2100	Lower part of St Lucia area	Zatarín Fernández, 1898
					1860	628.90	3550	Elevation corrected from Marquina.	Marquina, 1945
11	Santa María de la Horta (south entrance)	270931.82	4598047.596	626.8	1597	628.30	3200	St. Maria de Horta 1.5 m depth. Flood level slightly higher than 1739-flood	Zatarín Fernández, 1898; Revista Contemporánea, Año VI, Tomo XXV, 1880, Madrid. p. 38
					1788	627.30	2550	Flood reach the church	Puig y Larraz, G. 1883.
					1962	627.15	2235	Photos local press (Imperial Newspaper)	
12	Santo Tomé church	271060.707	4598041.019	626.528	1597	626.528	>2500	Santo Tomé flooded	Puig y Larraz, G. 1883.
					1739	626.528	>2500	Santo Tomé flooded	Revista Contemporánea, Año VI, Tomo XXV, 1880, Madrid. p. 38
13	San Leonardo church	270856.731	4598127.648	629.207					
14	Cuartel de Caballeria (at Jacinto Benavente Highschool)	270086.72	4597989.22	626.70	1788	627.50	2500	Flooded the old cavalry barracks. 13 palmos (1.5 m)	Puig y Larraz, G. 1883. Marquina, 1945
					1843	~627.5	~2500	Flooded the old cavalry barracks. Similar to 1788	Puig y Larraz, G. 1883. Marquina, 1945
15	Mengue Avenue	270791.779	4597946.434	625.84	1959	627.20	2350	Evidence from historical photographs	
					1962	627.05	2200	Evidence from historical photographs	
16	Iron bridge (road Zamora-Salamanca (pavement at northern side)	271307.635	4598009.809	631.485	1860	628.910	3000	Water stage draw on bridge diagram marked at 1.8 m below bottom iron structure	Map draw by Prudencio de Gaudalfajara, July 29, 1890
					1873	627.980	2200	Water stage draw on bridge diagram marked at 2.73 m below bottom iron structure	Map draw by Prudencio de Gaudalfajara, July 29, 1891
17	Old railway bridge	271413.79	4598005.973	634.785					
18	Cabañales watermill (basal level)	270782.197	4597730.007	626.572	1941	625.14	1150	Documented marks surveyed by Marquina according to wall marks and eyewitness descriptions	Marquina, 1945
	Cabañales watermill (upper level)	270789.617	4597728.447	622.907	1936	626.05	1550	Documented marks surveyed by Marquina according to wall marks and	Marquina, 1946

								eyewitness descriptions	
					1939	624.92	1000	Documented marks surveyed by Marquina according to wall marks and eyewitness descriptions	Marquina, 1947
19	San Jerónimo Monastery								
20	N.P. 1482 (IGN 1925) at the monument base	270633.251	4597668.049	628.903				GPS point surveyed at the base of the monument to D. Federico Requejo	
20bis	N.P. 1482 (IGN 1925) current mark level (630.7m)	270633.256	4597668.049	630.452				GPS point at the line with elevation 630.7 m above sea level in Alicante (Spain)	
21	IGN Survey mark 305004	270603.262	4597656.188	628.532				Survey mark, IGN network No 305004 (628.6277). Elevation difference: -0.0957	
22	IGN Survery mark 305005	270265.199	4597463.865	624.783				Survey mark, IGN network No. 305003 (628.1924). Elevation difference: -0.103	
23	IGN Survey mark 305003	271138.229	4598013.347	628.089				Survey mark, IGN network No. 305005 (624.8178). Elevation difference: -0.0348	
24	Old bridge remnants	270259.319	4597519.508	621.48				Bridge destroyed by flooding in 1310	Zatarín Fernández, 1898
	Farm La Candelada (road Zamora to Gijón watermill)	267944.99	4598377.25	627.1	1860	627.15	3200	Landmark at the entrance of Candelada Farm, referred by Marquina 1945	Marquina, 1945
	Aceñas de Gijón (Water mill)	268788.573	4597801.025	622.088				Repeated written evidence of flooding	Zatarín Fernández, 1898

Table S1. Flood landmarks and epigraphic marks with historic references used for the estimation of historic flood peak discharges. Location and elevations were obtained from GNSS GPS measurements. Site numbers refer to Fig. 2.

Year	Month	Temperature anomaly	Precipitation rate anomaly	Monthly NAO-index	Predominant circulation type during 5 days precedent to flood
1843	2	-0.67	2.46	-3.50	WZ
1855	1	-2.26	-3.21E-02	-1.84	WZ
1860	12	-1.12	3.76	-0.69	SWZ
1873	1	0.62	0.69	0.17	WZ
1880	2	0.80	1.39	1.91	WZ
1881	1	-1.02	4.72	-3.59	TM
1895	2	0.42	4.23	-4.13	TRM
1900	2	0.25	4.53	-2.35	WS
1909	12	0.83	2.34	-0.10	WZ
1936	2	1.62	3.29	-2.43	SZ
1947	3	8.25E-02	3.74	-1.27	HNFZ
1948	1	1.21	3.00	1.53	SWZ
1956	3	-1.47	2.59	0.01	WZ
1960	2	-7.68E-02	1.99	-0.99	SWZ
1962	1	0.58	1.65	2.44	BM
1979	2	0.52	3.48	0.61	WZ
2001	3	1.56	3.51	-0.88	WZ

Table S2. Temperature and precipitation anomalies (wrt: 1980-2010) derived from 20CRV3, monthly NAO index (NAO index refereeing to Gibraltar – Stykkisholmur; Jones et al., 1997; source: Climate Explorer); and the predominant circulation type during the 5 days previous to the flood records according to Katalog Der Grosswetterlagen Europas (1881-2004) (source: https://www.pik-potsdam.de/en/output/publications/pikreports/.files/pr100.pdf). WZ (facing west over Central Europe, predominantly cyclonic); SWZ (south-west over Central Europe, predominantly cyclonic); WS (South-west facing); HNFZ (high North Sea Fennoscandia over Central Europe predominantly cyclonic); TM (Depression over Central Europe); TRM (trough over Central Europe); BM (high pressure bridge Central Europe); and SZ (facing south over Central Europe, predominantly cyclonic). The circulation types for flood events before 1881 are defined according to the composite Sea Level Pressure 5 days before the flood (Figure S3).

Year	Month, day	Daily Q (m^3/s) at Carrascal (46,700 km^2)	Calculated Peak Q (m^3/s) in Zamora (46,137 km^2)	Comments
1924	Mar, 28	1650	1733	
1927	Dec, 26	1697	1781	
1936	Feb, 21	1840	1930	
1939	Jan, 20	1878	1878	
1941	Jan, 26	1810	1900	
1947	Mar, 7	1869	1960	
1948	Jan, 31	1909	2001	
1956	Mar, 31	1928	2021	
1960	Feb, 21	2343	2451	
1962	Jan, 5	2100[b]	2260	[b]Corrected based on Villachica and Toro. Reported at Carrascal: 3071 m^3/s
1964	Feb, 26	1636	1719	
1966	Jan, 22	1768	1855	
1978	Mar, 4	1635	1717	
1979	Feb, 14	2255	2308	
1997	Dec, 21	1624	1707	
2001	Mar, 8	1978	2138[a]	*Recorded peak at Carrascal

Table S3. Peak discharges of the major 20th century floods exceeding 1700 m^3/s (~10-yr flood) in El Carrascal (since 1920) and Zamora (since 2002). Peak discharge values were calculated by fitting a daily (Qc) to instantaneous (Qci) discharge ratio over the period 2002-2014. [a]Measured peak in Carrascal; [b]Discharges estimated based on linear regression equation from Toro and Villachica records (R^2: 0.982).

HISTORICAL SOURCES:

Printed sources (maps)

Anton van der Wyngaerde (1570). View of Zamora. Source: Kagan, 1986, op. cit., p. 370-371. Available at https://es.wikipedia.org/wiki/Archivo:Zamora_(van_den_Wyngaerde).jpg

Rodríguez Méndez, FJ.; García Gago, JM. (2014). Wyngaerde en Zamora. EGE Revista de Expresión Gráfica en la Edificación, 8, 67-75. ISSN: 1888-8143. https://doi.org/10.4995/ege.2014.12486

Cermeño, J. M.1766. Proyecto de fortificación de Zamora. Cartoteca Histórica del Servicio Geográfico del Ejército, Sección de Documentación, nº 339. Historic map of Zamora (1:2900 in scale) published on March 11, 1766. Available at: Biblioteca virtual Ministerio de Defensa https://bibliotecavirtual.defensa.gob.es/;

Laurent, J. (c. 1860). General view of Zamora (photography). Source: Archive Ruiz Vernacci. IPHE. Ministerio de Educación y Cultura. Sig. C-435

Viloria, S. (1880). Collection of plans of the municipal architect for sewage system. Provincial Historical Archive of Zamora. Maps at 1:5000 in scale with 1 m contour lines.

Printed sources (photos)

Passaporte, A. (1927). Historical Photography of Zamora. http://catalogos.mecd.es/IPCE/cgi-ipce/ipcefototeca/O13172/IDb2758df4/NT1

Laurent, J. 1860-1886. Historical Photography of Zamora. http://catalogos.mecd.es/IPCE/cgi-ipce/ipcefototeca/O13172/IDb2758df4/NT14

Wunderlich, O. (1930-1936). Historical Photography of Duero River in Zamora. http://catalogos.mecd.es/IPCE/cgi-ipce/ipcefototeca/O13172/IDb2758df4/NT1

Instituto de Patrimonio de Cultura. Collection of postal carts of Zamora between 1906-1915. Source Photo Archive of the Instituto de patrimonio cultura. TP-0479

Loty Archive. Photographical documents. Puente Viejo restos foto de LOTY-02471_P Archivo Loty puente viejo y cathedral

Provincial Historical Archive of Zamora. Photographic view of Puerta del Pescado Source: Sueños de Plata. El Tiempo y los Ritos.

Memoria Gráfica de Zamora. 2000. Iglesia de San Frontis at 1940s. Published by La Opinión-El Correo de Zamora with collaboration of the Junta de Castilla y León y Caja España. Zamora, 2000. Zamora. Fotografía. Historia. Memoria. Arte.

Manuscript sources

Revista Contemporánea. Inundaciones del Duero. Año VI, Tomo XXV, 1880, Madrid. p. 33. Available at Biblioteca Nacional de España: http://hemerotecadigital.bne.es

Zataraín-Fernández, M., 1898. Apuntes y noticias curiosas para formalizar la historia eclesiástica de Zamora y su Diócesis. Ed. San José, Zamora. 355p. Digital copy: https://bibliotecadigital.jcyl.es/es/consulta/registro.cmd?id=3769

Puig y Larraz, G. 1883. Descripción física y geológica de la provincia de Zamora. Comisión del Mapa Geológico de España. Imp. y Fund. de Manuel Tello. 488 p., 2 h. pleg. de lám.; 28 cm

Marquina, R.J., 1941-1944. Proyecto del Salto de Villalcampo en el Río Duero (Zamora). In: Duero, S.d. (Ed.), Zamora, pp. 82. Historical Archive of Iberdrola.