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 1824 with the beginning of the systematic water level measurements it was the Old Town Mills profile upstream 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 city 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 in floodplain between the 16th and the mid19th 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 at al. (2010) for German Cologne (the Rhine). 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 relation 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 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 (Tables 2 and 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 12^{th}–18^{th} 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 16^{th} century (16 events), and in the 19^{th} century (15 events). The 17^{th} and 18^{th} 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 20^{th} century (4 flood events). In contrast, the high frequency of floods is striking in the 14^{th} century, when some 6 cases might have reached Q_{50} level. Flood frequency is obviously low in the 21^{st} 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 in Prague (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 major summer floods (1804 and 1824) and significant droughts (1811, 1823). 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, 1364, 1373, and 1374 (CEF).

Period FRP2 (1560–1600), 10 AMF (12 in total) flood events /40 years

Summer floods prevail in 1564, 1567, 1568, 1569 (CEF), 1575, 1582, 1587, and 1598 (CEF). Winter floods in 1570, and 1566 (CEF). The type of the 1575 flood is not known.

Period FRP3 (1650–1685), 6 AMF 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), 1786, 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 16th century) to eighth (in the 19th 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 16th 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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References

Bayliss, A.C., Reed, D.W.: The use of historical flood frequency estimation. CEH, Wallingford, 2001.

Beltaos, S. 2008 Progress in the study and management of river ice jams. Cold Regions Science and Technology 51, 2-19.

Beniston, M.: August 2005 intense rainfall event in Switzerland: Not necessarily an analog for strong convective events in a greenhouse climate, Geophys. Res. Let., 33, L05701, 2006.

Blöschl, G., Nester, T., Komma, J., Parajka, J. and Perdigão, R. A. P.: The June 2013 flood in the Upper Danube Basin, and comparisons with the 2002, 1954 and 1899 floods, Hydrol. Earth Syst. Sci., 17, 5197–5212, 2013.

Brázdil, R., Demarée, G.R., Deutsch, M., Garnier, E., Kiss, A., Luterbacher, J., Macdonald, N., Rohr, Ch., Dobrovolný, P., Kolář, P., Chromá, K.: European floods during the winter 1783/1784: scenarios of an extreme event during the "Little Ice Age". Theoretical and Applied Climatology, 100, 163–189, 2010.

Brázdil, R., Dobrovolný, P., Elleder, L., Kakos, V., Kotyza, O., Kveton, V., Macková, J., Müller, M., Štekl, J., Tolasz, R., and Valášek, H.: Historical and recent floods in the Czech Republic. Masaryk University/Czech Hydrometeorological Institut, Brno/Prague, 2005.

Brázdil, R., Glaser, R., Pfister, Ch., Dobrovolný, P., Antoine, J.-M., Barriendos, M., Camuffo, D., Deutsch, M., Enzi, S., Guidoboni, E., Kotyza, O., and Sanchez Rodrigo, F.: Flood events of selected European rivers in the sixteenth century, Clim. Change, 43, 239–285, 1999.

Brázdil, R., Kotyza, O., Dobrovolný, P.: July 1432 and August 2002 - two millennial floods in Bohemia? Hydrolog. Sci. J., 51, 848–861, 2006a.

Brázdil, R., Kundzewicz, Z. W., and Benito, G.: Historical hydrology for studying flood risk in Europe, Hydrolog. Sci. J., 51, 739–764, 2006b.

Böhm. O., and Wetzel, K.-F.: Flood history of the Danube tributaries Lech and Isar in the Alpine foreland of Germany, Hydrolog. Sci. J., 51, 784-798, 2006.

Böhm, O., Jacobeit, J., Glaser, R., and Wetzel, V: Flood history of the Bavarian Alpine Foreland since the late Middle Ages in the context of internal and external climate forcing factors. Hydrol. Earth Syst. Sci. Discuss., 18, 1–32, 2014.

Chow, V. T.: Open channel hydraulics, McGraw-Hill, New York, 1959.

Deutsch, M., and Pörtge, K. H.: Hochwasserereignisse in Thüringen. Ministerium für Landwirtschaft, Naturschutz und Umwelt, Freistaat Thüringen, Jena, 2003.

Elleder, L.: Pražský Bradáč, jeho stáří, účel a historie. Historica Pragensia, 1, 301–333, 2003. In Czech.

Elleder, L.: Flood Frequency and Seasonality in the Sazava River Catchment Based on Historical Cases, Acta Universitas Carolinae Geographica, 15–28, 2008.

Elleder, L.: Reconstruction of the 1784 flood hydrograph for the Vltava River in Prague, Czech Republic, Global Planet. Change, 70, 117–124, 2010a.

Elleder, L.: Využitelnost proxydat v hydrologii: rekonstrukce řady kulminačních průtoků Vltavy v Praze pro období 1118–2002 (Utilization of proxy-data in hydrology - reconstruction of peak discharge record from 1118–2002), disertační práce (PhD thesis). Praha, 150, 2010b, in Czech.

Elleder, L., Herget, J., Roggenkamp, T., and Nießen, A.: Historic floods in the city of Prague – reconstruction of peak discharges, Hydrol. Res., 44, 202–214, 2013.

Engel, H.: The flood events of 1993/1994 and 1995 in the Rhine River basin, in: Destructive Water: Water-Caused Natural Disasters, their Abatement and Control, IAHS Publication no. 239, edited by: Leavesly, G. H., Lins, H. F., Nobilis, F., Parker, R. S., Schneider, V. R., and Van de Ven, F. H. M., IAHS Press, Wallingford, UK, 1997.

Fritsch, K.: Über die constanten Verhältnisse des Wasserstandes und der Beeisung der Moldau bei Prag so wie die Ursachen von welchen dieselben abhängig sind nach mehrjährigen Beobachtungen. Sitzugsberichten Akademie der Wissenschaften, 156–192, 1851.

Fügner, D.: Historische Hochwasser-Marken des Elbestromes, BMBF-Projekt: "Integration von historischen und hydrologisch/ hydraulischen Analysen zur Verbesserung der regionalen

Gefährdungsabschätzung und zur Erhöhung des Hochwasserbewusstseins”. BTU Cottbus, 2007.

Girgus, R., and Strupczewski, W.: Wyjątki ze źródeł historycznych o nadzwyczajnych zjawiskach hydrologiczno-meteorologicznych na ziemiach polskich w wiekach od X do XVI (Excerptions of the historical sources of extraordinary hydro - meteorological phenomena in Poland in 10–16 century). In Polish. Wydawnictwa Komunikacji i Łączności, Warszawa 1965.

Glaser, R. and Stangl, H.: Historical floods in the Dutch Rhine Delta, Natural Hazards and Earth System Sciences (2003) 3: 605–613, 2003.

Glaser, R., Stangel, H., and Lang, M.: Floods in Central Europe since AD 1300 and their regional context. La Houille Blanche, 5, 43–48, 2004.

Glaser, R., Riemann, D., Schönbein, J., Barriendos, M., Brázdil, R., Bertolin, C., Camuffo, D., Deutsch, M., Dobrovolný, P., van Engelen, A., Enzi, S., Halícková, M., Koenig, S., Kotyza, O., Limanówka, D., Macková, J., Sghedoni, M., Martin, B., and Himmelsbach, I.: The variability of European floods since AD 1500, Clim. Change, 101, 235–256, 2010.

Herget, J., and Meurs, H.: Reconstructing peak discharges for historic flood levels in the city Cologne - Germany, Global Planet. Change, 70, 108–116, 2010.

Herget, J., Roggenkamp, T., and Krell, M.: Estimation of peak discharges of historical floods, Hydrol. Earth Syst.Sci., 18, 4029–4037, 2014.

Hladný, J., Krátká, M., and Kašpárek, L. (Eds.): August 2002 catastrophic flood in the Czech Republic. Ministry of Environment of the Czech Republic, Prague, 2004.

Hrdlička, L.: K Proměnám Středověké Prahy (Remarks to the changes of Prague in Middle Ages). In: A Hub of the European Culture. International Symposium ICOMOS, Prague, 49–53, 2000, in Czech.

Kašpárek, L., and Bušek, M.: Vliv vltavské kaskády na povodňový režim Vltavy v Praze. Vodní hospodářství, 7, 280–286, 1990. In Czech.

Kiss, A.: Floods and long-term water-level changes in medieval Hungary. Doctoral dissertation. Central European University, Budapest, 2011.

Kundzewicz, Z. W.: The Great Flood of 1997 in Poland, Hydrol Sci, 44 (6), 855–870, 1999.

Mudelsee, M., Börngen, M., Tetzlaff, G., and Grünewald, U.: No upward trends in the occurrence of extreme floods in central Europe. Nature, 425, 166–169, 2003.

Munzar, J.: Floods in Central Europe after the exceedingly severe winter season 1829/1830. Moravian Geographical Reports, 8, 45–57, 2000.

Munzar, J., Deutsch, M., Ondráček, S., Kallabová E.: Examples of great cross-border floods in Central Europe and lessons learnt (case studies of floods from September and November 1890 on the occasion. of their 120th anniversary), Moravian Geographical Reports, 18, 21-29, 2010.

Munzar, J., Elleder,L., and Deutsch, M., 2005. The catastrophic flood in February/ March 1784 - a natural disaster of European scope. Moravian Geographical Reports, 13, 8–24, 2005.

Munzar, J., Ondráček, S., Elleder, L., Sawicki, K.: Disastrous floods in central Europe at the end of July 1897 and lessons learnt. Moravian Geographical Reports, 16, 27–40, 2008.

Novotný, J.: Dvě stoleté hydrologické řady průtokové na českých řekách (Two hundred year hydrological records for the Czech rivers). Sborník prací. Hydrometeorologický ústav, Praha, 1963, in Czech.

Pekárová, P., Škoda, P., Majerčáková, O., and Miklánek, P. : Významné povodne na území Slovenska v minulosti (Important floods in Slovakia in the past), Acta Hydrol Slovaca, 12, 65 – 73, 2011, in Slovak.

Rohr, Ch: Extreme Naturereignisse im Ostalpenraum. Naturerfahrung im Spätmittelalter und am Beginn der Neuzeit, Böhlau, Köln, 2007.

Roggenkamp, T., and Herget, J.: Reconstructing peak discharges of historic floods of the River Ahr – Germany, Erdkunde, 68, 49–59, 2014.

Richter, J.: Způsob předchozích výpočtů stavů vody hořeního Labe (Method for water level forecast for the upper Elbe catchment), Technická kancelář rady zemědělské, Praha, 1893. In Czech and German.

Schmocker-Fackel, P., and Naef, F.: Changes in flood frequencies in Switzerland since 1500. Hydrol. Earth Syst. Sci., 14, 1581–1594, 2010.

Stedinger, J.R., and Cohn, T.A.: Flood frequency analysis with historical and paleoflood information. Water Res Res 22, 785–793, 1986.

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

A: catchment area

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	Q_{10}	270	2200
Nunnery of St. Ann	Q_{10-20}	250–320	2200–2500
St.Valentine – floor (Val)	Q_{10-20}	300	2400
St. Linhart (Li)	Q_{50}	>400	>3500
St. Giles (Ag)	Q_{100}	>480	>4100
St. Nicholas (Ni)	Q_{100}	>500	>4500
Old Town Square (OTS)	$>Q_{100}$	>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	

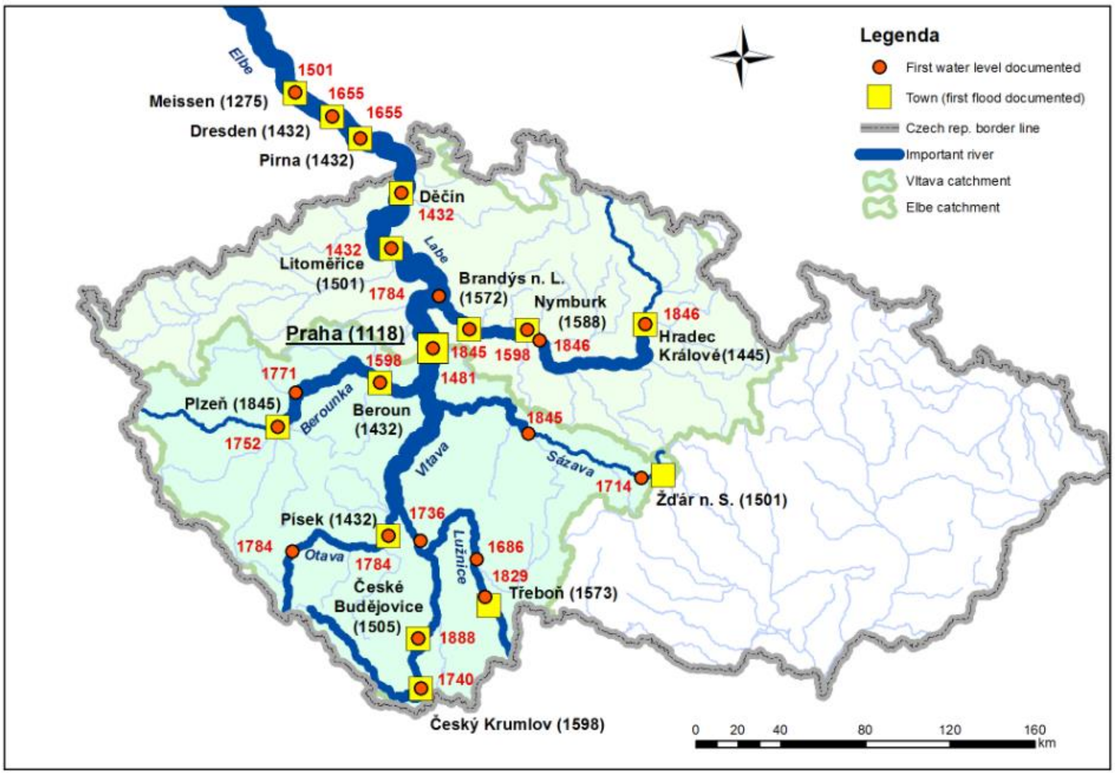

Figure 1. The Vltava River catchment. The major tributaries and sites with records of historic floods and flood marks are highlighted.

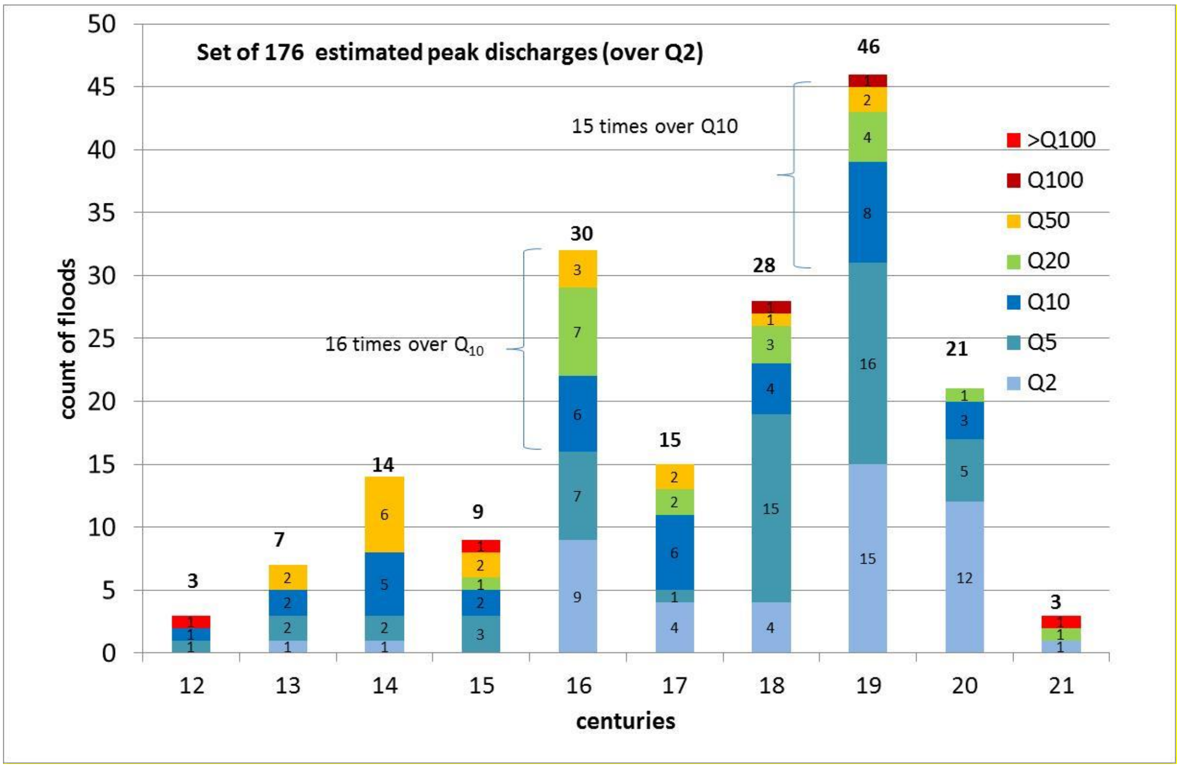

Figure 2. Frequency of floods in Prague over the centuries.

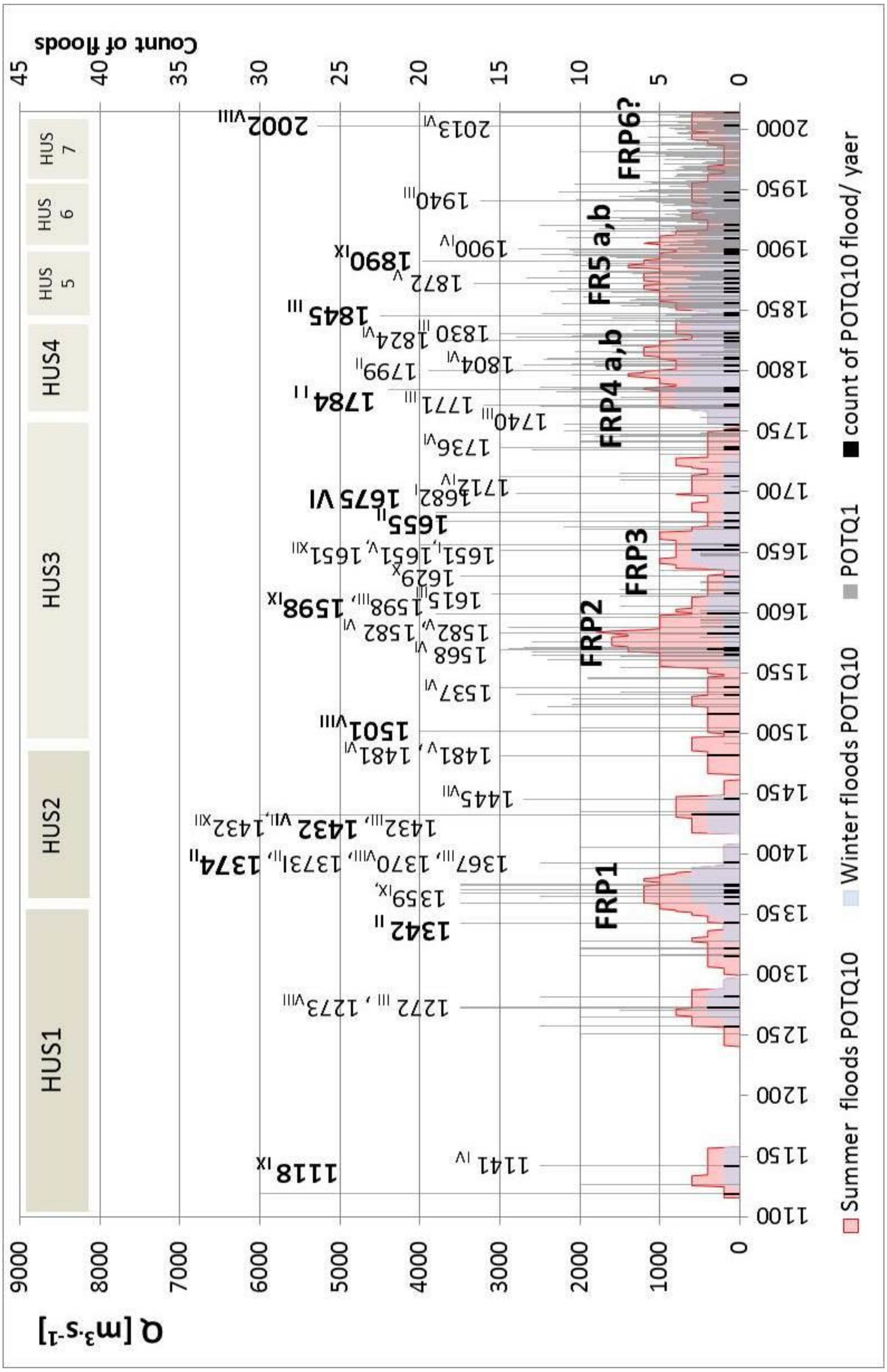

Figure 3. Final time-series presenting running 31-year frequencies in summer and winter floods in Prague with identification of flood rich periods, the extreme floods are in bold.