

# Documentary evidence of past floods in Europe and their utility in flood frequency estimation

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## **Abstract**

This review outlines the use of documentary evidence of historical flood events in contemporary flood frequency estimation in European countries. The study shows that despite widespread consensus in the scientific literature on the utility of documentary evidence, the actual migration from academic to practical application has been limited. A detailed review of flood frequency estimation guidelines from different countries showed that the value of historical data is generally recognised, but practical methods for systematic and routine inclusion of this type of data into risk analysis are in most cases not available. Studies of historical events were identified in most countries, and good examples of national databases attempting to collate the available information were identified. The conclusion is that there is considerable potential for improving the reliability of the current flood risk assessments by harvesting the valuable information on past extreme events contained in the historical data sets.

*Keywords:* flood frequency estimation, historical events, Europe,

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## **1. Introduction**

The reliable estimation of extreme flood events is challenging, but necessary for the design and operation of vital infrastructure such as flood defences, bridges, culverts and dams, and for more general flood risk management and

5 planning, e.g. emergency planning, flood risk mapping, and for defining  
6 flood insurance premiums. In practice, this information is obtained using  
7 flood frequency estimation techniques. Through statistical analysis of ob-  
8 served events, a probabilistic behaviour of flood events is inferred which is  
9 then extrapolated to provide estimates of the likely magnitude of future ex-  
10 treme events (e.g. the magnitude of the flood expected to be exceeded on  
11 average once every 100-year is estimated from a 40-year record). By nature,  
12 extreme flood events are rare and seldom observed locally and as a result  
13 hydrologists have little chance of gathering an adequate sample of recorded  
14 events to make confident predictions. This naturally raises the question of  
15 how best to extrapolate to extreme events, when no or only short series  
16 of recent events are available. As floods occur in almost all regions of the  
17 world, reliable flood estimation is a generic and shared problem. In Europe,  
18 the last couple of decades have witnessed a number of high-magnitude low-  
19 frequency flood events (Kundzewicz et al., 2013), causing widespread damage  
20 and destruction. But flooding in Europe is not a recent phenomenon, and  
21 there are multiple accounts of damaging flood events across the continent  
22 going back centuries (e.g., Glaser et al., 2004, 2010; Baptista et al., 2011).  
23 While the occurrence of extreme floods is a shared problem across Europe  
24 (and beyond), the lack of cross-boundary cooperation (national and regional)  
25 has lead to individual countries investing in research programmes to develop  
26 national procedures for flood frequency estimation. As a result, no standard-  
27 ised European approach or guidelines to flood frequency estimation exist.  
28 Where methods do exist they are often relatively simple and their ability  
29 to accurately predict the effect of environmental change (e.g. urbanisation,

30 land-use change, river training and climate change) is unknown (Castellarin  
31 et al., 2012; Madsen et al., 2012). Also, the problem of consistent estimates  
32 of extreme floods for trans-boundary rivers is rarely considered (Pappen-  
33 berger et al., 2012). The COST Action ES0901 *European procedures for*  
34 *flood frequency estimation* represents a novel opportunity to develop closer  
35 understanding of the methods of flood frequency employed across Europe.  
36 The Action is undertaking a pan-European comparison and evaluation of  
37 different methods available for flood frequency estimation under the various  
38 climatologic and geographic conditions found across Europe, and different  
39 levels of data availability. The availability of such procedures is crucial for  
40 the formulation of robust flood risk management strategies as required by the  
41 Directive of the European Parliament and of the Council on the Assessment  
42 and Management of Flood Risks (2007/60/EC).

43 Currently, flood frequency is most commonly based on systematic instru-  
44 mental data, collected from established networks of gauging stations oper-  
45 ated and maintained by a variety of station authorities/bodies across Europe.  
46 These gauging stations are of various forms and complexity depending on the  
47 level of data accuracy required. A more detailed discussion of availability,  
48 length and types of flood data records as well as procedures for flood fre-  
49 quency estimation procedures used across Europe is provided by Castellarin  
50 et al. (2012).

51 A well-known consequence of the extrapolation from short series is the  
52 high level of uncertainty associated with estimates of design floods with large  
53 return periods. For example, estimating the 100-year design flood peak from  
54 a 24-year record Stedinger and Griffis (2011) reported a factor of 4-to-1 be-

55 tween the upper and lower bounds of the 90% confidence interval. Given that  
 56 the average record length is typically in the range 20-40 years, hydrologists  
 57 have attempted to reduce the uncertainty levels by either: i) bringing addi-  
 58 tional gauged data from nearby and comparable catchments into the anal-  
 59 ysis (e.g., Hosking and Wallis, 1997), or ii) extending the available records  
 60 by bringing flood data from before the beginning of systematic flow record-  
 61 ing into the analysis in the form of historical and palaeoflood data (Guo and  
 62 Cunnane, 1991), or iii) using rainfall stochastic generators and rainfall-runoff  
 63 models to constrain extreme flood assessment by rainfall information (e.g.,  
 64 Paquet et al., 2013). The three methods all have merit, but only the second  
 65 is the focus of this review.

66 Realising the importance and utility of long-term datasets, flood hydrol-  
 67 ogists have increasingly turned their attention to historical flood information  
 68 (Brázdil et al., 1999, 2006; Glaser et al., 2004; Böhm and Wetzel, 2006; Mac-  
 69 donald, 2006; McEwen and Werritty, 2007; Glaser et al., 2010; Herget and  
 70 Meurs, 2010; Kobold, 2011; Santos et al., 2011; Brázdil et al., 2012), and  
 71 how best to incorporate documentary evidence of such historical floods into  
 72 flood frequency estimation (e.g., Stedinger and Cohn, 1986; Williams and  
 73 Archer, 2002; Benito et al., 2004; Gaume et al., 2010; Macdonald and Black,  
 74 2010; Gaál et al., 2010). However, the application of non-instrumental data  
 75 into flood risk analysis is not new, as is evident from already existing guid-  
 76 ance documents such as the Flood Studies Report (FSR) (NERC, 1975) in  
 77 the UK, a French handbook for flood risk assessment with historical data  
 78 (Miquel, 1984), the guidelines for flood frequency estimation in Germany  
 79 (DVWK, 1999), and the methodological guide to implement the Floods Di-

80 rective in Spain (MARM, 2011). For the purpose of this study we propose  
81 three definitions are adopted for the broad classification of different types of  
82 hydrological data.

- 83     • Instrumental: long records, where records have been kept using avail-  
84       able technologies, e.g. gauging stations or stage-boards (c. 1850-  
85       present)
- 86     • Documentary: data derived from sources which are intermittent e.g.  
87       documentary descriptions or flood levels marked on bridges (c. AD  
88       1000-present). Documentary evidence most often refers to historical  
89       events that occurred decades, centuries or even millennia ago, but it  
90       can also relate to more recent events in locations where no instrumental  
91       data are available.
- 92     • Palaeoflood: flood signatures recorded within depositional sequences,  
93       often sedimentary (channel cut-offs and lakes), though recent work has  
94       also witnessed flood signatures retrieved through dendrochronological  
95       approaches (Pleistocene present). As with documentary evidence, ge-  
96       omorphological evidence can also refer to recent flood events.

97 Regarding the historical and palaeoflood data we can add the following def-  
98 initions:

- 99     • Perception threshold: level or discharge above which contemporary  
100       society considered the event sufficiently severe to record information  
101       about it, e.g. epigraphic markings (Macdonald, 2006) or a written  
102       account in news media or a specialist publication.

103     • Censored data: unmeasured floods known to have occurred above or  
104       below the perception threshold, despite not knowing their exact magni-  
105       tude. Several researchers have shown that just knowing that a flood ex-  
106       ceeded a perception threshold can add significant value to the flood fre-  
107       quency analysis (e.g., Stedinger and Cohn, 1986; Cohn and Stedinger,  
108       1987; Payraastre et al., 2011)

109   An important complication when considering documentary and palaeoflood  
110   data is the impact of a changing environment (i.e. changes in climate and  
111   land-use, or river engineering works) on the characteristics of the flood series,  
112   and how to include this impact in future predictions.

113   The importance of data for assessing both the hydrology and impact of  
114   past events has been recognised as an integral part of flood risk management  
115   by the EU Flood Directive. The information collected in the Preliminary  
116   Flood Risk Assessment (PFRA) documents developed by the individual EU  
117   Member States starts with readily available or easily derivable information,  
118   such as records and studies on long term developments. Member States  
119   describe flood events that occurred in the past, which had significant adverse  
120   impacts, and for which the likelihood of similar future events is still relevant,  
121   reporting the frequency or recurrence of these events. The likely impact  
122   of climate change on the occurrence and impact of floods shall be taken  
123   into account in the review of the PFRA. For this, information beyond the  
124   instrumental records is acknowledged as being able to reduce the uncertainty  
125   of the assessment.

126   A key part of the COST Action ES0901 is to improve understanding of the  
127   barriers to new approaches to flood estimation. The results and discussions

presented in this paper are mainly based on responses from a questionnaire circulated among COST Action participants on the use of historical floods and documentary evidence in flood frequency estimation. Specifically, this paper will undertake, first, a review of the general challenges for the incorporation of documentary evidence within flood frequency estimation. The focus of this paper is not to address the issues of data sources and information, which have previously been examined in detail by others, such as Brázdil et al. (2006, 2012), but to examine the use and application of historical records and information in flood frequency analysis; specifically. Second, challenges with the application of historical information within a changing environment will be assessed. Then, a review of the use of historical information in flood frequency estimation across Europe is undertaken by examining the detailed questionnaire responses which represent the position and statements of the individual countries. Finally, the paper will conclude by considering the current barriers to further application and potential developments.

## **2. Challenges for broader application of historical information**

As documentary evidence most often predates the installation of gauging stations, and is not directly supported by other instrumental sources (using a limnometric scale e.g. stageboards), it generally provides indirect information on peak flood discharge, often in the form of a water level marker (Figure 1), or information that a specific location had been flooded, damaged or destroyed, or that the water level had reached a level relative to a structure (e.g. it had reached the top of the doorframe).

Different quantitative methods have attempted to extract the information



152 contained in historical data using a variety of approaches. The most com-  
153 mon approach is to consider a perception threshold for a historical period  
154 or sub-period, with the assumption that each flood exceeding this threshold  
155 has been recorded (e.g. NERC, 1975). As the consequences are important,  
156 this can sometimes be aided by thresholds within the environment of known  
157 exceedance. An example is the flooding of the Lincolnshire Plains by the  
158 River Trent in Central England when a low lying moraine (Spalford Bank) is  
159 overtopped, which is known to occur at flows in excess of  $1000 \text{ m}^3\text{s}^{-1}$  (Mac-  
160 donald, 2013). Having established the threshold, the number of exceedance  
161 events during a period can then be retrieved from historical records. A more  
162 detailed approach involves the use of hydraulic formulae (e.g. Manning equa-  
163 tion) or one or two dimensional hydraulic models (St Venant equations) to  
164 convert historical flood levels into historical discharges (Lang et al., 2004a).  
165 As shown by Neppel et al. (2010) it is important to ensure that the hy-  
166 draulic model calibrates with flood marks and rating curves (when available)  
167 and reassess the hydrological homogeneity of discharge estimates at several  
168 places. Hydraulic studies should provide a discharge estimate, but also a  
169 range of possible values within an interval, based on a sensitive analysis or  
170 an uncertainty analysis.

171 Several statistical approaches were developed in the past to improve the  
172 flood frequency curve estimation by extracting the information contained in  
173 the different types of historical records discussed above. In the USA, Bul-  
174 letin 17 B (USWRC, 1982) proposed the weighted moments (WM) technique  
175 for incorporating historical information in a flood frequency analysis. The  
176 WM technique is a straightforward method that is noticeable for ease of im-

177 plementation. Stedinger and Cohn (1986) developed a maximum likelihood  
 178 estimator (MLE), which was more flexible, efficient and robust than the WM  
 179 technique. Moreover, it allowed the introduction of binomial censored data  
 180 into the likelihood function; however, MLEs present numerical problems in  
 181 some occasions. To avoid this drawback, while maintaining the efficiency  
 182 of MLE technique, the expected moments algorithm (EMA) was developed  
 183 (Cohn et al., 1997). Reis and Stedinger (2005) proposed a Bayesian tech-  
 184 nique based on Markov Chain Monte Carlo methods (BMCMC) that im-  
 185 proves previous techniques by providing the full posterior distributions of  
 186 flood quantiles. Likewise, the BMCMC technique allows for the introduction  
 187 of uncertainty into historical peak discharge estimates. The WM technique  
 188 was adapted to the case of probability weighted moments (PWM), to pro-  
 189 duce the partial probability weighted moments (PPWM) approach (Wang,  
 190 1990). The EMA technique was also adapted to the PWM case, providing  
 191 the expected probability weighted moment (EPWM) estimator, which im-  
 192 proves the estimation of the shape parameter, but has also shown some bias  
 193 (Jeon et al., 2011).

194 An example of how the inclusion of historical events can help flood fre-  
 195 quency estimation to better represent the probabilistic behaviour of flood  
 196 events can be seen in Figure 2. It shows the results at the Tortosa gauging  
 197 station located on the River Ebro in Spain, a comparison between two Gen-  
 198 eralised Extreme Value (GEV) distributions fitted to i) a sample of 31 annual  
 199 maximum flood peaks recorded at the gauging station (instrumental) by the  
 200 method of L-moments, and ii) the same sample of instrumental events, but  
 201 enhanced with seven historical flood events by the method of PPWM. From

202 the frequency plot in Figure 2 it is clear that the GEV distribution fitted to  
203 the instrumental record only, would result in severe under-estimation of the  
204 real flood risk at the site of interest. However, the inclusion of the histori-  
205 cal records estimated from a set of flood marks recorded at a house close to  
206 the reach improved the estimation of extreme return period floods, as their  
207 magnitude was unknown from the short instrumental record.

208 Most of these analytical developments have been undertaken within the  
209 academic field. However, extending these improvements to routine practical  
210 use is not trivial, principally because of the mathematical complexity of most  
211 techniques. For instance, classical MLEs are efficient for sufficiently long  
212 records, but may produce numerical problems in application to case studies  
213 when sample size is small (El Adlouni et al., 2007); a significant drawback for  
214 recommending this technique for practical application. Bayesian techniques  
215 also present critical steps, such as the estimation of prior distributions and  
216 the computation of posterior distributions which are not always straightfor-  
217 ward. The elegant statistical models based on censored data sources and  
218 solved using likelihood functions, sometimes combined with Bayesian statis-  
219 tics (Reis and Stedinger, 2005), can provide very good results. Nevertheless,  
220 this review suggests that whilst these models exist, there is limited evidence  
221 that they have migrated from the academic field into operational guidelines.  
222 Potential barriers to the broader application of these approaches may reflect  
223 the complex computational requirements and site specific characteristics that  
224 may be best combined with specific methods, though the survey undertaken  
225 in this study did not contain information on why certain approaches are not  
226 applied. These problems lead to the use of the more simplistic, but robust,

227 methods in practice, as recommended by operational guidelines, such as the  
228 WM technique in the United States and the PPWM in Spain.

229 In addition to providing formal input into quantitative flood frequency  
230 estimation, documentary evidence of past events can be helpful in commu-  
231 nicating flood risk to non-specialist stakeholders (McEwen et al., 2013) and  
232 for better understanding variations in flood seasonality (Macdonald, 2012).  
233 The transformation of information from descriptive accounts of past events  
234 into more easily understood groups of flood magnitude has seen the use of  
235 indices, often using a scale dividing the events into a set of qualitative classes  
236 (Sturm et al., 2001; Llasat et al., 2005) for flood severity, see Brázdil et al.  
237 (2006, 2012); for example class 1 (low to intermediate events: damage and  
238 flooding are limited to restricted areas), class 2 (high events: flooded area  
239 and debris flow are important, structures such as dikes and roads have been  
240 destroyed for several hundred of meters), class 3 (extreme events: damage  
241 or destruction of important structures and flooding on the whole plain). Al-  
242 though a useful tool for categorising and visualising flood magnitude, this  
243 approach has yet to be useful in the estimation of flood frequency, and is  
244 unlikely to present any advances as the approach removes individual event  
245 information and groups the events, thereby reducing the potential value of  
246 the data.

### 247 **3. Assessment of environmental change**

248 There is some discussion provided as to means of accounting for the im-  
249 pact of environmental change on flood occurrence, with several countries  
250 undertaking comparison to nearby stations, for non-homogeneity and trend

251 studies. However, in a review of existing guidance in European countries  
252 on how to include considerations of environmental change in flood frequency  
253 estimation, Madsen et al. (2012) found that generally little or no guidance  
254 is provided for how to deal with trend or non-homogeneity when identified,  
255 and how this knowledge should be incorporated into flood estimation. This  
256 is clearly an area where much more effort is required to translate scientific  
257 research into operational guidelines.

258 Different types of non-stationarity can be considered within historical  
259 records, as the frequency distribution could change during the period for  
260 which historical and palaeoflood data are recorded: i) the changes related  
261 to non-homogeneity problems (historical data availability, transformation of  
262 indirect information to discharge estimate); ii) climatic variability over long  
263 time scales could limit the utility of historical data under a stationarity frame-  
264 work to some hundreds of years in the past (Hosking and Wallis, 1997). This  
265 topic remains an open field of research, with present interest amplified by  
266 the perspective of climate change for the 20th and 21st centuries; iii) chan-  
267 nel changes (natural and anthropogenic) over long timeframes (e.g., Brázdil  
268 et al., 2011a). As a means of minimising the potential impact of these cli-  
269 matic non-homogeneities, historical records used for flood frequency analysis  
270 are not extended back beyond around 400 years in Spain. This practice lim-  
271 its the influence of past climatic changes; as a greater frequency of extreme  
272 flood events are found in the period 1540-1640 (Benito et al., 2003). Similar  
273 timeframes are recommended in a number of academic papers (e.g. Parent  
274 and Bernier, 2003; Macdonald, 2013), but this often focuses on concerns re-  
275 lating to data quality and quantity prior to this (as discussed above) rather

276 than climatic variability, with several studies commenting on the longer time-  
277 frame providing greater climatic variability, and therefore a more uncertain  
278 climate range (e.g. Macdonald et al., 2006). These issues become even more  
279 important when attempting to merge gauged flow data with palaeoflood data  
280 stretching back millennia, though it could be argued that climatic variabil-  
281 ity over millennial timescales incorporates sufficient variability that climate  
282 phases become less significant. While some researcher have embraced the use  
283 of palaeoflood data (Baker et al., 2002), others remain more sceptical of their  
284 practical utility, especially when regional flood frequency methods are avail-  
285 able (e.g. Hosking and Wallis, 1986). Notably, Neppel et al. (2010) identified  
286 large error associated with historical flood magnitude estimation could lead  
287 to a reduction in the precision of design flood estimates when compared to  
288 estimates using gauged data only, supporting the view that palaeoflood data  
289 should be handled carefully when included into a flood frequency analysis.

290 Lang et al. (2004b) proposed a statistical test based on the Poisson process  
291 for the detection of changes in peak-over-threshold series. It has been applied  
292 to several historical series in France and Spain (Barriendos et al., 1999) and  
293 in central Europe (Glaser et al., 2004). The power of the test is limited when  
294 the number of historical floods is low. On the contrary, including low to  
295 intermediate historical floods increases the risk of non-homogeneity, as such  
296 floods can be strongly influenced by anthropogenic changes. It is therefore  
297 recommended to check the validity of the rating curves used for historical  
298 floods.

299 The development of slackwater deposits as a tool in the reconstruction of  
300 palaeoflood series has expanded extensively over the last couple of decades

301 Werritty et al. (2006); Jones et al. (2010); Huang et al. (2012); Dezileau et al.  
302 (2014), with a number of review papers (e.g. Benito and Thorndycraft, 2006)  
303 and books (Gregory and Benito, 2003) addressing the topic in detail.

304 Lakes can act as efficient repositories for sediments eroded from within the  
305 catchment and that are transported through the fluvial system (Mackereth,  
306 1966). The sediments reaching a lake are dependent on a number of variables  
307 which may vary through time and space; see Schillereff et al. (2014) for a  
308 full review. The sediments that reach the lake may be laid down providing a  
309 sedimentary record of high-magnitude flows which appear as distinct lamina-  
310 tions of coarse material. An increasing number of studies have examined lake  
311 sediment sequences with the intention of determining flood histories (Noren  
312 et al., 2002; Gilli et al., 2013; Wilhelm et al., 2013). The sediments preserved  
313 within the lake can contribute valuable information on flood frequency and  
314 potential magnitude of single events over timeframes reaching several mil-  
315 lennia (Noren et al., 2002). For example, Swierczynski et al. (2013) derived  
316 a 7,000-year flood chronology for the lake Mondsee in Upper Austria. Even  
317 the seasons of the palaeofloods could be precisely determined by the micro-  
318 stratigraphic position of a detrital layer within the annual succession of lake  
319 deposition. This flood chronology shows a striking variability in the flood  
320 occurrence from decadal to millennial time scales. There is a period of more  
321 than 200 years (21 B.C. 216 A.D.) without any flood documented, whereas  
322 the average frequency is 0.04 floods/year yielding 9 floods for such a time  
323 interval.

#### 324 4. Questionnaire on use of historical data in flood frequency esti- 325 mation

326 As part of the COST Action ES0901 *European procedures for flood fre-*  
327 *quency estimation* a review was undertaken examining if, and how different  
328 European countries incorporate historical information into flood frequency  
329 analysis. Responses were collected from 15 European countries, represent-  
330 ing the different participant countries of the COST Action; all participant  
331 countries were invited to contribute through the completion of a question-  
332 naire, which was initially distributed to COST participants, who completed  
333 or passed onto colleagues better placed to do so. The questionnaire applied  
334 the definitions detailed above so as to distinguish between historical and in-  
335 strumental data series. A summary version of the questionnaire responses is  
336 provided in Table 1.

337 TABLE 1

338 The following three sub-sections summarise the information collected  
339 from the questionnaires. In particular: i) the length of existing historical  
340 data series, ii) the accessibility to historical flood data, and iii) summaries of  
341 specific guidelines developed in European countries.

##### 342 4.1. Data availability

343 Each country was asked to provide details of the sites and locations where  
344 the most complete historical series are available. This information is used to  
345 provide an indication of the types and use of historical records as a series of  
346 national summaries, but cannot be considered as an exhaustive inventory.

347 For each reported case-study the ratio between the length of the instru-



348 mental record and the total time from the end of the instrumental record  
349 until the first recorded historical flood event was calculated. The average of  
350 the ratios calculated from the case studies within each country are reported  
351 (Table 2) together with the number of case-studies and the oldest recorded  
352 flood event. Note that the oldest flood refers to the oldest flood event as-  
353 sociated with an estimate of peak flow; in some countries, older events were  
354 recorded but could not be assigned an estimate of the discharge.

#### 355 TABLE 2

356 The average ratios are all below 0.50 suggesting that additional infor-  
357 mation of extreme floods can be found as far back in time as twice the  
358 period covered by the instrumental record. The countries listed in Table 2  
359 are representative of North, South, East and West Europe, indicating that  
360 historically augmented flood estimation could be useful across the continent.  
361 While no quantitative assessment of the benefit of the extended data series  
362 were conducted as part of this review, several previous studies have high-  
363 lighted the utility of such series. For example, Macdonald et al. (2013) found  
364 that extending a 40-year instrumental record with documentary evidence of  
365 flooding dating back to 1772 resulted in an almost 50% reduction on the  
366 uncertainty of the estimated design flood with a return period of 100 years.  
367 Similar conclusions have been reached by other researchers such as Payrastre  
368 et al. (2011). Thus, the data series listed in Table 2 represent an important  
369 resource for providing more reliable estimates of flood risk across Europe.

#### 370 4.2. Central depository of historical data

371 No centralised database exists as a depository for flood information at  
372 a European scale. But a variety of laudable national/regional/local and

individual databases exists. However, there is no common agreed format, and the databases often include either/or both qualitative and quantitative information with limited quality control on the information uploaded. The purpose of existing data varies, which often reflects the structure and types of information collected, the result is that some disciplines may feel insufficient or 'the wrong' type of data may be present, reflecting the varied uses of historical information, from those examining social impacts of past floods to those interested in using the information in flood frequency estimates, as such some disciplines may consider important information to be absent. These databases tend to be funded through a variety of different mechanisms, with few receiving continuous central support; as such they are funded initially, but then become reliant on individuals or professional societies for continuation, good examples being the British Hydrological Society Chronology for British Hydrology Events (BHS CBHE), as described by Black and Law (2004), or the French national Historical Database BDHI currently in development in the framework of the EU Flood Directive (Lang et al., 2012). Whilst a valuable resource the full potential of these databases cannot be realised in pan-European flood frequency estimation at present, due to the absence of a standardised method for construction and minimum data requirements. The National Disaster Archive compiled by the Disaster & Emergency Management Presidency (AFAD) in Turkey, for example, provides tabular and spatial information (date, location) about the entire spectrum of historic disaster events (e.g., floods, droughts, earthquakes, landslides, forest fires, nuclear accidents, etc.) associated with figures of deaths, injuries, affected populations, etc. However, this is not immediately utilizable

398 in flood frequency analyses due to the lack of data describing the physical  
399 characteristics of the events, such as flood levels and discharges.

400 Recent efforts by a group of researchers from the Slovak Academy of  
401 Sciences started with mapping of all historical flood marks and collecting  
402 historical reports of floods in Slovakia. Their results are continuously pub-  
403 lished, e.g. recent studies by Pekárová et al. (2011, 2013) give the overview of  
404 the history of floods and extreme events in Slovakia and in the upper Danube  
405 River Basin at Bratislava.

406 These databases provide pockets of knowledge, but large areas of Europe  
407 remain ungauged. The use of geospatial databases for the visualisation of in-  
408 formation and capability to embed images within such databases presents an  
409 important development, permitting flood levels and additional information  
410 beyond a basic descriptive account to be housed within each flood account,  
411 empowering the researcher to more rapidly and easily access required infor-  
412 mation. One of the principal constraints to the wider application of histor-  
413 ical information in flood frequency analysis has been the time requirements  
414 for collecting the necessary data; well developed and constructed geospatial  
415 databases present a valuable step towards removing these constraints.

#### 416 *4.3. Practical guidelines for inclusion of historical data*

417 A number of countries were identified as possessing practical guidelines  
418 for inclusion of historical flood information into flood frequency estimation,  
419 including: Austria, France, Germany, Ireland, Italy, Slovakia, Spain and the  
420 United Kingdom.

421

#### 422 **Austria**

423 In Austria historical information, where available, was included in the devel-  
424 opment of national maps of flood discharge (Merz et al., 2008). The historical  
425 information was included in flood frequency estimation procedure based on  
426 the use of likelihood functions of censored information and Bayesian mod-  
427 elling techniques as described by Merz and Blöschl (2008) and Viglione et al.  
428 (2013).

429

## 430 **France**

431 Miquel (1984) presented a methodological guide for the inclusion of histori-  
432 cal data in flood frequency analysis. It was based on a Bayesian approach to  
433 peak-over-threshold (POT) values with an a posteriori estimate of the flood  
434 distribution, by combining with the Bayes theorem and a priori distribution  
435 based on instrumental data and historical POT values. Parent and Bernier  
436 (2003) presented an application of this model, using a MCMC algorithm for  
437 computation. Naulet et al. (2005) used a maximum likelihood approach on  
438 annual maximum values, with different sub-periods (each one being related  
439 to a threshold of perception according to documentary sources availability)  
440 and different types of data (censored, censored with uncertainties, binomial  
441 censored). Lang et al. (2010) and Neppel et al. (2010) applied an error  
442 model on discharge estimate, accounting for random errors (sampling uncer-  
443 tainties) and systematic errors (water level and rating curve errors). They  
444 showed that ignoring the rating curve errors may lead to an unduly optimistic  
445 reduction in the final uncertainty in estimation of flood discharge distribu-  
446 tion. Gaume et al. (2010) and Payraastre et al. (2011) presented a Bayesian  
447 framework allowing the use of regional information of historical floods at un-

448 gauged sites. They also provided results on the usefulness of historical data  
449 in flood frequency analysis regarding the type of data (censored, censored  
450 with uncertainties, binomial censored).

451

## 452 **Germany**

453 The German Association for Water, Wastewater and Waste (DWA) and its  
454 predecessor DVWK have published guidelines which give recommendations  
455 for the use of historical sources and data: DWA (2008): Guidelines on how  
456 to exploit and interpret historical sources for determining extreme flood dis-  
457 charges. DVWK (1999): Guidelines for integrating large historical flood  
458 magnitudes in flood frequency analysis are based on the methods presented  
459 in Bulletin 17B (USWRC, 1982). This publication was superseded by the  
460 more recent guidelines on flood estimation which devotes a separate chap-  
461 ter to the integration of large historical flood magnitudes in flood frequency  
462 analysis (DWA, 2012). Three alternative approaches are offered to consider  
463 historical data in the parameter estimation of the frequency distribution.  
464 One of them is based on the definition of a set of likelihood functions repre-  
465 senting the actual nature of the available flood information, i.e.: i) discharge  
466 of historical information known, ii) discharge is known to fall within an inter-  
467 val (upper and lower bound specified), or iii) event is known to have exceed  
468 a perception threshold, but the actual discharge value is unknown.

469

## 470 **Ireland**

471 In Ireland, the generally accepted approach to incorporating historical flood  
472 data follows that put forward by Bayliss and Reed (2001) in a similar man-

ner to that described for the UK. With the imminent release of the Flood Studies Update (FSU) methodologies in 2014, growth curve analysis will use L-moment methods to derive growth curves, with the EV1 and LN2 distributions being the preferred distributions for use at gauged locations. It is envisaged that methods of incorporating historical information will move towards the use of L-moment based methods in the future. The central source of information on historical floods will remain the Irish flood hazard mapping website, [floodmaps.ie](http://floodmaps.ie).

## **Italy**

The gauging network for systematic river-stage monitoring in Italy was largely installed in the twentieth century, therefore Italian streamflow records are usually much shorter than 100 years (Calenda et al., 2009). In this context, historical and non-systematic information on flood events is a valuable resource. Historical evidence of flooding in Italy has been recorded (e.g., Aldrete, 2007), and national databases of historical disasters (mainly landslides and floods) have been established (Guzzetti et al., 1996, 2004). Nevertheless, these databases contain predominantly descriptive information such as: triggering mechanisms, economic losses and casualties, but little information related to peak discharge. Consequently, although basin authorities routinely use information on historical floods for geographically delineating the most vulnerable areas and acknowledge the value of this information for improving flood frequency estimation (see e.g., AdB-Po, 1999), no evidence of practical use of historical floods in flood frequency estimation was identified in Italy at a national level, though examples were found at regional and local scales.

498 For example an application to the Piedmont region reported by Claps and  
499 Laio (2008) and Laio et al. (2011), and local application by Calenda et al.  
500 (2009) on the River Tiber.

501

## 502 **Czech and Slovak Republics**

503 There are several methods for inclusion of historical flood data in flood fre-  
504 quency estimation in the Czech and Slovak Republics, which were published  
505 in reports e.g. Dub and Nemec (1969), Kašpárek (1984) and Novický et al.  
506 (1992). These methods are based on corrections of systematic errors by  
507 estimation of statistical parameters (coefficient of variability, skewness) of  
508 applied distribution functions. The German guidelines for using historical  
509 floods, published in DVWK (1999), was applied by Szolgay et al. (2008).  
510 Recent studies in Slovakia used a Bayesian framework to include both local  
511 and regional information about historical floods at ungauged sites, and to  
512 provide results on the usefulness of different types of historical data in flood  
513 frequency analysis (Gaál et al., 2010, 2013).

514 Flood frequency analysis in the Czech Republic is based on combina-  
515 tion of floods derived from documentary evidence and systematic hydrologic  
516 measurements, which permits the creation of 500-year series: examples in-  
517 clude the Vltava (Prague), Ohře (Louny) and Elbe (Děčín) series in Bohemia  
518 (Brázdil et al., 2005). In Moravia (eastern Czech Republic), similar compiled  
519 series are available for the River Morava, starting as early as 1691 (Brázdil  
520 et al., 2011b). More recently, knowledge of historical floods coupled with  
521 flood plain information in Prague was used for the estimation of hydraulic  
522 parameters, permitting the calculation of peak discharges of past disastrous

523 floods during the pre-instrumental period (Elleder et al., 2013).

524

## 525 **Spain**

526 In Spain, the use of historical records is generally recommended when pos-  
527 sible, by fitting a GEV distribution by the PPWM method. In addition,  
528 historical records were used in some Mediterranean basins (3) to improve:  
529 i) the results of the regional flood frequency analysis, and ii) estimates of  
530 high return period quantiles along the Mediterranean East coast of Spain  
531 (Jiménez-Álvarez et al., 2012).

532 The 92nd Region is located in the northeast of Spain, including the rivers  
533 of the left bank of the River Ebro with heads in the central Pyrenees (Figure  
534 3). In this region the regional coefficient of skewness (L-CS) estimated from  
535 instrumental records was improved by the use of historical information. It  
536 was seen that two high flood events that occurred in the 20th century affected  
537 most of this region (1907 and 1982). However, they were not recorded, as the  
538 former occurred before the existence of a gauging station network in Spain,  
539 while the latter exceeded the maximum capacity of the gauging stations.  
540 Values of at-site L-CS were improved by the use of a GEV distribution fitted  
541 with historical information by the PPWM method. The regional L-CS value  
542 was updated by a weighted mean of at-site L-CS with weighting factors  
543 dependent on the uncertainty of at-site estimations.

544 The 72nd and 82nd regions are located in the eastern part of Spain, in-  
545 cluding the lower parts of the Júcar and Segura catchments that are affected  
546 by rare and heavy rainfall events coming from the Mediterranean Sea (Figure  
547 3). These events are caused by cut-off lows occurring in spring and autumn,



when cold air in the upper part of the troposphere moves from northern latitudes to the south over the warm Mediterranean Sea, generating heavy convective rainfall events and, consequently, intense flood events. However, there is a lack of information recorded about these flood events; either they occurred in the past before a gauging station was installed, or they were not recorded, as they exceeded gauging station capacity. This lack of information can result in potentially severe underestimation of higher return period quantiles. Estimates with only instrumental records can lead to magnitudes around 5 to 10 times smaller for the 500-year return period. As floods come from two types of rainfall events, a Two-Component Extreme Value (TCEV) distribution (Rossi et al., 1984) fitted by MLE is recommended. In these regions, the use of historical information in flood frequency is crucial to achieve reliable estimation of higher return period quantiles. In Spain, the use of historical information to improve flood frequency analyses is recommended (MARM, 2011). A large catalogue of historical floods is supplied by the Spanish civil defence organization.

## **United Kingdom**

The use of historical record has been called for since the mid-1970s, initially through the early work of the Flood Studies Report (NERC, 1975) and Potter (1978). More recently, Bayliss and Reed (2001) provided the first approach designed specifically for practitioners on how to augment instrumental datasets with documental evidence of historical records. However, the uptake of this approach has been piecemeal and slow, in part as practitioners still require a user-friendly tool for incorporating historical data into

573 flood frequency analysis. Current methods widely employed for incorporating  
574 historical flood information into flood assessments often consist of a conven-  
575 tional flood frequency plot, with the historical levels/discharges marked on,  
576 but importantly not included within the statistical analysis. The use of an  
577 informal graphical plotting approach was advocated by Reed and Robson  
578 (1999) to permit greater confidence among practitioners in the application  
579 of historical data. By contrast, Macdonald et al. (2006) and Macdonald  
580 and Black (2010) have advocated the use of L-Moments, as they permit  
581 greater flexibility and retained an approach practitioners were already fa-  
582 miliar with in dealing with pooled data, compared to more mathematically  
583 involved Maximum-Likelihood approaches (Macdonald et al., 2013). Each of  
584 the approaches considered a preference for a Generalised Logistic distribution  
585 model to represent the flood growth curve. An interesting use of historical  
586 information was reported by Williams and Archer (2002) who used historical  
587 flood data to assess the return period of a recent large event.

## 588 **5. Discussion**

589 Despite general agreement in the scientific literature on the utility of  
590 historical flood information in flood frequency estimation, the survey un-  
591 dertaken has shown that there is only a limited transfer of methods from  
592 academia into practical guidance. A few good examples of guidelines and  
593 depositories for historical flood data were identified, but no single unified  
594 approach or database is evident. Depositories were identified both as part  
595 of larger government hydrometric databases, but also existing independently  
596 from official government databases, and operated mainly by volunteers and

597 populated by citizen science efforts (e.g. UK BHS CBHE). The lack of prac-  
 598 tical guidelines and fragmented access to historical information are practical  
 599 barriers towards more operational use of these data sources to support cur-  
 600 rent risk mapping efforts and decision-making problems. In addition, it is  
 601 also clear that the inclusion of historical information is not always straight-  
 602 forward, requiring a greater degree of scrutiny before application than typ-  
 603 ically required for instrumental data. In particular, it should be recognised  
 604 that historical information is fundamentally different from quality controlled  
 605 streamflow measurements obtained from gauging stations. For example, the  
 606 degree of certainty associated with discharge estimates from historical in-  
 607 formation requires special consideration. Research has shown that simply  
 608 ignoring uncertainties on discharge estimates will favour the use of histori-  
 609 cal information, as sampling uncertainty is reduced by increasing the length  
 610 of the flood period. Nevertheless, it is important to correctly describe the  
 611 uncertainties on peak discharge for the instrumental, historical and palae-  
 612 oflood data, including errors on water level  $H$ , on the rating curve  $Q(H)$ ,  
 613 on the threshold of perception and on the starting date of the historical pe-  
 614 riod. The latter should not be systematically the date of the oldest flood  
 615 in the historical data set (Strupczewski et al., 2013), but should include a  
 616 period prior to this. The Bayesian framework appears to be a suitable sta-  
 617 tistical tool, enabling inclusion of several kinds of data (e.g. single values,  
 618 intervals, number of exceedances) and able to include errors/uncertainties on  
 619 discharge estimates (i.e., systematic error on water levels and on the rating  
 620 curve transformation) into flood frequency analysis.

621 While this review has found that there is largely consensus in the sci-

622 entific literature as to the usefulness of historical data in flood frequency  
 623 estimation, the methods have overwhelmingly focussed on extending at-site  
 624 estimates. Few studies have reported on the use of historical information  
 625 in a regional context. A notable exception is the procedure for certain geo-  
 626 graphical regions of Spain, where the occurrence of very extreme events in  
 627 the past has resulted in a set of regional flood frequency curves adjusted up-  
 628 wards to represent the worst case, even if no actual events has been observed  
 629 at a particular site. This is potentially a very interesting methodological  
 630 development, recognising the limitations of fitting current statistical models  
 631 to datasets that are known not to include potentially very extreme events,  
 632 similar to events that have occurred in other locations within the region.  
 633 By contrast, Hosking and Wallis (1997) argue that historical information is  
 634 of limited use in regional flood frequency estimation; their reservations are  
 635 based on i) concerns about the accuracy and completeness of the historical  
 636 information (historical data are most often found in old and large human set-  
 637 tlements and not at a representative sample across all possible catchments),  
 638 ii) representativeness of catchment within a region where historical data are  
 639 available, and iii) using data so far in the past that the underlying frequency  
 640 distribution might have changed too much (non-stationarity). A regional  
 641 model combining both regional and historical data was presented by Jin and  
 642 Stedinger (1989) combining the index flood method with a GEV distribution  
 643 where the model parameters are estimated using a combination of probab-  
 644 ility weighted moments and a maximum likelihood procedure. Gaume et al.  
 645 (2010) also presented a maximum-likelihood approach to combining regional  
 646 and historical data within the framework of the index flood method. Sur-

647 prisingly, no or only little further development of these procedures appears  
648 to have been reported in the literature, but this is an area where further re-  
649 search is still required to develop a new generation of risk tools to effectively  
650 allow regional models to use historical information, and to define procedures  
651 to enable the transfer of historical data between catchments.

652 The potential of historical information in public awareness of flood risk is  
653 considerable, historical events are tangible, with epigraphic markings provid-  
654 ing an example of how communities have preserved evidence from past events  
655 to educate future generations of flood risk, which may not be witnessed within  
656 any single lifetime. Increasingly recognition of the non-quantitative informa-  
657 tion contained within historical flood accounts is being recognised, providing  
658 detailed descriptions of the social and cultural responses to extreme events,  
659 responses that inherently shape current flood risk management approaches  
660 through *learned knowledge* within communities. This informal knowledge  
661 is increasingly being sought and embedded within local flood risk manage-  
662 ment plans, as recognition of the value of local lay knowledge has developed  
663 (McEwen et al., 2013).

664 The development of national approaches in individual countries has re-  
665 sulted in no-single approach being applied at a European level, constraining  
666 the potential for cross border information transfer, and at worst leading to  
667 misunderstanding and poor communication to the public (e.g. flood maps  
668 with different flood extents at the boundary). Future research must address  
669 several key themes:

- 670 • construction of a single database framework within which data can  
671 be stored and managed, with both extraction, uploading (preferably

672 through approaches advocated by citizen science) and geospatial pre-  
673 sentation capabilities;

674 • move towards organisation data sharing across boundaries, with greater  
675 free access to data for benchmark sites;

676 • development of a computationally simple user interface toolbox, within  
677 which hydrological series comprising of different data types, lengths and  
678 completeness can be assessed together;

679 • development of a set of practices for the treatment of data uncertainty  
680 associated with historical records; and,

681 • a forum for the sharing and review of best practice at a European level.

682 Inevitably an assessment of the data has to be made by the individual under-  
683 taking the analysis and the purpose for which the data is compiled, but the  
684 above proposals would facilitate a more rapid and structured approach to the  
685 compilation and analysis of the data, overcoming a number of the obstacles  
686 currently cited as prohibiting expansion in the application of historical data.

## 687 **6. Conclusions**

688 There is increasing recognition that historical records of flooding provide  
689 a valuable means by which extreme rare events can be better understood,  
690 facilitating more enlightened flood frequency analysis where interest is fo-  
691 cused on extreme events (events with a return period in excess of 100 years).  
692 As evidenced within this research (Table 1 and 2), a number of examples of  
693 historical flood analysis are present within most European countries, with

694 a number of countries if not actively incorporating historical flood records  
695 into flood frequency analysis considering how they can be used, in compli-  
696 ance with the EU Floods Directive (2007/60/EC). Whilst no single approach  
697 is uniformly applied to historical flood frequency analysis across Europe, a  
698 number of national and regional approaches exists. As historical evidence is  
699 often found in connection with large rivers, the use of this information could  
700 be a key driver in both academic and practical investigations of transbound-  
701 ary flood management.

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Table 1: Use of historical data in flood frequency estimation.

Country	Routine use of historical flood data?	Existing recognised approach?	Preferred method	Information on catchment change?	Central depository of historical flood data?	Website
Austria	Yes	Yes	Bayesian methods	Yes	Yes	<a href="http://chyd.gv.at/">http://chyd.gv.at/</a>
Czech Republic	No	No	-	No	No	
Finland	No	No	-	No	Yes	<a href="http://www.ymparisto.fi/oiva">www.ymparisto.fi/oiva</a>
France	Not routinely	No, but guidelines available	Bayesian methods	When available	Yes	<a href="http://www.reperesdecruis-seine.fr/carte.php">http://www.reperesdecruis-seine.fr/carte.php</a>
Germany	No, but some practical use reported	No but guidelines available	Maximum Likelihood	Not routinely	Yes	<a href="http://undine.bafg.de">http://undine.bafg.de</a>
Ireland	No	No	-	No	Yes	
Italy	Not routinely	No	-	No	Yes	<a href="http://webmap.irpi.cnr.it/">http://webmap.irpi.cnr.it/</a>
Norway	No	No	-	No	Yes	
Lithuania	No	No	-	No	No	
Poland	Not routinely	No but guidelines available	-	No	No	
Portugal	Not routinely	No	-	Yes	Yes	<a href="http://geo.suinh.pt/AtlasAgua/">http://geo.suinh.pt/AtlasAgua/</a>
Slovakia	No, but some practical use reported	Yes	MCMC techniques	No	No	
Slovenia	No	No	-	Not routinely	Yes	<a href="http://vode.arso.gov.si/hidrarhiv/pov_arhiv_tah.php">http://vode.arso.gov.si/hidrarhiv/pov_arhiv_tah.php</a>
Spain	Yes	Yes	PPWM method	No	Yes	
Turkey	No	No but guidelines (DSI, 2012) exist	-	No	Yes	<a href="http://tuua.afad.gov.tr">http://tuua.afad.gov.tr</a>
United Kingdom	Not routinely	Guidance available	Graphical method	Not routinely	Yes	<a href="http://www.trp.dundee.ac.uk/cbhe/welcome.ht">http://www.trp.dundee.ac.uk/cbhe/welcome.ht</a>

Table 2: Summary of historical flood records. *Ratio* in column four refers to the average ratio between length of instrumental record and the total length of the historical plus instrumental records.

Country	No. studies	Year of	Ratio
		oldest recorded flood	
Czech Republic	8	1118	0.22
France	13	1601	0.23
Germany	1	1374	0.31
Lithuania	2	1427	0.33
Norway	12	1345	0.47
Slovakia	5	1012	0.24
Spain	11	1779	0.38
United Kingdom	14	1210	0.19



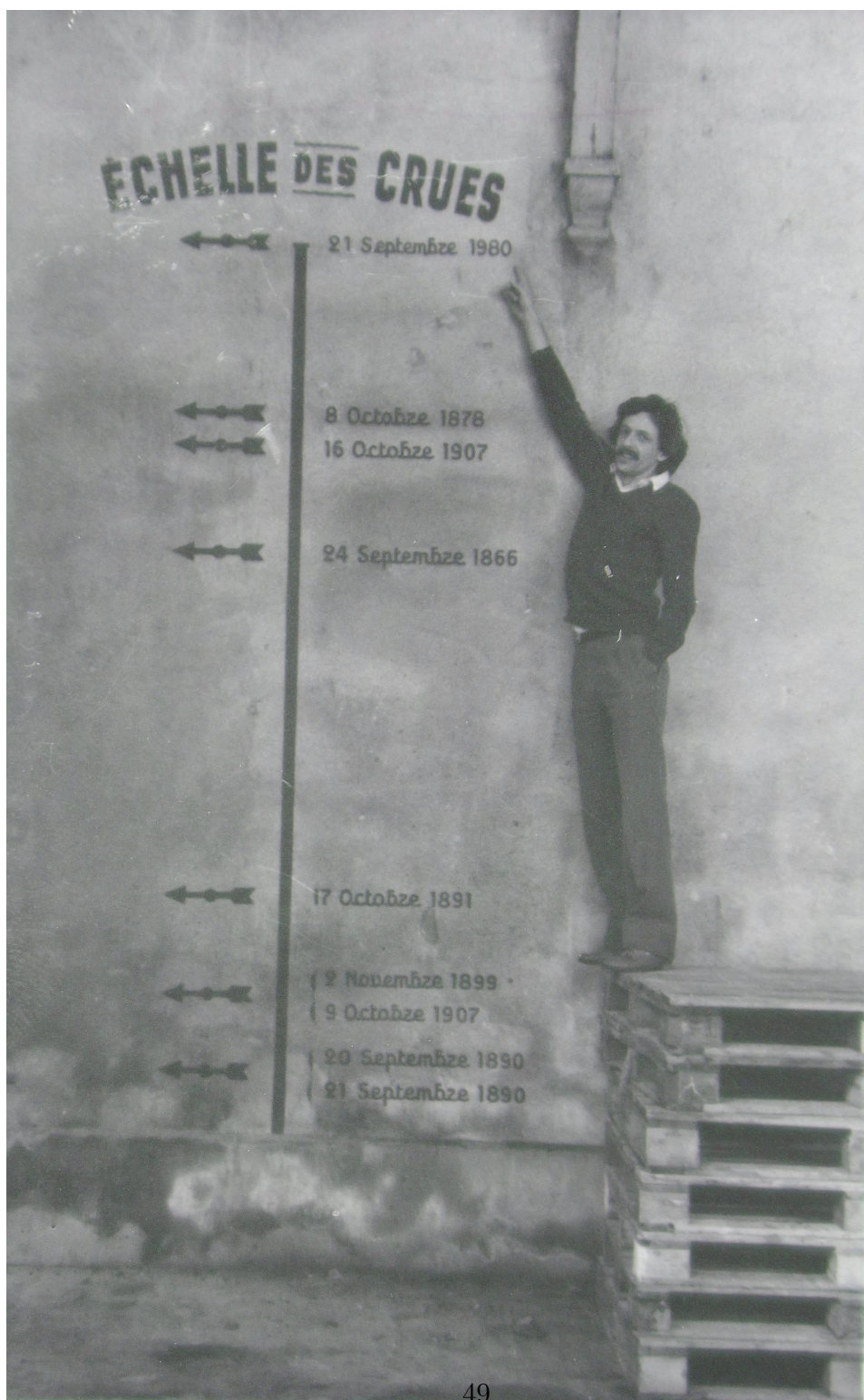


Figure 1: Flood marks on the Loire river at Puy-en-Velay (France).

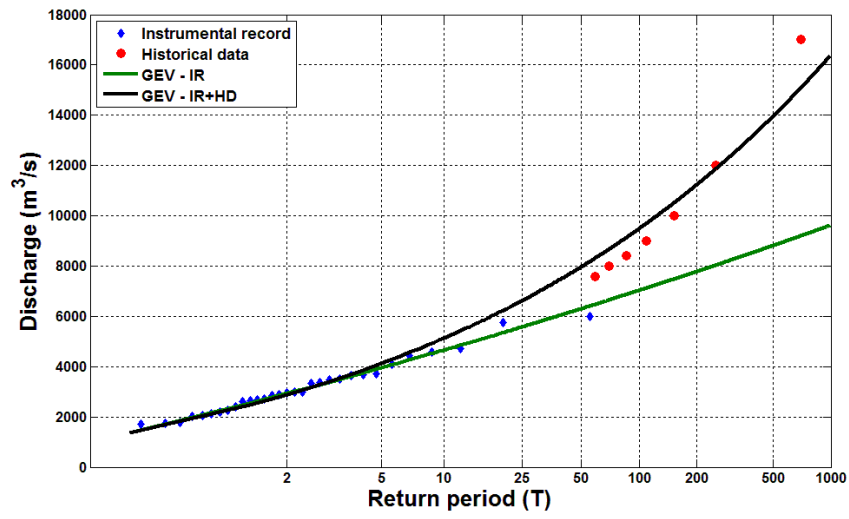


Figure 2: Improvement of the frequency curve estimation by the use of instrumental record (IR) and historical data (HD) available at the Tortosa gauging station in Spain.

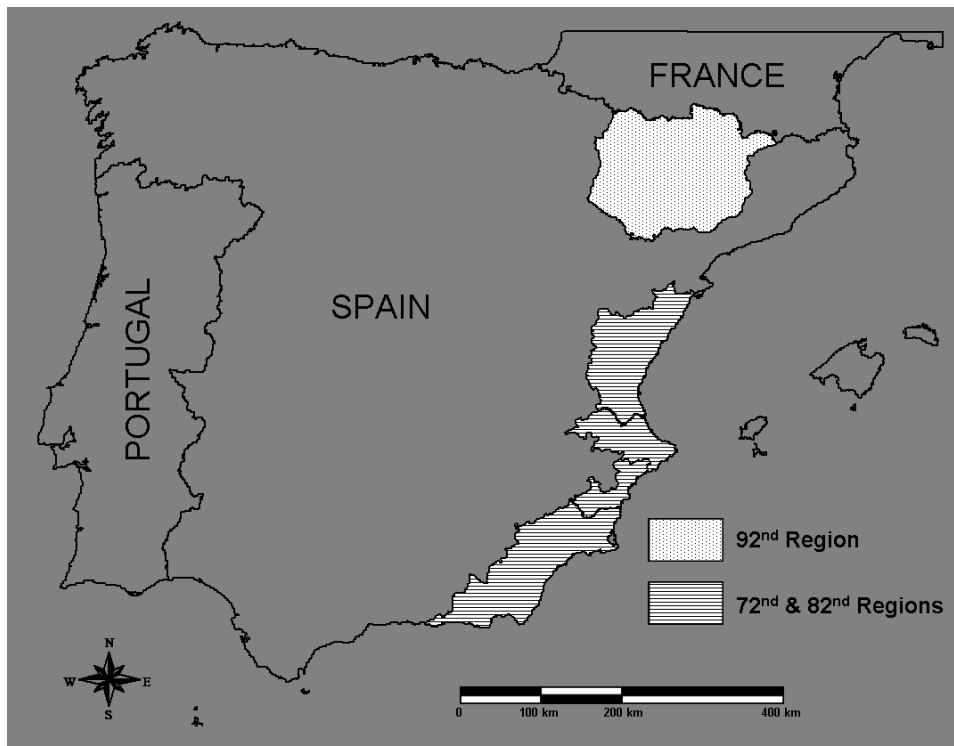


Figure 3: Location of regions in Spain where historical information was used for improving the estimation of the frequency curve.