Historic floods in the city of Prague – a reconstruction of peak discharges for 1481–1825 based on documentary sources

L. Elleder, J. Herget, T. Roggenkamp and A. Nießen

ABSTRACT

The paper aims to reconstruct peak discharges of historic floods in an urbanized area of the historic city of Prague based on documentary sources from pre-instrumental and the early instrumental period (1481–1825). Approximately 20–30 maximum water levels are denoted by flood-marks, accounts describing or related at unchanged sites, or by early instrumental measurements. The challenge in this reconstruction is the identification and consideration of man-made floodplain modifications influencing the cross-section area and the hydraulic roughness. In order to overcome this problem, a simple approach to estimate peak discharges of historic floods has been developed and applied to the River Vltava. This approach includes a procedure for reconstructing the hydraulic parameters of the river channel and inundated floodplain, coupled with an approach for the verification of estimated peak discharge reliability. As a result of the different hydraulic characteristics associated with ice jam floods all winter-flood events are excluded to avoid their potential inclusion. We present 18 reconstructed discharge maxima. The validation of the technique by comparison with the recent gauged flood of 2002 reveals results of adequate accuracy. The comparison also shows that the flood event of 2002 was conspicuously greater than all calculated summer floods in 1481–1825.

Key words | documentary sources, historical floods, Prague, urbanized catchment

L. Elleder (corresponding author)
Czech Hydrometeorological Institute Prague,
CPP-OHP,
Na Šabatce 17,
Prague 4,
143 06,
Czech Republic
E-mail: *elleder@chmi.cz*

J. Herget
T. Roggenkamp
A. Nießen
Department of Geography,
University of Bonn,
Meckenheimer Allee 166,
D-511315,
Bonn,
Germany

INTRODUCTION

The estimation of contemporary flood magnitudes and historical flood water level can provide important information. Historic flood levels can be found as epigraphic markings on historic buildings identifying the maximum flood level, or detailed accounts detailing seasonality, magnitude, and causative mechanisms can be found in documentary sources (Macdonald 2012). Typically, written descriptions are qualitative, such as this from the year 1118: 'Because our River Vltava, suddenly left its riverbed, oh how many villages, how many houses in the settlement below the castle, how many dwellings and churches it has taken away with the torrent!' (Brázdil *et al.* 2005). After careful interpretation and analysis, descriptive accounts can be used as an indicator of flood level and frequency during historic times, depending on the quality and quantity of the data. The approach of incorporating historical information into flood frequency analyses, augmenting gauged flood events, is well established, albeit it has to deal with the serious problem of statistical unsteadiness of datasets (e.g., Savenije 1995a; Benito *et al.* 2004; Kidson & Richards 2005; Macdonald 2013). By including an increased number of flood events before the installation of instrumental gauges these datasets gain an advantageous addition when estimating high magnitude events, events rarely recorded within instrumental series (e.g., Witte *et al.* 1995: Benito & Thorndycraft 2005). It is challenging to utilize stage records in order to predict actual flood discharges due to frequent, mainly anthropogenic, modification of channels and

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nearby floodplains during historic times. For comparable discharges, contemporary water levels would reach a different elevation, probably in most cases higher due to the decreased cross-section areas related to dykes, constructions and settlements in the floodplain. In view of methodological problems, flood discharge estimations based on historic flood levels in urban areas are quite rare (e.g., Savenije 1995b; Brázdil *et al.* 1999; Thorndycraft *et al.* 2003; Macdonald *et al.* 2006; Herget & Meurs 2010; Wetter *et al.* 2011). The main challenge remains the identification of man-made floodplain modifications influencing the cross-section area and the hydraulic roughness. In order to overcome this problem, a simple approach to estimate peak discharges of historic floods has been developed and applied to the River Vltava at Prague. This approach includes a procedure for reconstructing the hydraulic parameters of the river channel and inundated floodplain, as well as a final verification of the reliability of estimated peak discharges.

HISTORIC FLOOD LEVELS IN PRAGUE

Prague is located in central Bohemia in the Czech Republic on both sides of the River Vltava, the main tributary of the Elbe River. The catchment area of the river at Prague is 26,720 km², with the main tributaries being Otava, Berounka, Lužnice and Sázava. A stage record at Prague has existed since 1825, with a mean discharge of 150 $m^3 s^{-1}$, the 100-year flood is ~4,000 $m^3 s^{-1}$, with a peak discharge of 5,160 $m^3 s^{-1}$ recorded in August 2002 (Hladný *et al.* 2004). The oldest reliable record on floods in Prague is related to the disastrous 1118 flood. Brázdil *et al.* (2005) report about 150 floods identified from documentary sources, with about half described in a qualitative way, i.e., regarding the damages and impacts. Historic flood levels are often described in relation to the buildings flooded, with the worst floods affecting different buildings or sites in the historic 'Old Town' parts of Prague.

Changes to the floodplain until 1300 (Hrdlička 2005) make the interpretation of the early descriptions difficult; the accounts of the 1118 flood are described as five metres above the original wooden bridge. The level of the February 1342 flood, which destroyed the first stone bridge in Prague, is unclear. Fairly reliable descriptions of inundated areas can be found since 1432, with detailed descriptive accounts detailing the extraordinary maximum level of this flood in relation to parts of the Old Town Square (Tomek 1865; Brázdil *et al.* 2005, 2006).

In this paper we focus on accurate and reliable documented cases with respect to their peak water levels. The flood level of 1481 is the first to be presented in relation to the Bradáč, (Elleder 2003), an 80-cm high gothic relief of a head of a bearded man, in the wall near Charles Bridge; it has been used since to mark the greatest floods (Figure 1). Eighteen floods between 1481 and 1736 are documented by the water level reaching different parts (beard, mouth, nose, eyes and forehead) of the relief. The uncertainty of these records is estimated to be around 5–10 cm. The peak flood levels for the extreme floods of 1581 and 1598 were described as height above the head of Bradáč in Prague cubits (59 cm) and half-cubits (29,5 cm), i.e., with an approximated uncertainty of around 30 cm.

The flood of 1481 marks the beginning of the period of interest within this study, which ends with the installation of the first gauge in 1825. Due to the different hydraulic conditions associated with ice jam effects, all winter flood events from 1481 to 1825 are excluded (Beltaos 2008), with selected floods summarized and documentary sources identified in Table 1. The flood levels for the period 1481–1598 are based on records related to Bradáč (B) (Elleder 2003; Brázdil *et al.* 2005). Close to this site is the monastery of the Knights with Red Star, which has flood-marks (FM) from the period of 1675–1890 preserved. These were used

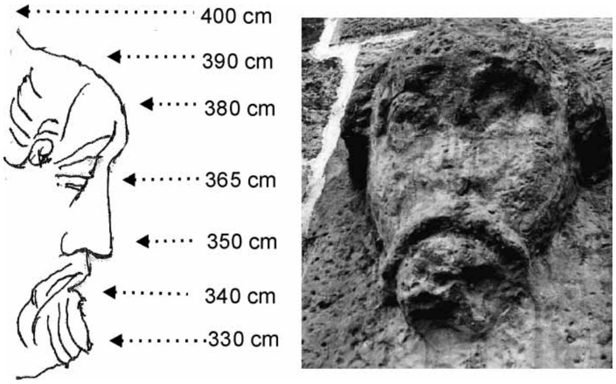

Figure 1 | 'Bradáč' or 'Hochbart' (The Bearded Man) near the Charles Bridge, with related water levels.

Table 1 | Selected flood events between 1481 and 1825 in Prague

Year	Date	Water level [m]
1481	May 25 (G: June)	3.43 (B)
1481	June 8 (G: June 17)	3.83 (B)
1501	August 15 (G: May 25)	5.03 (B)
1515	July 21 (G: July 31)	3.23 (B)
1531	May 1 (G: May 11)	3.58 (B)
1537	May 23 (G: June 2)	3.63 (B)
1569	June 20 (G: July 1)	3.63 (B)
1582	May 2 (G: May 12)	3.58 (B)
1582	June 4 (G: June 14)	3.73 (B)
1587	June 8	3.63 (B)
1598	August 17–18	4.73 (B)
1675	June 23–24	4.73 (FM)
1712	April 24	3.44 (FM)
1736	July 19	3.53 (B, FM)
1786	August 17	3.54 (K)
1804	June 15	3.67 (K)
1815	August 9–10	2.55 (K)
1824	June 26–27	3.83 (K)

Dates of flood peaks are presented in the calendar of the relevant period: until 1584 according to the Julian calendar (G: according to the Gregorian calendar). Water levels relate to Bradáč (B), flood-marks (FM), Klementinum diary (K).

for identification of flood levels for 1675, 1712 and 1736. The levels of floods from 1782 to 1825 (the flood events in 1786, 1804, 1815, 1824) we obtained from the Klementinum observatory measurements (Seydel 1956) held since 1782 very probably in profile of (FM) flood-marks (Brázdil *et al.* 2005).

PARAMETERS FOR THE ESTIMATION OF PEAK DISCHARGES

Based on the empirical Manning equation for mean flow velocity (Chow 1959), peak discharges for the selected historical flood events are estimated as

$$Q_\mathrm{p} = A_\mathrm{p} R_\mathrm{p}^{2/3} S^{1/2} n^{-1} \tag{1}$$

with Q_p peak discharge, A_p cross-section area during the highest flood level, R_p hydraulic radius during the highest flood level, S slope and n hydraulic roughness coefficient according to Manning. As will be explained in detail below, the peak discharge is calculated separately for four individual elements of the cross-section area and subsequently summed to a single value for the flood event. This approach was first applied by Herget & Meurs (2010) for the estimation of historic flood levels in Cologne, Germany.

Cross-section area (*A*)

The reconstruction of inundated floodplain areas is based on maps, etchings and drawings from historic times. Table 2 summarizes the most important documentary sources detailing floodplain changes and epigraphic markings. Due to the long history of the city of Prague, this material was compiled in the archives of Prague and covers most periods contemporary with the floods listed in Table 1. Based on these illustrations, topographic changes including land use of the floodplain can be traced back through time (Table 3). A cross-section (NW–SE) profile is constructed across the floodplain area reaching from the Prague district Malá Strana (from Herget's brick factory) adjacent to Prague Castle, through the River Vltava channel to the floodplain area of the Four Seasons Hotel (former Riding School), on the eastern embankment of the River Vltava and the historic city centre. Depending on the high-level floods considered in this investigation, the length of the profile is about 400 m.

The cross-section area is selected by excluding as many sources of interruption in the flow hydrodynamic as possible, e.g., bridges and weirs.

Therefore, the profile (Figures 2 and 3) is arranged approximately 150 m downstream of Bradáč (B) and the flood-marks (FM). Taking slope into account, the difference between water levels in both profiles (Brázdil *et al.* 2005) and water levels presented in Table 1 is 12 cm.

A major concern in any fluvial reconstruction of the river channel cross-section is possible changes in cross-section area as a result of incision or deposition. A bathymetric survey of the river channel was undertaken in 1810 (Scheiner & Franz 1891), unfortunately this was subsequently lost, but cross-sectional data from 1843 (River map 1843) are available, with more accurate surveys from 1900 (Bathymetry 1900) and 1910 (Figure 3). These early surveys illustrate 'natural' channel topography. A comparison shows smaller incisions as well as elevations, although

Table 2 | The most important documentary sources on floodplain changes and water level marks

Year	Description
1118	Oldest documented flood
1340	Established commission invited sworn millers (control of weirs – fixed water level marks)
1452	Fixed water level mark of Staroměstský weir and other weirs (Tomek 1891)
1481	First flood level related to Bearded Man – Bradáč
1493	View of Prague by Michael Wolgemut and Wilhelm Pleydenwurf
1536–7	Panorama of Prague from Pfalzgraf Ottenreich's diary (http://www.ottheinrich.info/)
1562	Panorama of Prague by Jan Kozel – Michael Petrle (NG)
1581	Depiction of the Vltava flood in 1581 (LRPCS)
1595	Panorama of Prague by Joris Hoefnagel (NG)
1608	Panorama of Prague by Egidius Sadeler (NG)
1636	Panorama of Prague by Václav Hollar (NG)
1675	Oldest saved flood-mark (Monastery Knight with Red Cross)
1685	Panorama of Prague by Folpert Ouden-Allen (MHMP)
1769	Orthographical view by J. D. Huber (OB)
1781	First gauge in Prague established (Brázdil *et al.* 2005)
1791	Accurate map of Prague by Professor Herget
1810	River map with water depths (documented by Schreiner, Franz 1891)
1825	Everyday water measurement started at Staroměstské mlýny mills (Brázdil *et al.* 2005)
1826–37	Langweill 3D-model of Prague (MHMP)
1843–8	River map Prague – Hřensko (River map 1843)
1889	1889 Topographical map of Prague (Topography of Prague 1889)
1890	1890 Geological profile of Charles Bridge (Geological profile 1890)
1900	Vltava Bathymetry (Bathymetry 1900)
1910	Vltava Bathymetry (Situation 1910)

NG, National Gallery Prague; MHMP, Museum of the Capital City Prague; LRPCS, Library of the Royal Premonstratensian Canonry in Prague Strahov; OB, Österreichische Bibliothek Wien.

Table 3 | Changes in floodplain in the cross-section selected

Year	Description
1200–50	Normal water level 3–3.5 lower than nowadays (Hrdlička 2005)
1250	Right bank: city walls against the Vltava river (Starec 2005)
1272	Right bank: urbanized increasing of altitude of floodplain (Hrdlička 2005)
1329	Start of systematically removing household refuse from Prague streets (Tomek 1891)
1342	Due to a flood destroying a weir 'Na písku' (Tomek 1891)
1358	Construction of the Charles Bridge began
1432	Due to catastrophic floods the Charles Bridge and all weirs collapsed (Brázdil *et al.* 2005)
1541	Big Fire of Malá Strana district (Hlavsa & Vančura 1983)
1541–1600	Left bank: stabilizing of Kampa embankment by remnants of buildings destroyed by a big fire in Prague (Hlavsa & Vančura 1983)
1560	Right bank: first saltpetre dung hills for production of gunpowder (Starec 2005)
1650	Right bank: removal of city landfill waste, establishment of riding school (Starec 2005)
1750	Right bank: instead of saltepetre dumps, the new Pachta palace was built (Starec 2005)
1781	Left bank: Herget's brick factory established (Hlavsa & Vančura 1983)
1785	Small island beyond 6th pillar of the Charles Bridge vanished (Semotanová 1995)
1816–28	Right bank: first sewerage caused changes on a bank (Jásek 2006)
1840–44	Right bank: upstream the Charles Bridge, first embankments
1875–77	Right bank: embankments downstream of the Charles Bridge
1890	Break in the Charles Bridge caused by flood (Brázdil *et al.* 2005)

no significant changes can be observed (Figure 4). The Staroměstský weir is located about 300 m upstream of the cross-section area and was built before 1452 (Soukup 1905; Malý 1966). The influence of the weir can be seen as constant (Tomek 1891; Table 3) during the period of interest; with a report by Vosyka (1893) detailing the continuity of the level of the Prague weirs to at least from 1730. In accordance with Tomek (1891), Malý (1966) provides evidence of stabilization, number and geometry of Prague weirs from at least the 15th century. As a result of the high levels of detail provided and the homogeneous state of the riverbed as presented in the bathymetric survey, the data from 1900 are used for the calculation of all flood events in the period 1481 to 1825.

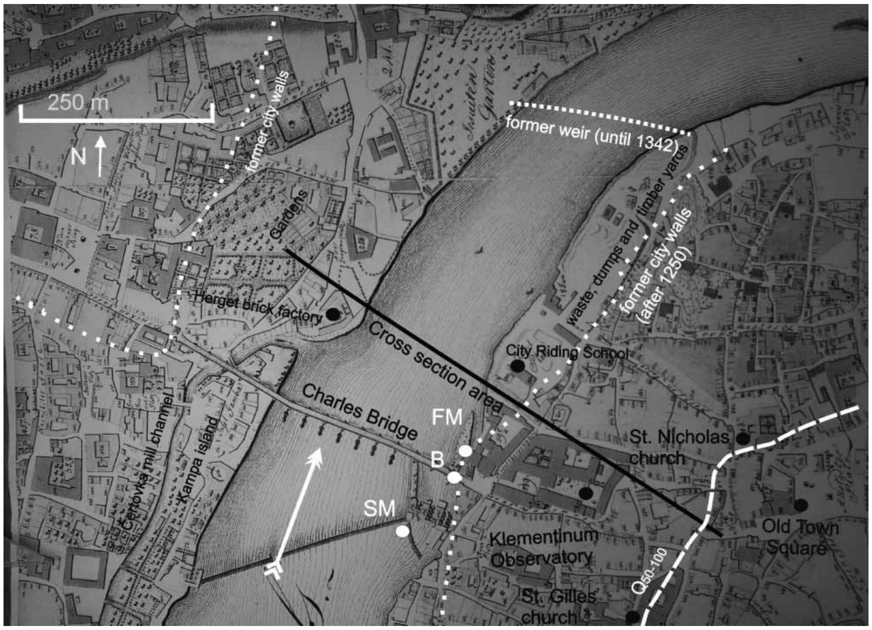

Figure 2 | Herget's map of Prague from 1791 with investigated sector 150 m downstream of the historic Charles Bridge.

Figure 3 | Bathymetry of the River Vltava at Prague 1910.

During the entire period of interest in this study, the fundamental components of the cross-section profile remained insignificantly modified aside from the floodplain. Considering different generalization styles within the maps, the settlements gradually occupy larger areas.

Hydraulic radius (R)

The hydraulic radius is calculated as $R = A/P$, with cross-section area (A) and wetted perimeter (P). Like the cross-section area, the wetted perimeter can be determined from

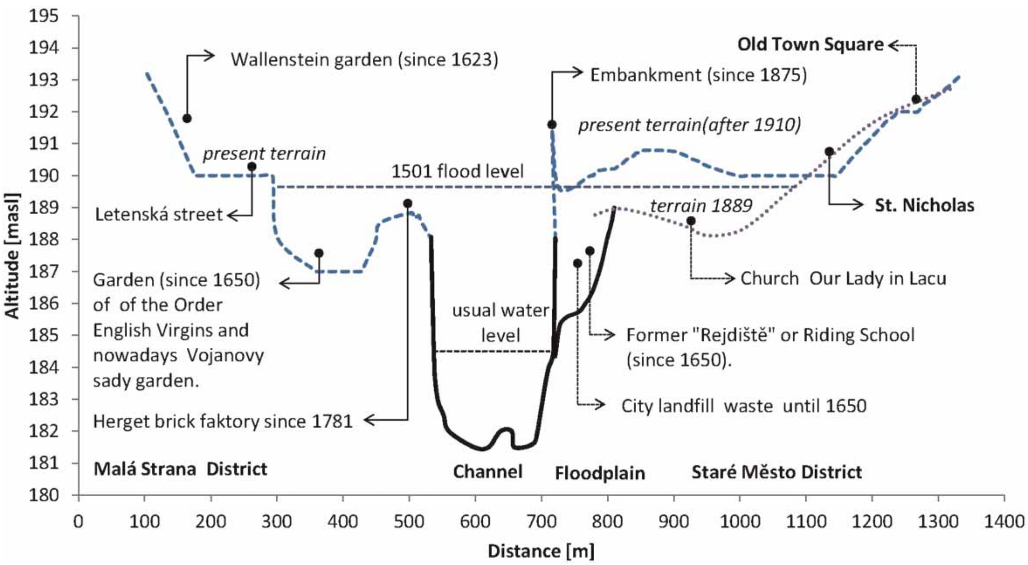

Figure 4 | Prague, cross-section profiles of the river channel based on Bathymetry (1900) and Topography (1889).

modern topographic maps and from archaeological investigations that show the floodplain topography.

Slope (*S*)

As in numerous previous palaeohydrological studies, the slope (*S*) is related to the slope of the water level instead of the slope of the energy line according to the Manning equation (Chow 1959). During and after the time of interest, no significant changes (in this context) took place. The modern value of 0.00084 m/m (estimated based on water levels and flood-marks from the 2002 flood) is applied for all water levels.

Manning's roughness coefficient (*n*)

Estimating the hydraulic roughness is the principal challenge in reconstructing flood discharges. Numerous factors influence the values, changing by place and time. Elements affecting the hydraulic roughness (Chow 1959, pp. 101f) are considered in the algebraic form of:

$$\mathrm{n} = (n_1 + n_2 + n_3 + n_4 + n_5 + n_6 + n_7 + n_8 + n_9)\,\mathrm{m} \qquad (2)$$

with n_1 surface roughness, n_2 vegetation, n_3 channel irregularity, n_4 channel alignment, n_5 silting and scouring, n_6 obstruction, n_7 stage and discharge, n_8 sediment load (density of water), n_9 seasonal changes, and m being a correction factor for meandering of the channel. For each of the four elements of the cross-section profile, a roughness coefficient n is estimated to take into account individual aspects of hydraulic roughness. Elements of uncertainty remain and to quantify these, a range for each factor of importance in each cross-section element mentioned above is given as $n_{x\ \mathrm{min}} < n_x < n_{x\ \mathrm{max}}$ and a most plausible value n_{xp} listed. The evaluation of Manning's n will be undertaken in four sections: the left bank, main channel, floodplain on the right bank and Old Town, and these are detailed in the following sections.

Prague district Malá Strana

The left river bank of the river was settled and urbanized during the entire period considered within this investigation, with increasing density after 1550 (Hlavsa & Vančura 1983). As a result of the narrow and winding roads and lanes it is expected that the mean flow velocity is assumed to be practically zero. This is confirmed by personal observations during the severe flood of 2002, during which large parts of the modern wide roads were inundated by virtually standing water, with no visible downstream movement of water. By algebraic expression, the value of obstruction roughness

n_6 equals to infinity ($v = 0$ m s^{-1}). In practice, this observation is an argument for leaving out the district Malá Strana and Kampa in the estimation. Due to the relatively large volume of water passing through the city of Prague within the river channel each second, the volume of water inundating the island of Kampa is negligible.

River channel

Recent investigations reveal that the channel bottom of the River Vltava in Prague consists of coarse gravels with minor irregularity expressed within bed forms (Geological profile 1890). According to Chow (1959, pp. 101f), this can be transferred to a surface roughness factor of $0.026 < n_1 < 0.028$ with $n_{1\mathrm{p}} = 0.027$ and a channel irregularity of $0.002 < n_3 < 0.008$ with $n_{3\mathrm{p}} = 0.004$. The channel has a minor degree of curvature that can be transferred to a channel alignment value of $0.000 < n_4 < 0.004$ with $n_{4\mathrm{p}} = 0.002$ (Chow 1959). The factor of obstruction has also a minor effect with a value of $0.000 < n_6 < 0.004$ with $n_{6\mathrm{p}} = 0.002$.

The correction factor for channel meandering is $m = 1.05$, reflecting the slight arc in the river at the profile location. During high flood levels, vegetation (n_2) within the channel and along the river banks is of minor hydraulic influence. According to scale, silting and scouring (n_5) are also of minor importance. Due to the separation of the cross-section area into different elements, which are studied individually, stage and discharge effects (n_7) are negligible. The influence of sediment load (n_8) cannot be quantified directly and, as a result, the generalizing empirical character of the Manning equation is assumed to be less important. Seasonal changes (n_9) mainly influence the vegetation and are not of significant influence for the river channel itself. As such, the hydraulic roughness for the channel is in the range of $0.029 < n < 0.046$ with a plausible mean value of $n_\mathrm{p} = 0.037$.

Floodplain

During the time of interest, a floodplain on the right side of the river between the historic city centre Staré Město and the river channel existed. Its topography can be reconstructed from archaeological investigations (Brázdil *et al.* 2005). Elleder (2010) reconstructed the relationship between the water levels at the main Prague gauge (Staroměstské mlýny) and the flooding area of the Old Town (Staré Město) from documentary sources. The shape of the floodplain has changed little since the 14th century (Hrdlička 1984, 1994, 1997, 2000a, 2000b). Different illustrations of the floodplain give information on the coverage of vegetation or the increasing building density. The floodplain was used for storage of shipped goods, and several buildings were constructed during the investigation time which requires a detailed analysis. Different illustrations of land use provide information on roughness elements (Figures 2 and 5). The soil of the floodplain consists of coarse sand and gravel, related to a surface roughness value of $0.026 < n_1 < 0.030$ (Acrement & Schneider 1989) with the most plausible value being $n_{1\mathrm{p}} = 0.028$.

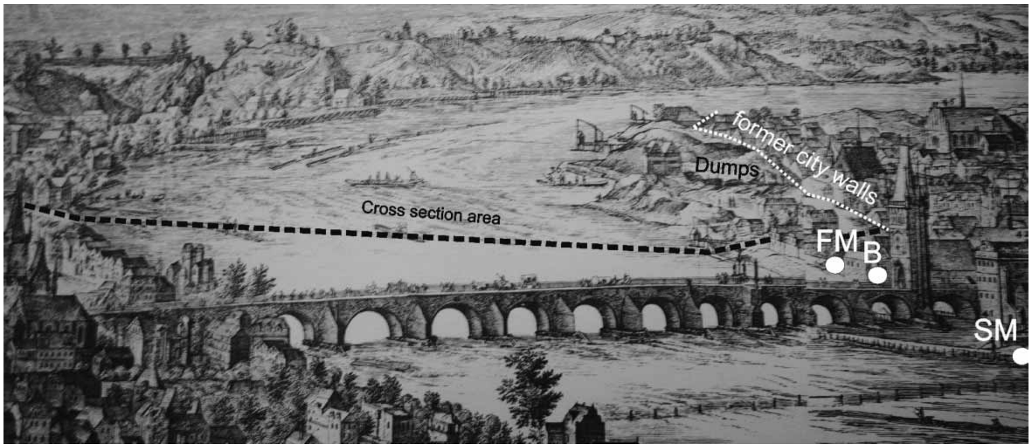

Figure 5 | Etching of the floodplain to the north of Charles Bridge in 1606. 'Sadeler prospect of Prague', by Filip van den Bosche, etching by Jan Wechter, MHMP (Museum of the Capital City Prague), inv.n. 17442/1–4 detail.

The influence of vegetation changed during the period of investigation. In the case of the flood events between 1481 and 1531, the floodplain was covered by occasional trees and low vegetation. Depending on the artistic representation of the area derived from paintings of this period, values with a wider range of 0.01 and 0.05 (Acrement & Schneider 1989) with $n_{2p} = 0.025$ are applied. In the period since 1531, the floodplain (behind the city walls) was used as a store for wood, public baths, ferries, and as a large dumping place for extraction of saltpetre for production of gun powder since 1560 (Starec 2005; Table 3, Figure 5); with vegetation (trees) removed to improve its use. The influence of grass-vegetation and smaller weeds are related to a vegetation-value of $0.005 < n_{2p} < 0.025$ (Acrement & Schneider 1989) with a plausible value of $n_{2p} = 0.01$. Given that winter flood events are not calculated, it is not necessary to estimate the influence of winter vegetation. Within the floodplain, some minor rises and dips have an effect on the degree of irregularity. These are quantified as $0.001 < n_{3p} < 0.005$ (Acrement & Schneider 1989) with $n_{3p} = 0.003$.

Alignment effects (n_4) are not relevant, as the entire plain is considered. Silting and scouring (n_5) cannot be observed by analysis of paintings. Due to the minor influence of silting and scouring in the roughness coefficient these effects can be disregarded.

The degree of obstruction changed during the period of investigation hence different values are calculated. Between 1481 and 1550, the far scattered obstructions have a minor effect with an estimated range of $0.00 < n_{6p} < 0.01$ (Acrement & Schneider 1989) with $n_{6p} = 0.004$. Between 1551 and 1725, the accumulation of logs have an effect with an estimated range of $0.004 < n_{6p} < 0.020$ (Acrement & Schneider 1989) with $n_{6p} = 0.01$. Between 1726 and 1824, some buildings were constructed on the floodplain. These buildings have a major effect on the obstruction value with an estimated range of $0.02 < n_{6p} < 0.03$ (Acrement & Schneider 1989) with $n_{6p} = 0.03$. Stage and discharge effects (n_7), the sediment load (n_8) and the correction factor for meandering (m) are not of further importance for this element of the cross-section profile. Due to exclusion of winter flood events, the effect of seasonal changes (n_9) is also not considered.

The historic city centre (district Staré Město)

For the area of the historic city centre located on the eastern bank of the river, estimates that are comparable with those for the district Malá Strana can be assumed. Most roads and lanes in this district are orientated perpendicular to the main direction (Figure 2). Hence, the urban area within the cross-section profile is not considered for discharge estimation because of the significant high hydraulic roughness caused by obstructions n_6.

RESULTS AND RELIABILITY CHECK

Based on the data and derived parameters, peak discharge for historic large-scale flood events were estimated (Figure 6). The principle of the approach is illustrated by the flood event of 1501 (Table 4). This extreme flood represented a considerable danger for the Charles Bridge, as wood from flooded lumber yards became stuck and constrained the river's flow. The water level reached more than 120 cm above the head of the Bradáč sculpture, which agrees with the description of flooding in the Old Town. Our Lady in Lacu church on Mariánské náměstí square in the Old Town was flooded, the water level reached St Gilles and St Nicholas church (Figure 4), with flood waters reaching up to Dlouhá ulice Street adjacent to the Old Town Square.

For verification of calculated discharges in Prague, we took advantage of the unique situation of a closing cross-sectional profile of the Elbe River in Děčín, where the discharge of most of the Czech Republic (CR) area is concentrated. The profile is situated in a relatively deep sandstone valley, which makes it stabile over long timescales. The preserved flood-marks on the castle rock in the city of Děčín (Brázdil et al. 2005) may be applied in a cross checking of calculated historic flood peak discharges in Prague. During the 2002 flood the peak discharge in Prague was 5,150 $m^3 s^{-1}$. The peak discharge in Děčín, reached 4,770 $m^3 s^{-1}$ (Kašpárek et al. 2005). Reduction of peak flows between Prague and Děčín is associated with the impact of a large floodplain at the confluence of the Labe and Vltava, providing an area over which flood waters spread, reducing peak discharges downstream of this point, relative to upstream.

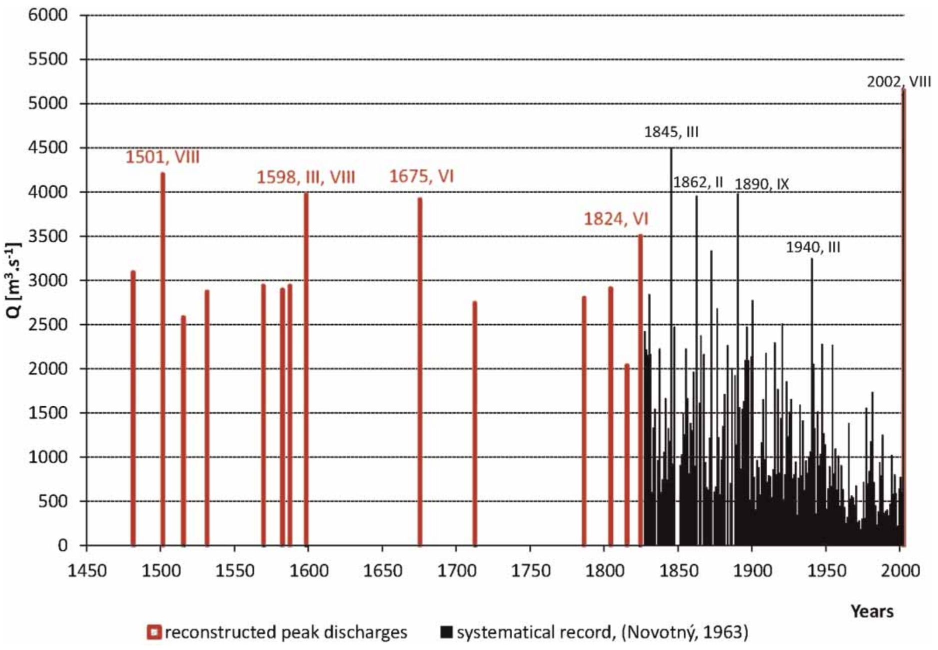

Figure 6 | Estimated peak discharges of historic floods compared with systematic records based on Novotný (1963) and the 2002 flood event.

Table 4 | Estimated parameters of the 1501 flood

	River channel	**Floodplain (right bank)**	**Entire relevant cross-section**
A_p cross-section area	1,337 m²	280 m²	1,617 m²
Min n-value	0.029	0.037	–
Max n-value	0.037	0.085	–
Mean n-value	0.037	0.06	–
V mean flow velocity (for n_p)	2.84 m s^{-1}	1.06 m s^{-1}	–
Q_p peak discharge	3,799 m³ s^{-1}	298 m³ s^{-1}	~4,100 m³ s^{-1}

Under the assumption that the ratio between discharges in Prague and Děčín remains the same, i.e., the discharge in Děčín represents about 92% discharge in Prague. The estimate therefore of the 1501 peak flood discharge in Prague is 4,100 m s^{-1}. If we used the current gauge rating curve for Děčín, the peak discharge would be equal to 3,800 m^3 s^{-1}; Figure 7 demonstrates the relationship between the flood peak discharges in Prague and Děčín.

DISCUSSION

Extreme floods in 1997 and 2002 coupled with exploration of likely impacts of climate change triggered the expansion of historical hydrology in the Czech Republic. Directly after the 2002 flood in Prague it was necessary to study this extreme flood with respect to its magnitude within the historical context (e.g., Brázdil *et al*. 2005). The presented attempt to improve the estimation of peak discharges for Prague based on a combination of knowledge of historical flood peak water levels, analysis of changes in floodplain, and hydraulic calculation, has so far remained unequalled. Although Svoboda (1990) presented an estimation of peak discharges in Prague and Dresden, this was based merely on a simple regression between peak flows at the two cities. Our approach is significantly more rigorous, taking into account and combining more sources of input data specifically of the

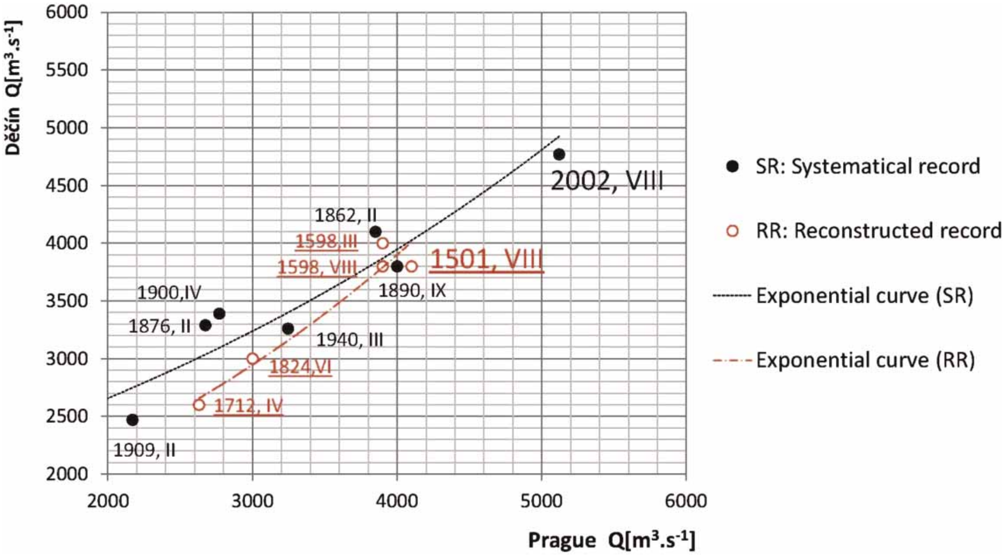

Figure 7 | The relationship between estimated flood peak discharges in Prague and Děčín.

location investigated. Moreover, the presented approach sets up a background for further refinement of the frequency analysis of historical floods presented by Brázdil *et al.* (2005), eventually for calculation of return periods taking into account historical discharge maxima.

The results reveal that in Prague the August 2002 flood was the largest, with respect to reconstructed discharge maxima, since 1481 (Figure 6). The most important from the period 1481–1824 was in August 1501. The 1501 flood generating mechanism was persistent rainfall over eastern parts of the Alps and the Bohemian massif, combined with high flows in the Danube and its tributaries, the Elbe and Oder rivers. The extreme flood recorded at Prague was also well documented at Linz and Vienna (Brázdil *et al.* 2005; Rohr 2007), and Dresden and Breslau (Girgus & Strupczewski 1965). Therefore, we can consider the flood on 15 August 1501, as a major event, with respect to its regional extent, but also in the context of Central Europe, which was comparable in many ways to that of August 2002.

Estimated discharges (Figure 6) within the floodplain represent about 5–10% of the total estimated discharge (in floodplain plus river channel). As compared with the discharges based on rating curves constructed by Professor Harlacher in 1892 (Richter 1892), our discharges are greater by about 7–8%, compared to discharges based on rating curves constructed by Professor Wiesenfeld in 1837 (Fritsch 1851), which are even lower by 20%. If we considered only the river channel, not taking into account the floodplain, the discharges would be lower by 15 and 25%, respectively.

Developed on the data of historic floods of the River Rhine (Herget & Meurs 2010), the presented method can be applied in numerous other areas of Europe (e.g., Brázdil *et al.* 1999; Pfister 1999; Benito 2003; Glaser 2008), China (Cheng-Zheng 1987) or India (Kale 1998), if flood inventories and information detailing the floodplain since historic times are available. Like the established slack-water deposit approach (Baker *et al.* 1983) frequently applied outside settled areas, the estimated peak discharge provides a valuable contribution for flood frequency analysis beyond just the timing of the event (e.g., Baker 1987; Kidson & Richards 2005; McEwen & Werritty 2007). Problems in adding single floods from historic times to the gauged datasets are discussed in detail, e.g., in Kirby *et al.* (1987), House *et al.* (2002), Benito *et al.* (2004) and Benito & Thorndycraft (2005). Flood frequency analysis considering the historic floods in Prague discussed in this study has previously been undertaken (e.g., Brázdil *et al.* 2005). The atmospheric circulation pattern in historic times resulting in local and regional extraordinary floods has also been investigated (e.g., Pfister 1999; Jacobeit *et al.* 2003; Mudelsee *et al.* 2004; Glaser 2008).

CONCLUSION

Our results for Prague clearly show that the approach to the peak discharge estimation of historic flood levels in a settled area presented in this paper can successfully be applied. Although we obtained results of adequate accuracy, room for further improvement still exists. This potential rests in gaining more information and knowledge on floodplain changes through the incorporation of new archaeological studies currently being undertaken in Prague. Nevertheless, even after such an anticipated possible refinement in the future, we do not expect our results presented here to be changed substantially. Based on presented analysis focused on reconstruction of peak discharges, we can summarize that the flood of 2002 has been, with respect to peak flow, the most important summer flood event in Prague since 1481.

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MAPS AND PLANS

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