## Cover letter for editor

Prague, July 20, 2015

Dear Professor Blöschl,

I would like to submit a revised version of my manuscript. I have taken into account all comments and suggestions of all three reviewers as well as your comments and suggestions.

I included the required information both on the data available for pre-instrumental and early instrumental period (1118–1824) and my results in a summarizing table with explanatory notes in a Supplement of my manuscript. It was rather complicated to include all information in one table and so I hope that you will find the result satisfactory.

I have included the explanation on possible ice jamming in Prague and commented in more detail a Central European flood reconstruction. I also revised the bibliography.

I hope that you will find the revised version acceptable for publishing in the HESS journal.

Kind regards, Libor Elleder

**List of changes in revised manuscript:**

- Inclusion of the Supplement
- Explanation of ice jamming in Prague
- Explanation regarding the problem of using the Prague profile for estimation Central European floods
- Explanation of reliability of documentary sources
- Introduction of the new term “Historical Urbanization Stage” (HUS) instead of “Period” to avoid the confusion with “Flood Rich Period”
- Revision of bibliography
- Revision of English by native speaker

***Response to Reviewer I. prof. Jürgen Herget***

JH: Flood frequency analysis (FFA) is a challenge for limited data sets, especially if one cannot be sure that the data set is complete (note, e.g. your comment about probably missing floods of minor magnitude page 1639 line 20 (= 1639-20). This problem should be explained in the beginning, reference to appropriate publications given (e.g. Stedinger, J. R., and Cohn, T. A., 1986, Flood frequency analysis with historical and paleoflood information. : Water Resources Research, v. 22, no. 5, p. 785-793. ——— Stedinger, J. R., R.M., V., and Foufoula-Georgiou, E., 1993, Frequency Analysis of Extreme Events, in Maidment, D. R., ed., Handbook of Hydrology: New York, McGraw-Hill.) and reasons explained why you have chosen your approach and what are benefits of it. It might be useful to give reference to previous publications on the topic as other approaches were applied (e.g. Glaser, R. et al., 2010a, The variability of European floods since AD 1500: Climatic Change, v. 101, no. 1-2, p. 235-256. ———— Mudelsee, M. et al., 2003, No upward trends in the occurrence of extreme floods in central Europe: Nature, v. 425, no. 6954, p. 166-169).

***Response:***

***The remark was accounted for, see line 24-26 with references. I also mentioned other authors, such as Macdonald (2006) and Bayliss and Reed (2001) referring to more detailed methodological remarks and examples focused on practical hydrological tasks (lines 39-40).***

JH: 1644-26: How can you make a conclusion for "Central Europe considered as a whole" if you only analyse data from Czech Republic? It might be useful to consider also previous studies on the topic and related your finding in detail (!) to what was found before (e.g. by Glaser, R. et al., 2010a, respectively Mudelsee, M. et al., 2003 – references like above)

***Response:***

***Though CEF, WCEF are not the main topic of my study, I believe, it is necessary to put every reconstructed flood event to the broader context, if possible. My idea was to point out that some of the Prague floods were part of more extensive floods striking synchronically major parts of Europe. My formulation in earlier version of the manuscript was unclear, obviously. It is corrected now. Specification of European framework of each flood (e.g. CEF, WCEF) was carried out based on references (starting from line 216). In lines 235–236 comparison of extreme flood water levels in 4 European cities is mentioned by Elleder (2010a), which is an objective criterion for identification of the 1651, 1658, 1740, 1784, and***

***1799 floods as WCEF. Other evidences based on Kiss (2011) for rivers in Hungary, Deutsch and Portge (2003) for the Saale, Herget and Meurs (2010) for the Rhine, Pekárová (2011) for Slovakia, Girgus and Strupczewski (1965) for some Oder tributaries. The above evidences were suplemented by flood marks (Libor Elleder´s personal database of European flood marks including currently ca 300 sites in Germany, Poland, France, UK, Switzerland and Italy). I believe that every old floodmark represents at least $Q_{10}$.***

JH: After reading the manuscript, I am a little bit confused about a definite calculation of frequencies or finding clusters of increased numbers of handed-down flood events. You mention periods (periods of homogenous topography in Prague and periods of increased flood events 1640-40) and calculate numbers of floods per century (1639-22). I assume not being the only one who gets confused.

***<u>Response</u>:***

***To avoid the confusion, I have newly introduced a term "historical urbanization stage" (HUS) for periods of more or less homogenous topography instead of period. So newly -– in the revised version of the manuscript - I refer to HUS1–HUS6 instead of P1–P6. Moreover, I added the required supplement presenting estimated Q peaks >=$Q_2$ during the period of 1118–1824.***

JH: In your publication (Elleder et al. 2013), no data table is listed. To give some impression of the data (in addition to the marks in your Fig. 3 in this manuscript) before starting an FFA on its base, please check if a data table is useful (e.g. as online-supplement for this manuscript). Make sure to differ for the origin of the data (previous publication /added on "acceptable level of reliability" (1638-1) in this manuscript) and give data on the date, reason, water level and estimated peak discharge.

**<u>Response</u>:**

***I have added the supplement with time (year, month, day in Gregorian calendar), reason, or more exactly approach for estimation based on water level indicator (description of flooded area by flooding important churches, buildings, squares, etc.), impact indicator (stopping of watermills operating, damages on buildings, mills, bridge, etc.), estimated water level and discharge. The reliability of information about the flood in Prague is expressed by documented synchronised flood on the Elbe in Dresden, in broader context by CEF, WCEF. In addition, the supplement presents authenticity of documentary source***

***(primary, secondary), and geographical accuracy of description (i.e. if the flood really occurred in Prague). Supplement presents the data from 1118–1824. The primary data from later period, after 1824, are the property of the Czech Hydrometeorological Institute and are not "per se" available for publication. I believe it is adequate for the purpose of this paper.***

JH: Technical corrections:

The structure of the manuscript might benefit of some modifications as origin of data is mentioned in the chapter of the explanation of the applied method or abbreviations are explained in details after their first use. Some details are listed below:

Chapter 2.2.: Can you find e.g. names for the periods P1-P7 (or find another term than "period") to avoid confusion with your flood rich periods FRP, which in the text are called "periods", too?

***Response:***

***It was done, explanation on AMF and POT are in lines 168–169 before the first use. The HUS abbreviation is explained above.***

JH :1638-1: what level of reliability is acceptable for you to consider the handed-down water level for further analysis (I know, hard to say in general, but please give some impression about your criteria like probably: "uncertainty of water level with in few centimetres, definitely less than ....").

***Response:***

***I preferred the primary sources, explicitly expressing that the flood event occurred in Prague, and for which the ranking of water level was possible (detailed explanation by Bayllis and Reed (2001).***

***I believe that during the flood event the maximum uncertainty was within 10 cm – this holds for the Vltava River in Prague nowadays. According to the rating curve in Prague, 10 cm of height corresponds to 60–100 $m^3.s^{-1}$. Regarding the water levels, my estimation was within 10 cm, regarding the discharges my estimation was within 200 $m^3.s^{-1}$.***

JH: 1638-10: please make sure, that no ice-jam ponded waterlevels are considered as regular discharge in your data set (e.g. Feb./ Mar. 1784).

***Response:***

***I believe it is a very important point and a reason for reconstruction of floods and their hydrographs (Elleder, 2010a). It is a basic information to differ between impact of ice-jamming and discharge floods. It is explained in detail in lines 142–156.***

1638-21: please explain the filling of missing values, was it extrapolation between two known datapoints? Probably a graphical illustration for which event data could be added could be useful (e.g. somehow a modification of your Fig. 3; cf. Further comments on this figure below)

***Response:***

***I filled the missing values based on a proximate sum of discharges from the Upper Vltava River and its tributaries (e.g. the Berounka River, the Sázava River), if these values were estimated based on the same methodology as in Prague. A regression equation (e.g. Elleder et al., 2013, Fig. 6) was applied. The problem is explained in lines 157–165.***

1638-26: What is the "B set" of Brazdil et al. 2005?

***Response:***

***B set is a set of 159 flood events published by Brázdil et al. (2005). This was a basic set of flood cases for estimations of water stages and discharges (line 65).***

1639-4f: please introduce abbreviations like AMF and POT before the first use (hence, move this paragraph towards somewhere above -POTQ10 mentioned already at 1638-11 without explanation)

***Response:***

***I did that.***

1639-12f: description of considered data again - move into previous chapter on data.

1644-5f: this is a conclusion - move into the following chapter

***Response:***

***I did that.***

1644-20: about the current period: how can you be sure that it is already terminated? Consequently, a mean frequency of floods cannot be determined!?

***Response:***

***I did not mean it is terminated, the end is opened. I just wanted to indicate that currently we are probably in a period with high frequency of floods. But the end is opened.***

Fig. 3: please spread the figure on twice its recent width and please explain:

# the different colours for different periods

# difference between bold and regular flood event labels

# avoid vertical accumulation of flood labels as they cannot be identified # FR1

might FRP1 - when does each period begin respectively end?

***Response:***

***Rankin of periods is solved by adding the supplement. I believe the different colour for each period would be a technical problem. I included the FRP and explanation of "bold" floods.***

As I am not a native speaker, I do not comment on phrases or expressions sounding

slightly strange to me - I suggest to ask a native speaker for some improvements on the

language after modifications of the content.

***Response:***

***A native speaker corrected my English for grammar and style.***

***Response to Reviewer III. Marian Melo***

MM:

Specific comments and technical corrections:

The number of flood events, with which the author has worked, is high. However, this number varies in various parts of the article: on p. 1639 he mentions some 350peak discharges in 306 years; on p. 1639 the author states that the time-series ofmeasured peak discharges from 1825-1954 for Prague available Novotny (1960) was extrapolated by 187 flood events for the pre-instrumental period using the documentary data, on p. 1636 he writes that Novotny (1963) presented 121 peak discharges over 1825-1953 period; on p. 1634 (in Abstract) he states that 187 flood peak discharges derived for the pre-instrumental period (1118-1824) augmented 150 records for the instrumental period of 1825-2013; in citing Brázdil (2005) on

p. 1635 (in Methods), 159 peak discharge records are mentioned from the period of 1118-1825; These numbers do not match the total number of floods (more than Q2) reported in Figure 2 (p. 1651), where a total of 163 of them are shown for the entire period (12th - 21st century). This discrepancy in the overall numbers of floods is not entirely clear to me. Similar

situation exists with the second selected criterion AMF (a total of 306 years with floods are mentioned on p. 1639, while on p. 1640 those are about 300 AMF).

***Response:***

***The basis for my analysis was the data set from 1118–1825 covering the entire Vltava River Catchment, marked as "B set" (Brázdil et al., 2005), which included 161 flood events. For Prague, I added some events to this basic set based on deduction from other parts of the Vltava River catchment, and some floods, in contrast, were deleted from the set as they were not relevant for Prague. Further, for the FFA I used the set of 176 estimated discharges=>Q2, 126 from these for 1118–1824 are presented in supplement.***

MM: The explanation of Qk abbreviation on y-axis, which can be seen in Figure 3 (p. 1652), is missing in the text. What discharge (Qk) does the author mean? I also propose to¨specify the title of this figure.

***Response:***

***I replaced it by Q (flood discharge). The title of Fig. 3 was specified.***

What does "B set" abbreviation mean in the text on p. 1638? (Brázdil set?)

***Response:***

***B set means Brázdil set published by Brázdil et al. (2005)*. Please, see the explanation above.**

MM: What is not entirely clear to me is the criterion for delineation of two sub-periods FRP4a, 4b (respectively FRP5a, 5b)? Is this to preserve a uniform period of about 30 to 40 years? In my opinion, based on Figure 3 (p. 1652) this could involve one longer period FRP4 (respectively FRP5).

***Response:***

***Regarding the FRP4 and FRP5. For FRP4 and 5 I considered suitable to delineate the two sub-periods as they differed in the flood character. I explained it in lines 207–211.***

MM: Regarding the seasonality of floods, I was surprised to see that the winter floods do not play a more dominant role on the Vltava River in Prague. Given that there are not many references in the text to the change in the seasonality of floods, I would recommend leaving out this word (seasonality) in the title of the article.

***Response:***

***I have deleted the word "seasonality" from the title. For the Vltava River, extreme floods prevail truly in summer, particularly in August.***

MM: 25 sources are found mentioned in the text, which are missing in the list of literature (references) on pp. 1645-1647. Those are the following citations: Hladny et al., 2005, Elleder 2013, Novotny 1963, Novotny 1960, Richter 1892, Kašpárek et al. 2005, Hladny et al. 2005, Hladny 2005, Danhelka 2012, Elleder and Kotyza 2007, Elleder et al. 2014, Munzar et al. 2014, Munzar 2000, Kakos and Kulasová 1895, Elleder et al. 2012a, Elleder et al. 2012b, Kakos 1990, Hrdlicka 2001, Elleder 2012, Fritsch 1850, Gyrgus and Strupczewski 1965, Böhm and Wetzel 2009, Böhm et al. 2014, Glasser et al. 2008, Rohr 2007. On the other hand, certain sources are mentioned in the list of literature, yet they are not cited in the text (Brázdil et al. 1999, Hladny 1998, Roggenkamp and Herget 2014). With some sources, the year of publication or composite authors differ in the text and in the list (Elleder 2004 on p. 1636 and Elleder 2003 on p. 1645, Fügner 2006 on p. 1635 and Fügner 2007 on p. 1646, Herget 2010 on p. 1640 and Herget and Meurs 2010 on p. 1646, Schmocker-Fackel and Naef 2009 on p. 1642 and Schmocker-Fackel and Naef 2010 on p. 1647).

***Response:***

***I corrected the references. I excluded some references in Czech.***

MM: With the flood of 1658 (on p. 1641), Dresden should be referred to under CEF acronym (not WCEF) based on the definitions of these areas (on pp. 1640 and 1641).

***Response:***

***The explanation is in lines 240–241.***

In my opinion, the abbreviations (SM), (A), (V), (L), (Ag), (N), (OS) are needless in Table 2 (p. 1649), if there is no more mention of them in the text or in the figures.

***Response:***

***The abbreviations are needed in a newly added Supplement.***

MM: I would also suggest comparing the time occurrence of historic floods on the Vltava River with the regions to the east of the Vltava basin (or to the east of the Czech Republic), as it might be possible to establish a possible correlation with this region. Although the reason for this absence is probably the fact that such studies are (so far) largely missing. The exception being the studies by, for instance, Kiss (2011) who studied the floods on the territory of the former medieval Hungary (until 1500) and by Pekárová (2011) who studied the past floods on the territory of the present day Slovakia. For instance, Kiss (2011) mentions the winter flood of 1374 and the winter flood of 1367 in Transylvania; Pekárová (2011) mentions the flood of 1568 in the Hornád River basin and in 1899 on the Hron River. According to my own records, there is a record on the great flood of 1675 on the Váh River in Opatová (Slovakia) although the author states about this particular year (p. 1641) that, except for the Czech lands, this summer flood has not been mentioned anywhere else. Recommended references: Kiss, A. (2011): Floods and long-term water-level changes in medieval Hungary. Doctoral dissertation. Central European University Budapest, Hungary, 323 pp. http://www.etd.ceu.hu/2011/mphkis22.pdf Pekárová, P., Škoda, P., Majercáková, O., Miklánek, P. (2011): Important floods of the past on the territory of Slovakia. Acta Hydrologica Slovaca, 12, 1, 65-73 (in Slovak with English summary). http://www.ih.savba.sk/ah/

***Response:***

***I used these references in lines 221–224.***

***Response to Reviewer II. anonymous***

A: Specific comments: Page 1640, line 25. River "Innn" by River "Inn"

***Response:***

***Corrected.***

A: General comments: I center my comments on chapter 2, after extense and complete review already available in HESSD of Prof. Herget. This chapter for me is very important. Definition as "Methodology" it seems short, and it could be completed because other aspects are also included. Or other option is definition of chapter as "Methodologies".

In this chapter, autor show how arrive historical information from different sources and it is analyzed and converted in modern data of hydraulic fieldwork (peak discharges, return period definitions...).

Description of process is enoughly clear but, in order to help other groups involved in similar processes, I would thank an effort to introduce informative tables and any figure to show exemple about process. One table with basic characteristics of every flood event would be very illustrative. May be in one annex? Information as bibliographical source, main documentary sources used, detailed dates of events, classification or flood type, peak discharge reconstructed...

***Response:***

***I added the supplement with detailed data (please, find more detailed explanation in supplement or above in answer on estimated discharge and water level to reviewer I.-prof. Herget. I added table 2 with explanation of water levels and impacts (warnings - flood protection, stopping some activities, damages, etc.). I believe that the added supplement and table 2 brought important improvement of methodology explanation as required. Moreover, I added remarks on hydrological balance (lines 85–87), explanation on behaviour of floodplain in Prague (lines 139–141). Further, I included an explanation for supporting profiles (lines 157–163). More explanation is in the Supplement, linked to the picture of Bearded man published earlier by Elleder et al. (2013).***

Any figure describing main bed river section of Prague would be very well received to illustrate"environment" of research and obtained results.

***Response:***

***This figure and detailed description of changes in river bed was published earlier (please, see Elleder et al., 2013). It was stressed in the revised version in lines 124–125.***

# Historical changes in frequency of extreme floods in Prague

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## Abstract

This study presents a flood frequency analysis for the Vltava River catchment using a major profile in Prague. The estimates of peak discharges for the pre-instrumental period of 1118–1824 based on documentary sources were carried out using different approaches. 187 flood peak discharges derived for the pre-instrumental period augmented 150 records for the instrumental period of 1825–2013. Flood selection was based on $Q_{10}$ criteria. Six flood-rich periods in total were identified for 1118–2013. Results of this study correspond with similar studies published earlier for some Central European catchments, except for the period around 1750. Presented results indicate that the territory of the present Czech Republic might have experienced in the past, extreme floods comparable, with regard to peak discharge (higher than or equal to $Q_{10}$) and frequency, to the flood events recorded recently.

## 1 Introduction

Research of historic floods significantly enhances our ability to better understand the behaviour of recent flood events in the context of global environmental change. Numerous studies have focused on this issue in last two decades (e.g., Brázdil et al., 2006b; Glaser et al., 2010). The augmentation of systematic hydrological series by interpreted historic records to provide a better and more accurate estimation of hydrological parameters is an important task. Flood frequency analysis (FFA) appears to be a real challenge, particularly for limited data sets as indicated for example by Mudelsee et al. (2003) and Stedinger and Cohn (1986). In this study, the estimated flood discharges are used for identification of flood rich periods.

In the Czech Republic, four extreme summer floods were recorded within the last 15 years (1997, 2002, 2010, and 2013). Two of these were classified as 500-year or even 1000-year events (Blöschl et al., 2013; Hladný et al., 2004); two out of the four stroke the Vltava River catchment. Taking into account the entire region of Central Europe, further extreme summer floods can be added: in the Alps in 2005, and in Slovakia and Poland in 2010. An interesting question thus emerges as to whether there is an analogy with a similar frequency of important or extreme floods in the past. The aim of this contribution is to answer two scientific questions: 1. Has the territory of the present Czech Republic experienced four summer extreme flood events within a mere 15 year period earlier in history? 2. Did the region of Central Europe record extreme large-scale floods during the last 500 years more often when compared to the present? Methodical approach used in this study was inspired by Bayliss and Reed (2001) and Macdonald (2006).

Prague is, with respect to floods, a key point for Central Europe. It represents a closing profile of the Vltava River, the most important tributary of the Elbe River. As compared to other major Elbe tributaries, such as the Saale, Spree, and the Elster, with respect to the catchment area, average discharge and $Q_{100}$, the Vltava River can be regarded as the most significant one. According to the above criteria, the Vltava River is even more significant as compared to the upper part of the Elbe River, where it flows to, 40 km downstream of Prague, at the town of Mělník. $Q_{100}$ values of the Otava and Berounka Rivers, the most important tributaries of the Vltava River, correspond merely to the $Q_2$– $Q_5$ level (Table 1). Interestingly, this also applies for the Elbe River prior to the confluence with the Vltava River, which implies that the Elbe River is a tributary of the Vltava River rather than the other way around (Table 1). These facts are absolutely essential for the examination of historical floods. According to the facts above, the Vltava River floods significantly influence the Elbe River floods, at least up to Torgau (before confluence with the Mulde and Saale River and Magdeburg) in Germany. There is a strong association between the peak discharges in Prague and the Elbe profiles in Northern Bohemia, and in Saxony – Pirna, Dresden, and Meissen (Elleder et al., 2013). A crucial issue for the presented study is that the flood marks and records of historic floods (Fig. 1) going back to 1432 are available for these sites (Brázdil et al., 2005; Fügner, 2007). In this study, Prague represents the major profile, while other profiles were used to supplement it, and for verification of the final estimates.

# 2 Methods

## 2.1 Input data

For the Vltava River catchment, 161 flood cases for the period between 1118 and 1824, when the regular daily water level measurements began, are available in (Brázdil et al., 2005, denoted as set B further in this study.

The most reliable 18 cases, associated with summer floods, are related to the flood marks and original Prague water gauge denoted as "the Bearded Man" used since 1481 (Elleder, 2003).

Novotný (1963) presented an additional 121 peak discharges (1825–1953) for the period before the Vltava River Cascade construction. The peak discharges from 1825 to 1880 were assessed earlier, with an assumption of the 1880–1890 rating curve validity (Richter, 1893). Water levels and peak discharges for Prague after 1954 are in the Czech Hydrometeorological Institute database, concurrently in simulation without the influence of the Vltava River dams (Hladný et al., 2004). The 2012 flood, with peak discharge of 5 160 $m^3.s^{-1}$, is the most important case over the instrumental period (Hladný et al., 2004). Interestingly, the flood of July 1432 was likely even more important (Elleder, 2010b). For other significant historic floods – bigger than $Q_{50}$ – in the Vltava River catchment, Brázdil et al. (2005) published brief descriptions. Detailed papers on Czech floods, though most of them only in Czech, were published. These available in English are only for the 1432 flood (Brázdil et al., 2006a), 1784 flood (Munzar et al., 2005), and 1830 (Munzar, 2000). Regretfully, the extreme flood cases, such as 1501, 1655, 1675, 1682, 1712, 1736, 1771, 1799, and 1824, have not been evaluated so far. For archiving of documentary sources related to floods over the Czech territory, the author has been developing a private relation database system "Krolmus" since 2000.

## 2.2 Major Vltava River profile in Prague, its changes over time and estimation of maximum water levels

Regarding the specific conditions of the Vltava River catchment, particularly in Prague, it was advantageous to use the estimated peak discharges. This approach enabled the author to use simple hydrological balance for filling and checking the final dataset.

The major Vltava River profile for Prague until 1824 was the monastery of the Knights with Red Star past the Charles Bridge; after 1825 with the beginning of the systematic water level measurements it was the Old Town Mills profile before the Charles Bridge. The overview of most important changes of floodplain and documentary sources available was presented by Elleder et al. (2013). The entire period under review, 1118–2013, has been divided into seven periods of more or less homogenous topography, with respect both to the reliability of input data and changes in the area near the major profile (Historical Urbanization Stage, HUS further in the text). The least reliable data are these relating to 1118–1350 (HUS1). After the construction of the new town walls (1250–1300) and reconstruction of the city, the Old Town terrain was more or less stabilized (Hrdlička, 2000). In 1351–1480 (HUS2) some floods are recorded as related to important town buildings (Table 2. During this period, the number and height of Prague weirs were fixed. In 1481–1780 (HUS3) the records of water levels are available. Since 1481 these are related to the "Bearded Man" water gauge (Elleder, 2003, 2010b, 2013). Since 1501 flood marks started to appear, but those from 1501 and 1655 were destroyed, and currently flood marks since 1675 are preserved (Brázdil et al., 2005). Changes between the 16$^{th}$ and the mid19$^{th}$ century were minor (Elleder et al., 2013). The first modern water gauge in Prague was set up in 1781 (Brázdil et al., 2005; Elleder, 2010b). Systematic records date back to 1825. The next 60-year period of 1781–1843 (HUS4) until the construction of the Vltava River embankment is used for calibration of the relation between measured water stages during flood events and flood impacts, such as the flooded area (Elleder, 2010b). For similar relations applicable for the HUS3 period it is possible to derive for flood damages and the Vltava River behaviour during ice-jamming. For the next period of 1844–1904 (HUS5), when the Vltava River embankment construction was undertaken, a rating curve is available. In 1904–1926 (HUS6a) the inundated area of the Old Town was raised to the embankment. In the next period 1927–1953 (HUS6b) no major changes occurred until construction of the Vltava River cascade dam. Construction of the Vltava River dam cascade in 1954–1961 resulted in a crucial change of the hydrological regime (Kašpárek and Bušek, 1990). The current period 1954–2013 (HUS7) has been affected by implementation of the cascade. Until mobile dikes were put into operation (2000–2013), no major changes were undertaken in Prague.

## 2.3 Peak discharge estimates based on hydraulic calculation

Reliable records of 18 summer floods from 1481–1825 were assessed using a hydraulic approach, similar to that applied by Herget and Meurs. (2010) for German Cologne. Herget et al. (2014) recommended support of the hydraulic approach with detailed knowledge of river cross-section and flood plain, and use of the Manning equation (Chow, 1959). The results of this approach for Prague including detailed information on cross-section of chosen Vltava profile were published earlier by Elleder et al. (2013). This evaluation, however, did not include winter floods, or flood events with less reliable or roughly estimated water level records. The objective of this study was the utilization of most of the data with an acceptable level of reliability for flood seasonality analysis. Some 90% of all data (B set) from the pre-instrumental period met the reliability or authenticity criteria according to Bayllis and Reed (2001). This applies mostly for evidence of major floods equal or higher to $Q_{50}$ (before 1481) and $Q_{10}$ (starting from 1481).

## 2.4 Rating curves, ice jamming and other interpreted data from supporting profiles

Relations between water stage or peak discharge and impacts relevant for HUS5 and HUS6 periods (Elleder, 2010b) were applied for the interpretation of historic floods. The rating curve for 1880–1890 (Richter, 1893) was used for HUS3 floods - events with a fairly reliably documented water level. The map presenting isolines for different water levels in Prague (Elleder, 2010a) was used for interpretation of flooding of different sites or buildings in floodplain of Prague.

For winter floods, a problematic association between water level and discharge due to ice jamming is to be accounted for. It is necessary to distinguish between the flood caused by ice jam making a barrier, and the flood caused by increase of discharge (Beltaos, 2008). No case, nevertheless, with a higher water level due to ice jamming, as compared to subsequent water level due to flood discharge, is known for Prague. For discharge higher than or equal to $Q_{10}$, the discharge was always sufficient for an ice barrier release. This holds for the 1784 February flood (Elleder, 2010a), and also for all recorded winter floods during 1800–1850 (Fritsch, 1851). It is evident from the reconstructed hydrographs for winter floods in 1830, 1845, 1862, 1876 (Elleder, 2010a, b). Water levels resulting from ice jam reached merely 100–250 cm in contrast to subsequent discharge floods with recorded water levels of 350–550 cm. It is particularly true for the Prague profile, but does not hold, in any case, for supporting profiles in Děčín, Dresden, and Meissen. The only exceptions might have been during HUS1 and HUS2 due to different conditions before Charles bridge construction. As an example, the February 1342 flood which destroyed former and smaller Judith bridge across the Vltava River can be mentioned.

Supporting profiles in the upper Vltava River (České Budějovice, Beroun, Písek) as mentioned for example by Elleder (2008) were used for providing a balance of estimated discharges in the upper Vltava River, while supporting profiles downstream (Litoměřice, Děčín, Pirna, Dresden, Meissen) were used for regression estimates published earlier by Elleder et al. (2013). This approach enabled the checking and specification of not only estimated discharges, but also the time of flooding in Prague. In some cases, this approach facilitated even the filling in of the missing values as for example for 1434, 1531, 1775.

The credibility of discharges estimated by this approach above is undoubtedly lower than discharges derived from authentic description and records of flood in Prague.

## 2.5 Selection of floods

In the framework of the analysis, two approaches are to be distinguished: Annual Maximum Flood (AMF further in the text), and Peaks over Threshold (POT further in the text) approach.

The original B set including 161 recorded Vltava floods was this augmented by 23 flood events. The results of my hydrological interpretation of the augmented B set are presented for all floods during 1118–2013 (Fig. 2). For further FFA only values higher or equal to $Q_2$ were considered. The floods lower than $Q_2$, recorded mostly for the Vltava River in České Budějovice, without other supporting material for other tributaries were excluded. Final set for FFA included 176 flood events (123 events before 1825). The entire historical set (1118–1824) including detailed information was presented earlier by Elleder (2010b).

Set of estimated maximal water levels and peak discharges (equal or greater then $Q_2$) including POTQ10 for pre-instrumental and early instrumental period 1118–1824 is presented in Supplement.

A perception threshold for recognising an event as a flood, and for drawing a flood mark, a discharge around $Q_{10}$ (Table 1) was generally accepted in Prague until 1781 (Table 2, 3). That is the reason for establishing $Q_{10}$ as a threshold for denoting the real extreme flood events, and the selection of such events is labelled $POTQ_{10}$.

## 3 Results and discussion

### 3.1 Frequency of floods over the centuries

Fig. 2 summarizes the frequency of floods over the centuries. The high variability in $Q_2$ flood events most likely does not reflect the reality - rather it is a consequence of the fact that many of these "unimportant" floods were not recorded in the 12th–18th centuries. Considerable equilibrium is obvious in $POTQ_{10}$ before 1500 (17 events in total, which means 4 events per century, on average), and after 1500 (55 events in total, that means 11 events per century, on average). This set is representative for the period after 1500 at least, when $POTQ_{10}$ can be considered a good approximation of the real count of floods. The highest occurrence of $POTQ_{10}$ flood events was recorded in the 16th century (16 events), and in the 19th century (15 events). The 17th and 18th centuries can be reckoned as average centuries, with 10, and 9 flood events, respectively. Interestingly, a low number of flood events was recorded in the 20th century (4 flood events). In contrast, the high frequency of floods is striking in the 14th century, when some 6 cases might have reached $Q_{50}$ level. Flood frequency is obviously low in the 21st century with respect to the number of years. It is notable, however, that we have already seen three $POTQ_{10}$ floods within 13 years, one in four years on average.

### 3.2 Periods with high flood frequency within European context

Fig. 3 presents an overview of about 300 maximal annual peak discharges (AMF, according Elleder, 2010b). For more accurate identification of periods with high flood frequencies, a 31-year running sum was used. The exceedance of $POTQ_{10}$ defines flood-rich periods (FRP, further in the text). Six periods FRP1–6 with two sub-periods (FRP4a, b and FRP5a, b), with minimal overlap with respect to $Q_{50}$–$Q_{500}$ occurrence, were identified in total. It was suitable to delineate the two sub-periods as they differed in the flood character. 1780s (FRP4a) were specific for major winter flood events and impact of Laki eruptions in 1783–1785. The FRP4b sub-period was in contrast characterised by significant drought (1811, 1823) and major summer floods (1804 and 1824). Similar reasons hold for FRP5, in which summer floods clearly prevail in FRP4b.

Some significant floods in HUS1 (1118, 1272, 1273), and HUS2 (1432) are not included in the above periods. This fact is most likely a consequence of the lack of documentary sources for HUS1 and HUS2 periods. It holds, however, also for the beginning of the HUS3 period with the extreme flood of 1501.

Some of the POTQ10 floods recorded in the Vltava River in Prague were part of more extensive events affecting a major part of Central Europe as well. If at least two or three major catchments out of five (the Elbe, Danube, Oder, Wesser, Warta) were simultaneously stroke, these events can be labelled as Central European Floods (CEF, further in the text). An example of such a CEF is the 1374 flood (FRP1), which is recorded, apart from the Vltava River, also in the Saale catchment (Deutsch and Portge, 2003), Danube catchment (Kiss, 2011) and the Rhine catchment (Herget, 2010). More additional information is needed to winter flood 1367 in Transylvania (Kiss, 2011) or in the Hornád River basin in 1568 (Pekárová, 2011). Synchronic winter floods (1655, 1682, 1784, 1799, 1862, 1876) were recorded by flood mark on the Main (Eibelstadt, Frankfurt am Main, etc.), the Danube (1682, 1784, 1799, 1830, 1862), and the Rhine (1651, 1784, 1799). For summer floods, an association with the Danube and Oder catchments is more common. Frequently, the Alpine tributaries of the Danube – the Inn, Enns, Traun – or the Danube itself between Passau and Vienna (1501, 1569, 1598, 1890, 2002, 2013) are involved. Flood marks of these are found at numerous sites (Linz, Schärding, Burghausen, Steyer). Synchronic floods with the Vltava River for some Oder tributaries (Nysa Łużycka [Lausitzer Neiße], Kwisa, Bóbr, Kaczawa, and Nysa Klodzka) for 1359, 1387, 1432, 1501, 1563, 1564, 1567, 1569 are presented by Girgus and Strupczewski (1965).

In cases when other catchments (the Seine, Loire, Maas) were also affected, the acronym WCEF (West-Central European flood) is used. These are, for example, 1651, 1658, 1740, 1784, and 1799 winter floods, as commented in detail earlier by Elleder (2010a) for Cologne, Dresden, Paris, and Vienna.

The overview of the identified periods with high flood frequencies with relevant flood events is presented below:

**Period FRP1 (1350–1390), [7 flood events/40 years]**

It includes summer floods of 1359 (CEF), 1370, and 1387 (CEF) and winter floods of 1367, 1370, 1373, and 1374 (CEF).

**Period FRP2 (1560–1600), [12 flood events /40 years]**

Summer floods prevail in 1564, 1568, 1569 (CEF), 1575, 1582, 1587, and 1598 (CEF). Winter floods in 1570, and 1595 (CEF).

**Period FRP3 (1650–1685), [6 flood events/35 years]**

Winter floods prevail in 1651 (WCEF), 1655 (CEF), and 1682 (CEF). Flood in 1658 (WCEF) was recorded for Dresden and Paris (Elleder, 2010a). It is unclear, however, if the high peak discharge was not due to ice jamming. Summer floods in 1651 and 1675 have not been mentioned so far outside of the Czech lands

**Period FRP4a (1770–1800), [6 flood events/35 years]**

Winter floods prevail in 1770, 1771, 1782, 1784 (WCEF), 1785 (CEF), 1799 (WCEF).

**Period FRP4b (1804–1830), [6 flood events/30 years]**

Winter floods in 1809, 1810, 1827, 1830 (CEF), and summer floods in 1804, and 1824

**Period FRP5a (1845–1880). [5 flood events/35 years]**

Winter floods prevail in 1845 (CEF), 1862 (CEF), 1865, and 1876 (CEF). Summer flood of 1872 was a flash flood with extreme intensity. This flood is related to the floods on the upper Rhine and Po tributaries. This period includes a catastrophic flood on the Elbe River in February 1846, and a no less deleterious flood in August 1858.

**Period FRP5b (1880–1920), [6 flood events/40 years]**

Summer floods dominate in 1890 (CEF), 1896, and 1915. In the Czech lands, there were simultaneous catastrophic floods, particularly in the Elbe catchment, in August and September 1888, 1897 (CEF), and 1899 (CEF), that reached a mere $Q_5$ in the Vltava River, however. Winter floods in 1882 (CEF), 1900 and 1920 (CEF).

**Period FRP6 (1994-?) [3 flood events/14 years]**

So far summer floods have prevailed in 2002 (CEF), and 2013 (CEF), after simulation (removing of the Vltava dam cascade influence), also the 2006 flood can be included (http://voda.chmi.cz/pov13/DilciZprava_DU_3_1_cast1-VyznamnaVD-final.pdf).

The flood periods identified correspond, more or less, with similar periods for Central Europe published earlier. The period corresponding with FRP1 was reported for example for the Isar River (Böhm and Wetzel, 2006), the Pegnitz, and the Rhine downstream the confluence with the Mosela (Glaser et al., 2004).

Schmocker-Fackel and Naef (2010) assessed the flood frequency in 14 catchments across Switzerland. This was further extended by Böhm et al. (2014), who studied in more detail Bavarian Forealps. Flood-rich periods in Central European catchments (Glaser et al., 2003), correspond with FRP2–FRP4. This is not a surprising result, as the major floods in the Vltava River catchment were obviously part of extended CEF (likely more often than stated above), rarely of WCEF. Mostly the records are lacking, however.

Results of this study show a minor peak around 1440–1450, which was recorded also in the Pegnitz River catchment (Glaser et al., 2004). This peak in Prague is associated particularly with three extreme floods in 1432, and with 1434. Interestingly, one of these, the flood of August 1432 is comparable with the extreme 2002 flood (Brázdil et al., 2006a; Elleder, 2010b).

There are also some discrepancies between the results of the presented study and results published for other catchments. Surprisingly, one of the most prominent flood-rich periods in the second half of the 16$^{th}$ century (FRP2) differs from the Isar and Lech Rivers catchments (Böhm and Wetzel, 2006), which are, with respect to geography, very similar to the Vltava River catchment. Nevertheless, in the very next Danube tributaries - the Traun and Enns River catchments - flood events parallel to the Vltava River catchment were identified (Rohr, 2007).

Identified flood-rich periods correspond with decadal frequencies for Prague (Brázdil et al., 2005), except for the period around 1750. This discrepancy is closely related to $POTQ_{10}$ selection. If the criteria for selection are strictly adhered to, only floods from 1712, 1734, and 1736 may be identified. For this reason, the peak around 1750 is reduced. Nevertheless, in this period also a fairly high number of summer floods with estimated peak discharge of $Q_5$–$Q_{10}$ (1751, 1755, and 1757), was recorded. If the peak discharge threshold were lower than $Q_{10}$, the peak around 1750 would be higher corresponding more to results of Brázdil et al. (2005), whose criteria of flood selection was $Q_2$.

With regard to flood frequency across the entire area of Central Europe, the present flood-rich period began around 1994. Major floods were recorded in 1994, and 1995 (the Rhine River: Engel, 1997), 1997 (the Oder River: Kundzewicz, 1999), 2002 (the Elbe and Danube Rivers: Hladný et al., 2004), 2005 (Upper Rhine and Danube tributaries: Beniston, 2006), 2010 (the Oder and Vistula Rivers) and 2013 (the Elbe, Danube, and Oder Rivers: Blöschl et al., 2013). This makes six or seven major floods over 20 years, including one large-scale event in the vast region between the Rhine and Vistula Rivers. For such events, however, no comparable period was found in last 100–200 years of the instrumental period. This reason further enhances an interest in examining the pre-instrumental period in search for analogy with recent records.

## 4 Conclusions

The presented set of estimated flood peak discharges for Prague specifies results of previous studies. Peak discharge estimates made it possible to utilize also the data from the tributaries, and profiles situated downstream of the examined river profile. In contrast, some discharges lower than $Q_2$ were excluded. That implies that the final set used for this study somewhat differed from data used for flood frequency analysis for the Vltava River catchment earlier (Brázdil et al., 2005).

In total, five historical periods with higher than $POTQ_{10}$ flood frequency were identified. The time span for each of these five periods was some 35–40 years. Results of this study clearly show that $POTQ_{10}$ flood is likely to occur 6–12 times in a period of higher flood frequency, which means every third (in the 16$^{th}$ century) to eighth (in the 19$^{th}$ century) year on average. Additionally, during the current period, in the Vltava River catchment we have recorded three major floods within 12 years (2002, 2006, and 2013), which means one in four years on average.

To summarize: the results of the presented analysis indicate that the territory of the present Czech Republic might have experienced in the past extreme floods comparable, with regard to peak discharge ($POTQ_{10}$) and frequency, to flood events recorded recently. With respect to Central Europe considered as a whole, the existence of a similar period can be fairly reasonably assumed at least for the 16$^{th}$ century. It cannot be excluded, however, that one or even several more periods of extreme floods over a relatively short time span, occurred in the past. As a matter of fact, the historical data available presently do not allow an unambiguous conclusion on this issue.

The results of this study clearly show that currently available historical data do not allow for deriving detailed conclusions on flood frequency in Central Europe. Further analysis of single flood events for the whole affected area (such as in Brázdil et al., 2010; Munzar et al., 2008, 2010) are urgently needed to be more certain in this aspect.

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Table 1. Important data on floods in the Elbe catchment.

| **Water gauge** | **Brandýs n. L.** | **Č. Budějovice** | **Beroun** | **Písek** | **Praha** | **Děčín** |
|---|---|---|---|---|---|---|
| **River** | **Elbe** | **Vltava** | **Berounka** | **Otava** | **Vltava** | **Elbe** |
| **A [$km^2$]** | 13109 | 2850 | 8286 | 2913 | **26730** | 51104 |
| **Qa [$m^3.s^{-1}$]** | 99 | 27.6 | 35.6 | 201 | **145** | 309 |
| **$Q_2$ [$m^3.s^{-1}$]** | 572 | 572 | 403 | 300 | **1220** | 1720 |
| **$Q_5$ [$m^3.s^{-1}$]** | 754 | 350 | 615 | 300 | **1770** | 2300 |
| **$Q_{10}$ [$m^3.s^{-1}$]** | 895 | 452 | 799 | 394 | **2230** | 2760 |
| **$Q_{50}$ [$m^3.s^{-1}$]** | 1230 | 751 | 1310 | 680 | **3440** | 3900 |
| **$Q_{100}$ [$m^3.s^{-1}$]** | 1390 | 908 | 1560 | 837 | **4020** | 4410 |

Table 2. Selected important sites (water level indicators) with relations between water levels and peak discharges

| **Site** | **Rec. interval** | **H [cm]** | **Q [$m^3.s^{-1}$]** |
|---|---|---|---|
| Old Town mill (SM) | $Q_{10}$ | 270 | 2200 |
| Nunnery of St. Ann (A) | $Q_{10-20}$ | 250–320 | 2200–2500 |
| St.Valentin – floor (V) | $Q_{10-20}$ | 300 | 2400 |
| St. Linhart (Li) | $Q_{50}$ | >400 | >3500 |
| St. Agidius (Ag) | $Q_{100}$ | >480 | >4100 |
| St. Nicholas (Ni) | $Q_{100}$ | >500 | >4500 |
| Old Town Square (OS) | $>Q_{100}$ | >580 | >5000 |

Table 3. Selected important impacts with relations between water levels and peak discharges

| **Warning signals and impacts** | **H [cm]** | **Q [$m^3.s^{-1}$]** |
|---|---|---|
| 1st level of canon warning signal | *ca* 130 | 900 |
| Flooding of meadows and fields | > 150 | 1200 |
| 2nd level of canon warning signal | *ca* 180 | 1400 |
| Water out of chanell | > 200 | >1500 |
| Danger for lumberyards | >220 | >2000 |
| Watermill shafts flooded (MOr) | *ca* 220 | |
| Water takes wood away (WT) | >250 | >2100 |
| Mills and lower situated houses damaged (DM) | *ca* 300–350 | 2400–3000 |
| Possible barriers in front of bridge (Bar) | >350–400 | 3000–3200 |
| Heavy damages (D!) | >400 | |

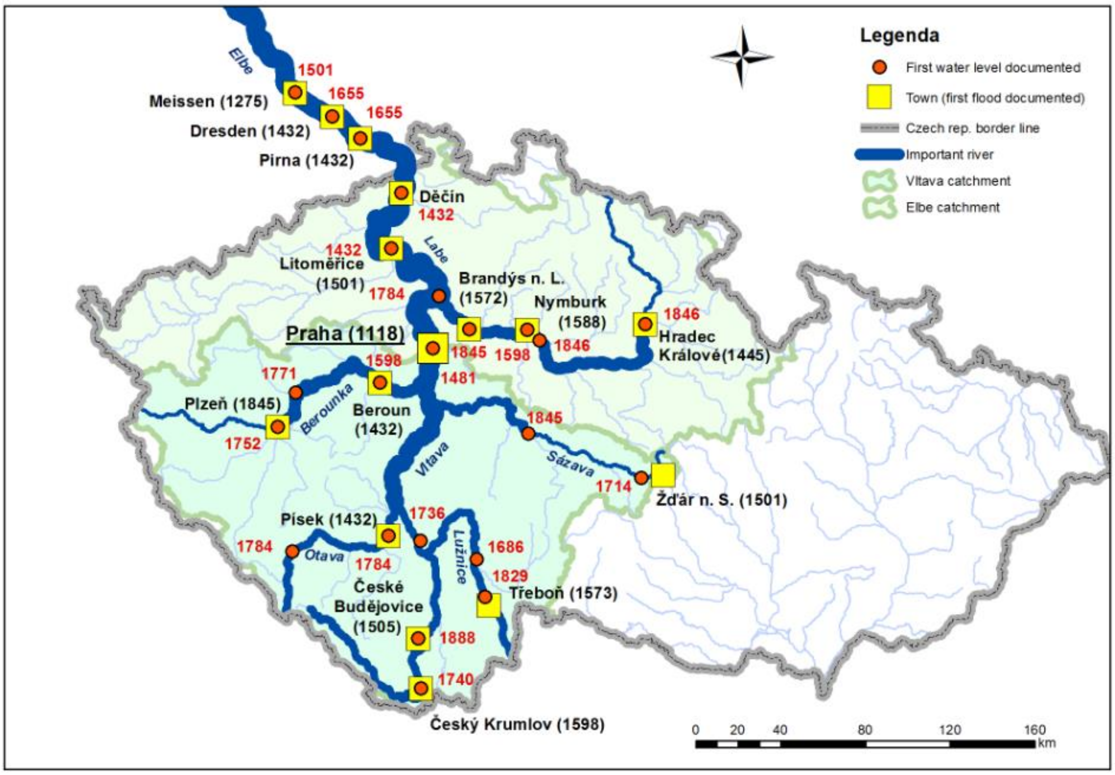


Figure 1. The Vltava River catchment. The major tributaries and sites with records of historic floods and flood marks are highlighted.

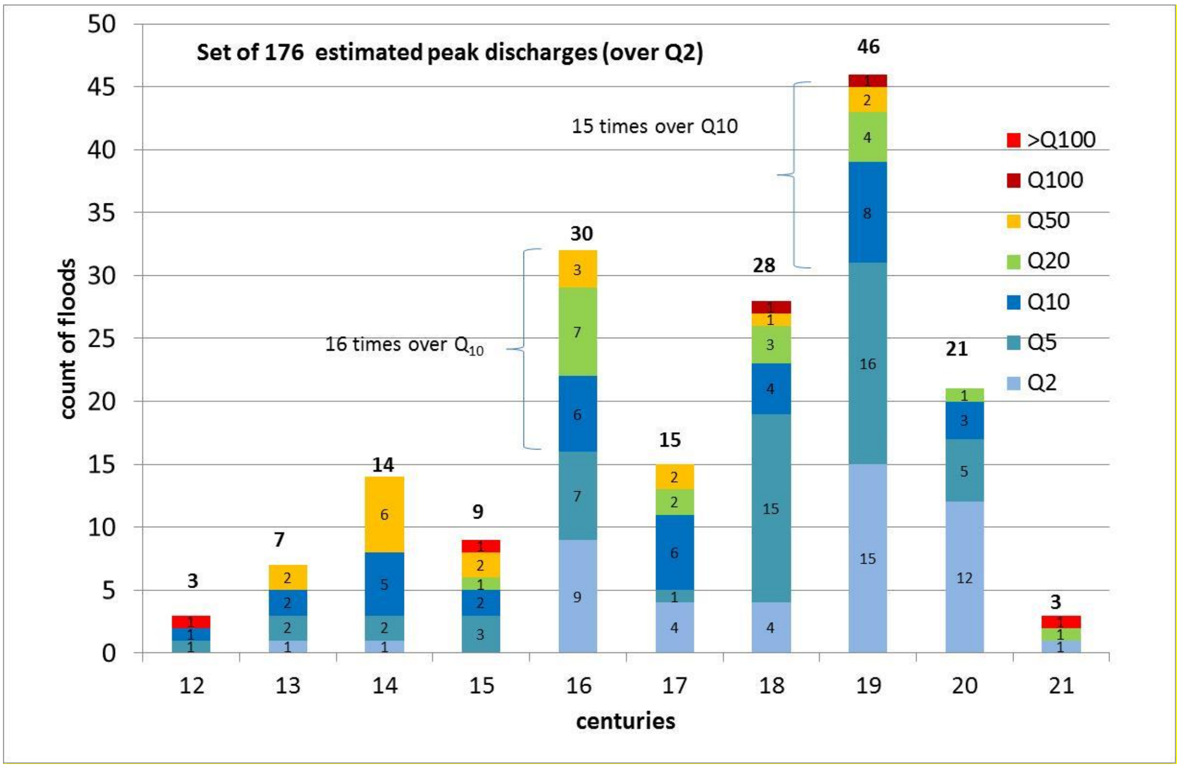


Figure 2. Frequency of floods in Prague over the centuries.

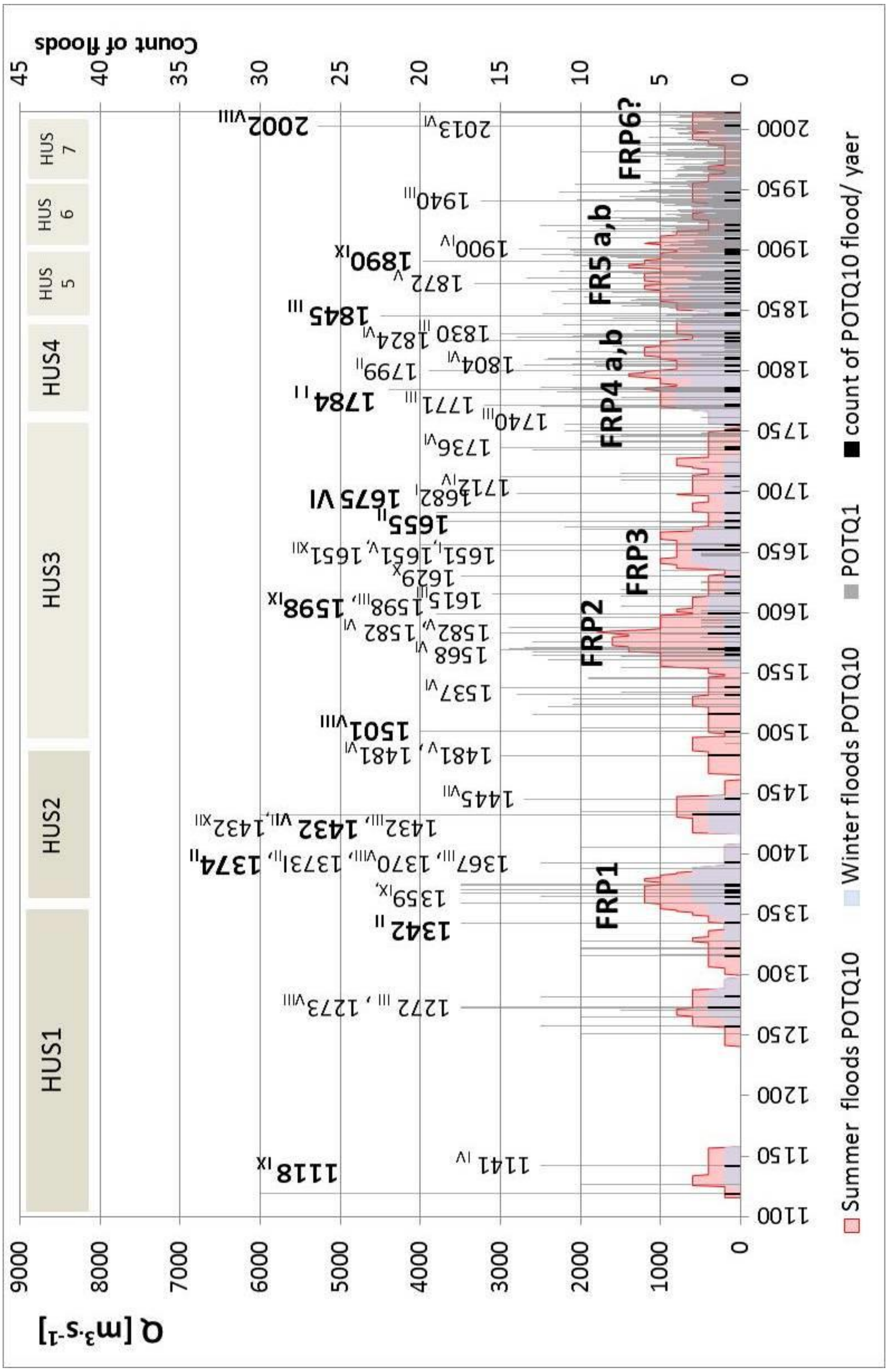


Figure 3. Final time-series presenting running 31-year frequencies in summer and winter floods in Prague with identification of flood rich periods, the extreme floods are in bold.