



MINISTERIO  
DE ECONOMIA  
Y COMPETITIVIDAD



Dear Prof. Blöschl,

Thank you very much for your help in the review process of this manuscript. Find enclosed the revised copy of the text and figures. We have made all the specific changes suggested by the three reviewers, and we have added new paragraphs, as indicated in the reply to their comments.

We appreciate very much the time and comments made by the reviewers and the editor which were very valuable to improve the quality and understanding of the material presented in our study.

Yours sincerely,

Dr. Gerardo Benito  
Researcher Professor at the Spanish Research Council  
National Museum of Natural Sciences

Reply comments to Neil Macdonald:

We appreciate very much the reviewer comments and particularly the suggested improvements to the English use of the manuscript. We have changed the text accordingly.

Regarding some of the specific recommendations:

1.- We have extended the text regarding the synergies of documentary floods with other methods of Palaeoflood studies, namely lichenometry and dendro-geomorphology. The following paragraph was included.

In non-varved lake systems, palaeoflood stratigraphy can be compared to historically documented flood records, as a mean to improve the age-depth model of the stratigraphic log (Schillereff et al., 2014). Another group of palaeoflood techniques suitable to combine with documentary sources are those based on botany-ecology (Bodoque et al., 2014). The presence of lichens on boulders in river channels can be used to date the flood responsible of their transport, once a lichenometric growth curve for the lichen species for the area of study has been established (Foulds et al., 2014). Dendrogeomorphology uses information from flood damages in trees and bushes, dating floods at annual scale (Bodoque et al., 2014). Commonly, these palaeoflood methods are most suitable for mountain streams environments, where documentary sources provide a mean to establish the age biases to minimize errors during the calibration process

2.- We have not under One of the comments on the annotated manuscript w

In the case of the River Findhorn in UK, the official gauged discharge for the 1970-flood was ca. 60% higher than the reconstructed peak flow for the 1829-flood, although the former plots above the envelope curve for Scottish runoff, raising doubt about their credibility (Werritty and McEwen, 2003). Comment by Neil the reassessed and recalculated flow below the EC is now excepted edition of the manuscript that improved the submitted HESSD manuscript.

Comment by Carmen Llasat	Answer or action taken in the reviewed version of the manuscript.
P.4416, 1.1: Please add a comment about the China reports: are they continuous and homogeneous for any long period?	China documents on historical floods date back in some cases to 2000 years ago, with detailed descriptions over the recent 600 years and complete and homogenous data over the last 200 years (Luo, 1987).
P. 4416, 1.11: Introduce a full stop before starting the paragraph about the early stages of hydrology.	Done
P. 4416, 1.18-25: It would be better to follow a chronological argument, starting from the longest series (paleofloods), following by historical floods and ending with early instrumental period	The argument is not intended to follow a chronological order but the relevance of European historical hydrology on the international context.
P. 4416, 1.14: It would be better to cite Fig.1 in another place, because it shows a general framework of different sources of information and in its present position in the text, it only does reference to gauge stations and data-loggers	Figure 1 reference was deleted from this site.
<p>2. Quantitative historical hydrology</p> <p>The section does not correspond to this title. It is a mix of different things that are already included and developed in other parts of the paper, and some general aspects with other more detailed ones. In order to better contribute to the learning of the reader, the better would be: a) to maintain the introductory style and removing it to the introduction doing the necessary changes; or b) to develop more the different aspects commented in the section, merging with other parts of the text. For instance, when you speak about the quantification (numerical or categorical), you should introduce here the classifications that you present in other parts of the paper in basis to return period, peak of discharge or types like catastrophic or extraordinary floods.</p>	<p>We agree that this section could be included in the introduction. However, we think that including a longer introduction may confuse either further to the reader. The introduction section is mainly devoted to explain that this review paper will be focus only on studies that have quantified flood magnitudes from the historical record, and not to the whole set of historical flood studies. The title in section 2 is needed to justify the data sources and methods used in the literature to hydrological quantification of historical floods.</p>

<p>P.4420: It would be better to numerate the equations</p>	<p>Done</p>
<p>P.4421, 1.26: For the non expert it would be better to say the meaning of “ca.”</p>	<p>All ca. was either change to circa or other full complete words.</p>
<p>P. 4424, 1.5: Databases are not usually printed sources</p>	<p>Database was removed from the example list</p>
<p>P. 4424, 1.11: Remove from the bracket the reference of Barriendos and Coeur (2004), it is cited explicitly in the following sentence. On the other hand, in the paper of Barriendos et al, 2003, the qualitative classification showed is better than in Barriendos and Coeur, 2004, because it synthetizes both classifications, this one used in the papers from Coeur and Lang for French rivers and this other one commonly used by Barriendos and other authors for Spanish rivers.</p> <p>Please, displace here the classification that you show in the first paragraph of page 4436.</p>	<p>Barriendos and Coeur paper was deleted from the text and reference and used instead Barriendos et al., 2003.</p> <p>In page 4436 is describe only a part of Barriendos et al., classification, because Ordinary floods are not considered in the applied examples used for Figure 8. I would rather to leave this short description of flood categories on page 4436</p>
<p>P. 4425, 1.4. The River Ter series has been updated until 2002 in Llasat et al (2005) and until 2012 in Barrera-Escoda and Llasat (2015). Please, update the references.</p>	<p>In page 4425 the discussion is not about the Ter historical series, but in relation to the number of floods having data with exact information on flood depth, in relation with the total number of events recorded. I have read the indicated papers and none of these shows that kind of details or supplementary list of historical flood data.</p>
<p>p. 4435, 1.8. As before, the River Llobregat series has been upated in the papers cited previously Particularly, Llasat et al (2005) was published into the SPHERE project and Barrera-Escoda and Llasat (2015) updates the SPHERE series and introduces new analysis and results.</p>	<p>The sentence refers to studies that combined historical and palaeoflood data, and neither Llasat et al 2005, or Barreda and Llasat 2015 addressed palaeoflood information.</p> <p>Please, read the focus of the sentence:</p> <p>“The SPHERE Project has revealed the complementary of palaeoflood and historical flood information (Benito and Thorndycraft, 2004) with major gain on the quality of past flood records in terms of time and discharge, as it is demonstrated in the studies performed</p>

	for the rivers Gardon ....”
P.4435, l.18: Why do you consider rare floods when T>50 years? Any reference to justify it?	In the sentence on page 4435 “rare” is a relative term or differentiate from frequent (2-year floods). This is why is on quotation marks, and the 50-yr T is justified as it is the one used by Knox 1993 paper ,as referred at the end of the sentence.
For this part, and having in mind that this is a review paper, I would recommend you to consider in your paper the recent papers published by Mediero et al (2014) about flood frequency in Spain, Barrera-Escoda and Llasat (2015) and Peña et al (2015) where the influence of climatic aspects in flood frequency and magnitude are widely discussed.	Several sentences referring to these papers are now included in the text.
On the other hand, the impact of climatic features is not the same for catastrophic or largest floods than for extraordinary ones that can be more affected by non climatic factors like changes in the use of soil, increasing vulnerability and so on. I would recommend you to read and include in the references, the paper from Hall et al (2014), where a deep analysis on the different factors that can affect flood frequency changes is presented.	The section aims to detect changes and trends on historical floods quantified by discharge estimates. The analysis of climatic and environmental factors influencing the changes at basin scale are described on the on-site studies referred in the papers cited in this section. Anyway, the reference by Hall et al 2014 was referred now in the text, to indicate the different perspective of flood change obtained from the historical record (flood rich episodes vs flood-poor period) in relation to flood trend detection when the observational period is used.
Finally, this section is a little confusing, because there are a lot of quantitative data that are mixed (in some occasions is difficult to know to which river they refer). Please, try to organize better all this information.	The section is mainly referred to the analysis of the eight case studies from figure 8. The order of the data and descriptions follow those case studies.

## Reply to Lothar Schulte comments

The authors are very gratefully for the very constructive comments of the reviewer, and their high value to improve the submitted manuscript. Most of them have been included in the updated version of the text.

Regarding the specific comments:

a) P. 4435, L. 9-15:

The overview paper presents in chapter 5.2 recent trends of multi-proxy analysis (P.4435, L. 9-15).

We appreciate this comment, and following the suggestions, several new sentences were included in the section 5.2 Multi-proxy analysis of past hydrological extremes, as follow:

“Recent developments on palaeoflood reconstruction from floodplain sediments analysed geochemical proxies from continuous alluvial records and investigate local documentary flood data to calibrate the palaeohydrological records (e.g. Swiss Alps, Shulte et al., 2008, 2015; River Severn in mid-Wales, Jones et al., 2012; River Rhine in The Netherlands, Toonen et al., 2015). Flood sediments accumulated on floodplain sinks (e.g. palaeomeanders and flood-basin environments) can be analysed with high resolution techniques (e.g. X-Ray-scanned samples) to obtain continuous records of grain-size and geochemical content (Zr/Ti, Zr/Rb and Sr/Ti) indicative of detrital fraction deposited by floods (Schulte et al., 2015). The reconstructed palaeoflood magnitudes are obtained after calibrating their ages obtained by geochronological techniques (radiocarbon) with known historical events and normalizing grain-size and geochemical content, where the coarse tail of grain-size distribution is used to estimate peak flood discharges or severity indexes (Toonen et al., 2015). “

The reference by Dominguez-Castro et al., (2008) was not included because it is related to historical reconstructions of floods in Toledo, and there is not any use of proxy data. The reference by Wirth et al., 2013 is also included in the sentences related to lake records and documentary floods.

b) P.4434 L.1: Also in many mountain catchments the historical floods are considerable larger than the instrumental data. There are several reasons (Schulte et al., 2015; Peña et al. 2015, HESS this issue):

Following the suggestions by the referee, the following sentence was modified:

The largest difference in discharge between historical and gauged flood is mainly characteristic for small catchments, in mountain basins and in Mediterranean rivers (e.g. Llobregat, Ter, Ticino, Tiber and Isère rivers).

A new sentence was added as follow:

In many mountain catchments historical floods are considerable larger than the instrumental data, that can be explained by different reasons (Schulte et al., 2015; Peña et al., 2015): (i) changes on atmospheric dynamics (e.g. from 1930s to 1977 in Switzerland); (ii) possible inaccuracy of instrumental data during flood peak conditions (inundation o malfunction of gauge station); (iii) changes on discharge contribution from snow and glacier melt during past cooler climate periods (e.g. Little Ice Age), as well as influence of other flood producing mechanism (e.g. ice jams).

c) P. 4434, L. 1:

As the paper is concerning the quantification of European floods I recommend the authors to write a short paragraph (or some lines) about the characteristics of European mountain catchments and progress in related research activities

The reviewer arise a very interesting topic, although include a detail analysis on European mountain catchments may be a different paper by itself. Our paper do not intent to provide a detail analysis of historical floods and their frequency across Europe, since different reviews have been published by qualified authors (e.g. Pfister, 1999, Brázdil et al., 2005 and Glaser et al, 2010). Our paper only address those papers on historical floods with some hydraulic calculations about the rconstructed records. This narrow focus limits the number of papers to be included in our discussion.

d) P. 4467, Figure 8; PP. 4436-4438: Did you identified periods of enhanced flooding when comparing the bi-decadal flood frequencies of the 8 European rivers?

As indicated in the previous comments, we didn't want to discuss on the historical flood episodes on the records provided in figure 8, because other previous papers have been addressed this topic (Glaser et al., 2010). Figure 8 shows several examples where discharge magnitudes could be estimated or classified in the indicated categories. The focus of the analysis was to provide a perspective of the current flood magnitudes in relation to the historical discharge record.

### 3. Technical comments:

e) P. 4467, Figure 8:

There are some minor problems with the typesetting of the text of figure 8 (text overlaps text or symbols).

The figure has been revised to solve the problems of the text and symbol overlapping.

The attached version of the manuscript shows the new paragraphs included marked in yellow:



## Quantitative historical hydrology in Europe

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**Abstract.** In recent decades, the quantification of flood hydrological characteristics (peak discharge, hydrograph shape, and runoff volume) from documentary evidence has gained scientific recognition as a method to lengthen flood records of rare and extreme events. This paper describes the methodological evolution of quantitative historical hydrology under the influence of developments in hydraulics and statistics. In the 19th century, discharge calculations based on flood marks were the only source of hydrological data for engineering design, but were later left aside in favour of systematic gauge records and conventional hydrological procedures. In the last two decades, there is growing scientific and public interest in understanding long-term patterns of rare floods, in maintaining the flood heritage and memory of extremes, and to develop methods for deterministic and statistical application to different scientific and engineering problems. A compilation of 45 case studies across Europe with reconstructed discharges demonstrates that 1) in most cases present flood magnitudes are not unusual within the context of the last millennium, although recent floods may exceed past floods in some temperate European rivers (e.g. the Vltava and Po rivers); 2) frequency of extreme floods have decreased since the 1950s, although some rivers (e.g. the Gardon and Ouse rivers) show a reactivation of rare events over the last two decades. There is a great potential of gaining understanding of individual extreme events based on a combined multiproxy approach (palaeoflood and documentary records) providing high-resolution time flood series and their environmental and climatic changes; and to develop non-systematic and non-stationary statistical models based on relations of past floods with external and internal covariates under natural low-frequency climate variability.

**Key words:** Historical hydrology, historical flood, palaeohydrology, extreme flood, flood hazard.

## 43 **1 Introduction**

44 Historical hydrology is the study of the hydrological cycle before the continuous  
45 instrumental recordings on the basis of highly-resolved man-made documentary  
46 evidence (Brázdil et al., 2006b, 2012). Most of the documented pre-instrumental records  
47 refer to hydrological extremes (floods and droughts) that produced major disruption on  
48 past societies. In this context, historical floods have been frequently reported through  
49 written, pictorial and epigraphic documentation across Europe (Brázdil et al., 2012;  
50 Herget, 2012). Historical hydrology is on the interface between hydrology and  
51 environmental history: Based on data derived from documentary sources (non-  
52 instrumental human observations), its analysis involves the use not only historical-  
53 archival methods, but of hydrological modelling, and stochastic frequency analysis.  
54 Traditionally, the collection of historical flood information has been mainly addressed  
55 within the field of historical climatology together with other natural phenomena such as  
56 heavy rains, storms at sea, snowfalls and droughts (Brázdil et al., 2005b). Over the last  
57 20 years, the study of historical floods has gained recognition in Europe as key to  
58 understanding the natural hazards dynamics and their response to climate variability.  
59 Some major efforts were done in the topic within the European projects SPHERE  
60 (Systematic, Palaeoflood and Historical data for improvEment of flood Risk Estimation;  
61 Benito et al., 2004) and the FLOODCHANGE Advance Grant (Deciphering River  
62 Flood Change; Kiss et al., 2015). The possibility of extending river records towards the  
63 past have opened new perspectives in the study of extreme hydrological events whose  
64 analysis in terms of return periods, variability and tendency to clustering requires long  
65 hydrological data sets (Hall et al., 2014). However, documentary flood data are, in most  
66 cases, descriptive information, limited to a location (at human settlements), depending  
67 upon human perception (caused damages) and eventually bias by the political,  
68 legislative and administrative (local, regional and national) contexts. Recent advances  
69 on hydrological and hydraulic modelling and statistical-mathematical methods allow  
70 better dealing with the uncertain and categorical data characteristic of historical floods  
71 developing new applications in the study of flood hazards and climate change studies.

72

73 In Europe, historical documentary flood sources go back to Roman times (Camuffo and  
74 Enzi, 1996) although continuous and homogeneous written archives are known to be  
75 available only for the past 500 years (Brázdil et al., 2005a; Glaser et al., 2010).  
76 European richness on flood historical documents is only comparable to China with  
77 100,000 reports from 8000 localities, although quantitative description of the flood  
78 hydrographs in Chinese rivers didn't start till the 18th century (Luo, 1987). China  
79 documents on historical floods date back in some cases to 2000 years ago, with detailed  
80 descriptions over the recent 600 years and complete and homogenous data over the last  
81 200 years (Luo, 1987). The oldest historic nearly continuous flood record is not to be  
82 found in Europe or Asia, but in Africa, in ancient Egypt (Popper, 1951) whose  
83 economic wealth depended on the flooding of the River Nile and the annual deposition  
84 of fertile sediments along the river flood plain. In the Nilometer of Egypt, flood levels

85 were observed and measured since 3000 BC. In the USA, historical floods include  
86 information about extreme hydrological events observed in staff gauges (water-level  
87 readings), and therefore data derived from non-recording, attendant-read, staff gauges  
88 are traditionally considered historical data (Cook, 1987). Early stages of hydrology in  
89 Europe (1780-1860) involved human observations of water level readings on staff  
90 gauges, which were not always continuous throughout the year. This problem was  
91 gradually solved with the modernisation of gauge stations that made possible to record  
92 continuous flow stage on counters and data-loggers. This early instrumental period, that  
93 started around the 18th century and comprehends the initial flood observations at staff  
94 gauges, has been considered part of the historical hydrology (Brázdil et al., 2012).

95

96 Another source of long-term pre-instrumental floods data, though sometimes with a  
97 lower time resolution, are sedimentary and botanical records, known as palaeofloods (cf.  
98 Baker, 2008; Fig. 1). Palaeostage indicators include various types of geologic evidence  
99 (flood deposits and geomorphic features; 3) and woody debris, as well as morphologies  
100 related to direct physical damages on riverine vegetation (e.g. scars on trees and tilting;  
101 Herget, 2012; Benito and Díez-Herrero, 2015). A number of studies have combined  
102 both historical and geological indicators to ascertain the magnitude and frequency of  
103 past flood, increasing the robustness of the frequency analysis of rare floods (Benito et  
104 al., 2010).

105

106 This paper aims to describe the different techniques and approaches used in order to  
107 obtain quantitative information from historical flood data, as well as to draw attention to  
108 its different scientific and engineering applications. The specific targets are (1) to  
109 describe the historical flood data sources leading to robust estimations of long-term  
110 flood discharge records, (2) to review different techniques used for reconstructing the  
111 magnitude and frequency of specific past floods using documentary evidence, (3) to  
112 describe the approaches used in flood frequency analysis with historical discharges, and  
113 (4) to illustrate how historical quantitative hydrology can contribute in the solution of  
114 environmental and engineering problems.

115

## 116 **2 Quantitative historical hydrology**

117 The primary goal of historical hydrology is to collect information on past extreme  
118 floods such as date, relative magnitude, damages and socio-economic impacts at the  
119 time (Brázdil et al., 2006b, 2012; Glaser et al., 2010). Most recently, there has been a  
120 growing interest on quantifying these descriptive data in the reconstruction of flow  
121 depths, discharges and hydraulic properties associated to historical flooding (Fig. 1).  
122 This quantification may be numerical (peak flow) or categorical (damage classification).  
123 Regarding numerical data, the observed flood-water levels associated to a given  
124 historical flood can be transformed by hydraulic calculations into velocities and  
125 discharges in a procedure analogous to the depth-discharge relationships used to  
126 determine the flow rate in gauge stations (Cook, 1987; Benito et al., 2004; Herget et al.,

127 2014). Flood magnitudes can also be classified in terms of resulting damages, or social  
128 impacts (e.g. Sturm et al., 2001). The use of secular records for the analysis of possible  
129 changes in the magnitude and frequency of individual floods at specific sites or for  
130 specific rivers can support not only flood hazard assessment analysis, but enable the  
131 identification of interconnections between flood frequency and severity and climate,  
132 land-use and river morphology (Macdonald and Black, 2010). Moreover, historical  
133 flood data often includes other less commonly used information and data regarding the  
134 societal and economic consequences of these natural disasters (Coeur, 2003). Yet, this  
135 valuable data on the role of floods, through time, on local and national societal and  
136 policy changes are still an unexplored field that can bring new insights on the public  
137 perception of risk.

138

139 The use of documentary flood data in hydrological studies usually comprises four  
140 phases of analysis: (1) compilation and assessment of flood dates and water levels; (2)  
141 classification of events according to flood water-level (exact stage), described  
142 inundation zones (minimum or maximum flood level) and from reported damages; (3)  
143 estimation of flood magnitude, usually peak discharge, associated with documented and  
144 site-observed evidence; and finally (4) use of historical flood data in the flood frequency  
145 analysis. The implementation of the first two initial analysis steps entails a previous  
146 command in historical archives research, both written and cartographical that will not  
147 only produce a record of historical floods, but will also identify flooded sites and  
148 morphological changes on river channel and floodplain in the course of historical  
149 analysed period. The third task requires the implementation of hydraulic and  
150 hydrodynamic analyses, mainly drawn from engineering applications, to assign a flow  
151 magnitude derived from documentary evidence. Finally, historical estimated discharge  
152 data can be merged with instrumental records in a flood frequency analysis in order to  
153 determine discharges associated to probability quantiles.

154

### 155 **3 History of hydraulics and early flood estimations in Europe**

156 The first hydraulic parameter described in rivers was the water-level reached during  
157 extraordinary events. Ancient Romans observed and recorded flood water levels at  
158 bridges (e.g. Albenga, 1940), and the Roman engineers used this knowledge for  
159 designing their infrastructures (Lorenz and Wolfram, 2011). The study of flood levels  
160 was important ensuring efficient and long lasting hydraulic structures, and leave this  
161 legacy to future generations as it can be read in the inscription placed at the 30 m high  
162 Alcantara Bridge (Spain): “*Pontem perpetui mansurum in saecula mundi*” (Bridge to  
163 last forever in the perpetuity of the world; Fernández-Casado, 2008). Nowadays, the  
164 preservation of written records about flood data from antiquity is anecdotal since most  
165 written records were destroyed. During Medieval times, water marks associated with  
166 large floods were made on bridges, houses and even on bedrock outcrops although in a  
167 non-systematic way (Brázdil, 1998; Deutsch and Pörtge, 2009; Brázdil et al., 2012).  
168 Systematic water-level readings at gauges didn’t start before the later 18th century,

169 namely in Germany, France, Austria and Czech Lands. A review about the history of  
170 these first gauge water-level readings in Europe was compiled and published by Brázdil  
171 et al. (2012), though at the national level several papers have been published recently  
172 regarding the development of discharge measurements (e.g. for northern Germany,  
173 Deutsch, 2010). The revolutionary step on flood hydrology records which enabled to  
174 register and calculate flow discharge after stage level at gauge stations didn't take place  
175 till the 19th century with the measurement of flow velocity. The first rotor current meter  
176 was developed by Woltman (1790) and underwent several improvements during the  
177 19th and 20th centuries (Lanser, 1953). Current-meter gauging stations permitted the  
178 measurement of the flow rating curve (depth-discharge relationship) at the first  
179 established gauge stations in European rivers (Fig. 2). Rating curves were established  
180 and rated most reliably for low-to-moderate flows. The extreme flow discharges were  
181 frequently obtained from extrapolation of the rating curve. As this approach is less  
182 reliable and implies numerous uncertainties due to missing calibration, discharges  
183 associated to high flood levels were estimated by hydraulic formulae. Hence,  
184 reconstructions of historical floods gained robustness simultaneously to the advance in  
185 hydraulic research.

186

187 The first equations accounting for resistance law in open channels were established  
188 during the late 18th and 19th century. In 1775 the French engineer Antonie Chézy  
189 (1718-1789) proposed the first resistance formula based on a study of the water transfer  
190 from the River Yvette to Paris by an earthen canal (Herschel, 1897). Chézy's formula  
191 can be derived mathematically from two assumptions, as described by Chow (1959).  
192 First, Chézy assumed that the force resisting the flow due to friction per unit area is  
193 proportional to the square of the velocity  $V^2$  multiplied by a constant of proportionality  
194  $K$ , the length of the canal  $L$ , and the perimeter  $P$  of the section in contact with the water,  
195 i.e.  $KV^2LP$ . The second assumption in Chézy's formula is equality of the total force of  
196 resistance to the effective gravity-force component which is parallel to the channel  
197 bottom, namely  $\omega ALS$ , where  $\omega$  is the unit weight of water,  $A$  is the cross-section area,  
198  $L$  is the channel length and  $S$  the slope. Since  $\omega ALS = KV^2 PL$ , where  $A/P$  is the  
199 hydraulic radius  $R$  and  $\sqrt{\omega/K}$  can be replaced by a factor  $C$ , then it is obtained Chézy's  
200 equation as:

201

$$V = C\sqrt{RS} \quad (1)$$

202

203 In this formula, the factor  $C$  is the main uncertainty for velocity calculations estimated  
204 for known river cross-sections by indirect methods or assumptions. For instance, the  
205 first discharge estimates of the 1857-flood in the Ardèche (France) were obtained from  
206 multiplying the calculated velocity by 0.7 to reflect the unequal distribution of flow rate  
207 and channel roughness (De Mardigny, 1860). During the 19th century different  
208 experiments were performed to determine the involved variables in Chézy's factor  $C$ ,  
among which the most relevant were proposed by Ganguillet and Kutter (1869) and

209 Bazin (1897). Henri Emile Bazin (1829-1917) conducted laboratory studies on channels  
210 made on cement, brick, wood and rock proposing a formula where  $C$  is a factor of  $R$ :

$$211 \quad C = \frac{87}{1 + m/\sqrt{R}} \quad (2)$$

212 where  $m$  is a roughness coefficient that varies between 0.06 for canals made of concrete  
213 to 3.17 for earth channels with rough conditions (Bazin, 1897).

214

215 In 1868, Philippe Gascard Gauckler (1826-1905) engineer at *Ponts et Chaussées*,  
216 proposed two formulae for the estimation of the flow velocity  $V$  as:

$$217 \quad V = \lambda_1 R^{4/3} S \quad \text{for } S > 0.0007 \quad (3)$$

$$218 \quad V = \lambda_2 R^{2/3} S^{1/2} \quad \text{for } S < 0.0007 \quad (4)$$

219 where  $\lambda_1$  and  $\lambda_2$  are coefficients describing the boundary roughness. The second formula  
220 (4) applies for laminar flow regime, that may also be expressed as  $\lambda_2 = 1/n$  being  $n$  a  
221 roughness parameter, as it was proposed later by the Irish engineer Robert Manning  
222 (1816-1897), although apparently Manning was unaware of Gauckler's work. The  
223 popular Manning equation (Manning, 1891) is expressed in metric units as

$$224 \quad V = KR^{2/3} S^{1/2} \quad (5)$$

225 where  $K$  is a factor of flow resistance that later was modified to  $1/n$ , where  $n$  is known  
226 as Manning's roughness coefficient. Later, Strickler (1923) proposed a new expression  
227 of the Chézy's  $C$  coefficient  $C = KR^{1/6}$  that applied in the Chézy's formula provides a  
228 similar expression of the Gauckler-Manning's formula (5). There is still an open debate  
229 on the significance of the different contributions to the still recently frequently applied  
230 approach (Williams, 1970; Dooge, 1992; Hager, 2005). Consequently, this equation is  
231 also named Gauckler–Manning–Strickler formula. Another fundamental set of hydraulic  
232 equations for unsteady open channel flow was formulated by Barré de Saint-Venant in  
233 1843 who published the correct derivation of the Navier-Stokes equations identifying  
234 the coefficient of viscosity and its role in the local acceleration and fluid turbulence  
235 (Anderson, 1997).

236

237 The Gauckler–Manning formula has been used extensively since early estimates of  
238 historical floods to calculate the mean flow velocity at sections with observed historical  
239 flood levels (Pardé, 1925b). During the first half of the 20th century the research on  
240 historical floods was developed with a great influence of physical geographers. Maurice  
241 Pardé (1893-1973), Professor of Potomology in Grenoble, was probably the most  
242 prolific European author in the study of extreme historical floods, with over three-  
243 hundred papers and two-thousand hand-written notes and letters on the subject  
244 including a vast compilation of documentary floods worldwide. In Austria, the first  
245 known publications calculating discharges using historic flood-marks were carried out  
246 by Schwarzl (1956) and Kresser (1950, 1957). The highest flood level marked on public  
247 buildings and passage near the river corresponds to the 1501-flood estimated as circa  
248  $14,000 \text{ m}^3\text{s}^{-1}$  in Engelhartzell in Upper Austria (Kresser, 1957). In Italy, early

249 discharge estimations from historical flood levels were carried out by engineers at the  
250 service of water authorities, and data were reported as internal publications (e.g. HOPR,  
251 1935; Giovannelli and Allodi, 1960's, cited in Zanchettin et al., 2008). In the River Po,  
252 the 1857, 1868, and 1872 flood levels were studied in the context of large flooding  
253 recorded during the early decades of the 20th century (Visentini, 1936, 1938; Visentini  
254 and Pardé, 1936), concluding that historical flood peaks were of lower magnitude than  
255 contemporaneous extreme events.

256

257 These early 20th century advances on hydraulic models and stream flow measurements  
258 supported the re-estimations of discharge associated with certain large historical floods  
259 For instance, in the River Isère the 1740-flood discharge originally estimated as 1844  
260  $\text{m}^3\text{s}^{-1}$  by the engineer Christophe Dausse in 1780 (Lang et al., 2003) was later revised in  
261  $2000 \text{ m}^3\text{s}^{-1}$  by Pardé (1925b) using Chézy and Gauckler equations. Pardé (1961)  
262 provided the first worldwide inventory of flood discharges including a large number of  
263 pre-instrumental floods, many obtained from letters and unpublished reports with a  
264 reliability difficult to verify. The compilation of discharges from these early historical  
265 flood studies resulted in the plotting of regional envelope curves of maximum flood  
266 peaks or discharge per unit area versus drainage area (Wundt, 1949; Pardé, 1961;  
267 Francou and Rodier, 1967). The envelope curve is a deterministic method to transpose  
268 space-for-time under the assumption that there is a limit of precipitation supplied to a  
269 basin under a given climatic and geographic domain (Myers, 1967).

270

271 The study of past floods declined since the mid-20th century as databases of stream  
272 flow measurements supported by statistical analysis provided standard hydrological  
273 methods for flood hazard applications on which historical extremes were considered  
274 anecdotal, imprecise and outliers in relation to systematic gauged records (Klemeš,  
275 1989).

276

#### 277 **4 Quantitative historical flood records: approaches and methodology**

278 Most of the early historical flood discharge estimates were obtained from flood marks  
279 using hydraulic equations under the assumption of uniform flow conditions. However,  
280 there is a large amount of documentary evidence providing descriptive evidence of past  
281 inundation levels and flood damages (impacts) that offer a quantitative reference of the  
282 associated flood discharges after a critical analysis and interpretation (Benito et al.,  
283 2004). For the past 20 years, there has been a growing interest on reconstructing flood  
284 chronologies and their discharge estimates from documentary descriptions of flood  
285 water level (Benito et al., 2003a). The reconstruction of long historical flood records  
286 from documentary sources relies upon the availability of historic data for model  
287 implementation and calibration, uncertainty on the past river topography, and detailed  
288 configuration of the river channel and vegetation for roughness characterisation.  
289 Extracting quantitative hydrological data from documentary evidences leads typically to  
290 two phases of analysis: (1) documentation and assessment of documentary evidence of

291 flood stage during specific historical floods and (2) relating of identified flood evidence  
292 to flood discharge, based on hydraulic calculations. Documentary evidence of flood  
293 water level includes flood marks, with indication of single or multiple flood levels (Fig.  
294 3), and relative water levels obtained from narrative descriptions from places affected  
295 by flooding (e.g. a church, one of several streets, singular buildings). By the  
296 computation from water level to discharge, several correlative water surface evidences  
297 (marks, inundated sites) of a historical flood are matched to a water surface profile of a  
298 known discharge, obtained from hydraulic modelling. A major problem for this  
299 hydraulic analysis is the reconstruction of river channel geometry at the time of flooding,  
300 which produces a high uncertainty on the discharge calculations mainly in alluvial  
301 rivers (i.e. mobile river bed). The existence of historical maps showing the channel  
302 morphology at the flood time can be used to reconstruct its former morphology. The  
303 historical flood estimated discharges are then structured into different threshold levels  
304 that were exceeded by floodwaters over specific periods of time, the input data  
305 necessary for flood frequency analysis (Fig. 1b).

306

#### 307 **4.1 Documentary data sources and types**

308 Several review papers have described the main data sources of historical hydrology  
309 (Brázdil et al., 2006b, 2012). They are often grouped into three data categories: hand-  
310 written documents (e.g. narrative sources, administrative and ecclesiastic reports, and  
311 personal correspondence); printed sources (special prints newspapers, reports and  
312 technical papers); iconographic sources (stone-marks, historical photography and  
313 paintings, old cartography and cross-sections).

314

315 Narrative descriptions about floods may be biased by perception, both from the writer  
316 and from the present day researcher (Brázdil et al., 2006b). Since information from  
317 documentary sources is mainly qualitative, several classifications have been suggested  
318 taking into account the severity of flood impacts (Sturm et al., 2001). Barriendos et al.  
319 (2003) proposed a qualitative classification of flood severity for records prior to the pre-  
320 instrumental period, taking as reference the channel overflow: ordinary flood - when  
321 water remains within the channel and banks; extraordinary flood - resulting in localised  
322 overbank flow, with any damage but without major destruction; and catastrophic flood -  
323 with inundation resulting in general damage and destruction of infrastructures.

324

325 A study of historical hydrology involves: (1) collection of documentary sources (e.g.  
326 municipal, ecclesiastical and private archives) and consideration of already compiled  
327 information (e.g. books, databases and reports); (2) compilation of instrumental data for  
328 the area of investigation (rainfall, flow and level of the river, synoptic information); (3)  
329 collection of graphic information (e.g. paintings, photographs); (4) cross-reference of  
330 historical and palaeoflood (geological records) information, instrumental data and  
331 graphic information. It is convenient to produce a standardised data form to be filled for

332 each documentary flood reference (Fernandez de Villalta et al., 2001; Casas et al., 2003;  
333 Barriendos et al., 2003; Barriendos et al., 2014).

334

335 As mentioned above, early studies on historical floods were carried out mainly at sites  
336 with flood marks, for which peak flow values were calculated. However, most of the  
337 documented historical flood information is not recorded as engraved flood marks (plates  
338 or inscriptions) but as descriptions of inundations that affected out-of-channel areas.  
339 This is the case for instance of the River Ter (NE Spain) for which a record of 170  
340 floods was compiled for the period between 1322-1987 (Barriendos and Martin-Vide,  
341 1998), from which only 77 floods were found to be registered in plates or wall  
342 inscriptions. The majority of the flood events mentioned in documentary sources were  
343 nevertheless associated to a comprehensive description of the sites, or streets affected  
344 by the flood water-level. The reconstruction of flood discharges from descriptive flood  
345 levels beyond rough extrapolations and estimations (e.g. Schiller, 1987) was addressed  
346 firstly for the River Tagus in central Spain (Benito et al., 2003a). Discharges associated  
347 with documentary-based floods were reconstructed at four places, namely in Aranjuez  
348 (since AD 1557), Toledo (AD 1113), Talavera (AD 1203) and Alcántara (AD 1856).  
349 The hydraulic analysis and interpretation of the flood level from historical documents  
350 was inspired by methods commonly used in palaeoflood hydrology (Baker, 2008).  
351 Flood levels associated with documentary data at these locations include: (1) flood  
352 marks on houses, mills, monasteries and bridges; (2) descriptions of flooded areas as  
353 orchards, roads, streets; (3) descriptions of non-flooded areas (e.g. singular building  
354 surrounded by water but non-inundated); (4) relative flood level with respect to  
355 previous floods (e.g. the 1840 flood was 2 m higher than the flood occurring in 1820).  
356 The interpretation of these flood water level indicators provides four different discharge  
357 information records: (1) highest water level or peak discharge (equal to the flood stage),  
358 (2) minimum flood discharge, (3) maximum flood discharge, and (4) discharge quoted  
359 as a range in the case of two recorded levels. Field work is required to accurately locate  
360 (GPS survey) the sites referred in the historical documents (location of buildings, streets,  
361 bridges, gates, walls, etc.), as well as to ascertain the altitudes of the referred flood  
362 stages or levels. Thus, for all documentary evidences along the study reach, the flood  
363 height can be estimated and the associated flood discharge reconstructed (Fig. 4).  
364 Similar studies have been conducted later in other European sites (Table 1) with well  
365 documented floods and a rich historical archive. New methodological approaches were  
366 also developed as in the case of the study conducted by Roggenkamp and Herget (2014)  
367 for the River Ahr at Ahrweiler (Germany). The hydrograph of the 1910-flood was  
368 reconstructed based on sequenced historic photographs showing the same inundated  
369 street with a street clock hanging on a wall of a building, which precisely linked time  
370 and flood water level.

371

372 **4.2 Discharge estimation from documentary records**

373 The most critical component of applied historical flood hydrology is the estimation of  
374 discharge associated to documented floods. The flow estimates from hydraulic analysis  
375 is usually based on the elevation of flooded or non-flooded sites and epigraphic marks  
376 relative to local channel geometry. The approaches used to assess discharge estimation  
377 from known flood-water levels vary from simple hydraulic formula to the results  
378 derived from the running of one or multi-dimensional hydraulic models (Kutija, 2003;  
379 Lang et al., 2004). Most historical flood studies assume a one-dimensional flow with  
380 calculations based on (1) uniform flow equations (e.g. Gauckler–Manning equation), (2)  
381 gradually varied flow models (e.g. standard step method calculation), and (3) one  
382 dimensional Saint-Venant equations. In complex reaches, multi-dimensional modelling  
383 may reduce uncertainties associated with reconstructing flood discharge (Denlinger et  
384 al., 2002).

385

386 The Gauckler–Manning equation is applied for uniform, steady and one-dimensional  
387 flow conditions of straight channels of even gradient and regular width (Chow, 1959).  
388 In most hydraulic computations, the result of the calculated discharge depends on the  
389 uncertainty in the selection of the roughness parameter, changes on cross-section  
390 topography and urban configuration on the floodplains since historic times. The typical  
391 method for estimating Manning’s  $n$  is obtained from reference tables, from examination  
392 of photographs of typical channels whose roughness coefficients are known, or based on  
393 the experience of the researcher in similar river settings. Herget et al. (2014) proposed a  
394 method based on the Manning equation in which discharge is calculated separately for  
395 individual homogeneous units of the inundated cross-section area. At each sub-section,  
396 the intervenient parameters of the Manning equation ( $R$ ,  $S$ ,  $n$ ) are assessed at the time of  
397 the historical flooding based on old maps and written descriptions. The uncertainty on  
398 the estimation of roughness and of hydraulic geometry is introduced as different  
399 scenarios based on varying assumptions considered. Herget and Meurs (2010) applied  
400 this method to the 1374 flood of the River Rhine in Cologne, the highest in the local  
401 record. The calculated discharge was validated by application of this equation on recent  
402 floods and comparison of results with nearby cross-sections. Since flow in natural  
403 channels is typically not uniform, large errors can be expected when the Gauckler–  
404 Manning equation is applied to a single flood mark and one cross-section. The  
405 separation of the cross-section area into more or less homogenous units reduces this  
406 problem significantly. This approach cannot be used for floods caused by ice-jam or  
407 those with temporal bridge obstruction by woody debris raising the flow level instead of  
408 an increased discharge (Herget et al., 2014).

409

410 The most common historical flood discharge calculations are applied to gradually-  
411 varied flow conditions (Benito et al., 2003a; Lang et al., 2004; Naullet et al., 2005).  
412 River channel geometry is generally irregular in shape and surface roughness resulting  
413 in non-uniform flow conditions. Gradually-varied flow analyses usually assume a  
414 steady state (constant discharge) for which flow depth varies with distance but not with

415 time (Chow, 1959). The typical approach relating historical flood evidence to discharge  
416 uses the step-backwater method for gradually-varied water-surface profile computation  
417 (Benito et al., 2003a). In this method, water-surface profiles are calculated from the  
418 resolution of the conservation of mass and energy equations in their one-dimensional  
419 forms. Available public-domain computer routines, such as the U.S. Army Corps of  
420 Engineers HEC-RAS Hydrologic Engineering Center (2010), provides computation of  
421 water-surface profiles for specified discharges, and energy loss coefficients. Multiple  
422 analyses give synthetic rating curves at sites of interest, thus providing a basis for  
423 calculating historical flood discharge from the elevation of a water mark, known  
424 inundated locations or other high-water evidence (Thorndycraft et al., 2006).  
425 Uncertainties in flow modelling variables can be assessed for their resulting influence in  
426 historical flood discharges by testing outcomes of plausible ranges of Manning's  $n$   
427 values and possible changes in channel geometry. Challenging for this approach is the  
428 demand for several quantified cross-sections along a valley which are usually hard to  
429 determine from historic descriptions. Consequently, the variation of the geometry and  
430 roughness parameters along a valley can only be assumed.

431

432 Recent advances in two-dimensional computing flow hydraulics (Kutija, 2003) have  
433 been considered for historical flood studies (Fernandez Bono and Grau-Gimeno, 2003;  
434 Calenda et al., 2005). In alluvial rivers, flow over the banks show a three dimensional  
435 behaviour and this should be analysed by two-/three-dimensional models. However,  
436 already even 2D-modelling requires a large amount of high resolution channel and  
437 floodplain topographic information to define the working mesh as well as detail data  
438 about changes in historical topography after construction of buildings and roads, as well  
439 as spatial variability of roughness.

440

441 Flood hydrographs are essential for different engineering applications including dam  
442 operation and safety (Swain et al., 2006). The few essays to obtain hydrographs from  
443 palaeoflood studies have used probabilistic hydrographs (England et al., 2003; Benito et  
444 al., 2011). Recently, Elleder (2010) reconstructed the February 1784 flood of the River  
445 Vltava in Prague based on peak flood marks, daily newspapers and explanatory notes  
446 accompanying early instrumental measurements on the Klementinum observatory. The  
447 hydrograph showed only 45 hr time to peak in Prague with a 4 m water level rise during  
448 a 12 hours, a steep rise exceeded only by the August 2002 flood (Brázdil et al., 2005a,  
449 2006a) (Fig. 5).

450

### 451 **4.3 Assumptions and uncertainty evaluation of the estimated historical discharges**

452 The reconstruction of historical flood records is subject to assumptions, limitations and  
453 uncertainties that may affect the interpretation of the number of floods and estimated  
454 discharge. A key element in this quantitative analysis is the transformation of known  
455 information of flow level to accurate discharge estimates. In this task, it is of critical  
456 importance to confirm that the identified flood marks and sites used as flood level

457 indicators are not removed since the time of flood event. Previous experience shows  
458 that (1) epigraphic marks could be easily removed from the original site during  
459 restoration works (Fig. 6); (2) some original land mark (street, wall, or floor) could be  
460 buried or their names changed (Deutsch et al., 2006; Munzar et al., 2006; Macdonald,  
461 2007). Non-typical examples of flood marks are signs of flood levels recorded on the  
462 River Vltava in Prague with respect to the head of “bearded man” (in Czech *Bradáč*)  
463 (Elleder, 2003; Brázdil et al., 2005a) or for the River Elbe at Děčín on the Czech-  
464 German border located on the castle rock (Brázdil et al., 2005a; Kotyza, 2006).

465

466 A second set of uncertainties is related to the hydraulic setting and transformation of  
467 water level into discharge. The hydraulic calculations assume a precise characterisation  
468 of the channel geometry which remains invariant during the flood event and, in most  
469 cases, steady flow in subcritical flow conditions. In a given cross-section, the portions  
470 of effective flow (flow in the downstream direction) should be distinguished from  
471 regions of the channel that do not convey discharge downstream (e.g. eddy flows).  
472 Ideally, the model should be calibrated using known water surface elevation and  
473 discharges from contemporary floods, and if necessary carry out changes according to  
474 the historical vegetation and past urban configuration. Although the discharge  
475 estimation can be made on the basis of a single historical mark or flood evidence,  
476 confidence in the discharge determination is enhanced when calculated water surface  
477 profiles are matched by several flood marks or other inundation references along the  
478 study reach (Machado et al., 2015).

479

480 The effect of bridges, channel constrictions and obstacles in general, if they get blocked  
481 by ice jams or woody debris during the flooding, constitute another issue to be  
482 considered during the hydraulic modelling implementation (Fig. 5a). This blocking is  
483 likely to produce a back-flooding effect raising the flood level upstream. River lining  
484 and encroachment of the river bank may vary the floodway area and change the  
485 hydraulic conditions through time of referred flood marks. For instance, the Danube  
486 inundated ca 1000 km<sup>2</sup> of floodplains during the September 1899 flood whereas flood  
487 storage during the June 2013 flood was only a few hundreds of km<sup>2</sup> producing  
488 significant effects on the flood peak discharges (Blöschl et al., 2013). Note that the  
489 largest pan-European flood event of March 1784 was also caused by sudden release of  
490 water from local ice jams (Brázdil et al., 2010) (Fig. 5).

491

492 Assumptions concerning the hydraulic method and models applied to calculate  
493 discharge, type of flow (uniform versus non-uniform), the effective flow area and  
494 choice of energy-loss coefficients cause uncertainty in discharge estimates. For instance,  
495 in the River Elbe in Dresden, the official peak discharge of the 1845 flood is 5700 m<sup>3</sup>s<sup>-1</sup>  
496 whereas the water profile calculations by means of one- and two-dimensional hydraulic  
497 models provides a value of 4335 m<sup>3</sup>s<sup>-1</sup>, a discrepancy attributed to an inaccurate stage-  
498 discharge relationships at the gauge (Pohl, 2008).

#### 500 4.4 Flood frequency analysis

501 A fundamental problem in flood hydrology is the analysis of the flood frequency or  
502 discharge corresponding to an occurrence interval (return period). This estimation is  
503 necessary to the correct design and location of structures (dams, bridges, industrial  
504 buildings) and in the flood hazard mapping. The statistical analysis of extreme values  
505 has been highly improved since earlier work by Foster (1924), describing the  
506 application of frequency curves to engineering problems. Fisher and Tippett (1928)  
507 developed frequency distributions of maximum values, subsequently applied by  
508 Gumbel (1945) to floods. The flood-frequency analysis (FFA) was presented as a  
509 replicable method for quantification of uncertainty based on a large number of flood  
510 data. There are several important problems in applied flood statistics to the study of  
511 large floods. The first concern is the complexity of natural phenomena and the second is  
512 the assumption that data collected on river gauges are representative of the largest and  
513 rarest floods (Baker, 1994). The design engineer Vance A. Myers (1967) highlighted the  
514 consequences of using FFA methods with short flow measurements for dam design: “In  
515 reading the early reports one can sense a confidence by the less cautious that the flood  
516 record was stable, that nature had shown what she could do on a particular stream in a  
517 relatively few decades. This confidence was later found to be misplaced. The more  
518 cautious showed a feeling that major floods were among the imponderables, whose  
519 evaluation was impossible by the techniques then available. Some earth dams built  
520 during this period have failed due to insufficient spillway capacity”. The design of  
521 sensible infrastructures was highly improved when historical flood data was considered.  
522 For instance, the spillway capacity of the Saucelle ( $13,282 \text{ m}^3\text{s}^{-1}$ ) and Aldeadávila  
523 ( $12,500 \text{ m}^3\text{s}^{-1}$ ) dams in the River Duero (Spain) were designed on the basis of a  
524 deterministic application of reconstructed historical discharges from the 1597, 1739 and  
525 1909 flood marks (Rodríguez-Marquina, 1949a, 1949b).

526 The use of historical floods for FFA has been more frequent since pioneer publications  
527 by Benson (1950) and Leese (1973) incorporating non-systematic (historical) data  
528 together with gauge records. Documentary data are particularly valuable where there is  
529 an account of all floods exceeding a certain stage (threshold), or censured level, over a  
530 long period prior the instrumental gauging (Fig. 1). Generally, this minimum flood level  
531 required to assure documentary evidence of flooding is related with a perception  
532 threshold to which the contemporary society was susceptible in terms of damage or  
533 social disruption (Stedinger and Cohn, 1986; Francés et al., 1994). This perception  
534 threshold is frequently related to a flood water-level within urban zones and buildings  
535 with distinct characteristics (e.g. market, bridge, church) (Barriendos et al., 2003). The  
536 most common approach assumes that each flood exceeding this threshold has been  
537 recorded in the documentary record (Fig. 1a,b). For instance, flooding of the Aranjuez  
538 Royal gardens (Spain) is produced when the River Tagus overtopped the river banks

539 during discharges exceeding  $300 \text{ m}^3\text{s}^{-1}$  (Benito et al., 2003a). A list of  $k_i$  observations  
540 above an arbitrary specified discharge threshold  $X_i$  in  $n_i$  years is similar to the analysis  
541 of partial duration series (data censored above threshold; Stedinger and Cohn, 1986;  
542 Francés et al., 1994; Francés, 2001). Statistically it is important to confirm that years  
543 with lack of historical flood record corresponded really to flows smaller than the  
544 discharge threshold  $X_i$ . The threshold level of flood perception may vary through time  
545 with regards to various human activities and occupation of riverside areas. Naulet et al.  
546 (2001) classified the documentary flood data on four types (Fig. 1b): (1) exact type  
547 when flood discharge is known (e.g. water mark); (2) lower bound type if we know that  
548 the flood level was higher than a lower bound ( $X_i$ ), which is known; (3) upper bound  
549 type if it is only known that the flood at time  $t$  was smaller than  $X_u$ , which is the upper  
550 bound; and (4) double bound type if it is known that flood discharge was bracketed by a  
551 double bound where  $X_i$  and  $X_u$  are known. These historical flood data (known as non-  
552 systematic) can be combined with systematic annual data from the gauge stations. FFA  
553 commonly uses parametric models (defined finite number of parameters) combining a  
554 cumulative probability distribution function and a parameter estimation method  
555 (Stedinger and Cohn, 1986). Most of the distribution functions (Gumbel, Log-Person,  
556 GEV) that are used in conventional FFA has been applied with historical data  
557 (Stedinger et al., 1993). Several methods have been used in the estimation of the  
558 statistical parameters for the selected distribution functions (Strupczewski et al., 2014).  
559 The most efficient methods to incorporate imprecise and categorical data are: (1)  
560 maximum likelihood estimators (Leese, 1973; Stedinger and Cohn, 1986; Francés,  
561 2001); (2) the method of expected moments (Cohn et al., 1997; England et al., 2003);  
562 and (3) Bayesian methods (Kuczera, 1999; O'Connell et al., 2002; O'Connell, 2005;  
563 Reis and Stedinger, 2005). Several reviews of these methods have been published by  
564 Stedinger et al. (1993) and Francés (2004), and case study applications in Europe can be  
565 found, among others in Calenda et al. (2009), and Botero and Francés (2010).

566 A recent review by Kjeldsen et al. (2014) observed a scarce use of historical data for  
567 frequency estimates in 16 countries of Europe, identifying three main reasons: (1) the  
568 lack of unified database depositories, (2) uncertainty associated with discharge  
569 estimates, (3) concerns about violation of stationary assumption when using historical  
570 data, i.e. annual probabilities are equated to historical frequencies of occurrence.  
571 Concerning the second item, Macdonald et al (2014) showed that frequency analysis  
572 using exact discharges or minimum discharges exceeded by the historical event has  
573 almost the same uncertainty value. Viglione et al. (2013) demonstrated that the number  
574 of floods exceeding the perception threshold is more important than the uncertainty on  
575 discharge value A reduction on the error is obtained for a return period of the largest  
576 historical flood about twice length of the pre-instrumental record (Strupczewski et al.,  
577 2014). Many documentary-based flood studies shown that flood frequency has been  
578 influenced by the internal variability of atmospheric circulation, with flood clusters at  
579 some time periods (Glaser et al., 2010), or by impacts on the environmental patterns

580 such as land-use (Benito et al., 2010) and engineering works (Machado et al., 2015). A  
581 simple test of stationarity for censored samples (systematic and/or non-systematic) was  
582 proposed by Lang et al. (1999) assuming that the flood series can be described by a  
583 homogenous Poisson process (Naulet et al., 2005). It is recommended to select a sample  
584 above a high discharge threshold in order to produce an exhaustive and homogeneous  
585 set, avoiding bias in relation with archive availability or flood risk exposure (Barriendos  
586 et al., 2003). Macdonald et al. (2014) analysed the sensitivity of the application of  
587 different discharge thresholds, showing that the selection of a high discharge threshold  
588 decreased the uncertainty for high magnitude flood estimation.

589

## 590 **5 Discussion and perspectives**

### 591 **5.1 Discharge of historical floods in the context of instrumental records**

592 Quantitative historical hydrology provides a multi-centennial perspective of extreme  
593 flood magnitudes. In Europe, there is a long tradition in the study of historical floods in  
594 the context of historical climatology (Brázdil et al., 2005b; Glaser et al., 2010) although  
595 reconstruction of peak discharges associated to documentary data is still scarce (Fig. 7).  
596 Table 1 shows a compilation of 45 case studies with historical discharge estimates at  
597 sites with multiple floods with discharge estimates published in peer review papers or  
598 being cross-checked with the original historical sources. Numerous studies suggest that  
599 current flood magnitudes are not unusual within the context of last 1000 years, with  
600 good examples for the rivers Rhine (Herget and Meurs, 2010; Wetter et al., 2011), Tiber  
601 (Calenda et al., 2005), Llobregat (Thorndycraft et al., 2005), Trent (Macdonald, 2013)  
602 and Gardon (Sheffer et al., 2008; Neppel et al., 2010). In general, the largest historical  
603 floods from the last 500 years show higher peak flows than the largest gauged floods  
604 (Fig. 7). The largest difference in discharge between historical and gauged flood is  
605 mainly characteristic for small catchments, in mountain basins and in Mediterranean  
606 rivers (e.g. Llobregat, Ter, Ticino, Tiber and Isère rivers). In these regions, the  
607 knowledge of historical peak flows may provide important insight in flood hazard  
608 prevention. For example, the 2002 flood of River Gardon (France), that claimed the  
609 lives of 23 people and cause €1.2 billion worth of damage, was larger than any gauged  
610 flood since 1890 (DDE, 2003). However, a documentary and palaeoflood-based study  
611 demonstrated that at least five floods larger than the 2002-flood occurred in AD 1400-  
612 1800, i.e. during the Little Ice Age (Sheffer et al., 2008). In many mountain catchments  
613 historical floods are considerable larger than the instrumental data, that can be explained  
614 by different reasons (Schulte et al., 2015; Peña et al., 2015): (i) changes on atmospheric  
615 dynamics (e.g. from 1930s to 1977 in Switzerland); (ii) possible inaccuracy of  
616 instrumental data during flood peak conditions (inundation o malfunction of gauge  
617 station); (iii) changes on discharge contribution from snow and glacier melt during past  
618 cooler climate periods (e.g. Little Ice Age), as well as influence of other flood  
619 producing mechanism (e.g. ice jams).

620

621 In some cases, recent flooding in central and northern Europe reached similar  
622 magnitude or even higher than those reconstructed from documentary records, such as  
623 the River Vltava in Prague (Brázdil et al., 2005a; Elleder et al., 2013), and the records in  
624 the lower River Po (HOPR, 1935; Zanchettin et al., 2008) (Fig. 7). In the case of the  
625 River Findhorn in UK, the official gauged discharge for the 1970-flood was initially  
626 60% higher than the reconstructed peak flow for the “Muckle spate” flood of 1829,  
627 although later the 1970 peak flow was recalculated below the 1829-flood (McEwen and  
628 Werritty, 2007).

629

## 630 **5.2 Multi-proxy analysis of past hydrological extremes**

631 Documentary archival data on floods in general are ubiquitous across Europe although  
632 the computation of peak discharges depends on the availability of reliable epigraphic  
633 flood marks or thoroughly documented water level descriptions. In most cases, these  
634 flood marks are located in urban settings with frequent changes of the river channel  
635 topography that increase uncertainty of the values obtained when computing flood  
636 discharge. The combination of historical and palaeoflood (sedimentary) flood data has  
637 been demonstrated to be a very effective tool for improving the catalogue of past  
638 flooding and reducing uncertainties on flood discharges (Thorndycraft et al., 2005).  
639 Palaeostage indicators from sedimentary records (slackwater flood deposits) are  
640 frequently preserved within bedrock-stable cross-sections which are suitable settings for  
641 hydraulic estimation of flood discharges (Benito and O'Connor, 2013). Moreover, the  
642 age uncertainty of numerical dating (radiocarbon respectively optically stimulated  
643 luminescence methods) used in palaeoflood studies may be refined based on known  
644 documentary floods (Medialdea et al., 2014). The SPHERE Project has revealed the  
645 complementary of palaeoflood and historical flood information (Benito and  
646 Thorndycraft, 2004) with major gain on the quality of past flood records in terms of  
647 time and discharge, as it is demonstrated in the studies performed for the rivers Gardon  
648 (Naulet et al., 2005; Sheffer et al., 2008), Ardèche (Sheffer et al., 2003; Naulet et al.,  
649 2005), Llobregat (Thorndycraft et al., 2005), and Guadalentin (Benito et al., 2010;  
650 Medialdea et al., 2014). Recent developments on palaeoflood reconstruction from  
651 floodplain sediments analysed geochemical proxies from continuous alluvial records  
652 and investigate local documentary flood data to calibrate the palaeohydrological records  
653 (e.g. Swiss Alps, Shulte et al., 2008, 2015; River Severn in mid-Wales, Jones et al.,  
654 2012; River Rhine in The Netherlands, Toonen et al., 2015). Flood sediments  
655 accumulated on floodplain sinks (e.g. palaeomeanders and flood-basin environments)  
656 can be analysed with high resolution techniques (e.g. X-Ray-scanned samples) to obtain  
657 continuous records of grain-size and geochemical content (Zr/Ti, Zr/Rb and Sr/Ti)  
658 indicative of detrital fraction deposited by floods (Schulte et al., 2015). The  
659 reconstructed palaeoflood magnitudes are obtained after calibrating their ages obtained  
660 by geochronological techniques (radiocarbon) with known historical events and  
661 normalizing grain-size and geochemical content, where the coarse tail of grain-size

662 distribution is used to estimate peak flood discharges or severity indexes (Toonen et al.,  
663 2015).

664

665 New emerging palaeoflood archives from lake records show a great potential for  
666 synergy with documentary floods to complete regional records of extreme events to  
667 understand flood-climate relationships (e.g. Wilhelm et al., 2012; Wirth et al., 2013;  
668 Corella et al., 2014). For instance, in Montcortés Lake (NE Spain) a varved sediment  
669 core accumulating since the 14th century contains detrital layers associated to intense  
670 rainfalls (>80 mm/day) recording higher storm frequency during AD 1347-1400 and  
671 AD 1844-1894, both periods coincide with severe floods from the nearby River Segre  
672 (Corella et al., 2014). In non-varved lake systems, palaeoflood stratigraphy can be  
673 compared to historically documented flood records, as a mean to improve the age-depth  
674 model of the stratigraphic log (Schillereff et al., 2014). Another group of palaeoflood  
675 techniques suitable to combine with documentary sources are those based on botanical  
676 and ecological evidences (Bodoque et al., 2014). The presence of lichens on boulders in  
677 river channels can be used to date the flood responsible of their transport, once a  
678 lichenometric growth curve for the lichen species for the area of study has been  
679 established (Foulds et al., 2014). Dendro-geomorphology uses information from flood  
680 damages in trees and bushes, dating floods at annual scale (Bodoque et al., 2014).  
681 Commonly, these palaeoflood methods are most suitable for mountain streams  
682 environments, where documentary sources provide a mean to establish the age biases to  
683 minimize errors during the calibration process

684

### 685 **5.3 Flood magnitude sensitivity to climate change**

686 Climate variability may affect both flood frequency and magnitude with greater  
687 sensitivity on largest “rare” floods (50-year flood and higher) than on smaller frequent  
688 floods (2-year floods; Knox, 1993; 2000). The study of historical floods in the context  
689 of climate variability has been focussed on high-quality complete datasets classified  
690 according to severity of damage (Sturm et al., 2001) to infer changes in flood frequency,  
691 meteorological causes and seasonality (Glaser et al., 2010). The classification of  
692 historical floods according to peak discharge or discharges over some threshold allows  
693 further analysis on the sensitivity of flood frequency in relation to their magnitude.  
694 Furthermore, this classification based on discharge classes allows consideration of the  
695 most recent instrumental records in an integrated analysis avoiding the bias of  
696 classifications based only on flood damages which varied over time with regards to  
697 exposition and vulnerability. Based on literature sources (cf. for details below), eight  
698 records compiled from different European rivers where numerical or categorical flood  
699 magnitude during the historical period was completed with comparable data from  
700 gauged records (Fig. 8). Two flood categories were differentiated: (1) catastrophic  
701 floods (CAT) associated with high flood discharge or severe damages, and (2)  
702 extraordinary floods (EXT) causing inundation of the floodplain with moderate-to-  
703 minor damages. The detected flood changes are highly dependant on the observational

704 window (Hall et al., 2014) with identification of flood-rich and flood-poor periods over  
705 the historical record and flood trend detection over the instrumental period.

706

707 In Central Spain, increased flood frequency of large floods was identified in AD 1000-  
708 1200, 1525-1625 and in the late 19<sup>th</sup>-early 20<sup>th</sup> centuries (Benito et al., 2003a; Fig.  
709 8a). During the second half of the 20<sup>th</sup> century, the frequency of floods decreased, in  
710 connection with a dominant positive mode of the North Atlantic Oscillation during  
711 winter months; however, flow regulation by dams also played an important role in this  
712 flood frequency decline since the mid-1950s. The decreasing trend in annual maximum  
713 floods was also detected on the flood analysis from gauge records of a set of rivers  
714 within the Tagus River basin under quasi-natural flow conditions (Mediero et al., 2017).

715 In the River Segura (SE Spain) the frequency of catastrophic (autumn) floods decreased  
716 since the late 19<sup>th</sup> century together with the frequency of intense rainfall events except  
717 some decades (e.g. the 1970s and 1980s), in which intense rainfall and flooding co-  
718 existed with severe drought conditions (Fig. 8b; Machado et al., 2011). In the River  
719 Gardon (southern France), the frequency pattern of large floods (>50-yr floods) has  
720 decreased since the late 19<sup>th</sup> century, whereas the extraordinary and ordinary floods  
721 increased during the 20<sup>th</sup> century (Fig. 8c) (Sheffer et al., 2008; Neppel et al., 2010).  
722 Similarly, historical flood series from NE Spain indicate a lack of statistical significant  
723 trend for large-catastrophic floods, whereas extraordinary floods have seen a significant  
724 rise, especially since 1850 (Barreda-Escoda and Llasat, 2015).

725

726 In the River Tiber (Central Italy) extreme floods were particularly frequent in 1400-  
727 1500 and 1600-1700 (Camuffo et al., 2003). Large-catastrophic floods exceeding the 17  
728 m stage ( $<2900 \text{ m}^3\text{s}^{-1}$ ) at the Ripetta Landing ( $16,545 \text{ km}^2$ ) were not constant in time:  
729 four floods above 18 m ( $<3400 \text{ m}^3\text{s}^{-1}$ ) took place in only 80 years during the period  
730 1530-1606 (Calenda et al., 2005), intriguingly a period of reported low flood frequency  
731 by Camuffo and Enzi (1996). Recent flooding is difficult to evaluate in the context of  
732 climate change due to river regulation structures, although only three extreme floods  
733 ( $>2550 \text{ m}^3\text{s}^{-1}$ ) were recorded since 1900 (Fig. 8d). Extraordinary flood events exceeding  
734  $1400 \text{ m}^3\text{s}^{-1}$  prior to 1970 occurred with a mean frequency of seven floods per decade,  
735 whereas after 1970 the frequency decreased to about five floods. Frequent events within  
736 the historical context (2-year flood), such as the December 2008 flood (12.55 m,  $\sim 1400$   
737  $\text{m}^3\text{s}^{-1}$ ), are currently producing large economic impacts that demonstrates the increased  
738 flood vulnerability of the Rome region despite of decreasing flood hazard by flow  
739 regulation (Natale and Savi, 2007).

740

741 Several types of meteorological events and different storm types result in mixed flood  
742 distributions, each characterized by individual probability distribution parameters  
743 (Hirschboeck et al., 2000). Climatic variability can lead to flood magnitude / frequency  
744 changes affecting one or various types of flood populations (e.g. early spring snow-melt,  
745 convective storms) with relevant implications in the non-stationarity of the statistical

746 parameters supporting flood probability analysis (Milly et al., 2008). Documentary  
747 records provide information on prevailing circulation types producing floods based on  
748 changes in flood seasonality. Macdonald (2012) studying the River Ouse, a large  
749 catchment within a UK perspective, has identified a higher frequency of summer floods  
750 within AD 1700–1849 than in the AD 1850–1999 period. Furthermore, the combined  
751 documentary and instrumental flood record (Macdonald and Black, 2010) illustrates that  
752 the frequency of extraordinary floods within the range of 350 to 500 m<sup>3</sup>s<sup>-1</sup> have  
753 increased during the 20th century, in particular comparatively to the most extreme  
754 floods (>500 m<sup>3</sup>s<sup>-1</sup>; Fig. 8e). In Central Europe, long records of the Elbe and the  
755 Oder/Odra rivers showed a decrease in winter floods during the last 80 to 150 years (Fig.  
756 8g, h), while summer floods showed no significant trend (Mudelsee et al., 2003). This  
757 change in seasonal flood patterns is reflected in the recent trend towards an overall  
758 decrease on flood magnitude, although in the case of the River Vltava (Czech Republic)  
759 the August 2002 flood reached the highest peak flow on record (Fig. 8f; Brázdil et al.,  
760 2005a). In the River Rhine at Basel (Switzerland) severe summer (JJA) floods were  
761 particularly frequent between 1651 and 1750, in relation to enhanced precipitation;  
762 severe winter (DJF) floods have not occurred since the late 19th century, despite a  
763 significant increase in winter precipitation (Wetter et al., 2011).

764

765 In some regions, the potential for ice jams on rivers should be consider in the analysis  
766 and interpretation of winter peak flows along centennial records. An ice jam can  
767 generate water-levels above rainfall floods due to inundation of the area behind the ice  
768 blockage, or as a consequence of rapid release of water after the ice jam failure (Beltaos,  
769 2008). During the AD 1550-1850 period, ice cover on large mainland European rivers  
770 combined with late winter and spring snowmelt generated very large floods, similar to  
771 what is observed today at higher latitudes. In The Netherlands many floods over the  
772 1750–1860 period were associated with ice jams, particularly on the River Waal (e.g., in  
773 1781, 1784, 1799, 1805 and 1809; Driessen, 1994). Detailed records describing the  
774 winter ice jam floods in 1784 are widely recorded across much of western and central  
775 mainland Europe (Demarée, 2006; Brázdil et al., 2010, 2012) (Fig. 5). In the River  
776 Mosel, the 28 February 1784 flood water-level was significantly higher than any other  
777 recorded during the past millennium (Sartor et al., 2010), although any discharge  
778 estimation should consider that ice jams can raise water levels to much higher  
779 elevations than open-water floods (Beltaos, 2008). Other factors enhancing flood  
780 severity through time includes timing of melting of glaciers (Debret et al., 2010). Global  
781 warming is introducing changes in the spatial (latitudinal) and temporal (seasonal)  
782 distribution of flooding related to ice and snowmelt (Beltaos and Prowse, 2009). For  
783 example, changes in the hydrometeorological conditions that generate flooding may  
784 enhance flood magnitude in Norway, due to an earlier onset of snowmelt related to  
785 flooding in the region (Hisdal et al., 2006), whereas in mainland Europe, flooding  
786 related to ice-jams are now unlikely to occur (Kundzewicz et al., 2014).

787

#### 788 **5.4 Historical floods in a non-stationary hydrology**

789 The comparative analysis of historical records at different catchments across Europe  
790 points to the fact that the temporal distribution of flood frequency is predominantly  
791 modulated by regional meteorological triggers (Glaser et al., 2010). In regions where  
792 floods are generated by several types of weather conditions, each flood population is  
793 composed by a probability distribution resulting in mixed distributions. Long-term  
794 climate variability may alter the seasonal weather patterns producing floods (summer,  
795 winter, snowmelt, etc.) and consequently the assumption of stationarity of the flood  
796 frequency distribution. Stationarity has been qualitatively described as the idea that  
797 natural systems oscillate within an unchanging envelope of variability (Milly et al.,  
798 2008). In the case of extreme events, secular records of historical floods show a  
799 temporal variability (clusters) fluctuating at multi-decadal time scale. However, the  
800 underlying driving factors causing past departures from stationarity are far from being  
801 random phenomena. The temporal changes in the trajectory and statistics of a variable  
802 may be linked to natural, low-frequency variations of the atmospheric circulation,  
803 external forcings (solar cycles) or anthropogenic changes. Therefore, a detail  
804 characterisation of natural variability of past floods will facilitate the attribution and  
805 modelling of future variability due to nature and human impacts. The statistical  
806 parameters may show increasing/decreasing changes that can be modelled (as a trend or  
807 smooth function) using time as covariate (Villarini et al., 2009), or they can be related  
808 to hydro-climatic covariates such as circulation indices (e.g. Pacific Decadal  
809 Oscillation-PDO, North Atlantic Oscillation-NAO, Arctic Oscillation-AO)  
810 characterising this low frequency climatic variability (López and Francés, 2013). The  
811 application of these non-stationary models to historical and palaeoflood hydrology  
812 requires a numerical characterisation of the occurrence rate (covariate) during the  
813 recorded period. Several studies have demonstrated the relationships between flood  
814 frequency and magnitude with circulation indices, such as NAO index (Salgueiro et al.,  
815 2013). The application of a non-stationary flood frequency analysis in a 300 yr record  
816 with 32 documented floods ( $>350 \text{ m}^3\text{s}^{-1}$ ) of the River Tagus were successful to model  
817 the fluctuations of flood quantiles (e.g. “100-year flood”) using the North Atlantic  
818 Oscillation index and a reservoir index as external covariates (Machado et al., 2015).  
819 This non-stationary modelling was based on Generalized Additive Models for Location,  
820 Scale and Shape parameters (GAMLSS; Rigby and Stasinopoulos, 2005) that described  
821 the temporal variation of statistical parameters (mean, variance) in probability  
822 distribution functions (Villarini et al., 2010; López and Francés, 2013). In this example,  
823 the non-stationary models show that the peak flood associated with a “hundred year”  
824 flood (0.01 annual exceedance probability) may range between  $4180 \text{ m}^3\text{s}^{-1}$  and  $560 \text{ m}^3\text{s}^{-1}$ ,  
825 whereas the same model under stationary conditions provided the best fitting results  
826 to a log-normal distribution, with a discharge of  $1450 \text{ m}^3\text{s}^{-1}$  (Fig. 9). These results  
827 illustrate that under stationary statistics the risk assumed is much higher than the one  
828 established in the design of infrastructures. Moreover, concepts such as return period,

829 design quantile (return level), and risk under non-stationary conditions should be  
830 changed when the annual probability changes every year (Obeysekera and Salas, 2014).

831

## 832 **6 Concluding remarks**

833 This paper presents a review of the scientific progress in the quantification of large  
834 historical floods since the early stages prior to the automatic hydrological stations. In  
835 the last two decades, new approaches have been developed to obtain continuous and  
836 reliable flood magnitude data sets from documentary records, their statistical analysis  
837 and temporal patterns, illustrating the strength, limitation and future prospects of  
838 various methods. Most early discharge computations were obtained at sites with known  
839 water elevation from flood marks or by extrapolation of a rating curve at sites with staff  
840 gauge. Only in the last decades, flood descriptions from rich documentary evidence  
841 have been used to estimate discharges of floods exceeding a threshold of perception,  
842 extending the record of flood discharges up to several hundreds of years. The  
843 reconstruction of secular historical records of extreme floods is relevant to solve major  
844 scientific and engineering problems: (1) flood hazard assessment using FFA (data  
845 censored over thresholds of perception), and (2) quantification of the largest discharges  
846 in a given catchment as evidence for a deterministic approach in safety risk analysis of  
847 critical facilities (dams, bridges, power plants). The historical flood records have gained  
848 attention among hydrologists on the background of new statistical methods of FFA  
849 using non-systematic data and recently in the analysis of non-stationarity modelling.  
850 However, the use of historical flood records for flood hazard studies is still scarce in the  
851 practical realm. Documentary flood data can benefit from the combined use with  
852 palaeoflood records such as fluvial sediments, botanical- and dendrochronological  
853 records, flood-produced detrital layers in lakes and marine records. In particular, fluvial  
854 sediments deposited in slackwater environments have been demonstrated as very  
855 efficient to be combined with documentary data sets to improve the flood frequency  
856 analysis of rare and extreme floods. Europe holds numerous, unexplored archives in  
857 relation with historical floods, their causes and the socio-economic impacts. There is  
858 great opportunity to generate scientific knowledge about the largest and rarest floods  
859 reported through historical times and use them to improve the social conscience and  
860 perception of natural risks. The presented paper is a significant contribution to historical  
861 hydrology in Europe (Brázdil et al., 2006b, 2012) extending its potential on  
862 quantification of past documentary-based floods in Europe.

863

## 864 **Acknowledgments**

865 G. Benito and M. J. Machado were funded by the Spanish Ministry of Economy and  
866 Competitiveness through the research projects CLARIES (CGL2011-29176),  
867 PALEOMED (CGL2014-58127-C3-1-R), and by the CSIC PIE Intramural Project (ref.  
868 201430E003). R. Brázdil was supported by Grant Agency of the Czech Republic for the  
869 project no. P209/11/0956. J. Herget appreciates financial support from the German  
870 Research Foundation DFG (HE 3006/9-1). We wish to thank Neil Macdonald, Lothar

871 Schulte and M. Carmen Llasat for their valuable comments and suggestions during the  
872 discussion process.

873

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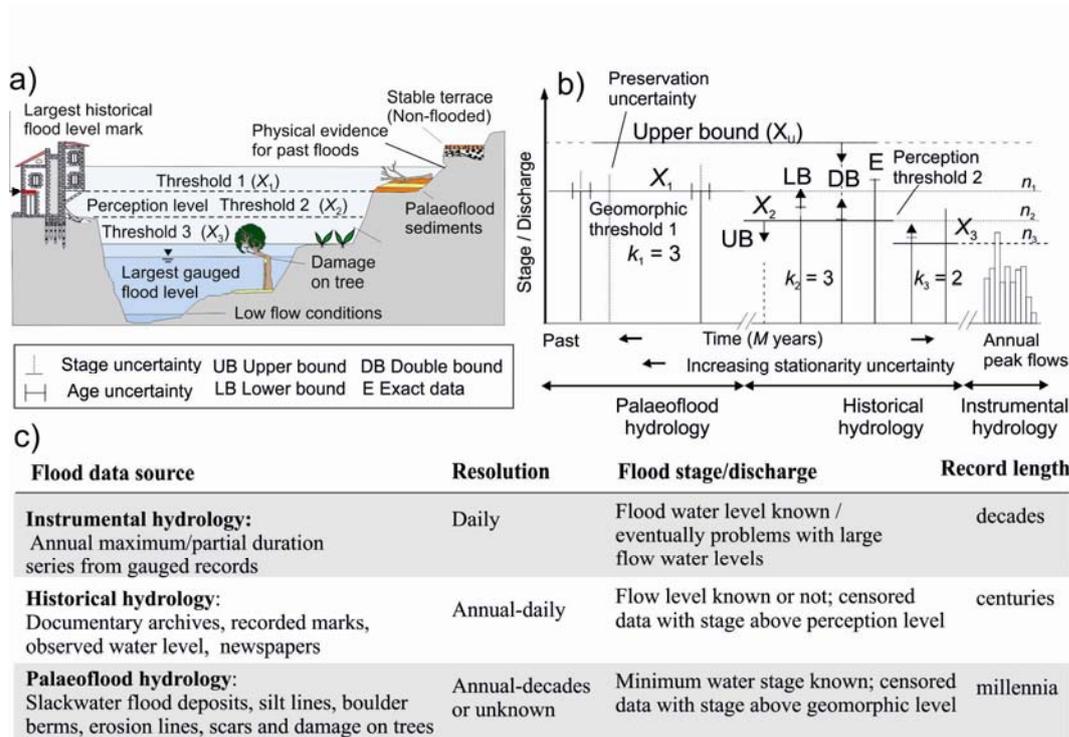


Figure 1. Sources of quantitative flood information. a) Sketch of a cross section showing various flood level indicators from palaeofloods (sediments and damage on trees), and documentary-based floods (i.e. those able to cause damage or socio-economic disruption). For historical hydrology, only floods exceeding a flood level related to a perception threshold ( $X_i$ ) over a period of  $n_i$  years ( $n_1 > n_2 > n_3$ ) are recorded. Palaeofloods from stratigraphic records are related to geomorphic thresholds. b) Organization of historical and paleoflood data, using the described thresholds ( $X_i$ ), and multiple types of observations to support flood frequency analysis.  $k_i$  corresponds to the number of flood peaks during the last  $n_i$  years that exceeded the  $X_i$  threshold but not the  $X_{i-1}$  threshold. Upper bound level ( $X_u$ ) may be used to limit the maximum discharge. Data types: E: flood peak is known. LB: flood was bigger than  $X_i$  which is known; UB: the upper flood level of known magnitude ( $X_u$ ) was not exceeded over a certain time period. DB: flow level was within the interval given by  $X_u$  and  $X_i$ . c) Data source characteristics, timing, stage information, and typical temporal framework of systematic (instrumental) and non-systematic data (palaeoflood and documentary evidence). Modified after Benito and O'Connor (2013).



Figure 2: Stream flow measurements at the gauge station "Borgo a Mozzano" ( $43^{\circ} 59'30.73''\text{N}$ ;  $10^{\circ} 33'10.04''\text{E}$ ) in the River Serchio (Italy), probably taken in the 1920s or 1930s. The observer is placed in a box suspended on cable that moved along the cross section from which manages an old device to measure the stream flow velocity (Photo courtesy of Regione Toscana - Genio Civile di Bacino Toscana Nord e Servizio Idrologico Regionale).

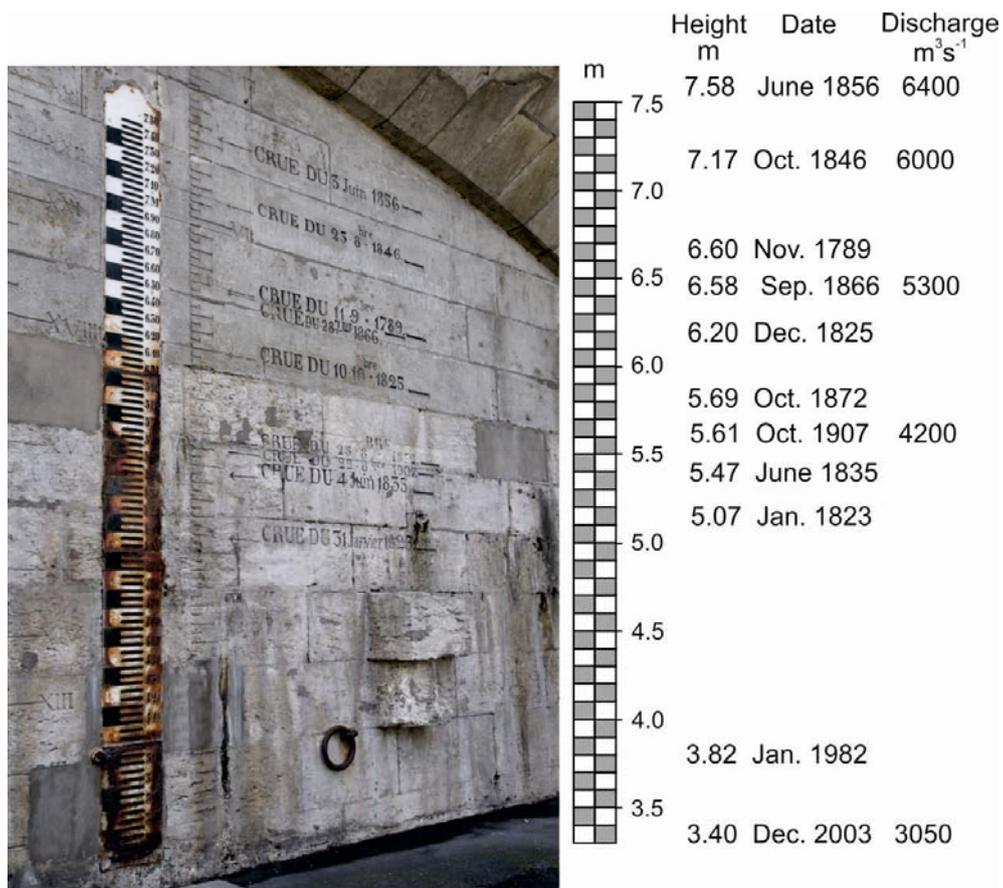


Figure 3: Historical flood marks of the River Loire in the Wilson Bridge in Tours (France). The elevations of the flood marks after the Direction regionale de l'environnement de l'Aménagement et du logement (DREAL), Centre-Val de Loire (<http://www.centre.developpement-durable.gouv.fr>). Discharge values associated to the flood levels after Duband (1996).

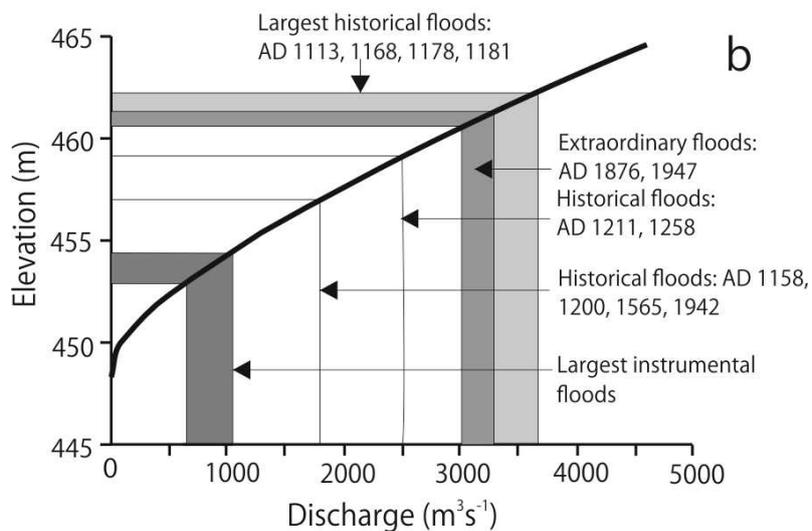
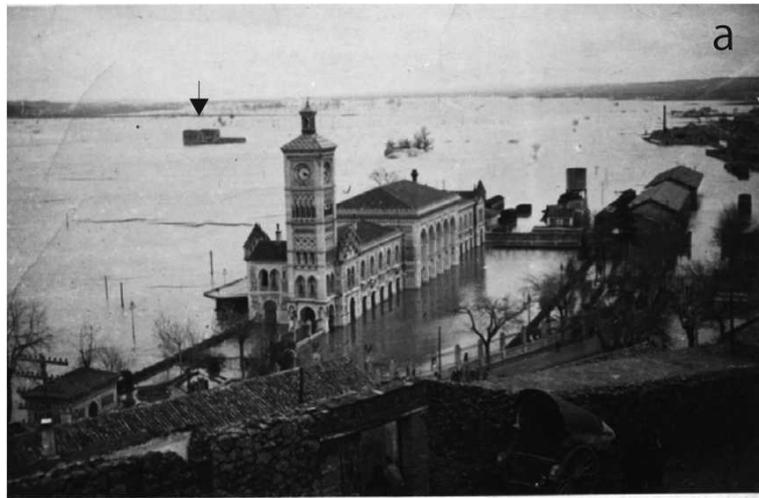


Figure 4. a) Upstream view of the River Tagus into the Huerta del Rey (King's Garden) during flooding on 6 March 1947 at Toledo. The peak discharge was reached at 10 a.m. and the picture was taken at 3.20 p.m. (by courtesy of Mariano García Bargueño). The water level at peak discharge was 1.5 m above the railway station ground level (main building at the centre of the photo). In the background the arrow points the Galiana Palace, on the left bank of the Tagus River, just over 1 km from the old part of Toledo (Galina Palace was built at the site of an earlier summer villa and Arab garden of Al-Mamun, king of the Taifa of Toledo in AD 1043-1075) (Benito et al., 2003a). b) Rating curve of a cross-section next to the upper picture obtained from step-back water calculations (HEC-RAS model) with the elevation of relevant historical flood evidences (flood marks and description of inundated sites). The largest historical floods occurred during the Medieval Climatic Anomaly and are followed by the 1876 and 1947 floods (Fernandez de Villalta et al., 2001).

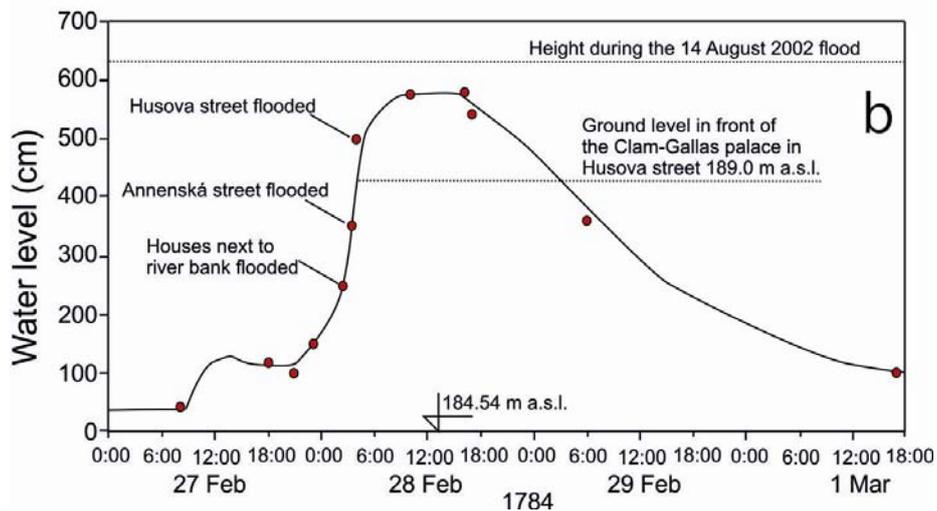


Figure 5. a) Pictorial representation of the River Vltava during the February 1784 flood, showing ice floes and woody debris accumulated at the Charles Bridge in Prague (copperplate by F. Erban, Museum of the City of Prague, catalogue no. 125.387). The ice jams at the bridge caused flooding upstream resulting to the highest known water marks until the August 2002 flood (Brázdil et al., 2005a). b) A flood hydrograph of the Vltava River in Prague at the Monastery of the Knights of Cross reconstructed from documentary data for 27 February – 1 March 1784 with an estimated discharge rate of  $4560 \text{ m}^3 \text{ s}^{-1}$  (Brázdil et al., 2005a).



Figure 6. Stone brick with an inscription of the 1906-flood mark of the River Rhine in Koblenz. The block was originally placed on a railway bridge destroyed during World War II and later used for reconstruction of this building (Herget, 2012). This confirms the necessity to work only with original position of flood marks and use multiple documentary evidences to reconstruct flood levels.

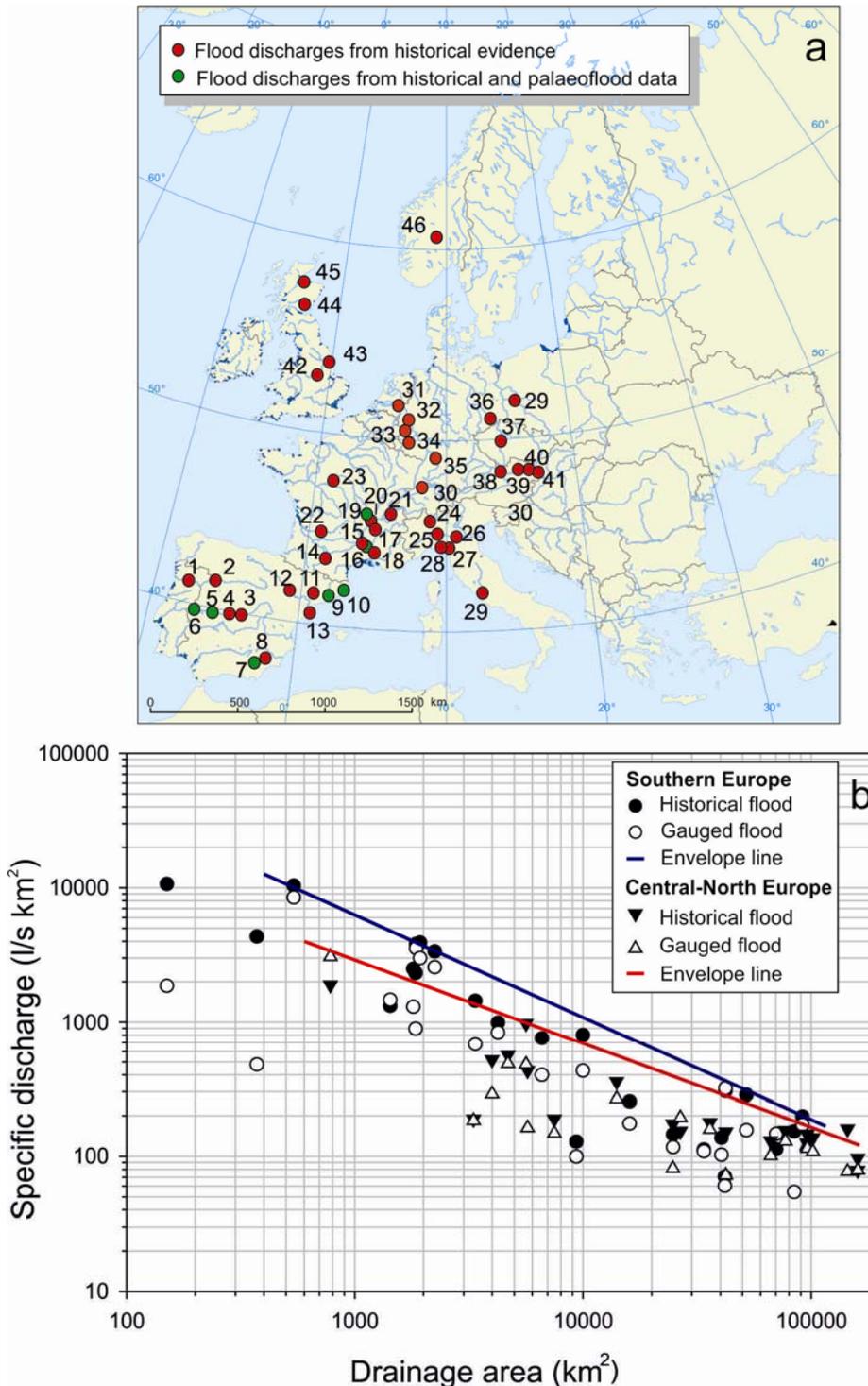


Figure 7. a) Major rivers and streams of Europe and studied sites with multiple historical flood discharge estimates. Numbers refers to places cited in Table 1. b) Maximum specific discharge ( $l/s\ km^2$ ) of the largest historical and instrumental floods recorded in the sites referred in Table 1. Southern Europe includes sites from Portugal, Spain, Italy and France (except the Dordogne, Isère, Loire, Rhone and Garonne rivers) and Central-North Europe the rest of rivers. Lines are envelope boundaries of the largest specific discharges for these two data sets. Most of the historical specific discharges are above the instrumental ones, except some rivers in Central-North Europe.

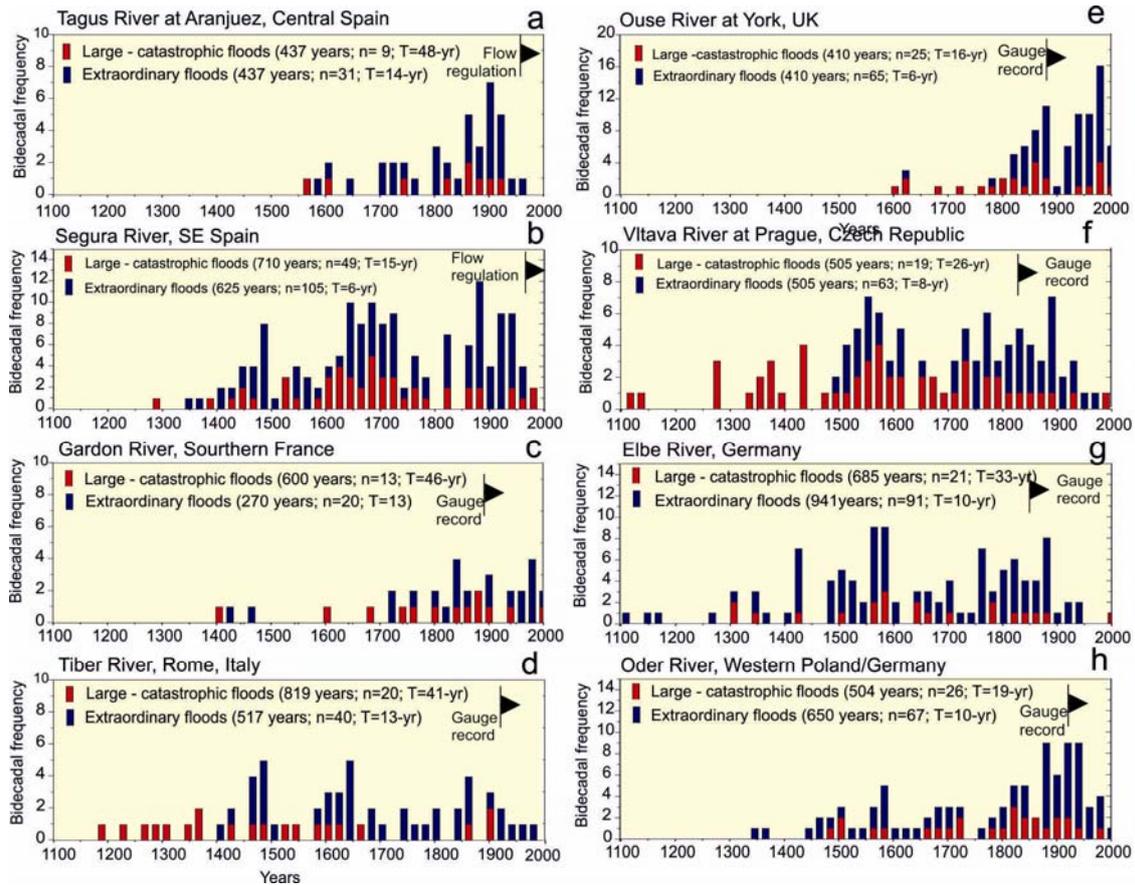


Figure 8: Bi-decadal (20-yr) flood frequency based on documentary and instrumental records in the selected European rivers (floods exceeding a particular discharge threshold or height). Two flood categories were differentiated: catastrophic floods (CAT) associated with high flood discharge or severe damages, and extraordinary floods (EXT) causing inundation of the floodplain with moderate-to-minor damages. The length of record in years, number of recorded floods ( $n$ ), and the mean occurrence interval ( $T$  in years) for each category and river are indicated. a) The River Tagus in Aranjuez, documentary and instrumental data, CAT:  $>400 \text{ m}^3 \text{ s}^{-1}$ , EXT:  $100\text{--}400 \text{ m}^3 \text{ s}^{-1}$  (Benito et al., 2003a; Machado et al., 2015). b) Segura-Guadalentín rivers at Murcia (Barriendos and Rodrigo, 2006; Machado et al., 2011). c) The River Gardon, documentary data since the 15th century, historical and daily water-level readings at Anduze (1741–2005; Neppel et al., 2010), CAT:  $>3000 \text{ m}^3 \text{ s}^{-1}$ ; EXT:  $1000\text{--}3000 \text{ m}^3 \text{ s}^{-1}$ ; complemented with discharges from palaeofloods at La Baume (Sheffer et al., 2008). d) The River Tiber in Rome, observed historical levels since the 12th century, continuous water-level readings since 1870 at the Ripetta Landing (Calenda et al., 2005), CAT:  $>2900 \text{ m}^3 \text{ s}^{-1}$  (flood level  $>17 \text{ m}$  at Ripetta), EXT:  $2300\text{--}2900 \text{ m}^3 \text{ s}^{-1}$ . e) The River Vltava in Prague, documentary and instrumental data (Brázdil et al., 2005a), CAT:  $Q >2900 \text{ m}^3 \text{ s}^{-1}$  or a flood index 2 and 3, EXT:  $2000\text{--}2900 \text{ m}^3 \text{ s}^{-1}$  or flood index 1. f) The Elbe River, documentary and instrumental date (Mudelsee et al., 2003); classes refer to Mudelsee et al. (2003) strong (EXT) and exceptionally strong (CAT) flooding. g) The Oder River, documentary and instrumental data (Mudelsee et al., 2003). h) The River Ouse, documentary and instrumental data (Macdonald and Black, 2010), CAT:  $>500 \text{ m}^3 \text{ s}^{-1}$ , EXT:  $350\text{--}500 \text{ m}^3 \text{ s}^{-1}$ . Data before AD 1500 are incomplete due to lack of documentary evidence. Modified from IPCC (2013).

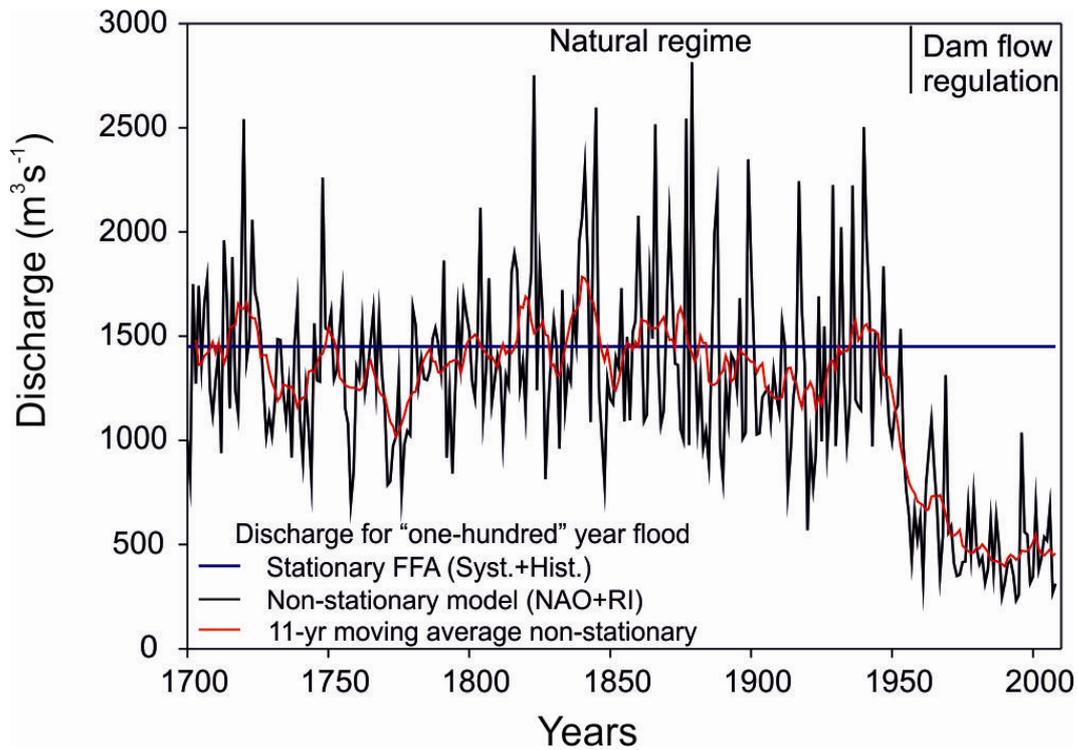


Figure 9: Non-stationary model of the “one-hundred year” flood over the last 300 years based on the dependence of the distribution parameters with the associated external covariates (winter NAO index and Reservoir index). The horizontal line represents the 100-yr flood from a log-normal distribution using documentary and instrumental records under a stationarity assumption (after Machado et al., 2015).