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Historical changes in frequency and seasonality 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 (POTQ_{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).

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 (Hladný et al., 2005; Blösch et al., 2003); 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

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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?

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 levels (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, 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, 2006). 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, 159 peak discharge records for the period between 1118 and 1825, when the regular daily water level measurements began, are available

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(Brázdil et al., 2005). 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, 2004). 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, 1892). Water levels for Prague after 1954 are in the Czech Hydrometeorological Institute database, concurrently in simulation without the influence of the Vltava River dams (Kašpárek et al., 2005).

The 2012 flood, with peak discharge of 5160 $m^3 s^{-1}$, is the most important case over the instrumental period (Hladný et al., 2005). Interestingly, the flood of July 1432 was likely even more important (Elleder, 2010; Daňhelka, 2012). For other significant historic floods – bigger than Q_{50} – in the Vltava River catchment, Brázdil et al. (2005) published brief descriptions. Detailed papers, though most of them only in Czech, were published for the following floods: 1432 (Daňhelka, 2012), 1582 (Elleder and Kotyza, 2007), 1714 (Elleder et al., 2014), 1784 (Munzar et al., 2014), 1830 (Munzar, 2000), 1845 (Kakos and Kulasová, 1995), 1862 (Elleder et al., 2012b), 1872 (Elleder et al., 2012a), and the 1890 (Kakos, 1990). Regretfully, the extreme flood cases, such as 1501, 1598, 1655, 1675, 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 and its changes over time

The major Vltava River profile for Prague until 1825 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 entire period under review, 1118–2013, has been divided into seven periods (P1–P7), with respect both to the reliability of input data and changes in the area near the major profile. The least reliable data are these relating to 1118–1350 (P1). 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, 2001). In 1351–1480 (P2) 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 (P3) the records of water levels are available. Since 1481 these are related to the "Bearded Man" water gauge (Elleder, 2004, 2012). 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 16th and the mid19th century were minor (Elleder et al., 2012). The first modern water gauge in Prague was set up in 1781 (Brázdil et al., 2005; Elleder, 2010). Systematic records date back to 1825. The next 60 year period of 1781–1843 (P4) 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, 2010). For the next period of 1844–1909 (P5), when the Vltava River embankment construction was undertaken, a rating curve is available. In 1910–1926 (P6a) the inundated area of the Old Town was raised to the embankment. In the next period 1927–1953 (P6b) 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 (P7) has been affected by implementation of the cascade. Until mobile dikes were put into operation (2010–2013), 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. 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 were published earlier by Elleder et al. (2012). 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

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was the utilization of most of the data with an acceptable level of reliability for flood seasonality analysis.

2.4 Other interpreted data

Relations between water stage or peak discharge and impacts relevant for P5 and P6 periods (Elleder, 2012) were applied for the interpretation of historic floods. The rating curve for 1880–1890 (Richter, 1892) was used for P3 floods – events with a fairly reliably documented water level.

For winter floods, a problematic association between water level and discharge due to ice jamming is to be accounted for. 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 POTQ_{10}, the discharge was always sufficient for an ice barrier release. This holds for the 1784 February flood (Elleder, 2000), and also for all recorded winter floods during 1800–1850 (Fritsch, 1850). It is particularly true for the Prague profile, but does not hold, in any case, for supporting profiles in Děčín, Dresden, and Meissen.

Supporting profiles in the upper Vltava River (České Budějovice, Beroun, Písek) 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. 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. The credibility of discharges estimated by the approach above is undoubtedly lower than discharges derived from authentic description and records of flood in Prague.

2.5 Selection of floods

The results are presented for all floods, including events higher than or equal to Q_2. Out of the total of 159 floods of B set (Brázdil et al., 2005), 13 events were excluded,

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as they were recorded merely for the Vltava River in České Budějovice, and without other supporting material, the assumed discharge in Prague is likely to be less than Q_2. 56 similar cases before 1852 are in the database.

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. A perception threshold for recognising an event as a flood, and for drawing a flood mark, a discharge around Q_{10} was generally accepted in Prague until 1781 (Table 2). 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

The time-series of measured peak discharges from 1825–1954 for Prague available (Novotný, 1960) was extrapolated by 187 flood events for the pre-instrumental period using the documentary data. These 187 events represent, however, only 149 years with floods, as in 23 years floods were recorded 2–3 times annually. The total time-series include some 350 peak discharges in 306 years. After excluding the events equal to or lower than Q_2, we have a set of 180 flood events (119 events before 1825).

Figure 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 (13 events in total, which means 6 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 (14 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

Figure 3 presents an overview of all floods – about 300 AMF. 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 and two sub-periods, with minimal overlap with respect to Q_{50}–Q_{500} occurrence, were identified in total. Some significant floods in P1 (1118, 1272, 1273), and P2 (1432) are not included in the above periods. This fact is most likely a consequence of the lack of documentary sources for P1 and P2 periods. It holds, however, also for the beginning of the P3 period with the extreme flood of 1501. POTQ_{10} floods recorded in the Vltava River affected a major part of Central Europe as well, at least two or three major catchments out of five: the Elbe, Danube Oder, Wesser, Warta. These floods 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 (Deutch and Portge, 2003), and the Rhine catchment (Herget, 2010). 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 Innn, 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 Gyrgus 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, 1658, 1740, 1784, and 1799 winter floods (Elleder, 2010).

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

3.2.1 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).

3.2.2 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).

3.2.3 Period FRP3 (1650–1685), (6 flood events/35 years)

Winter floods prevail in 1651 (CEF), 1655 (CEF), and 1682 (CEF). Flood in 1658 (WCEF) was recorded for Dresden. 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.

3.2.4 Period FRP4a (1770–1800), (6 flood events/35 years)

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

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3.2.5 Period FRP4b (1805–1830), (6 flood events/30 years)

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

3.2.6 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 (Elleder, 2012). This period includes a catastrophic flood on the Elbe River in February 1846, and a no less deleterious flood in August 1858.

3.2.7 Period FRP5b (1881–1920), (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).

3.2.8 Period FRP6 (starting 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.

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, 2009), the Pegnitz, and the Rhine downstream the confluence with the Mosela (Glaser et al., 2004).

Schmocker-Fackel and Naef (2009) 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., 2008), 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

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(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, 2010; Daňhelka, 2012).

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 16th century (FRP2) differs from the Isar and Lech Rivers catchments (Böhm and Wetzel, 2009), 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, 2005), 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.

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., 2010) are urgently needed to be more certain in this aspect.

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

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excluded, however, that one more 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.

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

Water gauge River	Brandýs n. L. Elbe	Č. Budějovice Vltava	Beroun Berounka	Písek Otava	Praha Vltava	Děčín Elbe
A [km^2]	13 109	2850	8286	2913	26 730	51 104
Q_a [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

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Table 2. Selected important sites with relations between water levels and peak discharges.

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

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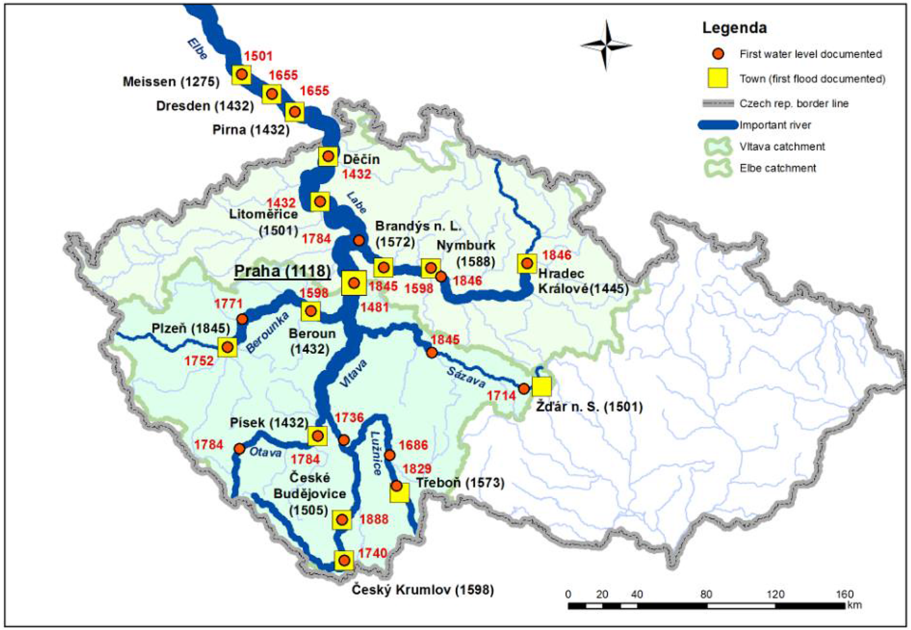

Figure 1. The Vltava River catchment. The major tributaries and sites with records of historic floods and flood marks are highlighted.

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Historical changes in frequency and seasonality of extreme floods in Prague

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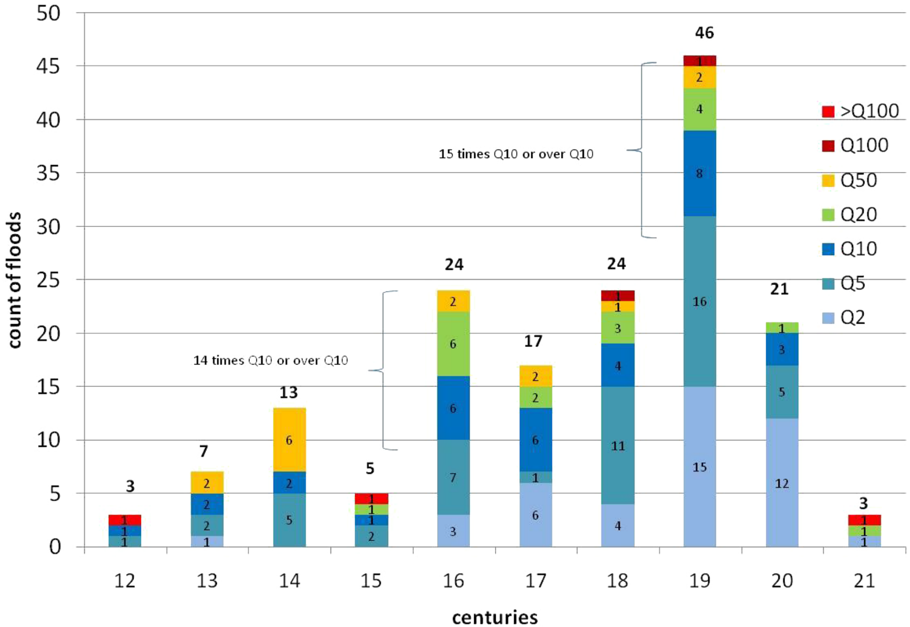

Figure 2. Frequency of floods in Prague over the centuries.

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Historical changes in frequency and seasonality of extreme floods in Prague

L. Elleder

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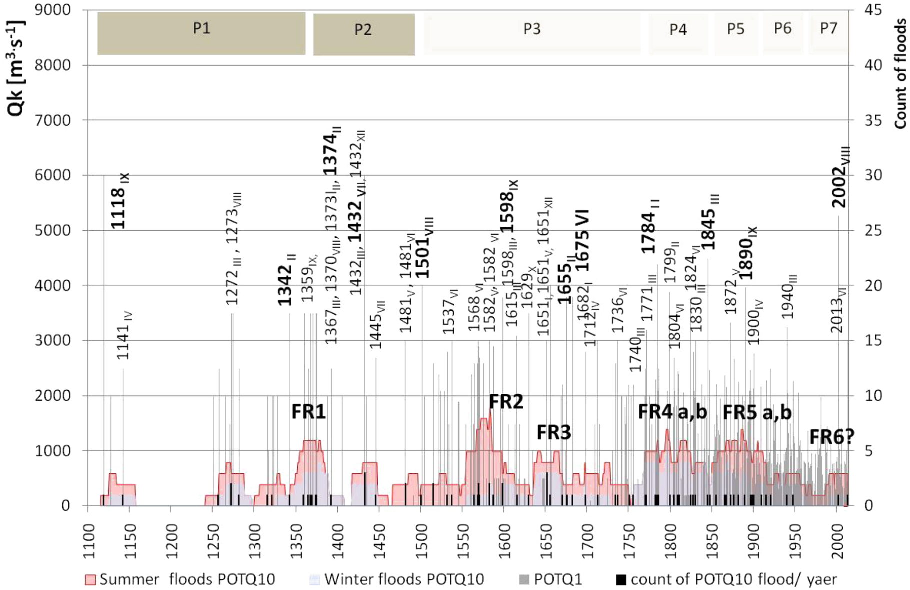

Figure 3. Final time-series presenting running 31 year frequencies in summer and winter floods in Prague.

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