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Trends in flood risk of the River Werra (Germany) over the past 500 years

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Abstract A record of floods from 1500 to 2003 of the River Werra (Germany) is presented. The reconstruction is based on combining documentary and instrumental data. Because both data types have overlapping time intervals, it was possible to apply similar thresholds for flood definition and obtain a rather homogenous flood series. The kernel method yielded estimates of time-dependent flood risk. Bootstrap confidence bands helped to assess the significance of trends. The following was found: (a) the overall risk of floods in winter (November–April) is approximately 3.5 times higher than the summer flood risk; (b) winter flood risk peaked at around 1760 and 1860 – it increases again during the past decades; and (c) summer flood risk peaked at around 1760 – it shows a long-term decrease from then on. These trends for the Werra contrast with those of nearby River Elbe, reflecting the high spatial variability of orographic rainfall.

Key words bootstrap confidence band; Central Europe; documentary climate data; flood risk; kernel estimation; orographic rainfall; runoff measurement; Thuringia

Tendances du risque d'inondation dans la vallée de la rivière Werra (Allemagne) durant les 500 dernières années

Résumé Nous présentons un inventaire des débordements de la rivière Werra (Allemagne) de 1500 à 2003. La reconstitution est basée sur une combinaison de données documentaires et de mesures. Le fait que les deux types de données concernent des intervalles de temps qui se chevauchent partiellement, a permis d'utiliser des seuils similaires pour la définition des crues et d'obtenir des séries assez homogènes. La méthode du noyau nous a permis d'établir des estimations du risque d'inondation au cours du temps. Les intervalles de confiance estimés par la méthode du bootstrap ont contribué à apprécier la signification des tendances observées. L'étude a donné les résultats suivants: (a) le risque général d'inondation en hiver (novembre à avril) est environ 3.5 fois plus élevé que le risque d'inondation en été; (b) ce risque connaît un pic autour de 1760 et de 1860 – il augmente à nouveau au cours des dernières décennies; et (c) le risque d'inondation en été culmine aux environs de l'an 1760. Il est suivi d'une diminution à long terme depuis cette date. Les résultats concernant la rivière Werra contrastent avec ceux relatifs à l'Elbe, rivière proche, reflétant ainsi une variabilité spatiale élevée des précipitations orographiques.

Mots clefs intervalle de confiance par la méthode du bootstrap; Europe centrale; données climatiques documentées; risque d'inondation; estimation de noyau, précipitations orographiques; mesure de débit; Thuringe

INTRODUCTION

The *Encyclopedia of Statistical Sciences* gives a short definition of risk: "adverse probability" (Gardenier & Gardenier, 1988). Flood risk is considered in this paper as the probability of a flood; and flood occurrence rate is used to denote flood risk per time interval. The latest IPCC report (Houghton *et al.*, 2001) considered the risk of river floods over the next decades to rise as a result of an intensified hydrological cycle caused by elevated temperatures. This idea can be tested using sufficiently long records of past flood risk. Because instrumental measurements go back only to the

19th century, it is necessary to include other information such as documentary data (Brázdil *et al.*, 2005). Historical climatology has added considerably to the understanding of past climatic extremes such as floods (Thorndycraft *et al.*, 2003, 2005, 2006; Glaser & Stangl, 2004; Wanner *et al.*, 2004; Kundzewicz *et al.*, 2005).

The results on flood risk changes in central Europe obtained so far have been reviewed by, for example, Hunt (2002) and Mudelsee *et al.* (2004). The results appear to fail to reveal unambiguous upward trends in flood risk over the past decades. This may be owing to several reasons: (a) inadequate methodology: estimation of time-dependent risk is a difficult statistical task (Mudelsee, 2005). For example, analyses based on regressions or *t* tests fail because they study the mean and not the extremes of a hydrological variable (Mudelsee *et al.*, 2004). Any meaningful flood risk estimation has to provide error bars or confidence bands to allow assessment of whether a trend is real, or may have come by chance into the data. (b) Insufficient resolutions: in the temporal domain, this means that winter and summer floods should not be jointly analysed because their hydrological properties are different. Whereas some previous studies seem to have neglected this point, seasonal differentiation has become standard practice today. Winter floods in Central Europe have often been caused or enhanced by a melting snow cover or a jam of breaking river ice, as a result of a more sudden thawing in spring. Summer floods are related to rainfall, mostly over longer (several days) time scales. An example is the Elbe flood in mid-August 2002, caused by extended rainfall over the preceding two weeks (Ulbrich *et al.*, 2003). Note that in hydrology winter is from November to April and summer is from May to October (Schmidt, 1984). In the spatial domain, flood risk analyses have to reflect the high spatial variability of rainfall (Liljequist & Cehak, 1984).

The study by Mudelsee *et al.* (2003) was an effort to overcome the limitations mentioned in the preceding paragraph. In this paper, modern statistical techniques (kernel flood risk estimation and bootstrap confidence band construction) are applied to temporally (winter, summer) and spatially (middle Elbe, middle Oder) resolved, reconstructed flood records. No upward trends were found in the occurrence of summer floods, while downward trends in the occurrence of winter floods were detected. While some events occurred simultaneously in the neighbouring rivers, in general, there is a weak correlation between Elbe and Oder floods (Mudelsee *et al.*, 2003). This emphasizes the high spatial resolution required. It has been argued (Kundzewicz, 2004, page 529) that the "failure to detect a significant trend is not a proof of the absence of change." This argument misses the point that, in empirical natural sciences, there exist no mathematical proofs. Instead, hypotheses are tested (Popper, 1935). In this regard, the paper by Mudelsee *et al.* (2003) failed to reject the null hypothesis of "no trend in summer flood risk." Even if, one day, enough data were available to find a significant trend, the question would remain whether, despite its statistical significance, such a trend would be "physically significant" (von Storch & Zwiers, 1999). It has further been argued against the findings of Mudelsee *et al.* (2003) that "monthly interval is not adequate temporal resolution for studying intense precipitation and floods" (Kundzewicz *et al.*, 2005, p. 179). However, the runoff records analysed by Mudelsee *et al.* (2003) had daily resolution. (We assume that daily resolution would be adequate according to Kundzewicz *et al.*, 2005.) Further, it may be asked whether the long memory of runoff or water stage time series (Hurst, 1951; Hosking, 1984) does not support obtaining meaningful results also from monthly resolved flood records. Indeed, the verdict of Kundzewicz *et al.* (2005) would practically rule out the use of historical sciences in hydrology because documentary data are hardly ever obtained that allow one to construct flood records at better than monthly resolution. On the contrary, we think that historical sciences can provide useful data that allow quantitative insight not obtainable from measurements alone (Mudelsee *et al.*, 2006).

The present paper is a step in the direction of the flood risk research programme indicated previously (Mudelsee *et al.*, 2004):

(a) Produce records of floods in individual rivers, at monthly or at least seasonal resolution over the past centuries.
(b) Combine documentary with instrumental evidence to achieve data homogeneity.
(c) Use quantitative flood risk estimation methods with error band.

Here, a new record and analyses of floods are presented for the German River Werra, from a region where abundant historical information for the past five centuries is available. Although the Werra is a relatively small river, its basin location is important because a spatial gap is closed. To the west and southwest of the Werra is the River Main, for which floods have been previously analysed by, for example, Brázdil *et al.* (1999) and Tetzlaff *et al.* (2002). To the east is the basin of the River Elbe (Mudelsee *et al.*, 2003).

The geographical–hydrological setting is explained in the next section, followed by a section on the documentary and measured data. A table of Werra floods for the interval 1500–2003 is provided. Flood risk is then estimated with kernel functions and confidence bands.

GEOGRAPHICAL SETTING

The Werra (Figs 1 and 2) drains a small basin (5505 km^2) that is under a continental, low-range mountainous climate, on the southwesterly slope of the Thüringer Wald and the western part of the Thüringer Schiefergebirge. These mountain ranges (altitudes up to 900 m a.s.l.) support the formation of precipitation. In the hydrological winter season (November–April), westerly winds prevail. Precipitation events in that area are often enhanced by up-slope winds. It should be kept in mind that, to form flood-producing rains, additional ingredients are required such as a slow moving frontal system and also enough water vapour in the atmosphere. Winter floods can be enhanced by breaking river ice, functioning as a water barrier. Also snowmelt contributes to winter floods.

The Meiningen station is located 223 km above the Werra mouth, at a height of 282 m a.s.l. The Werra at Meiningen drains a basin of 1170 km^2. The Meiningen runoff data serve to construct the flood record for the instrumental period.

In the hydrological summer season (May–October), the mountain range of the Thüringer Wald acts as an obstacle to the atmospheric flow. The water vapour content of the atmosphere is then higher than in winter. The empirical frequency of disturbances large enough to produce area-covering precipitation is, however, lower than in winter. Thus the probability of large quantities of rain falling on the whole catchment area of the River Werra and, hence, of floods, is assumed to be higher in winter than in summer.

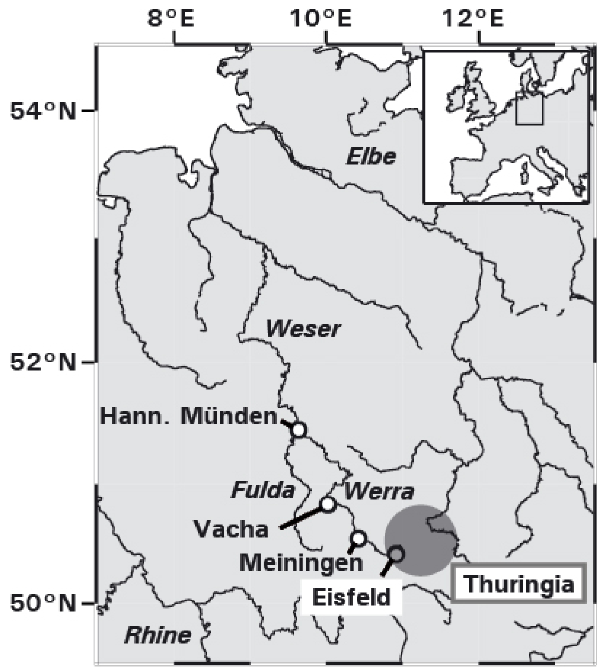

Fig. 1 Geographical setting. The Rivers Werra and Fulda join at Hann. Münden to form the River Weser. Focus in the present study is on the upper and middle Werra, between Eisfeld and Vacha stations. The runoff time series from Meiningen station is analysed. "Thuringia" refers to the low-mountainous regions of Thüringer Wald and Thüringer Schiefergebirge. Inset shows setting within European region.

DATA

Documentary period, 1500–1900

Our work focuses on the upper and middle parts of the river, between Eisfeld and Vacha (Figs 1 and 2). The time frame is the interval from 1500 to 1900. We consulted almost exclusively primary historical sources in order to preserve the original information. Most data entries are manuscripts located at the Thüringisches Staatsarchiv Meiningen (Schloß Bibrabau, Meiningen, Germany) and Thüringisches Staatsarchiv Gotha (Schloß Friedenstein, Gotha, Germany). Of further importance were official announcements, orders and other official files. In particular, the sources of the offices of road construction or river engineering in the former Duchy of Sachsen-Meiningen contain detailed descriptions of individual flood events. As an example, the river engineer Eduard Fritze (1849–1926) rendered an expert opinion about the severe flood of the River Werra in November 1890. These two documents can be found at the Thüringisches Staatsarchiv Meiningen as: (1) *Sammelakte zu verschiedenen Verwaltungsvorgängen, darunter auch: Acten des Herzogl. Verwaltungs-Amtes Salzungen betr. Naturereignisse.* Kreisarchiv, KA 3903; (2) *Technische Berichte zum Hochwasser am 24./25. November 1890,* Staatsministerium, Abt. des Innern, Nr. 3132.

Further original documents consulted include the following: (1) *Beobachtung des höchsten Wasserstandes an der Werra* (1871–1878); Thüringisches Staatsarchiv Meiningen, Kreis Hildburghausen, Nr. 03126; (2) *Räumung der fließenden Gewässer* (1886–1887); Thüringisches Staatsarchiv Meiningen, Kreis Meiningen, Nr. 1521;

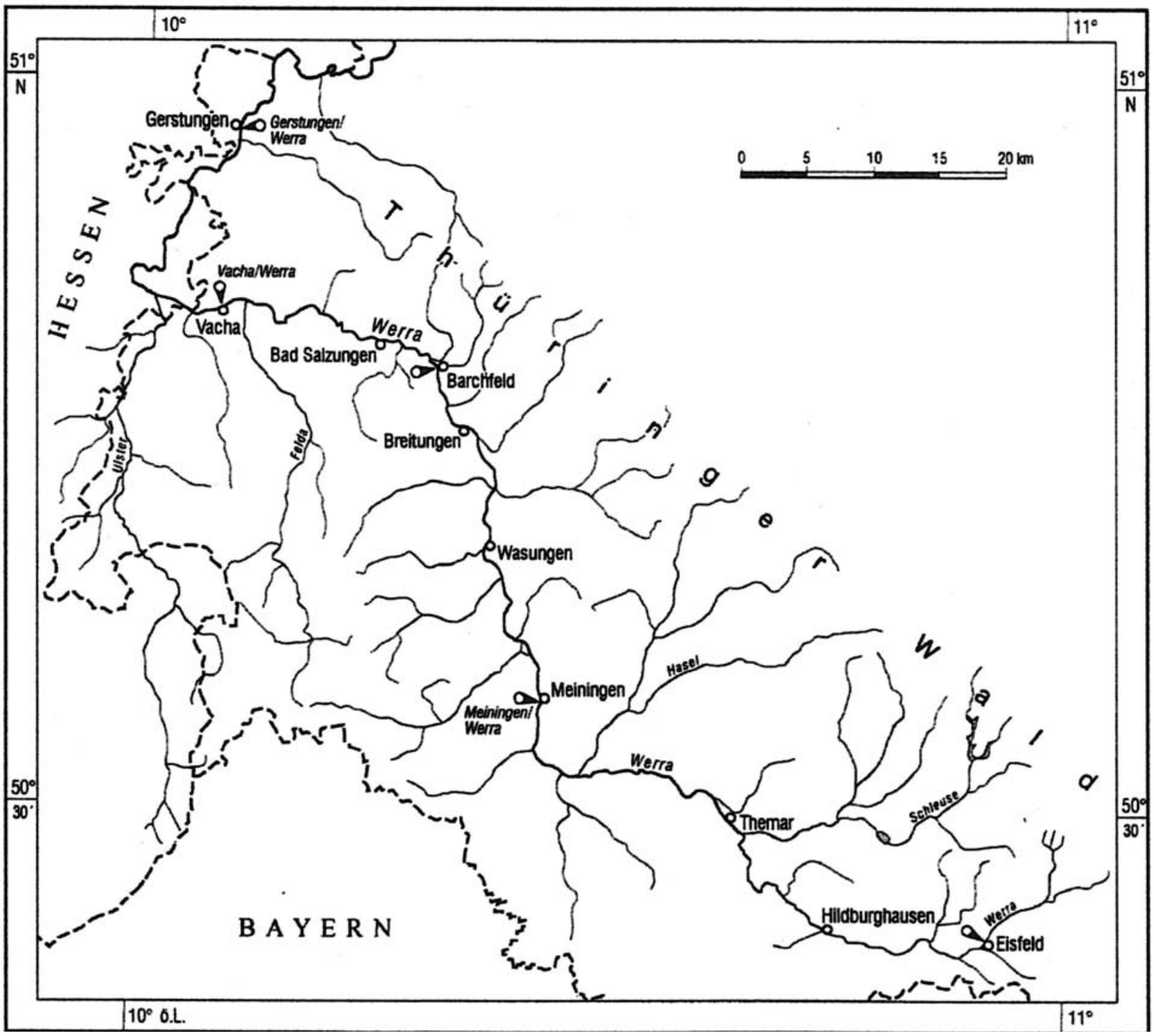

Fig. 2 Detailed map of the Werra catchment area. Bayern, Bavaria; Hessen, Hesse; ö.L., longitude E.

(3) *Ufer- und Wasserbau im Bezirk Breitungen* (1849–1866); Thüringisches Staatsarchiv Meiningen, Kreis Meiningen, Nr. KA 42; (4) *Auszüge Dorfordnung Obermaßfeld* (1722); Thüringisches Staatsarchiv Meiningen, Kreis Meiningen, Nr. KA 740; (5) *Wasserbaupolizei* (1830); Thüringisches Staatsarchiv Meiningen, Kreis Meiningen, Nr. KA 4909; (6) *Hochwasser* (1891–1904), Thüringisches Staatsarchiv Meiningen, Staatsministerium, Abt. des Innern, Nr. 4106; (7) *Setzen des Wassermaßes bei der Wiesenmühle allhier* (1717–1775); Thüringisches Staatsarchiv Meiningen, Kreis Hildburghausen, Nr. 02236; (8) *Räumung der Werra* (1762–1806), Thüringisches Staatsarchiv Meiningen, Kreis Hildburghausen, 03141; (9) *Grundriß der alten Werra zwischen Ober- und Untermaßfeld* (1803); Thüringisches Staatsarchiv Meiningen, Kartensammlung, Schrank 1, Nr. 368; and (10) *Verlauf des Werraflusses von der Wernshäuser Brücke bis Salzungen, 2 Blätter* (1748); Thüringisches Staatsarchiv Meiningen, Kartensammlung, Schrank 3, Nr. 244.

For cross-checking the partly hand-written documents, secondary, printed sources were also consulted, such as the Meiningen chronicles from Güth (1676) and Schaubach (1834), or, in the case of the 1529 flood, the compilation by Weikinn (1960). Since about 1800, local newspapers have given numerous reports on river floods. Caution is required when interpreting them because of biases (exaggerations) in the size of an event. Finally, information was drawn from an analysis of Werra floods made at the Institut für Wasserwirtschaft of the German Democratic Republic (Krause, 1966).

Besides the written flood reports, river maps and engineering plans could be inspected. Maps of flood inundation areas exist from about 1850 onward. Photographs of the strong flood events in June/July 1871 and November 1890 allowed cross-checks of the reported flood inundation areas. Photographs from another flood (February 1909) are shown in Fig. 3. Although flood marks on buildings exist (Meiningen, Wasungen and Bad Salzungen), we did not use them, because flood marks in that region have been displaced during renovations, mainly after 1990 (Deutsch, 1997).

The total number of entries collected (upper to middle Werra, 1500–1900) is about 450. The following descriptive properties of each flood were derived: (a) date (year, season, month, often also day and hour); (b) causes (melting snow cover under thawing, jam from breaking ice under thawing, long-lasting rainfall and cloudburst); and (c) the magnitude of a flood, assessed by means of the following information: extent of inundated areas, degree of economic damage and number of casualties. Because of the limited accuracy inherent in such data types, only three magnitude categories were formed (Table 1), following current hydrological practice (Brázdil *et al.*, 1999; Mudelsee *et al.*, 2003).

The compilation and analysis of documentary data on Werra floods began 1993. This work is documented in publications such as Deutsch & Pörtge (2003) and Deutsch *et al.* (2004). More information on "Historical Floods and Historical Flood Protection" and the related database can be obtained from http://www.matdeutsch.de (Mathias Deutsch).

Instrumental period, 1880–2003

The Meiningen station (Figs 1 and 2) provides a long runoff record. These data were inferred from water stage measurements and runoff–stage relationships. For the interval from November 1880 to October 1920, only monthly minima, means and maxima are available, without a documented runoff–stage relationship. The uncertainty introduced thereby should, however, be clearly smaller than the widths of the magnitude classes defined in the following subsections, because only three classes were used. For the purpose of connecting the documentary Werra flood record to the present, only the maximum values are useful. Unfortunately, the maxima show several data gaps: in particular, the interval from January 1891 to December 1900 is missing, as well as the hydrological year 1917. Two maximum values have been corrected downward (Kowalski, personal communication, January 2006): November 1890 (from 458 to 300 $m^3 s^{-1}$) and February 1909 (from 361 to 220 $m^3 s^{-1}$). The trends of mean monthly and mean maximum runoff values from 1880 to 1920 show good overall visual agreement, which supports the quality of the reconstruction.

Fig. 3 The February 1909 Werra flood at Meiningen. (Photographs courtesy of Staatliches Umweltamt Suhl, Germany.)

Daily runoff values are available from 1 November 1918 to 31 October 2003. In the overlapping interval (November 1918–October 1920), an excellent agreement (median absolute deviation about 1 $m^3 s^{-1}$ or 6.5%) is found between monthly maxima as given and monthly maxima calculated from daily averages. A data gap from 1 November 1944 to 31 October 1945 exists in the daily runoff record from Meiningen. However, this gap could be closed (Table 1) by employing the daily runoff series from Hann.

Table 1 Flood database River Werra, 1500–2003.

Year	Month	Season * (S, W)	Cause † (I, S, C, R)	Q_{max} Meiningen ($m^3 s^{-1}$)	Q_{max} Hann. Münden ($m^3 s^{-1}$)	Magnitude ‡
1505	Jul	S	C			2
1524		W	S			2
1524	Dec	W				?
1529	Aug	S				2
1530		S				2
1539	Jan	W	S			2
1551	Jan	W	R			1
1552	Jan	W	R			2
1553	Mar	W	S			1
1565	Mar	W	I, S			2
1569	Jul	S				1
1582	Jul	S	C			2
1595	Feb	W	S			2
1607	Apr	W	C			3
1609	May	S	R			1
1610	Jan	W				?
1616	Jun	S				?
1624		W	I, S			2
1633	Jan	W				2
1643	Jan	W				2
1652		W				1
1652	Jun	S	R			?
1655	Feb	W				2
1660	Nov	W	S			1
1667	May	S	R			1
1670	Jan	W	I, S			1
1670	Dec	W				2
1673	Jun	S	R			2
1675		S	R			1
1677	Jan	W	I, S, R			2
1682	Jan	W	S, R			3
1688	Jun	S	C, R			1
1692	Nov	W	I?, R			1
1695	May	S	C			1
1702	Jan	W	S			1
1702	Dec	W				?
1709	Jan	W	I, S			2
1719	Dec	W	S, R			2
1720	Dec	W	R			3
1725	Jan	W				?
1728	Jan	W	S, R			1
1729	Jan	W	I, S, R			1
1729	Mar	W	R			1
1730	Feb	W				2
1730	Mar	W	I, S			3
1735	Jul	S	R			2
1739		W				2
1740	Mar	W	I, S			?
1740	Dec	W	R			?
1741	Jan	W				?

Table continued overleaf /…

Year	Month	Season * (S, W)	Cause † (I, S, C, R)	Q_{max} Meiningen ($m^3 s^{-1}$)	Q_{max} Hann. Münden ($m^3 s^{-1}$)	Magnitude ‡
1743	Jan	W	I, S			2
1743	Apr	W				1
1744	Mar	W	I, S			2
1745	Aug	S	C			2
1752	Jul	S	R			1
1752	Aug	S	R			1
1756	Jun	S	C			1
1759	Dec	W	I, R			2
1760	Jan	W				2
1760	Feb	W				1
1761	Feb	W				1
1764	Jan	W	R			3
1765	Apr	W	C			1
1766	Jun	S	C			1
1767	Sep	S	R			1
1767	Dec	W	R			2
1768	Sep	S	C			1
1769	Dec	W	S, R			1
1770	Mar	W	S, R			2
1770	Nov	W	C			1
1773	Jan	W	R			1
1775	Feb	W	I, S, R			2
1776	Feb	W	I, S			2
1778	Jan	W	S			1
1779	May	S	R			1
1781	Feb	W	S			1
1783	Nov	W	S, R			1
1784	Feb	W	I, S			3
1785	Apr	W	S			1
1795	Feb	W	I			?
1799	Mar	W	I, S, R			2
1808	Jun	S	R			2
1809	Jan	W	I, S			?
1816	Jun	S	R			2
1818	May	S	R			2
1820	Jan	W	S			1
1830	Feb	W	I, S			2
1830	Mar	W				2
1830	Aug	S				?
1831	Mar	W	I		864	2
1831	Nov	W	S		652	1
1833	Dec	W			911	1
1838	Mar	W	I, S		324	1
1841	Jan	W	I, S		1184	1
1842	Apr	W			692	1
1843	May	S	R		442	1
1844	Feb	W			911	2
1845	Mar	W	I, S, R		1440	2
1846	Jan	W	S, R		1768	3
1848	Feb	W	I, S		634	1
1852	Feb	W	R		1055	1
1853	Apr	W			444	1

Year	Month	Season * (S, W)	Cause † (I, S, C, R)	Q_{max} Meiningen ($m^3 s^{-1}$)	Q_{max} Hann. Münden ($m^3 s^{-1}$)	Magnitude ‡
1854	Dec	W	R		1055	1
1862	Jul	S	R		575	1
1865	Apr	W	S, R		1037	1
1867	Feb	W	S, R		1280	?
1867	Apr	W			911	?
1869	Nov	W	R		547	2
1870	Dec	W			988	1
1871	Feb	W	S		690	1
1871	Jun/Jul	S	R		1037	3
1876	Feb/Mar	W			908	2
1880	Oct	S			620	1
1881	Mar	W	S, R	193	1156	1
1882	Nov	W		176	1341	2
1883	Jan	W	R	150	956	1
1888	Mar	W	C	164	1027	1
1890	Jan	W		144	873	1
1890	Nov	W	R	300	1248	3
1891	Jan	W	I, S		520	1
1895	Mar	W		154	478	1
1899	May	S	R		162	1
1904	Feb	W		136	602	1
1909	Feb	W		220	1394	3
1914	Mar	W		144	687	1
1925	Dec	W		133	1295	1
1939	Dec	W		128	991	1
1945	Feb	W			715	1
1946	Feb	W		151	1537	1
1947	Dec	W		131	765	1
1965	Dec	W		139	726	1
1967	Dec	W		161	620	2
1970	Apr	W		136	440	1
1979	Jan	W		171	320	2
1981	Mar	W		202	812	2
1982	Jan	W		168	618	2
1987	Jan	W		142	715	1
1994	Apr	W		181	803	2
1995	Jan	W		125	1010	1
1998	Sep	S		138	264	1
1999	Mar	W		129	564	1
2002	Jan	W		156	684	2
2003	Jan	W		174	903	2

* S: Summer season, May–October; W: winter season, November–April.

† I: ice and thawing; I?: eventually ice and thawing; S: snow and thawing (no ice); R: long-lasting rainfall; C: cloudburst.

Q_{max}, maximum runoff; Meiningen Q_{max} values are from records (Kowalski, personal communication) of monthly maxima for November 1880–October 1918 (several data gaps and interval from January 1891 to December 1900 nearly completely missing) and daily values for 1 November 1918–31 October 2003 (interval 1 November 1944–31 October 1945 missing); Hann. Münden Q_{max} values are from daily values (Thomas de Couet, personal communication, GRDC, Koblenz, March 2006) for 1 January 1831–31 December 2003 (no missing data);

‡ Magnitudes of flood events: 1: minor; 2: strong; 3: exceptionally strong; ?: unknown; the February 1945 flood is uncertain because it is based only on Q_{max} at Hann. Münden.

Münden (Fig. 1), which goes from 1 January 1831 to 31 December 2003. The monthly distribution of floods shows a pronounced seasonal dependence, with winter floods occurring more often than summer floods (Fig. 4).

The stage–runoff relationship at Meiningen (Fig. 5) shows, for the upper (flood) values, a marked shift in 1986/87. This is likely to be related to hollowing of the inundation area started at around that time (Kowalski, personal communication). For fixed runoff, the associated water level became lower, especially for higher (flood) values (Fig. 5). A quantification of the effects of changes in river geometry on runoff can be carried out using the Manning–Strickler equation (Tetzlaff *et al.*, 2002). However, this is beyond the scope of the present paper.

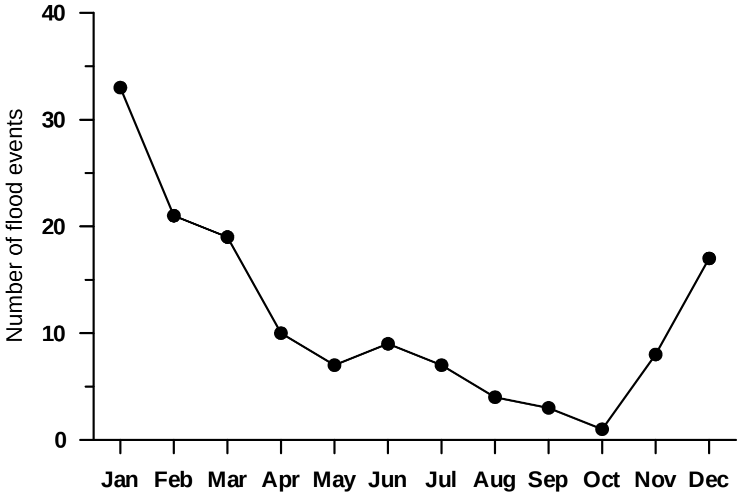

Fig. 4 Monthly distribution of the Werra flood events, all magnitude classes, 1500–2003.

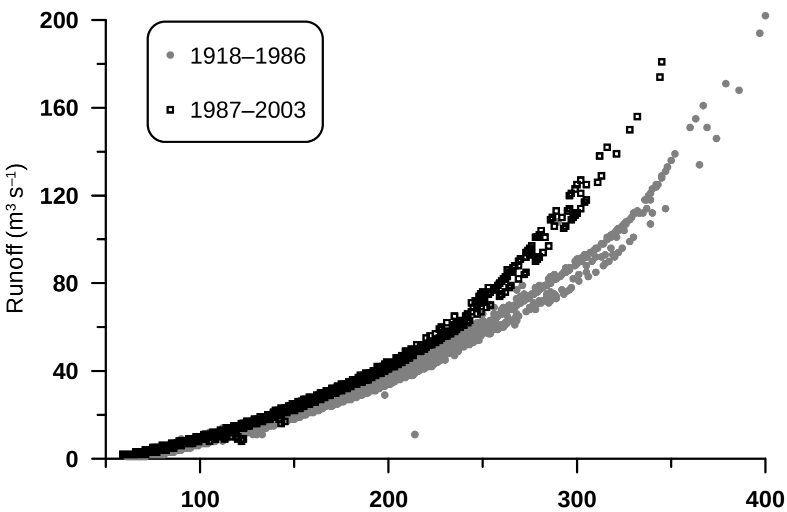

Fig. 5 Stage–runoff relationship, Werra at Meiningen, based on daily values from 1 November 1918 to 31 October 2003.

Total period, 1500–2003

Owing to the overlapping time interval for which both documentary and instrumental data are available (see preceding subsections), construction of a combined Werra flood record for the interval 1500–2003 was straightforward. From the floods within 1880–1900 that are inferred from documentary data, the January 1890 event had the lowest measured runoff value (144 $m^3 s^{-1}$ at Meiningen). From the data within 1880–1900, for which no documentary information was found, i.e. from the "no-flood" data, the May 1882 runoff was highest (124 $m^3 s^{-1}$ at Meiningen). This means that a suitable choice of the threshold for defining a flood event should lie between 124 and 144 $m^3 s^{-1}$ runoff. Because it turns out (see following section) that flood risk during the 20th century is lower than in the preceding century, we set the threshold at 125 $m^3 s^{-1}$ in a conservative approach. This ensures that the low 20th century flood risk (Fig. 6) is not an artefact of a too high threshold. As regards the other thresholds (defining a Magnitude-2 or Magnitude-3 event), we set them such that the relative proportions (number of Magnitude-1 floods to number of Magnitude-2 floods to number of Magnitude-3 floods) from the documentary period are retained in the instrumental period. The boundary between Magnitude 1 and Magnitude 2 was set as 155 $m^3 s^{-1}$ runoff at Meiningen; the boundary between Magnitude 2 and Magnitude 3 as 210 $m^3 s^{-1}$.

RESULTS

The simplest method to quantify flood risk over time is to form intervals (say, 1500–1550, 1550–1600, and so forth) and count the number of floods that occurred within each interval. The problem here is that only few estimation points (ten in the case of the Werra) would be produced. An improvement is to use quasi-continuously shifted intervals (as in running mean smoothing). The method is then called kernel smoothing, and the kernel function used is a uniform function (Silverman, 1986), because all floods within an interval have the same weight. Uniform kernel functions for flood risk estimation have been used by, for example, Glaser & Stangl (2004). The method can be further enhanced by adopting a smooth kernel function (that means, weighting) and using a mathematical method to solve the smoothing problem (choice of interval width). Finally, a confidence band around the estimated flood risk curve can be constructed using bootstrap simulations. See Mudelsee *et al.* (2004) for a detailed explanation of the method.

A Gaussian kernel function, K, was used to weigh observed flood dates (Table 1), $T(i)$, $i = 1, ..., n$ (number of floods), and calculate the occurrence rate (probability per time unit), λ, at time t as (Mudelsee *et al.*, 2004):

$$\lambda(t) = h^{-1} \sum_i K\{[t - T(i)]/h\} \quad (1)$$

Selecting the bandwidth, h, that means, solving the smoothing problem, was achieved by cross-validation (Mudelsee *et al.*, 2004). To reduce boundary effects, pseudodata generation (rule "reflection") was employed (Mudelsee *et al.*, 2004).

A confidence band around estimated $\lambda(t)$ is essential for interpreting the statistical significance of the "wiggles" in the risk curves (Fig. 6). We constructed this band by means of bootstrap simulations (Cowling *et al.*, 1996; Mudelsee *et al.*, 2004). A

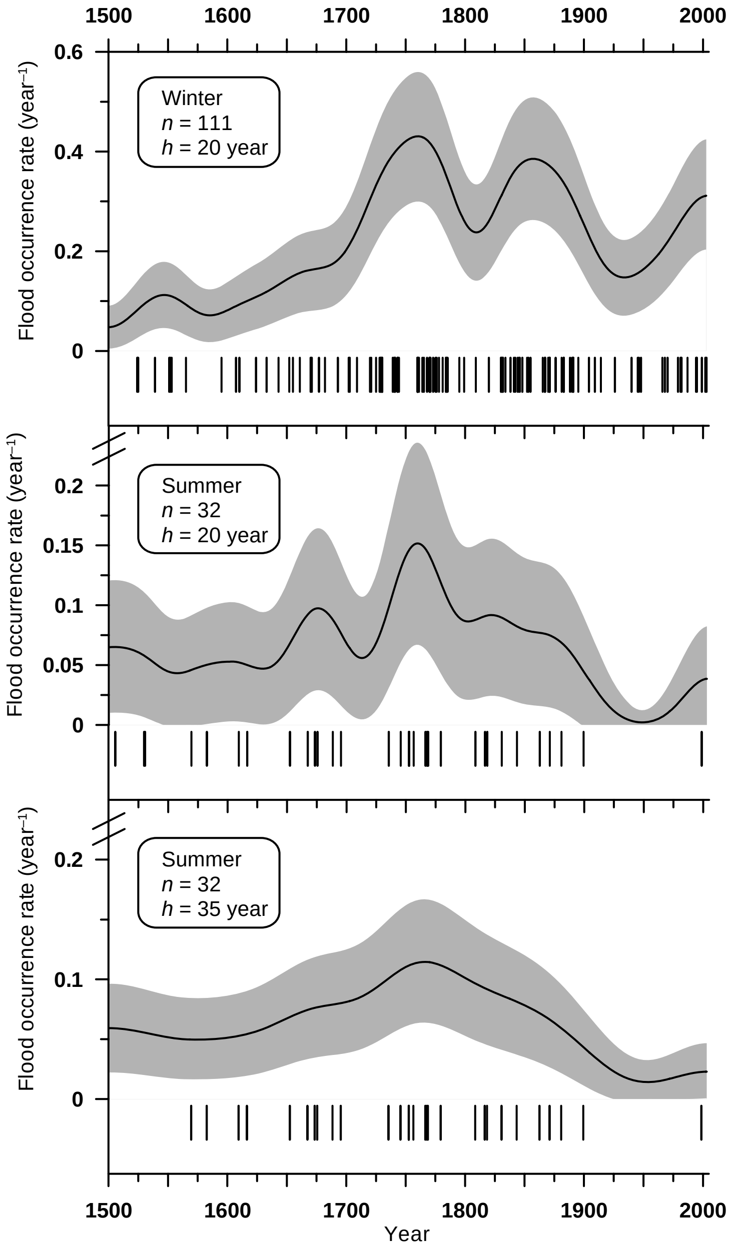

Fig. 6 Trends in Werra flood occurrence rates (risk probability per time unit), 1500–2003, showing the estimated flood occurrence rates (heavy lines) with 90% bootstrap confidence bands (shaded). The flood events (Table 1) are marked at the bottom of each panel. Winter and summer floods are analysed separately; summer floods are examined using two different smoothing bandwidths. *n*, number of flood events; *h*, bandwidth of the kernel function (equation (1)).

number of n simulated floods were drawn from $T(i)$ with replacement and simulated $\lambda(t)$ calculated. This procedure was repeated 2000 times. From the 2000 simulated curves we then calculated a percentile-*t* confidence band (Cowling *et al.*, 1996).

In the case of winter floods, cross-validated bandwidth, h, is 20 years, which allows to resolve decadal-scale changes in flood risk. The bootstrap confidence band confirms the significance of those changes (Fig. 6). For example, the peak in winter flood risk at around 1760 is approximately 0.42 year^{-1}, which is higher than the upper bound of the confidence band at t = 1810 (approximately 0.32 year^{-1}). For facilitating comparison, we also calculated summer flood occurrence rates using h = 20 years. However, because of the clearly smaller data size of summer floods (n = 32) in comparison with winter floods (n = 111), the summer flood trends are less significant. Therefore we calculated summer flood trends also using h = 35 years.

For the winter, the resulting estimates (Fig. 6) demonstrate that flood risk for the upper and middle Werra is clearly higher (approximately 3.5 times) than summer flood risk. From 1500, winter flood risk, as reflected in the documentary data, increased steadily until a peak was reached at around 1760. A significant low at around 1810 followed, then again a peak at around 1860. From then until the mid-20th century, winter flood risk dropped strongly. Since 1935, there is a notable upward trend in the risk of Werra winter floods. This tendency is likely to be significant and not an artefact of a too low threshold: The 1935 date is approximately one bandwidth after the date (1918) from which homogenous, daily runoff values are available.

Summer flood risk shows a similar peak to winter flood risk at around 1760. There are several wiggles in the less smoothed (h = 20 years) trend, but these are hardly significant (Fig. 6). This means that, broadly speaking, summer flood risk increased from 1500 to 1760 and decreased since then (Fig. 6, bottom panel).

DISCUSSION AND CONCLUSIONS

The natural question arises whether in the early part (16th and 17th centuries) the upward trends in risk of winter and summer floods (Fig. 6) reflect what really occurred in nature, or instead they result from a trend toward reduced document loss. Arguing from a historical–critical perspective, we at present believe that document loss played only a minor role, because historical information is quite abundant and well preserved for the Werra catchment area. On the other hand, we had to include minor floods (Magnitude 1) into the analyses to achieve statistically significant results. The influences of inhomogeneities such as document loss or perception bias are evidently greater for minor floods than for heavier floods (magnitudes 2 and 3). However, our data source selection (see section on data) reduced the degree of bias in the flood records (Table 1).

In the later part (1700 to present), Werra flood risk (winter and summer) exhibited significant changes, as was previously found for the longer, more eastward, rivers Elbe and Oder (Mudelsee *et al.*, 2003). However, Werra winter flood risk peaked low at around 1810, when Elbe winter flood risk was at its height. In the case of the rivers Elbe and Oder, the gradual decrease in winter flood risk from the mid-19th to mid-20th century was related to a reduced freezing rate, meaning a reduced ice-jam probability, of those rivers (Mudelsee *et al.*, 2004). The cause was probably regional warming (Folland *et al.*, 2001). In the case of the River Werra, it is more speculative to relate the decrease in winter flood risk from the mid-19th to mid-20th century to a reduced freezing rate, because ice conditions in the Werra have not yet been systematically analysed. Unlike the Elbe or Oder, the Werra winter flood risk increased during the past six decades. The downward trend in Werra summer flood risk since about 1760 is interesting, because the Elbe and Oder also do not reflect upward trends over the past hundred years.

The occurrence of large amounts of rainfall in the Werra catchment area usually involves a combination of several factors (Mudelsee *et al.*, 2004):

(a) westerly and cyclonic airflow;
(b) high atmospheric water vapour content;
(c) embedded convective instability; and
(d) prolonged (at least half a day) flow against the orography (Thüringer Wald).

It would be naïve to assume that with climate changes ("global warming") only factor (b) would change (via the Clausius–Clapeyron equation). In particular, the role of factor (d) should be analysed in the case of flood-risk changes in Central European regions under low-mountainous climate. The reason for this is the differences among the Werra, Elbe and Oder flood-risk curves, which indicate that the orographic differences among the catchment areas introduce a strong nonlinear component into the complex climate–hydrosphere system.

Our future work on central European floods shall therefore include the following:

(a) quantifying data inhomogeneities from document loss;
(b) analysing the role of non-climatic influences (deforestation, river engineering); and
(c) modelling climatic influences on flood risk, such as the North Atlantic Oscillation (Mudelsee *et al.*, 2004) and regional orography.

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