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The largest floods in the High Rhine basin since 1268 assessed from documentary and instrumental evidence

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Abstract The magnitudes of the largest known floods of the River Rhine in Basel since 1268 were assessed using a hydraulic model drawing on a set of pre-instrumental evidence and daily hydrological measurements from 1808. The pre-instrumental evidence, consisting of flood marks and documentary data describing extreme events with the customary reference to specific landmarks, was "calibrated" by comparing it with the instrumental series for the overlapping period between the two categories of evidence (1808–1900). Summer (JJA) floods were particularly frequent in the century between 1651–1750, when precipitation was also high. Severe winter (DJF) floods have not occurred since the late 19th century despite a significant increase in winter precipitation. Six catastrophic events involving a runoff greater than 6000 $m^3 s^{-1}$ are documented prior to 1700. They were initiated by spells of torrential rainfall of up to 72 h (1480 event) and preceded by long periods of substantial precipitation that saturated the soils, and/or by abundant snowmelt. All except two (1999 and 2007) of the 43 identified severe events (SEs: defined as having runoff > 5000 and < 6000 $m^3 s^{-1}$) occurred prior to 1877. Not a single SE is documented from 1877 to 1998. The intermediate 121-year-long "flood disaster gap" is unique over the period since 1268. The effect of river regulations (1714 for the River Kander; 1877 for the River Aare) and the building of reservoirs in the 20th century upon peak runoff were investigated using a one-dimensional hydraulic flood-routing model. Results show that anthropogenic effects only partially account for the "flood disaster gap" suggesting that variations in climate should also be taken into account in explaining these features.

Key words historical climatology; historical hydrology; High Rhine basin; pre-instrumental floods; river corrections; river hydraulics; flood routing; St Venant equation; numerical hydrodynamics; circulation patterns; extreme events; daily sea-level pressure

Les plus grandes crues du bassin du Haut-Rhin depuis 1268 évaluées à partir de données documentaires et de mesures instrumentales

Résumé Les débits des plus grandes crues du Rhin à Bâle ont été évalués à partir d'un modèle hydraulique basé sur un ensemble de données proxy à partir de 1286 et de mesures hydrologiques depuis 1808. Les données proxy se composent de marques d'inondation et de preuves narratives indiquant le plus haut niveau de chaque crue par rapport à un système de points de repère situés dans le voisinage du vieux pont. Ce système fut maintenu jusqu'au 19ème siècle tardif, ce qui a permis de "calibrer" les données avec la série des mesures instrumentales pendant la période de chevauchement des deux catégories de données. Des crues étaient fréquentes dans la période estivale de 1651 à 1750 marquée par des précipitations accrues. Il n'y a pas eu de grande crue hivernale depuis la fin du 19ème siècle, bien que les précipitations dans cette saison aient bien augmenté depuis le 19ème siècle tardif. Six événements "catastrophiques" impliquant un débit de plus de 6000 $m^3 s^{-1}$ sont documentés avant 1700. Ils ont étéconditionnés par de longues périodes de précipitation saturant les sols et/ou par une fonte de neige abondante, et déclenchés par des pluies intensives d'une durée allant jusquà 72 heures (1480). Les 43 évènements "sévères"

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ayant un écoulement estimé compris entre 5000 et 6000 m^3 s^{-1} ont eu lieu avant 1877, à l'exception de ceux de 1999 et 2007. Aucun évènement "sévère" n'a cependant été mesuré entre 1877 et 1998. Une telle "lacune de calamités" (disaster gap) n'est pas documentée depuis 1268. Les effets de deux corrections de rivières (la Kander en 1714 et l'Aar en 1877) et de la construction de réservoirs au 20ème siècle sur les débits extrêmes ont été analysés avec un modèle unidimensionnel numérique de propagation. Les résultats montrent que les effets anthropogéniques expliquent seulement un part de la "lacune de calamités", ce qui suggère que des variations climatiques ont aussi joué un rôle.

Mots clefs climatologie historique; hydrologie historique; bassin du Haut Rhin; crues pré-instrumentales; corrections de rivières; hydraulique de rivière; propagation de crue; équations de St Venant; hydrodynamique numérique; types de circulation; événements extrêmes; pression au niveau de la mer journaliére

INTRODUCTION

Unexpectedly large floods, outside the known range of extreme events involving substantial monetary and non-monetary impacts, are likely to increase in frequency and severity (Rosenzweig *et al.* 2007). However, the magnitude of floods with a return period of >200 years cannot be confidently assessed from the short instrumental period encompassing, in most cases, less than 150 years (Glaser & Stangl, 2004). Moreover, the comparison of pre-instrumental with instrumental floods would suggest that runoff conditions did not change over the last centuries: a situation which is rarely the case, as most rivers are affected by anthropogenic effects (regulations, construction of reservoirs, land-use change etc). Finally, effects of changes in spatio-temporal climatic patterns since the end of the Little Ice Age in the late 19th century should also be taken into account (Pauling *et al*., 2005; Pauling & Paeth, 2007).

Palaeohydrological information encapsulated in geophysical archives may provide clues with which to assess the magnitude of pre-instrumental mega-events (see e.g. Baker, 2002; Baker *et al*., 2002; Benito *et al*., 2004). Likewise, the methodologies arrived at in the field of Historical Climatology (Brázdil *et al*., 2005, 2006, 2010a) open up ways to reconstruct extreme events for several centuries previous to the availability of hydrological measurements, that improve the reliability and significance of river discharge time series (Grünewald, 2010). Often, such events are *in extenso* described in documentary reports (Sutcliffe, 1987; Pfister & Hächler, 1991; Gees, 1997; Sturm *et al*., 2001; Tetzlaff *et al*., 2003; Bürger *et al*., 2006; Pfister *et al.,* 2006; Thorndycraft *et al.,* 2006; Scherrer, 2007; Scherrer *et al*., 2008; Sudhaus *et al*., 2008 MacDonald, 2006; Brázdil *et al*. 2010b). Many long-term reconstructions using documentary data date back to 1500 (Brázdil *et al*., 1999; Wanner *et al*., 2004; Mudelsee *et al*., 2006; Glaser, 2008; Stucki, 2010), some to the 15th century (e.g. Brázdil *et al*., 2006b; Cyberski *et al*., 2006; Llasat *et al*., 2005; de Kraker, 2006; Rohr, 2006; Glaser *et al*., 2010; Schmocker-Fackel & Naef, 2010), or even prior to 1400 (Barriendos & Rodrigo, 2006; Böhm & Wetzel, 2006; Benito *et al*., 2003; Meurs, 2007; Glaser & Stangl, 2003). Herget & Meurs (2010) demonstrated for Cologne that the two floods of the River Rhine in 1993 and 1995 were the largest documented for the period of streamflow measurements (1782–2009), but were exceeded at least four times in the pre-instrumental period. The evidence of extreme pre-instrumental floods is already used for flood hazard mapping (Zaugg, 2003; Merz & Emmermann, 2006). At the same time, it improves the public risk awareness of catastrophic events (Grünewald, 2010).

This paper returns to suggestions by Pfister (1984) in his attempts to reconstruct the peak runoff of the largest floods of the River Rhine in Basel over the last 740 years, drawing on a long series of instrumental measurement (from 1808), a set of flood marks, a historic river profile (1819), and documentary data describing the stage of extreme floods with reference to specific landmarks in the town centre. It seeks to provide answers to the following questions:

(a) How large were the peak discharges of the most severe floods in the High Rhine basin since 1268, when the first flood of the Rhine in Basel is reported?
(b) What is the seasonality of these flood events? How stationary are the flood conditions, i.e. are any trends discernable?
(c) What were the climatic, meteorological and hydrological conditions that produced floods of this magnitude?
(d) Can we identify the effects of climate and river regulation on the flood conditions during the last 200 years?

The arguments are structured as follows: the next section includes a short overview of the High Rhine drainage basin; then the evidence and discussion of the methods are presented in the third and fourth sections, respectively. Results, including longer-term changes in flood frequency, severity and seasonality are presented in the fifth section. The effect of river regulation on peak runoff, as well as the meteorological reasons for Catastrophic Events (CEs), are discussed in the sixth section. Conclusions are drawn in the final section.

THE CATCHMENT AREA OF THE HIGH RHINE

The High Rhine basin upstream of Basel, with an area of approximately 36 000 km^2 and a mean elevation of 1022 m a.s.l., is drained by two main rivers, the Aare and High Rhine (Fig. 1). In both basins, maximum seasonal and monthly flows occur in summer, whereas the minimum is in winter**.** Sixty-seven percent of the Swiss territory is drained by the River Rhine at Basel (Fig. 1). Large floods in this town thus always result from extreme events affecting large parts of Switzerland.

The long-term mean (1892–2008) discharge of the Rhine at Basel, 1052 m^3 s^{-1}, comprises almost half of the mean discharge of 2200 m^3 s^{-1} measured close to the German–Dutch border at Lobith (Viviroli & Weingartner, 2002; Vischer, 2006). Hence, results from this study might also be of relevance for the regions situated further downstream (Viviroli & Weingartner, 2004). The runoff of the Aare was first affected by the artificial diversion of the Kander to Lake Thun in 1714, and between 1868 and 1891 it was controlled by the First Jura-Waters Corrections (FJWC), the cornerstone of which was the diversion of the Aare into Lake Biel in 1878. This regulation considerably affected the peak discharges of the River Aare and, thus, those of the Rhine at Basel. The runoff of the High Rhine was always modulated by Lake Constance, which, however, is still one of the few unregulated lakes in western Central Europe (Vischer, 2003) (Fig. 1). For more detailed information about the High Rhine catchment area (outline of geological structure, outline of soils and land use, outline of precipitation, etc.) see Belz *et al*. (2007).

THE EVIDENCE

The evidence documenting the historical hydrology of the Rhine at Basel consists of four kinds of data (Fig. 2):

The Basel gauge

One of the longest runoff series in Europe is that known for Basel. A gauge was installed in 1808 near the only bridge in existence at that time. Two years before, official instructions had been published for building and reading water-level gauges in Pfalz (Bavaria) (Göttle *et al*., 2010). In 1810 similar instructions were issued in Prussia (Deutsch, 2010). Initially, the gauge in Basel was read once a day. Then a recorder was installed. A time series from 1808 up to now is available without any interruptions (Fig. 2, I). The first part of the series up to 1913 was carefully analysed by the engineer Carlo Ghezzi (1926). The results of statistical tests show that the series for 1869–2006 is homogeneous under mean-flow conditions (Pfister *et al*., 2006).

Flood marks

Eleven flood marks covering the period from 1641 to 1882 are preserved at the "Schönbeinhaus" situated 400 m upstream of the above mentioned bridge (Fig. 2, II).

Chronicles

A rich legacy of chronicles was composed in Basel from the Late Middle Ages, in which the most disruptive floods are consistently described between 1268 and the 19th century (Fig. 2, II), when they give way to corresponding reports in the daily press. Most chroniclers described the magnitude of floods in the form of standard narratives, referring to specific landmarks in the built environment around the bridge (Pfister, 1999), and 19th century journalists pursued this tradition for some decades.

River profile

The condition of the river bed in the early 19th century (1819) is known from a cross-section of the river bed drawn by trained hydraulic engineers (Source S1; Fig. 2, III).

METHODS OF FLOOD RECONSTRUCTION

The assessment of the frequency and the magnitude of large pre-instrumental floods comprises four steps:

1. Critical evaluation of source reliability and validity.
2. Cross-checking the different kinds of evidence during the period of overlap in the 19th century and "calibrating" it with the instrumental observations (Fig. 3).

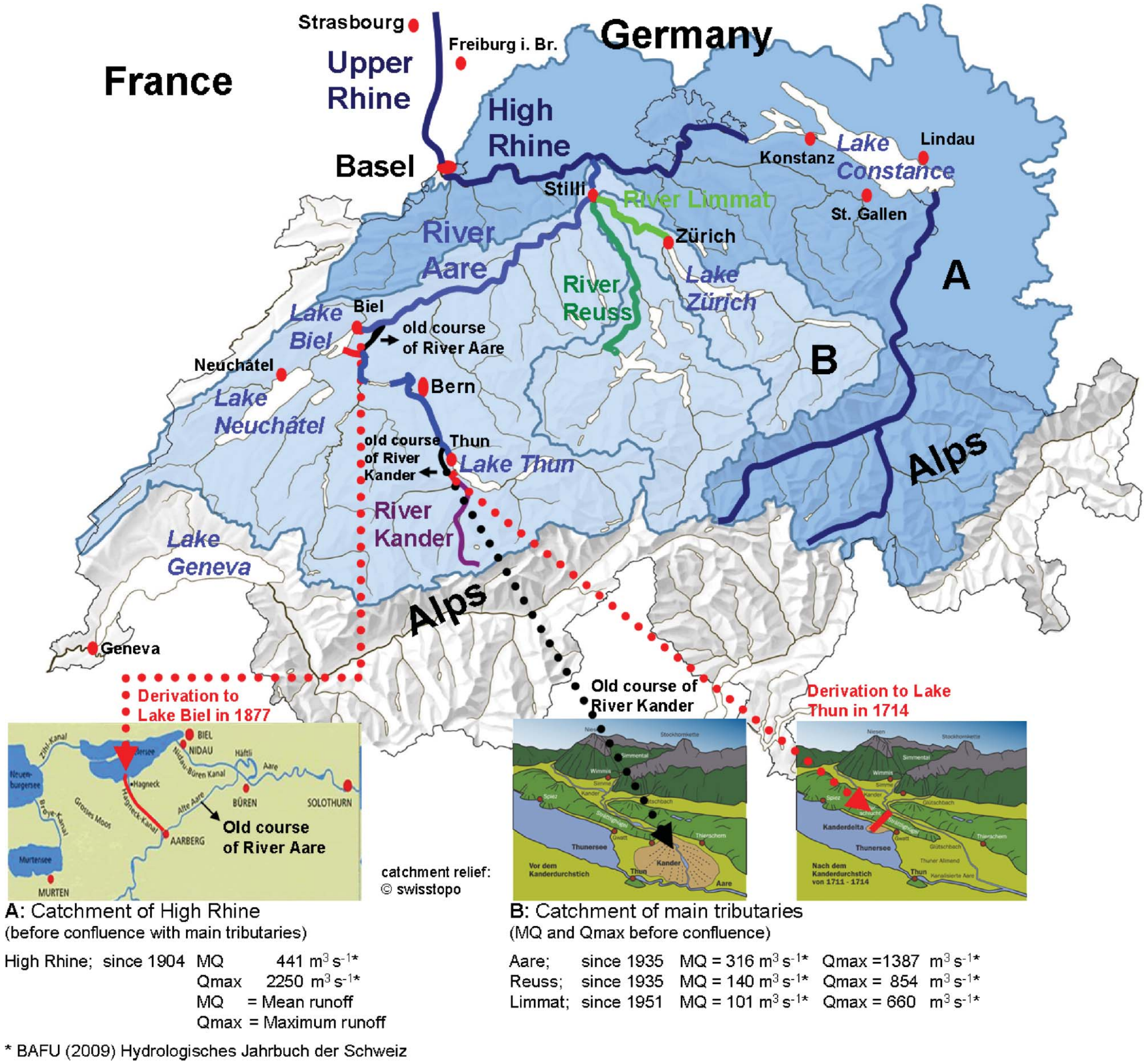


Fig. 1 River Rhine drainage basis, including old and new courses of the rivers Kander and Aare. Images of diversions from Hasler & Egli, 2004.

3. Reconstructing the peak level of very large floods for the pre-instrumental period.
4. Assessing pre-instrumental discharges with a hydraulic model.

These four steps are described below in greater detail.

Step 1: Evaluation of sources

As a first step, a critical assessment of historic documentary sources is essential (Sudhaus *et al*., 2008). The reliability of written sources needs to be ensured by confirming that the author lived at the same time as, and close in space to, the events he purports to describe (Bell & Ogilvie, 1978). Chroniclers were clerics, or educated laymen, who often wrote their memories by order of a town or regional authority. They focused on chronologies of outstanding events memorable for society, such as weather extremes, natural disasters, fires and famines. Communication of risk was one of their motivations, and in this view chroniclers attempted to compare the magnitude of recent floods to preceding ones (Pfister, 2009). Quite often they copied information from older chronicles without, however, quoting their sources, this not being a tradition at that time (Camuffo & Enzi 1992). Moreover, it is a necessity that dates are consistently given in Gregorian style as introduced in the

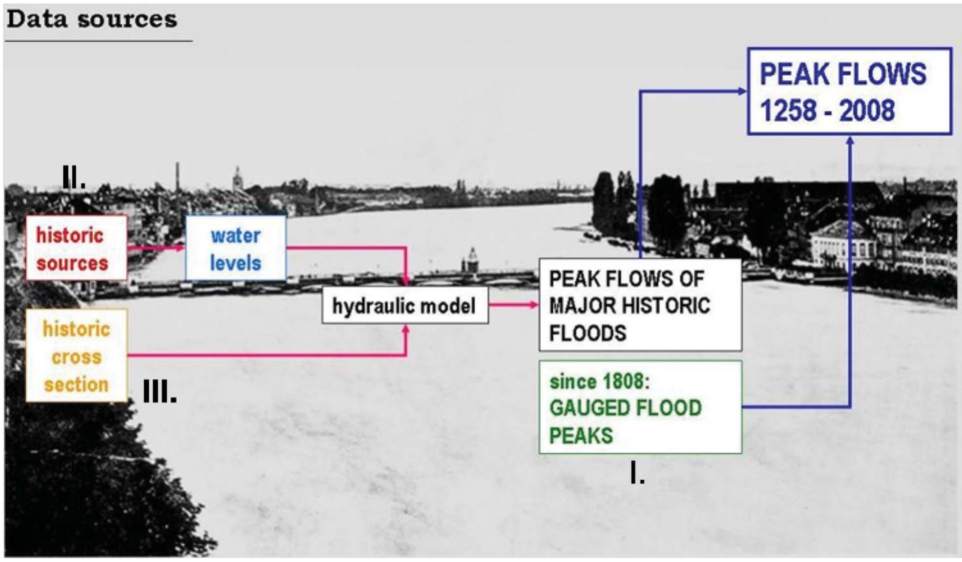


Fig. 2 Model of data sources. See text for explanation of I.–III.

Roman Catholic world in 1582. Previously, the Julian style was used and, in most Protestant territories such as Basel, it was retained until 1700 (Dershowitz & Reingold, 1997).

The reliability of flood marks needs to be checked against narratives that describe a given event in more detail. Of course, an assemblage of flood marks rarely provides a complete survey of the severe events documented within written sources. Munzar *et al*. (2006) distinguished three basic types of flood marks, namely:

Type a: simple notches without any additional information.
Type b: a notch and the year.
Type c: a notch and the date of the event.

The flood marks attached at the Schönbeinhaus are of Type b (Table 1; Fig. 2, II.) (Pfister, 1999). They had thus to be related to narratives providing the data of the event and describing it in more detail. At the same time, this cross-checking served as a reliability check (Table 1). Cross-checking of the marks with associated narratives revealed that all marks except one had a counterpart in the form of flood reports: no event is documented for 1726. Otherwise, the well-known severe flood of 11 July 1762 (Krapf, 1900) is missing in the panel, which suggests that the chiseller misread 1726 instead of 1762 (Pfister, 2006a).

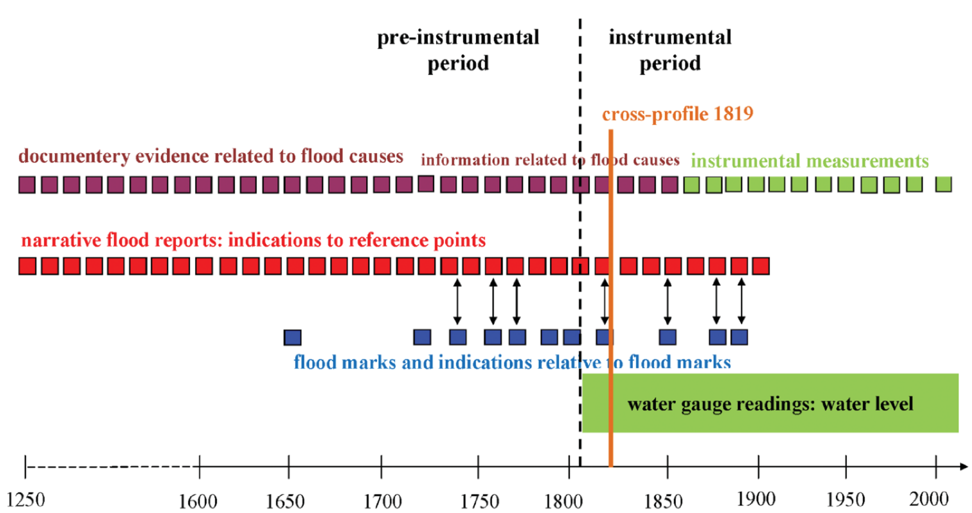
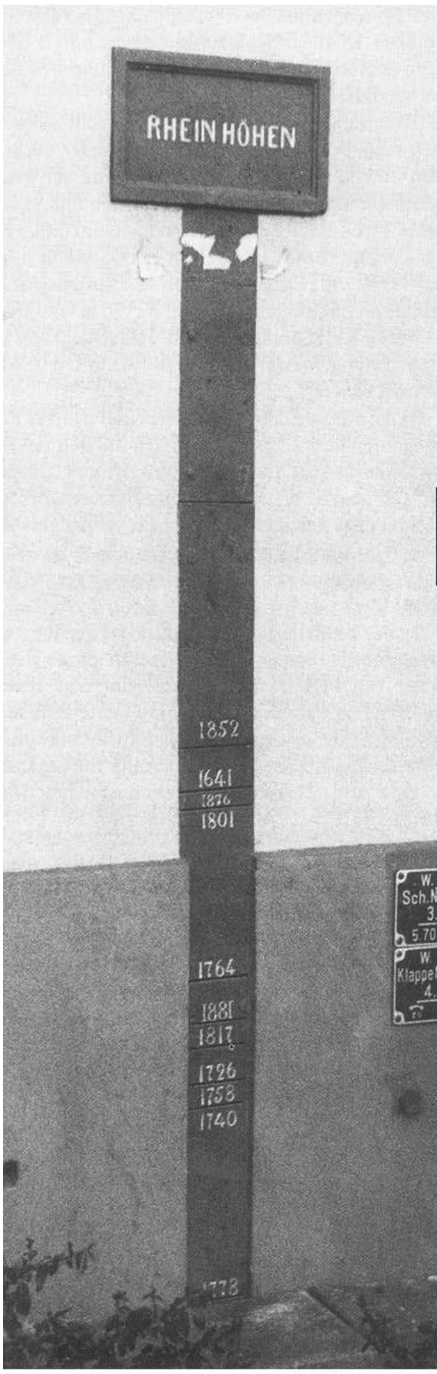


Fig. 3 Qualitative calibration; assigning gauges to pre instrumental "flood information systems" such as flood marks and/or narrative flood reports.

Step 2: Calibration of descriptive data

Step two of the approach involves cross-checking and comparing five sets of overlapping evidence during the 19th century, namely narrative flood reports (Fig. 3, red dots), flood marks (blue dots), daily gauge readings (green dots), instrumental measurements of temperature and precipitation (violet dots), and a river profile (vertical orange line). The comparison of flood marks with gauge readings revealed some minor inconsistencies. It is well known, that flood marks usually exhibit a scatter about the actual

Table 1 Reconstructed altitude of flood marks posted on the Schönbeinhaus at Oberer Rheinweg 93 in Lower Basel. Dates of floods (Gregorian calendar) were obtained from documentary evidence. **Bold** indicates measured discharge (Ghezzi, 1915; Rima, 1962); *italics*: discharge estimated by adding or subtracting the difference between the flood marks and the gauged 6.59 m in 1876.



Date of flood	Altitude of flood marks (official survey levelled in 2009) m a.s.l.	Measured peak flood altitude (near bridge) put on a level with flood marks (about 400 m upstream) m a.s.l.	Calculated discharge based on reconstructed peak flood altitude $m^3 s^{-1}$
18 Sep 1852	250.95 m	**250.58 m**	**5642 $m^3 s^{-1}$**
11 Jul 1641	250.88 m	*250.55 m*	*5579 $m^3 s^{-1}$*
13 Jun 1876	250.85 m	**250.52 m**	**5700 $m^3 s^{-1}$**
31 Dec 1801	250.85 m	*250.52 m*	*5532 $m^3 s^{-1}$*
22 Aug 1764	250.55 m	*250.22 m*	*5118 $m^3 s^{-1}$*
3 Sep 1881	250.48 m	**250.07 m**	**5280 $m^3 s^{-1}$**
6 Jul 1817	250.44 m	**250.04 m**	**4790 $m^3 s^{-1}$**
11 Jul 17***62***	250.38 m	*250.04 m*	*4879 $m^3 s^{-1}$*
26 Jul 1758	250.33 m	*250.00 m*	*4816 $m^3 s^{-1}$*
20 Dec 1740	250.33 m	*250.00 m*	*4816 $m^3 s^{-1}$*
25? Oct 1778	250.00 m	*249.67 m*	*4386 $m^3 s^{-1}$*
15? Jan 1791	250.00 m	*249.67 m*	*4386 $m^3 s^{-1}$*

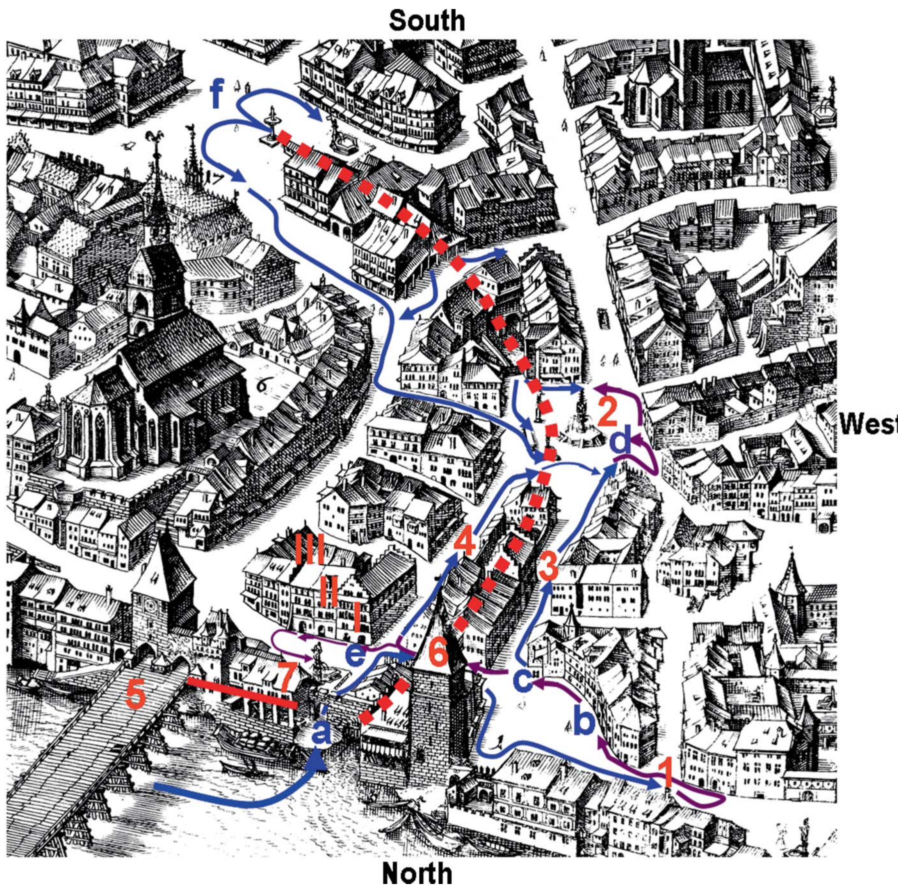


Fig. 4 Bird's-eye view by Matthäus Merian, 1615 (Source S20). Blue arrows indicate the direction of water flow; purple arrows – water accumulation; red bar: approx. the same height of the bridge and the windows of the Guildhouse; and red dotted line: underground flow of Birsig brook.

Legend (a)–(f) Landmarks related to water accumulation: (a) pier; pre-instrumental "distinction" between flood or non-flood; (b) accumulation of water up to (c); (c) flow off Schwanengasse (leading to Fish Market); (d) flow off / accumulation from lowest part of Fish Market; (e) accumulation up to house corner of guest house Krone; (f) overspill of the underground Birsig brook onto Grain Market because of a backlog effect by the increased water level of the Rhine. 1: lowest point of the inundation area; 2: Fish Market; 3: Schwanengasse, alley leading to Fish Market; 4: Kronengasse, alley leading to Fish Market; 5: city gate and bridge; 6: salt tower; 7: Guildhouse. I: Guest house "Krone"; II: Guest house "Tête d'Or"; and III: Guest house "Kopf".

flood levels. This can be caused by many factors, such as wave action, obstructions immediately up- or downstream of the flood mark, and water marks on buildings being higher than actual flood levels because of moisture rising up the walls by capillary action etc. (Water Resources Commission, 1986). In the case of Basel, the estimated peak runoff in 1852 is 1% lower than that of 1876, whereas the notch for 1852 is 10 cm higher. This example shows that small differences between flood marks should not be overestimated. The height of the lowest notch documenting the floods of 25 October 1778 and 15 January 1791 was determined at 250.00 m by official survey. It is worth mentioning that there is a difference of 0.38 m between the altitude (a.s.l.) of the notches of flood marks and the corresponding levels of the gauging station installed 400 m downstream close to the only bridge existing at that time (Table 1). It makes sense to refer the flood marks to the instrumentally gauged flood peaks instead of using their "correct" altitudes, because the measured heights correspond directly to the peak water levels at the area of interest; which is the Greater Basel flooding zone. Flood reports describing the level of floods with reference to specific landmarks in the built environment around the bridge remained the practice until the late 19th century. The bridge built in 1225 was only reconstructed between 1903 and 1905 (Baer, 1932), and most of the other historic landmarks also survived until that time. Thus, there is a substantial overlap between the daily gauge readings (from 1808) and the continuation of traditional flood severity assessments, which allows one to relate the landmarks to specific gauge levels. In order to understand the chronicler's landmark-related flood severity assessments, the reader needs to become familiar with the location and altitude of the specific landmarks which were being referred to. Likewise, he needs to comprehend in which sequence the streets and squares of the town were inundated by the rising water level in the case of a flood. The bird's-eye "View of the Town of Basel taken from the North", drawn by the famous copperplate engraver and publisher Matthäus Merian in 1615 (Fig. 4; Source S20), provides a full overview of the bridge and its surroundings. Numbers indicate the main flood severity landmarks referred to in the descriptive evidence. Arrows demonstrate the sequence of flooding (Fig. 4). The lowest of the landmarks was the pier (Fig. 4: a), which was an important collecting point for goods since the Middle Ages. Its height of 249.6 m (a.s.l.) was reconstructed from the cross-section of the river bed (Fig. 5). Most probably, this level was not changed until the construction of the new bridge in 1903–1905. This is also true for the rest of the area. The first houses with stone foundations were built in the early 14th century, and since then these comprised the general ground level of the whole inundation area (Matt, 1996).

As soon as the Rhine overflowed the pier, chroniclers used the term "flood". According to the calculations of the FLUX/FLORIS^{2000} model, which is described later, the flooding of the pier corresponds to runoff of 4300 m^3 s^{-1}. The qualitative notion of flood used in the pre-instrumental period can thus be related to a specific runoff in the instrumental period: an advantage scarcely found in other studies (Sturm *et al*., 2001). The process of flooding and flood magnitude assessment is explained by reference to the two floods of 18 September 1852 and 13 June 1876. As soon as the pier was submerged, the water flowed off from east to west to the lowest point of the area, dictated by the slope of the terrain (the slope is indicated by the alignment of the basements of the houses in Merian's bird's-eye view) (Fig. 4: 1).

The course of the flood in June 1876 is described in rather more detail: the press at first reported flooding of several basements on the morning of 12 June near the lowest point of the inundation area (Fig. 4: 1). The water then accumulated (up to c: Fig. 4) before it ran off to the Fish Market through the alley "Schwanengasse" (Fig. 4: 3). At 16:00 h, the Fish Market was partially flooded (Fig. 4: 2). The following morning, the inundation level reached up to the guest house Tête d'Or (*Schweizer Volksfreund*, 13 June 1876) (Fig. 4: II, or Fig. 7: II) located at 250.52 m a.s.l. The view of the Rhine at that time, corresponding to runoff of 5700 m^3 s^{-1}, is visualized on an early photograph (Fig. 6).

The flood peak of the 18 September 1852 flood was 6 cm higher than that of the 1876 event, according to the gauges (Ghezzi, 1926; Rima, 1962). Indeed, the submerged area was reported to be more extensive, reaching the fountain at the Fish Market (Fig. 4: d) and reaching almost to the corner of the guest house "Kopf" (Fig. 4: III); in 1876 it only went to the lower corner of the guest house Tête d'Or (Fig. 4: II). The extent of the flood of 1852 is shown in a painting by Louis Dubois (Fig. 7; Source S21).

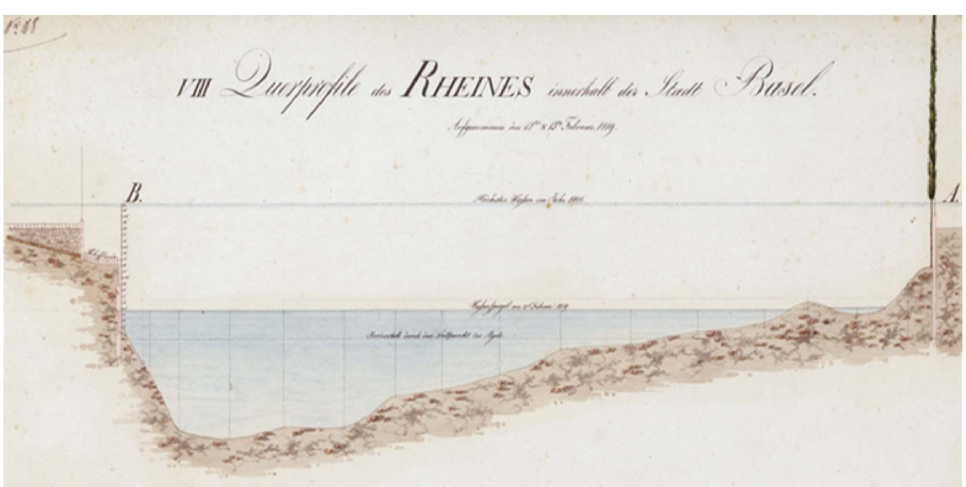


Fig. 5 Cross-section of the Rhine at Basel, drawn on 15 February 1819 (Source S1).

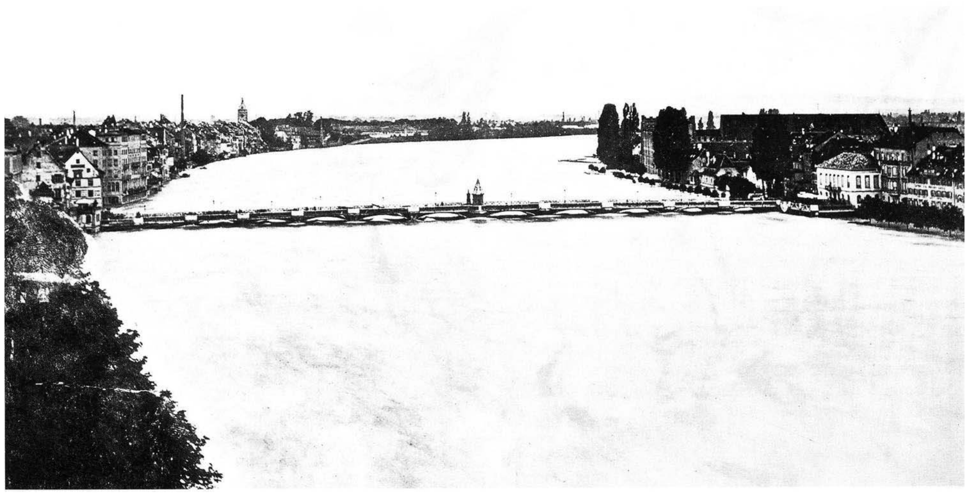


Fig. 6 Photographic view of the flood on 14 June 1876; gauged with 5700 m^3 s^{-1} discharge (Source S22).

Fig. 7 "The Great Rhine of 18 September 1852" Painting by Louis Dubois (Source S21). I: Guest house "Krone"; II: Guest house "Tète d'Or"; III: Guest house "Kopf".

Step 3: Reconstruction of catastrophic events (CE)

The third step involves reconstruction of peak levels of CEs that were beyond the maxima known from the instrumental period and not documented by flood marks. They were described in detail with reference to familiar locations. Floods next in size to the events of 1876 and 1852 were often described by mentioning that the "Fish Market was completely flooded", and that the city walls of Lower Basel next to the Rhine were submerged. Whenever the water was reported to have reached the Grain Market (Fig. 4: f), this was related to a backlog effect, as the Rhine then blocked the runoff of a subterranean brook, which thus flooded the Grain Market (Fig. 4: red dotted line). Often, the bridge itself was used as a reference point. In some cases, "destruction of the bridge" was reported, which implies that it was no longer passable. In such circumstances, boats were moored in the gap to allow passage. The bridge, built in 1225, was originally supported by five stone and seven wooden pillars. One wooden pillar was replaced by a stone structure in 1457. Since then, the construction and the elevation of the bridge were not changed until it was replaced in 1903/05 (Baer, 1932) (Fig. 4: 5). Further references to the bridge are available: some chroniclers reported that people standing on the bridge washed their hands in the Rhine, or that the bridge looked like a "float on the river"; others mentioned that boats had to be boarded through the windows of the Guildhouse.

According to this narrative information, describing precisely the magnitude of CEs, a quite accurate reconstruction of the corresponding peak water level can be achieved. This reconstruction is now explained in greater detail, as it is an excellent example for the reconstruction of pre-instrumental flood discharges based on a combination of different historic sources, and represents very well the underlying reconstruction methodology of this paper.

The narrative information "*the bridge looked like a float on the river*" (Source S2) and "*people standing on the bridge washed their hands in the Rhine*" (Source S3) clearly tells us that the river's water level must have reached approximately the level of the bridge. According to a very accurate drawing by Emanuel Büchel showing the Greater Basel townscape of 1759 (Source S4), it can be clearly demonstrated that the bridge and the window of the Guildhouse were on approximately the same level (Fig. 8, top left: red line), and this perfectly fits the narrative information "*boats needed to be boarded through the windows of the guild house*" (Source S5). The level of the window could be reconstructed by combining the information given on a cross-section from 1819 (Source S1) and a nearly natural painting from the early 19th century showing the Guildhouse of the fishermen (Source S6), which was situated at the pier, exactly where the cross-section was taken (Fig. 8, top right, bottom). On the top-right painting (Fig. 8), two different ground levels are shown by steps. These different ground levels were also recorded on the cross-section, right next to the gauge on the left-hand side (Fig. 8, bottom). Thus, the difference in ground level on the painting can easily be quantified with the scale unit of the gauge of the cross-section; then, the height of the window of the Guildhouse above the ground level of the pier can be deduced by simple trigonometric calculation (Fig. 8, top right). Finally, the difference from the ground level of the pier to the gauge datum must be added (according to the cross-section) to the reconstructed height of the window to make the reconstructed peak water level comparable to instrumentally gauged floods. Since the window and the bridge were on approximately the same level, the reconstructed CE peak water level of 7.20 m above the gauge datum may also be used for the height of the bridge (see Fig. 8, top left: red line; Fig. 4, red bar). Even though the bridge was rebuilt several times after the occurrence of destructive flood events, it can be strongly assumed that the level of the bridge never changed between 1225 and 1903/05, as the bridge always needed to fit to the standard ground level of the city gate. This reconstructed peak water level may thus be used for quantifying pre-instrumental flood discharges whenever trustworthy flood reports indicate a CE.

A reconstruction of pre-instrumental flood discharges also needs to consider changes in the river bed. The cross-section established close to the bridge in 1819 (Fig. 5) represents the situation before the embankments were built (Bürgin & Rossé 1994). The correction of the Upper Rhine (1817–1857) initiated by Tulla involved a straightening and shortening of the course between Basel and Karlsruhe, Germany, from 219 to 188 km, as well as the reduction of 60% of the original retention area (Vischer, 2003). The engineered change led to accelerated flow and thus intensified river-bed erosion downstream of Basel. This effect might also have accelerated the runoff inside the town. However, the profile (Fig. 5) was drawn just a few months after Tulla initiated his work near Karlsruhe. Therefore, this regulation could not yet have affected the river bed in Basel significantly. Moreover, verifications carried out by the Civil Engineering Office over the last four decades revealed that the river bed was hardly altered by the runoff (pers. comm. Tiefbauamt Basel). This suggests that the river bed near the (only) bridge was also more or less stable prior to Tulla's Rhine correction downstream of Basel. However a very strong argument for the supposition of a long-term stable river bed in Basel is the fact that the bridge (built in 1225 and reconstructed 1903/05) survived for such a long time, which most probably would not have been the case in an alluvial stream with an unstable bed.

Step 4: Quantification of pre-instrumental peak water levels

Quantification of the runoff obtained from the evidence available for the pre-instrumental and instrumental periods was done by applying the one-dimensional (1D) hydraulic model

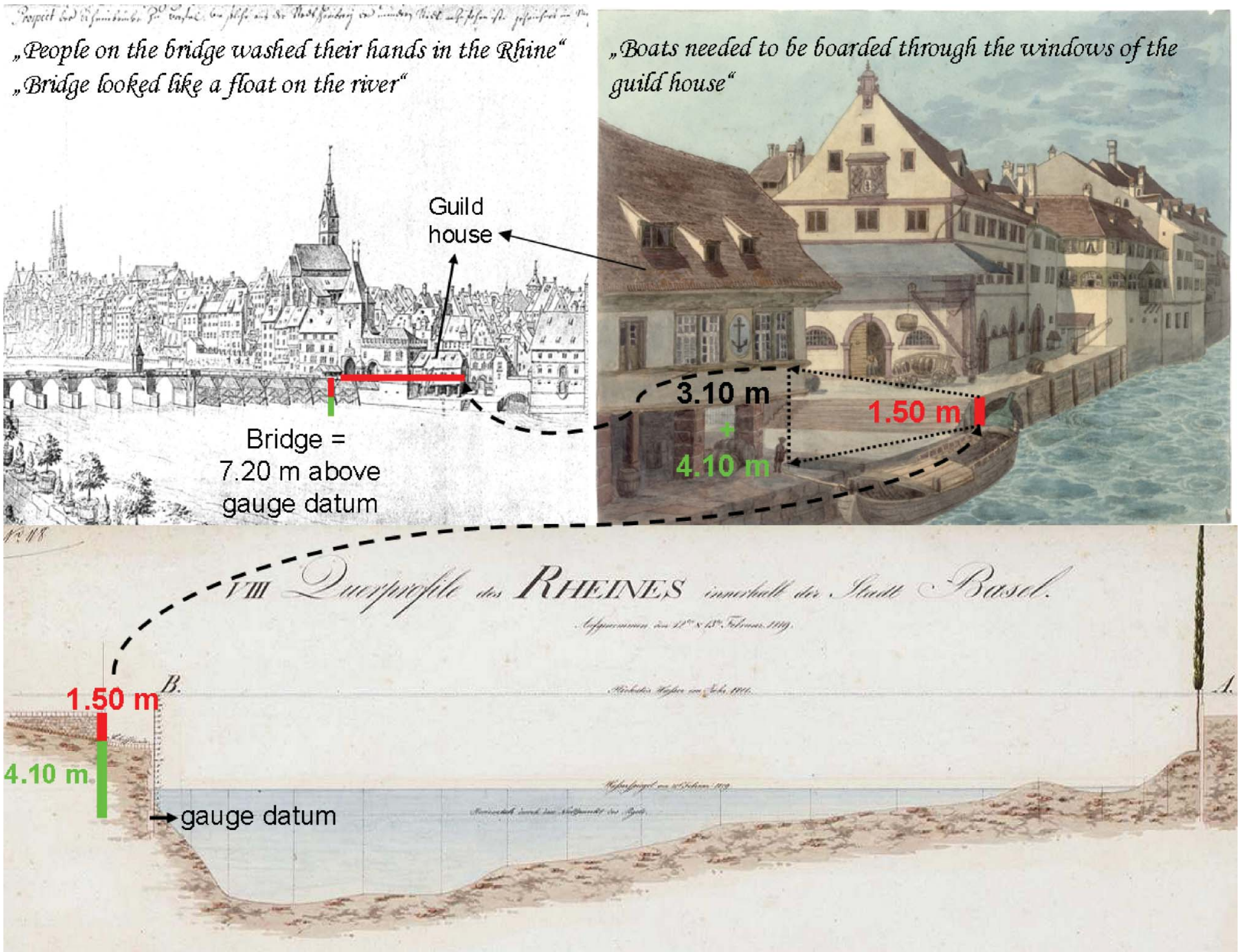


Fig. 8 Reconstruction of CE peak water level based on a variety of different historic sources. Upper left: "View on the left riverside, 1759" by Emanuel Büchel. Staatsarvchiv Basel-Stadt; Collection Weber-Oeri, Topo 2. Upper right: "Pier shown from the bridge" Staatsarchiv Basel-Stadt; l 537. Bottom: Cross-profile from 1819 (at pier). Staatsarchiv Basel-Stadt; Planarchiv A 6,8.

FLUX/FLORIS^{2000}, which is flood routing software that calculates the transient 1D flow in river systems based on the de-Saint Venant equations (Ven Te Chow, 1973), these being the Navier-Stokes equations for flow, integrated over the cross-sections of the river. The 1D flow equations are solved with a finite volume method. Measured cross-sections are used to discretize the river branches. The program package includes options for automatic calibration and flow regulation. FLUX/FLORIS^{2000} was applied in our analyses to route major floods both through the unregulated and through the regulated Aare catchment. The purpose was to estimate the influence of manmade regulations, particularly of the FJWC, on the flood peak at Basel. Moreover, the corresponding peak flows of historical flood marks at Basel could be quantified with the support of FLUX/FLORIS^{2000}: The model can be used with a prescribed inflow and the results are the water levels for every cross-section. To quantify the peak flow for each historical flood mark, the inflow in the model of the river is increased until the historical water level is reached. Thus, for every observed water level, a corresponding flow can be calculated. To account for uncertainties, the calculated floods were assigned to one of three categories derived from the peak levels estimated from the available documentary and instrumental data (Table 2): The first two categories are further subdivided into subcategories, each being set about 0.1 m apart. The uncertainties are rather small for MEs and SEs because the subcategories were "calibrated" within the instrumental period (up to the maximum of 5700 m^3 s^{-1} measured on 13 June 1876) and because the documentary evidence

Table 2 Categories of flood magnitudes; reconstructed flood peak levels and their quantified discharges.

Category of flood magntitude	Observed inundation levels	Altitude (m a.s.l.) / Discharge (m^3 s^{-1})
ME Minor Events	ME-1: Pier / "Blumenplatz" flooded	249.6/4300
	ME-2: Up to Fish Market Houses at beginning of market place	250.1/4900
SE Severe Events	SE-1: Almost up to corner of Guesthouse "Krone"	250.2/5100
	SE-2: Up to corner of Guesthouse "Krone"	250.3/5300
	SE-3: Guesthouse "Krone" entirely flooded	250.4/5400
	SE-4: Almost up to Guesthouse "Tète d'Or"	250.5/5500
	SE-5: Up to well on Fish Market • Almost to Guesthouse "Kopf" • Fortification in Lower Basel overflowed	250.6/5700
CE Catastrophic Events	• Fish Market deeply flooded • Partial destruction of bridge • Surface of Rhine reaches bridge level • Boats boarded through windows of guild house • Surface of water reached with scoop from window of Guildhouse	251.1/6400

is detailed. Uncertainties are largest for the highest category. The category of CE is inferred from the peak water levels of the floods in relation to the height of the bridge, which corresponds exactly to the height of the Guildhouse window (Fig. 4: 5, red bar). Whenever it was reported that people on the bridge could wash their hands in the Rhine or that the bridge looked like a float on the river or that boats had to be boarded through the window of the Guildhouse, the peak water level was assumed to have reached this height. Such reports are always embedded in supporting information, such as the flooding of the Grain Market (Fig. 4: f), or the submerging of the city walls of Lower Basel alongside the river. If narrative flood information is weaker, and if there is only one indication for a CE, one cannot be too sure that this event really belongs to the topmost category.

RESULTS

The reconstruction of the largest Rhine River floods in Basel for the period 1268–2010 yielded a series of six CEs and 43 SE-5s (Fig. 9). The six CEs can be definitely attributed to the topmost category according to the descriptions of the river level. Six out of the 43 SE-5 events (1268, 1275, 1302, 1404, 1451 and 1679), marked with dotted lines in Fig. 9, possibly also belong to the topmost category, but the evidence was not defined well enough to allow this classification. All in all, it is thought that events of this severity were hardly overlooked by the chroniclers, because they had a disruptive effect on the daily life in the town.

Of all the SEs and CEs, 52% occurred in summer (JJA), primarily in July and August (Fig. 10), which is also characteristic of the eastern Alpine foreland (Böhm & Wetzel, 2006). Aebischer (1997), who analysed the 11 highest floods of the Rhine at Basel in the 20th century, clearly showed that extreme summer floods are caused by heavy rainfall, according to the precipitation maximum in June–July in combination with a high baseflow due to snow- and icemelt. The 0°C line was above 2500 m a.s.l. in most cases, i.e. a temporary retention of precipitation as snow occurred only in a small part of the basin.

The other major events occurred in winter (DJF) with a frequency of 21% (in agreement with the 500 year analysis of the Rhine river by Schmocker-Fackel & Naef, 2010), in spring (MAM)—16% and autumn (SON)—11% (Fig. 10) (Schmocker-Fakel & Naef, 2010). A temporary increase of the 0°C line causing snowmelt in a significant part of the basin, in combination with a long-lasting precipitation event, may be the main cause for the extreme winter floods, as was shown for the 20th century by Aebischer (1997). Varied seasonal patterns emerge on a centennial scale, but the number of cases is too small to deduce these patterns from variations in climate. The only exception is the period 1651–1750 ($N > 15$), when summer floods were very frequent (Fig. 11). These results are in agreement with a recent 500 year flood frequency

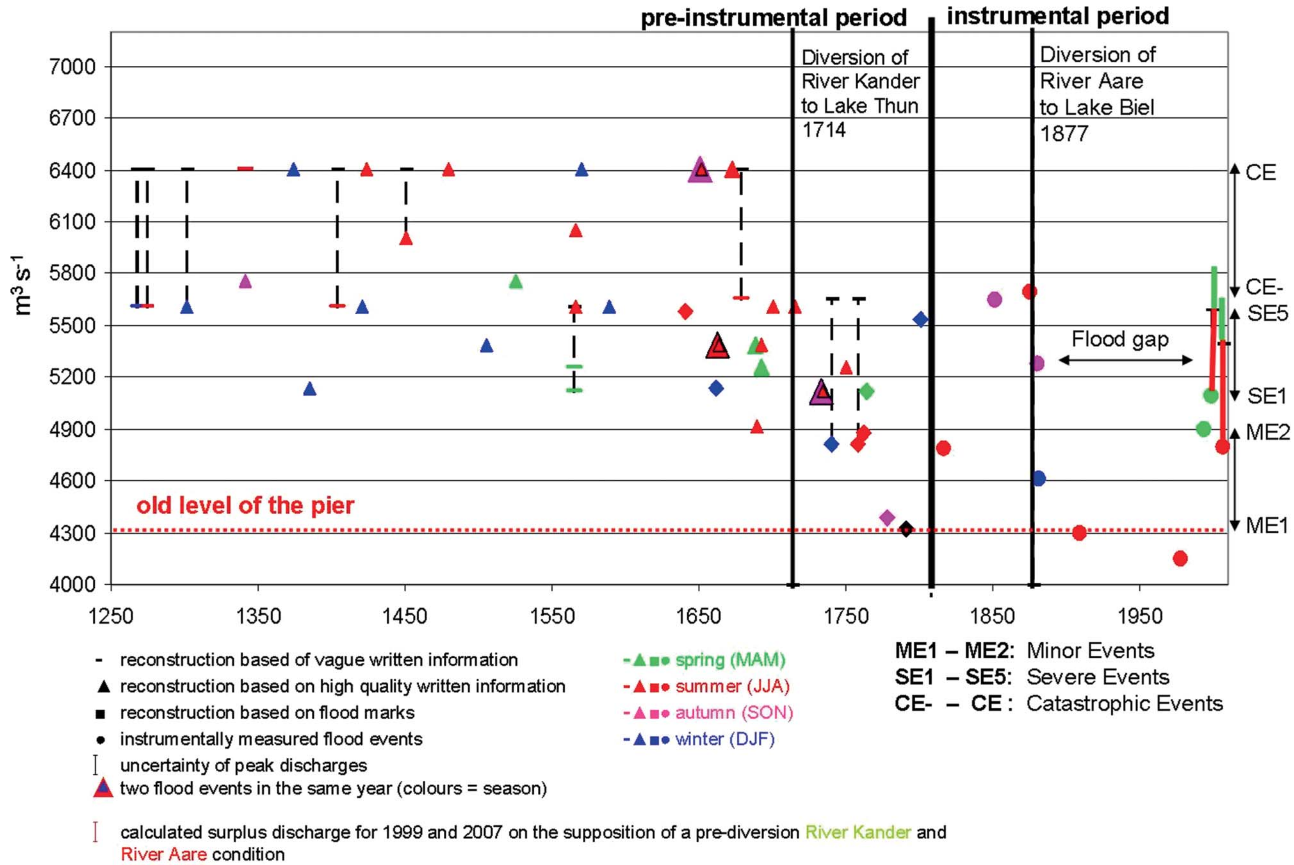


Fig. 9 Rhine River discharge quantities 1250–2010; calculations based on documentary and instrumental evidence (peak discharge values are given as they were observed; no adjustment to either pre- or post-Kander/Aare diversions was made).

analysis of different Swiss catchments (Schmocker-Fakel & Naef, 2010). Average June and July precipitation from 1651 to 1750 in the Swiss Mittelland (midland) assessed from documentary precipitation indices (Pfister, 1998) was 9% above that for the 1901–1960 reference period.

Severe events in winter (DJF) are documented for every 100-year period up to 1850, but not a single event is known since 1883. This is surprising, because winter precipitation in Switzerland and in southwest Germany significantly increased from the late 19th century (Begert *et al.*, 2005; Schmidli & Frei, 2005).

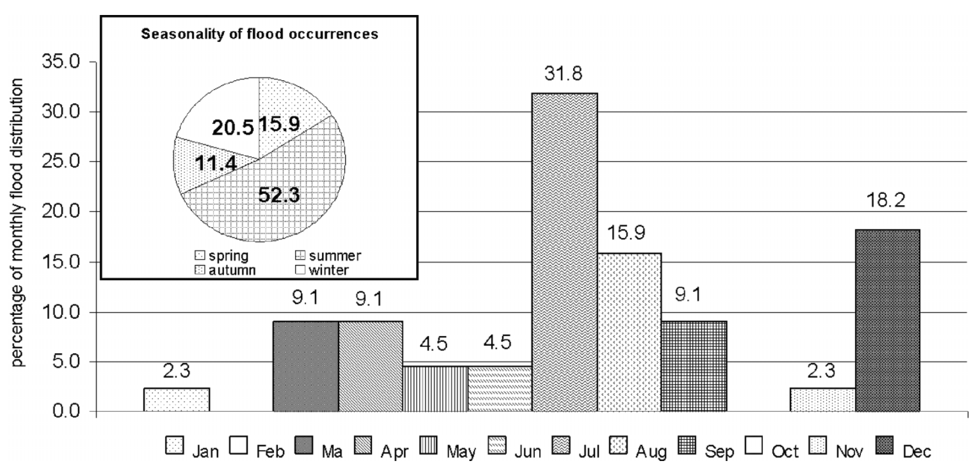


Fig. 10 Monthly and seasonal distribution of flood occurrences 1250–2010 (≥5000 m^3 s^{-1}; including SE-1–SE-5 and CEs).

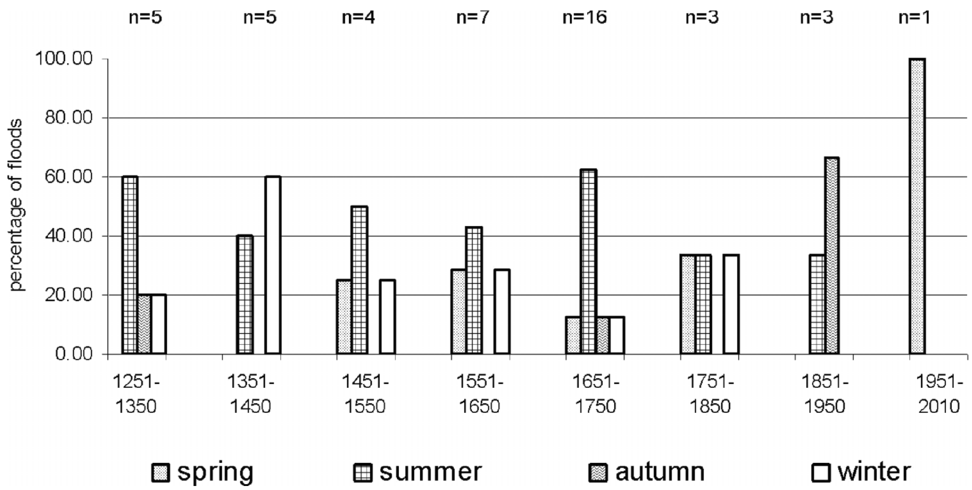


Fig. 11 Seasonality of floods 1250–2010 (100-year periods) ($\geq$5000 m^3 s^{-1}; including SE-1–SE-5 and CEs).

Mudelsee *et al.* (2004) found significant downward trends in winter flood discharge for the Elbe and Oder rivers during the 20th century as well (like our analysis) even though the comparative and quantitative analysis of flood variability and forcing of 12 major European rivers since AD 1500 points to the fact that the number of flood events is predominantly triggered by regional climatic forcing, with at most only minor influence on neighbouring catchments (Glaser *et al*., 2010).

DISCUSSION

In this section, we address the causes of longer-term changes in the magnitude, variability and seasonality of SEs and CEs. In order to unravel climatic and manmade effects, the effects of the FJWC and of the correction of the River Kander on the peak runoff of the rivers Aare and Rhine are assessed. Subsequently, the meteorological conditions leading to CEs and SEs are discussed.

Hydraulic considerations

A long-term decrease in the magnitude of the largest floods is shown in Fig. 9. Catastrophic events are not documented after 1679, while no SEs were measured between 1877 and 1999. This 121-year long gap in the occurrence of severe floods is the most outstanding feature of the entire curve (Fig. 9). Even for minor events just exceeding the level of the old pier ($\geq$4300 m^3 s^{-1}) and causing minimal damage, a 110-year long gap is documented by instrumental measurement between 1883 and 1993 (Fig. 9).

Additionally, the length of the database limits the extrapolation potential. Usually, a temporal span of three times that of the database is recommended (DVWK, 1999). Therefore, many observed flood events lay outside the range of the analysis (see the grey shaded zone in Fig. 12). An analysis performed on a 201-year period could provide more reliable return periods for the observed discharges. By including the 16 most reliable historic peak discharges presented in this paper, return periods for all observed flood peaks could be estimated. However, the data samples longer than 118 years contain inhomogeneities due to massive changes in the catchment, and should therefore not be used for the prediction of future events.

Variations in flood frequency are often attributed to anthropogenic factors such as land-use change, deforestation, wetland reduction, river regulation and variations in climate (Kundzewicz *et al*., 2004). According to Mudelsee *et al.* (2003), however, factors such as deforestation have only minor effects on the frequency and severity of floods. The influence of lakes and artificial reservoirs depends on their storage capacity. In the case of the High Rhine basin, variations in flood frequency prior to 1800 can hardly be attributed to human impacts, as the population size was small and the technological capacity for river regulation was rather low (Messerli & Pfister, 1990), if we disregard the enterprising project to divert the River Kander to Lake Thun that was completed as early as 1714 (Vischer, 2000) (Fig. 1). This river, originating in the Bernese Oberland mountains, originally discharged directly into the River Aare north of Thun (Vischer, 2000). Therefore, the flood peaks of the Kander were not attenuated by Lake Thun and

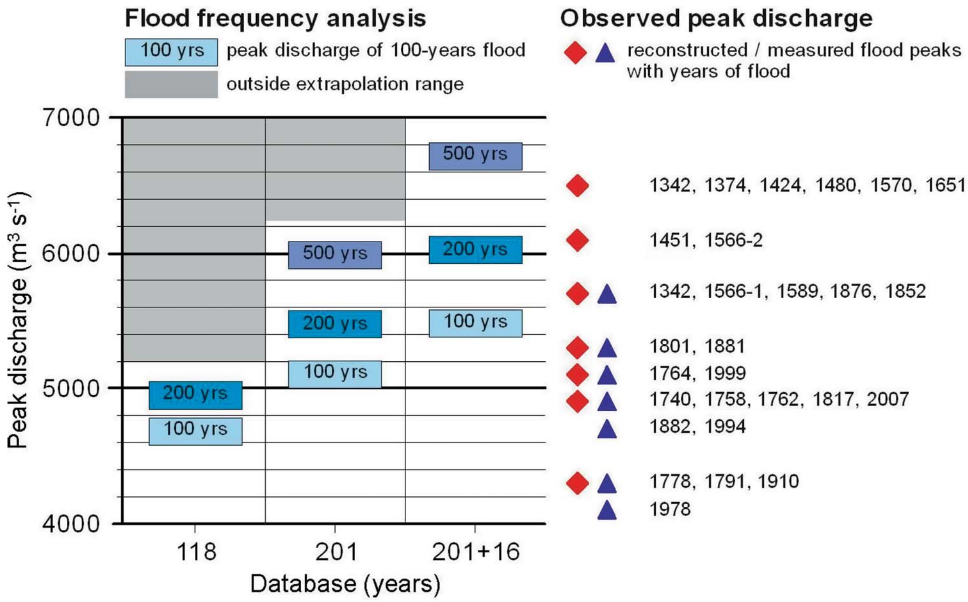


Fig. 12 (left) Flood-frequency analysis for the Rhine at Basel, performed on different sets of yearly discharge peak levels covering the periods: 1891–2008 (118 years: official standard flood-frequency analysis from the Federal Office for the Environment, BAFU, 2009b); 1808–2008 (201 years); and 1342–2008 (201 measured plus 16 reconstructed historic peaks). Computation: HQ-EX 3.0 (WASY, 2005) with generalized extreme value distribution / method of moments after the guidelines of DVWK (1999). (right) Observed peak discharge giving an overview of the reliable known flood peaks for the Rhine at Basel (values are given as they were observed; no adjustment to either pre- or post-Kander/Aare diversions was made).

may have had a direct influence on the flood peaks of the River Aare and eventually on the peaks at Basel (see Fig. 1). This interpretation is supported by the fact that CEs are only documented for the period prior to 1714. Likewise, the diversion of the Aare River to Lake Biel in 1877, under the auspices of the First Jura-Waters Correction (Vischer, 2003) (Fig. 1), coincides with the start date of the long 19th and 20th century "flood disaster gap" (Fig. 9).

In order to unravel human intervention from climatic factors in the causes for large floods, the effect of diverting the River Kander into Lake Thun and the River Aare into Lake Biel upon the peak runoff of the River Rhine at Basel was calculated by applying FLUX/FLORIS[2000] for the River Aare between Lake Thun and its confluence with the River Rhine. We simulated the peak flow of the River Aare for the 1999 and 2007 floods, which were two major flood events, under the assumption that both the Kander and Aare rivers would have flowed again through their old river beds instead of using the new channels constructed in the course of the regulations (see

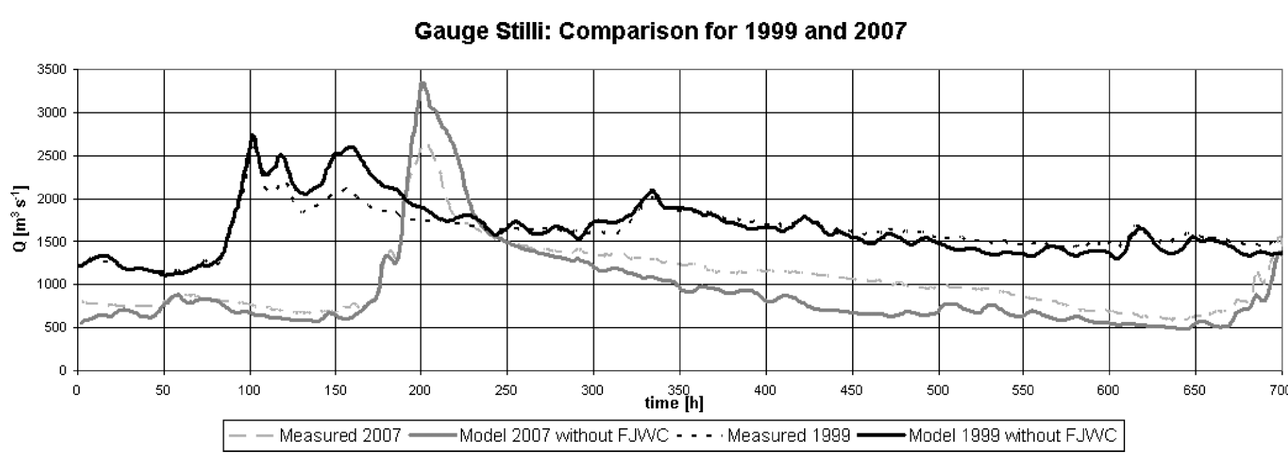


Fig. 13 Observed (including first Jura-Waters Corrections FJWC) and simulated (situation prior to 1868, i.e. without FJWC) flood hydrograph of the 1999 and 2007 flood events for the River Aare at Stilli.

Fig. 1). Furthermore, the historical meanders of the River Aare that were removed by the regulations were "reactivated", and the effects of the hydropower plants with their reservoirs built along the river were "suspended".

In Fig. 13, the observed and simulated flows of the 1999 and 2007 flood events are shown for the gauge at Stilli, which is located downstream of the confluence of the Aare, Reuss and Limmat, 12 km upstream of the confluence with the Rhine (see Fig. 1). The 2007 event was a quite large event with a short time to peak. The flood peak of the River Rhine at Basel was 4800 $m^3 s^{-1}$ (Bezzola & Ruf, 2009). This value corresponds to a return period of >100 years based on the 118-year instrumental period 1892–2008 (see Fig. 12). The peak flow of the 1999 event, at 5100 $m^3 s^{-1}$, was even larger. At the same time, the peak flows of both events were quite similar at the Aare gauge at Stilli. The 1999 and 2007 events were the largest and second largest events of the last 110 years. However, the peak flows differ significantly if we assume these events to have taken place in the historical channel situation prior to the FJWC. The 2007 event would be as much as 630 $m^3 s^{-1}$ higher due to the missing lake retention capacity. Moreover, the flood peak would have arrived earlier at Stilli. In 1999 the situation was different, as the rivers Limmat and Reuss also contributed to the flood: The first peak results from the River Limmat, the second from the Reuss and the third from the Aare. Again, this third peak was attenuated by lake retention, as suggested in Fig. 13. The maximum discharge of the River Aare without the FJWC would have been 500 $m^3 s^{-1}$ higher. Thus, the reduction of the peak discharge by the retention of Lake Biel was similar for the floods of 1999 and 2007.

The effect of diverting the River Kander into Lake Thun (1714) is calculated in the same way as that of FJWC. The peak at Stilli (see Fig. 1) for the flood of 2007 with the old river course is shown in Fig. 14. It can be concluded from Fig. 14 that the Kander correction reduced the flood peak of the River Aare at its confluence with the Rhine by as much as 270 $m^3 s^{-1}$ for major flood events similar to 2007. Thus the effect of both corrections yields 900 $m^3 s^{-1}$. The overall discharge volumes in the assumed historical channel situations always equal the measured overall discharge volumes. The significant peak differences are explained by the retention capacities of lakes Thun, Biel and Neuchâtel, we can conclude from these model simulations based on the two largest events since 1900 that flood peaks of severe events at Basel after 1877 would have been larger by about 900 $m^3 s^{-1}$; those between 1714 and 1876 would have been 270 $m^3 s^{-1}$ larger without the regulation of the River Kander (Fig. 9). These figures have to be taken into account when all flood events from 1268 onwards are directly compared. The results suggest that the non-occurrence of CEs after 1714 might be connected, to some extent, to the regulation work. However, the result of the modelling study also suggests that, besides the regulation, the "flood disaster gap" from 1877 to 1998 may also be connected to the absence of climatic situations promoting the occurrence of extremely severe floods. Furthermore, this conclusion is supported by the fact that Lake Constance, gauged at Lindau since 1797, did not flood its banks between 1910 and 1999 (BWG, 2000; Gasser, 1957).

Climatic considerations

It is worthwhile exploring the climatic context of the most severe known floods involving both the "pre-instrumental" CEs and the SE-5s documented from the instrumental period since 1808 (dates of all events below are in Gregorian Calendar style). If the magnitude of these floods was outstanding, we should expect that the meteorological circumstances initiating them were equally exceptional. The subsequent interpretation of the above-mentioned events is arranged according to the "Weather Hindcast" approach (Pfister, 1999): this involves reviewing the evidence in descending chronological order, beginning with the most recent cases for which all parameters, e.g. atmospheric circulation, temperature and precipitation are usually fully documented. A good knowledge of "instrumental extremes" provides useful clues for interpreting floods in the pre-instrumental period for which the evidence is more fragmentary.

Table 3 surveys the longer-term climatic situation preceding the events (disposition), and the initiating meteorological situation by means of differentiating between the duration, intensity and the affected proportion of the catchment basin.

Disregarding topography and land use of the catchment basin, soil saturation and available water storage capacities by snow cover are the most important conditioning factors for flood generation (Wanner *et al.*, 2004). Rainfall duration and intensity and the proportion of the catchment area affected by these factors are the most important factors triggering the event in addition to the abundance of the snowmelt.

Table 3 Climatic disposition and structure of rainfall events initiating CEs and SEs documented for the instrumental and the pre-instrumental periods.

Year	Date(s) of flood peak	Type	Disposition	Duration	Precipitation (intensity)	Catchment area involved (%)	References
2007	8 Aug.	SE 5*	p: Jun.+ Jul.+ Aug.++	48 h	157 L/m ^{2} 7–8 Aug.	90	BAFU, 2009a
1999	22 May	SE 5*	sn:++; p: May++	48 h	150 L/m ^{2} 11–14 May	<80	BWG, 2000
1876	13 Jun.	SE 5	p: ? 10–13 Jun.	60 h	280 L/m ^{2}	>40	Röthlisberger, 1991
1852	17 Sep.	SE 5	p: Aug. 15–16 Sep.	3 d	146 L/m ^{2}	>80	Röthlisberger, 1991
1801	31 Dec.	SE 5	p: Nov. 26–31 Dec.	(6 d)	280 L/m ^{2}	50	Pfister, 1985
1673	5 Jul.	CE	p: Apr.+ May+ Jun. sn: ?	(9 d)		>80	Pfister, 1985
1570	12 Dec.	CE	sn:+ p: Nov.	60 h	i:+	>80	Röthlisberger, 1991
1566	30 Jun.–23 Jul.	SE 5	sn:++ p: Jun.	2 months of uninterrupted increased water level		>80	Röthlisberger, 1991
1480	1 Aug.	CE	sn:++	72 h	i:++	most	Source S10
1424	31 Jul.–2 Aug.	CE		72 h			Source S8
1374	14 Jan. 29 Jan.	CE	sn:+		i:+(+)	>80	Source S14
22 Feb. 1374			p: Dec.	3 months of increased water level			
1342	29 Jul.	CE		8 d?	?	>80	Röthlisberger, 1991
1275	6 Jul.	SE-5	sn:+ p: Jun.	?	?	>80	Röthlisberger, 1991

CE: catastrophic event; SE: severe event, p: precipitation; sn: important snowmelt contribution; i: intensity of rainfall.
+: high intensity; ++ extremely high intensity.
*assessed without river corrections.

9 August 2007 This summer flood was preceded by heavy thunderstorms in June and July, leading, in several regions, to above long-term average precipitation for the corresponding months and to saturated soils. The total precipitation amount for August was twice the long-term average and in some regions three times the average (Swiss Mittelland, Swiss Jura), these extremes were mainly the result of heavy rainfall prior to the flood (IDAWEB, KKS Basel-Landschaft, 2009).

12 May 1999 The so-called Whitsun Flood was brought about by huge snow accumulations at higher altitudes of up to 700 cm in February, leading to frequent avalanches (WSL, 2000). As a result of below-average temperatures, the snow failed to melt before mid-April. A warm spell then initiated a period of intensive snowmelt promoting a rapid rise and a long-standing high level of lakes in the Alpine foreland. Lake Constance remained at a high level for more than 50 days, which is unique in the 20th century. The SE was triggered by intensive rainfall (150 L/m^2) affecting almost the entire catchment (BWG, 2000). On 10 May, the northern part of Switzerland lay between a high-pressure system centred over Italy and a low-pressure system west of the British Isles. Warm and wet air was advected from the southwest and, during 11 May, the main moist southwesterly flow continued. During 12 May, the high-pressure centre weakened and the low pressure stretched more towards the south. Central Europe was affected by the continuous advection of moist Atlantic air connected with heavy precipitation (Fig. 15).

13 June 1876 The SE of 13 June 1876, the largest within the instrumental period, was preceded by the largest amount of precipitation ever measured in Zurich for February and March, suggesting that soils were probably still saturated (Pfister, 1999) when the triggering wet spell began on the evening of 10 June. On 9 June 1876, the northern part of Switzerland lay on the southern flank of a low-pressure system centred over southern England. High pressure extended from the Azores to Iceland. Between those two pressure systems, cool and wet air was advected from north to northwest towards central Europe. On 10 June, both the high-pressure and low-pressure systems moved eastward, giving rise to a persistent flow of moist air

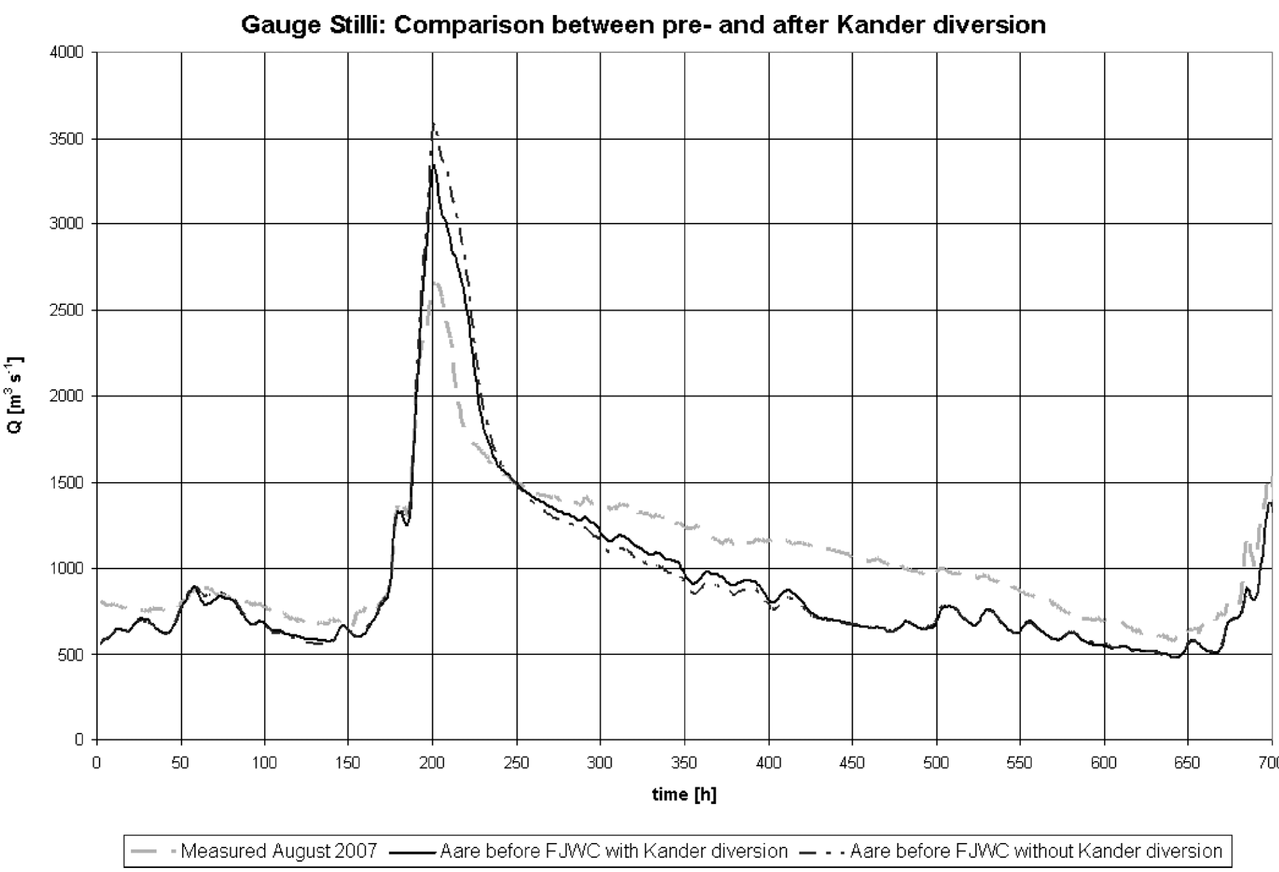


Fig. 14 Observed and simulated hydrographs for the River Aare at Stilli: simulated effects on peak discharge of the River Aare on the supposition of pre-Kander (1714) and pre-Aare (1877) diversions.

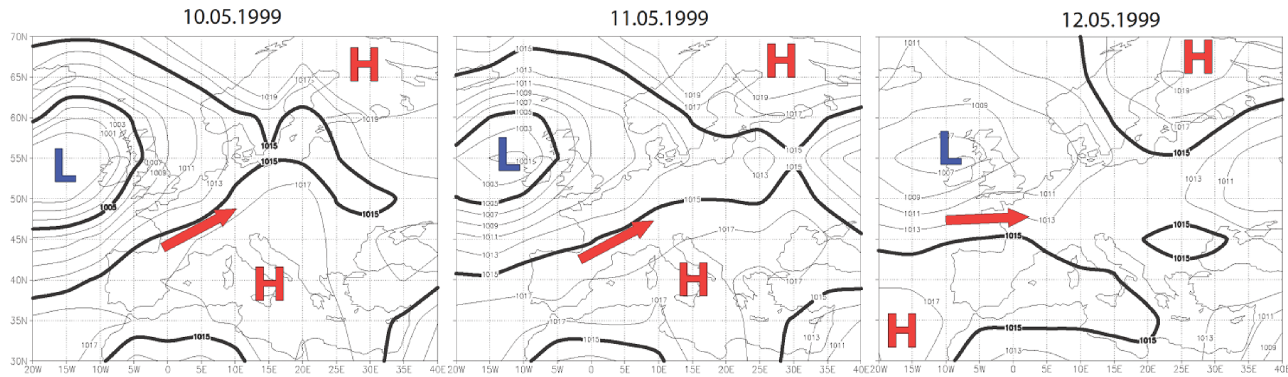


Fig. 15 Synoptic situation of the flood in May 1999; daily sea-level pressure maps for 10–12 May (Ansell *et al*., 2006).

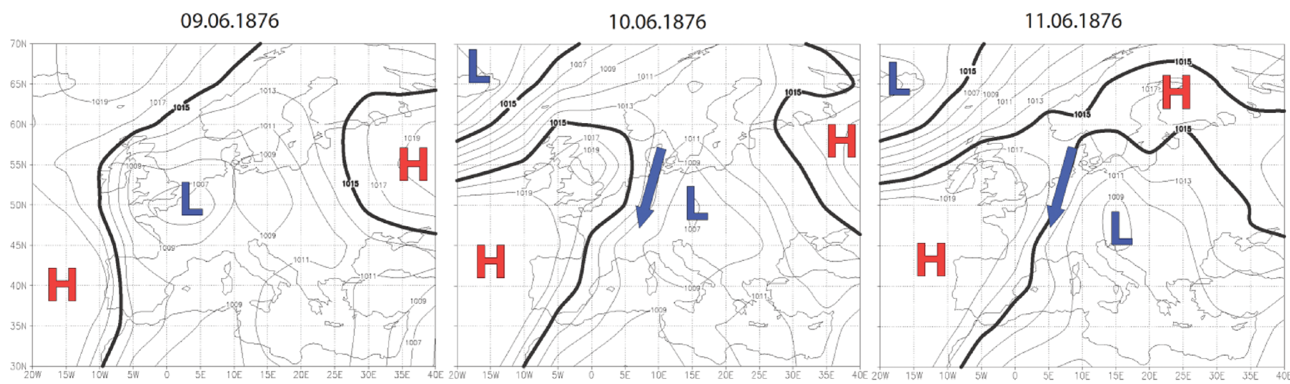


Fig. 16 Synoptic situation of the flood in June 1876; daily sea -level pressure maps for 9–11 June (Ansell *et al*., 2006).

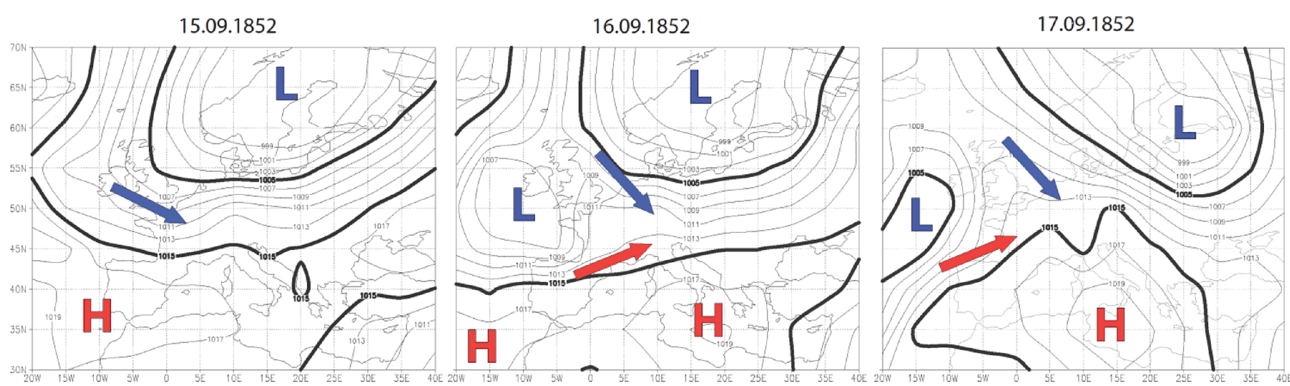


Fig. 17 Synoptic situation of the flood in September 1852; daily sea-level pressure maps for 15–17 September (Ansell *et al*., 2006).

from north to northeast and also from the southeast. The northeastern flow of cool and wet air continued on 11 June. In addition, wet and moist air from southeastern Europe was advected around the low-pressure system, increasing the potential for strong and intensive precipitation north of the Alps (Fig. 16) (Ansell *et al*., 2006). For about 60 hours it rained non-stop, but the zone of intensive rainfall was centred on the northeastern part of the catchment basin (Source S23) (Müller, 2004).

18 September 1852 This SE was preceded by a wet August. From 15 to 16 September 1852 Central Europe was influenced by a moist westerly air stream (Fig. 17). The warm and moist southwesterly air stream was connected with heavy precipitation affecting most of the Rhine catchment, but the intensity was less than in the other events and snowmelt was scarcely a factor (Ansell *et al*., 2006; Müller, 2004)

31 December 1801 This SE was preceded by a wet November. It was triggered by six days of rainfall from 26 to 31 December, yielding a total of 540 L/m^2 in Geneva (Bibliothèque Britannique, 1801). Very high water levels were reported for the rivers Rhine and Rhône. At the same time lakes Geneva, Neuchâtel and Biel flooded their banks (Pfister, 1984). However, no floods are reported from the eastern part of the Swiss Mittelland.

5 July 1673 This CE was preceded by a cool and rainy period from April to June (Pfister, 1984; Glaser, 2008), probably leading to snow accumulation in the Alps. It rained on nine days preceding the flood in most of the catchment. On 5 July 1673, the level of the Rhine in Basel exceeded the level reached on 30 November 1651 by about 45 cm (Source S7). The Aare caused particularly widespread damage (Weikinn, 1961). Severe floods are also reported by many German (Glaser, 2008) and French chroniclers (Champion, 1864).

12 December 1570 The CE of 1570 affected large parts of Western and Central Europe (Champion, 1864; Glaser, 2008). November was rainy, and abundant fresh snow fell in early December. According to the Geneva Chronicler Jean Savion, a five-day period of continuous intense rainfall ("day and night") from 8 December brought about by warm southerly winds then melted the snow cover up to 1800 m a.s.l. surrounding the town of Geneva (Geisendorf, 1942). The unprecedented duration of this rain spell must have produced significant runoff superimposed on the snowmelt water, perhaps on already frozen ground. The Basel chronicler Johannes Gross (Source S2) equates the magnitude of this CE with that of 1 August 1480, which agrees with the reconstructions (see section Results and Discussion sections, and Fig. 9). He points out that the bridge in Basel looked like a float on the river, without, however, being destroyed (Source S2).

29–30 June and 23 July 1566 Enormous snow masses were accumulated during the winter of 1566 at altitudes between 1000 and 2000 m a.s.l., the melting of which led to a long period of high level of lakes in the Alpine foreland. The Rhine remained at a high stage for 57 (66?) days (Source S8). Two floodwaves, on 29–30 June and on 23 July 1566, destroyed the bridge in Basel. The meteorological conditions leading to the two floods are not known in sufficient detail—June is just described as being wet—but it was probably a result of intensive precipitation affecting most of the catchment (Pfister, 2006b). The disposition was similar in June 1817, when the Rhine remained at a high stage for 89 days as a result of the melting of exceptional snow masses accumulated over the two winters of 1816 and 1817 and the intermediate "year without a summer" (Harington, 1992). However, in the absence of longer spells of intensive rainfall, the flood peak on 6 July 1817 was not very pronounced (see Table 1) (Pfister, 1999).

1 August 1480 This CE is undoubtedly the largest flood documented for the High Rhine catchment in Basel since the High Middle Ages. The Bern chronicler Diebold Schilling the Elder (~1445–1485) described the "Deluge of the Rhine", as contemporaries named the disaster, in a comprehensive 5000-word account (Source S10). The situation is described by Schilling's report of a sudden warm spell in late July "promoting rapid snowmelt", which is surprising. Indeed, even in the Little Ice Age the lion's share of snow in the Alps had usually melted at this time of year (Pfister, 1985b). However, in 1480, the period from March to July was very cold (Wetter *et al*., 2011) and might have delayed snowmelt in the Alps considerably. The period of intensive snowmelt was followed by "*three days of heavy rainfall without interruption*". The flood was thus initiated by unusually abundant snowmelt augmented by 72 h of intensive rainfall. Schilling reports in detail on the appalling destruction, interlacing stories of peoples' sufferings drawn from life and from the response of authorities. People standing on the bridge in Basel could easily touch the water (Source S6). The urban salt provisions stored at the level of the bridge in a tower situated beside the river (Fig. 4: 6) were ruined (Source S9). Massive logs carried down by the huge water masses of the Rhine destroyed all bridges upstream of Basel and finally led to the collapse of three pillars of the bridge in the town itself. The inundated area in the town reached beyond the Grain Market (Fig. 4: f). It was the only known case in which buildings had to be demolished after the Rhine had fallen to a normal level, to let the water drain off (Source S10). In the Upper Rhine plain north of Basel, the water masses extended over a breadth of "two [Roman?] miles" (3.5 km). Countless people were drowned; others escaped to roofs or climbed trees, where they had to stay for at least 24 hours before help could be organized (Source S10).

2 August 1424 According to the chronicler Christian Wurstisen (1544–1588), the CE of 2 August 1424 was initiated by three days of rainfall (Source S8). Although Wurstisen was not an eye-witness for this event, his report is valuable because he seems to have copied the observation from a lost contemporary chronicle. At least, his descriptions of the submerging of the city walls of Lower Basel and of the destruction of the bridge fit perfectly with the observations provided by two contemporary chronicles (sources S11, S12). Both of them report the destruction of most of the bridges up- and downstream, and the collapse of two pillars of the bridge in Basel. Henmann Offenburg additionally reports the flooding of the Grain Market (Fig. 4: f), which clearly indicates a CE (Source S11). A less reliable chronicler (Source S5) specifies that "*hands could be washed in the Rhine while one was standing on the bridge*" and that "*boats were boarded through the windows of the Guildhouse*", all of which agrees with the contemporary evidence.

Spring 1374 The CE in winter and spring 1374 is unusual with regard to the duration and intensity of wet spells in the cold season. According to Krahe (1997), it was the wettest winter within the millennium. December 1373 was warm and rainy which points to saturated soils (Source S13). From January to March 1374 the Rhine was continuously running "half a man's stature [i.e. 60–85 cm] higher than usual" from "long rains". Three times, namely on 14 January, 29 January and 22 February, this level was superseded by flood peaks triggered by spells of intensive rainfall, probably in combination with snowmelt at higher altitudes. At times, rainfall seems to have reached intensities that were generally only witnessed in the summer months. The chronicler Jacob Twinger von Königshofen describes "*water flows suddenly breaking out of a slope*" (Source S14), which suggests the occurrence of piping (Selby, 1993). The Fish Market and Grain Market (see Fig. 4: f, 2) were flooded and even the fountain on the Grain Market was submerged (Source S15). The extent of the inner city inundation thus points to a CE, whereas Königshofen points out that the event was somewhat minor compared with the "Magdalenenflut" of July 1342 (Source S14). In Cologne, the peak discharge of the Rhine in the winter of 1374 was assessed at 13 500 m^3 s^{-1} (Herget & Meurs, 2010). This is about twice the calculated peak discharge for the same event in Basel (6400 m^3 s^{-1}), which agrees with the runoff characteristics of the High- and Lower Rhine, whose long-term mean discharges amount to 1100 m^3 s^{-1} (High Rhine, Basel) and 2200 m^3 s^{-1} (Lower Rhine, Cologne) (Viviroli & Weingartner, 2004; Vischer, 2006).

29 July 1342 The well known "Magdalenenflut" (Bork & Herrmann, 1988) was primarily caused by an immense discharge of the River Main, for which Tetzlaff *et al*. (2002) calculated a return period of about 10 000 years. This catastrophe is recorded by several chroniclers from the Upper and High Rhine area: processions for sunshine were held in April and later in June, which points to long periods of rainfall and saturated soils. An eight-day period of "excessive rainfall" in July initiated the deluge (Source S16). According to Mudelsee *et al*. (2004) a "Zugstrasse Vb" situation might have prompted the event which is detailed in dozens of chronicles (Weikinn, 1958). Basel chroniclers reported "*widespread damage to towers and villages*" and "*destruction*" of the bridges upstream and downstream of Basel (Source S17). Subsequent reports made in 1374 looking back to 1342 lead one to conclude that both the Fish Market and Grain Market, including the two fountains, were flooded (Source S15) (see Fig. 4: f, 2). In Zurich the water level of the lake even reached up to the steps of the Fraumünster Church (Weikinn, 1958; Source S18)

6 July 1275 The bridge in Basel was partly destroyed on 6 July 1275. According to the Basel Annals, all bridges along the Rhine would have collapsed had it not suddenly ceased raining. Grain and vine harvests were delayed due to the cold temperatures, and copious rainfall from the beginning of May to the end of the year, which suggests that 1275 was a "year without a summer" throughout Central Europe (Source S19). Details about the triggering rainfall event are not known.

In conclusion, the magnitude of severe floods of the River Rhine at Basel seems to be most often conditioned by the preceding saturation of soils and the contribution of snowmelt. Snowmelt was particularly abundant in 1566 and 1817, but it also contributed substantial to the CEs of 1480 and 1570, and to the SE of 1999. The significance of the triggering rainfall events varies according to the affected share of the catchment, as well as to the duration and intensity of the rain. The uninterrupted intensive 72-h rainfall in 1480 that affected most of the catchment was undoubtedly the most substantial event of this kind. The flood of 1570 was triggered by five days of continuous rainfall; however, this was probably less intensive than that in 1480. The flood in 1801 was initiated by six days of continuous rainfall, but it affected only the western part of the catchment. The rainy periods preceding the events of July 1342 and July 1673 were perhaps longer than in the case of the above-mentioned events, but they are not described in sufficient detail. The same applies to the floods in 1424 and 1374. In comparison with the SEs documented with rainfall measurements, the magnitude of the climatic impact seems also to have been greater in the case of CEs, which supports the assessed magnitude of peak runoff.

CONCLUSIONS

This study confirms the fact established in historical hydrology that the inclusion of pre-instrumental flood reports from documentary evidence gives valuable hints for the estimation of return periods of >100 years. It benefited from an outstanding cluster of interrelated data comprising: one of the longest uninterrupted series of daily hydrological measurement in Europe (from 1808); a panel with flood marks encompassing 240 years; a centuries-long tradition of describing the magnitude of floods with reference to the same range of specific landmarks in the built environment; and a cross-section in the river bed established near the only bridge at the onset of Tulla's Rhine correction in 1819. There are strong arguments that the river bed in Basel was more or less stable over the past centuries. Six Catastrophic Events (CEs) involving a runoff of more than 6000 $m^3 s^{-1}$ are demonstrated to have occurred during the period 1268–1700, whereas flood frequency analysis performed on a database of the last 118 years resulted in a discharge of almost 4700 $m^3 s^{-1}$ for a 100-year flood (BAFU, 2009b), a level that has been surpassed twice in the last decade (1999 and 2007) and six times within the 202-year-long measurement period.

The dispositions leading to CEs involved very long spells of rainfall and/or abundant snowmelt. The events were initiated by phases of intensive rainfall of up to 72 h (e.g. "Deluge of the Rhine", 1 August 1480). All except two (1999, 2007) of the 43 demonstrated Severe Events (SE: 5000 < runoff < 6000 $m^3 s^{-1}$) occurred before 1877. Not a single SE is documented between 1877 and 1998. The intermediate 121-year-long "flood disaster gap" is unique in the period from 1268. In order to distinguish between human interference and climatic impacts, calculations were made using a 1D hydraulic model to indicate to what extent the magnitude of floods on the River Aare (being the main tributary of Rhine) was affected by the two major river regulations diverting the River Kander into Lake Thun (1714) and the River Aare into Lake Biel (1877). The result suggests that the "flood disaster gap" from 1877 to 1999 may not be entirely accounted for by the two river correction schemes, or by other human intervention such as the building of power plants. Rather, it seems that the absence of climatic situations leading to extremely severe floods was also a factor. Further work is needed to compare the case of the High Rhine with that of other rivers in Western and Central Europe, and to explore the climatic reasons for the "flood disaster gap".

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ARCHIVE SOURCES

Source S1: VIII Querprofile des Rheines innerhalb der Stadt Basel. Aufgenommen den 12. & 13. Februar 1819. Staatsarchiv Basel-Stadt: STABS Planarchiv A 6, 8.

Source S2: Gross, J. (1624) *Kurtze Bassler Chronick*: Oder / Summarischer Begrieff aller denckwürdigen Sachen und Händeln / so sich von vierzehendhundert Jahren biss auff das M. DC. XXIV Jahr / in und bey der Statt Basel / mit grossen Potentaten / und anderen benachbarten Fürsten, 1624.

Source S3: Bernoulli, A. (1915) Die Aufzeichnungen des Kaplans Hieronymus Brilinger. 1474–1525. In: *Basler Chroniken*, vol. 7. Leipzig: Historische und Antiquarische Gesellschaft Basel.

Source S4: Emanuel Büchel *Blick auf das linke Rheinufer*, 1759 (View of the left river bank, 1759). Staatsarchiv Basel-Stadt: Collection Weber-Oeri, Topo 2.

Source S5: Bernoulli, A. (1890) Anonyme Zusätze und Fortsetzungen zu Königshofen, nach der Abschrift Erhards von Appenwiler 1120–1454. In: *Basler Chroniken*, vol. 4. Leipzig: Historische und Antiquarische Gesellschaft Basel.

Source S6: *Schifflände von der Rheinbrücke aus gesehen* (Pier shown from the Rhine bridge). Staatsarchiv Basel-Stadt: STABS I 537.

Source S7: *Baselsche Geschichten*.

Source S8: Wurstisen, C. (1580) *Baßler Chronick*, Darinn alles, was sich in Oberen Teutschen Landen, nicht nur in der Statt vnd Bistumbe Basel, von jhrem Vrsprung her, nach Ordnung der Zeiten, in Kirchen und Welt händlen, biß in das gegenwirtige M.D.LXXX Jar, gedenckwirdigs zugetragen.

Source S9: Bernoulli, A. (1902) Die Anonyme Chronik der Mailänderkriege. 1507–1516. In: *Basler Chroniken*, vol. 6. Leipzig: Historische und Antiquarische Gesellschaft Basel.

Source S10: Tobler, G. (1897) *Die Berner Chronik des Diebold Schilling 1468–1484*, vol. I. Bern, Switzerland: Historischer Verein des Kantons Bern.

Source S11: Bernoulli, A. (1895) Die Chronik Henmann Offenburgs 1413–1445. In: *Basler Chroniken*, vol. 5. Leipzig: Historische und Antiquarische Gesellschaft Basel.

Source S12: Bernoulli, A. (1895) Die Rötteler Chronik 1376–1428. In: *Basler Chroniken*, vol. 5. Leipzig: Historische und Antiquarische Gesellschaft Basel.

Source S13: Hirzel, S. (1865) Chronik von 1368 bis 1406 mit Fortsetzung bis 1447. In: *Die Chroniken der Schwäbischen Städte – Augsburg*, vol. 1. Leipzig: Historische Commission bei der Königl. Academie der Wissenschaften.

Source S14: Hirzel, S. (1870) Chronik des Jacob Twinger von Königshofen 1400 (1415). In: *Die Chroniken der oberrheinischen Städte. Strassburg*, vol. 1. Leipzig: Historische Commission bei der Königl. Academie der Wissenschaften.

Source S15: Bernoulli, A. (1895) Die Grösseren Basler Annalen, 238–1416. In: *Basler Chroniken*, vol. 5. Leipzig: Historische und Antiquarische Gesellschaft Basel.

Source S16: Wyss, G. (1856) *Johannis Vitodurani Chronicon*. Die Chronik des Minoriten Johannes von Winterthur. Zürich: G. Wyss.

Source S17: Bernoulli, A. (1902) Die Grösseren Basler Annalen nach Schnitts Handschrift, 238–1416. In: *Basler Chroniken*, vol. 6. Leipzig: Historische und Antiquarische Gesellschaft Basel.

Source S18: Dierauer, J. (1900) Chronik der Stadt Zürich. In: *Quellen zur Schweizer Geschichte*, vol. 18. Zürich.

Source S19: Wattenbach, W. (1940) Die Jahrbücher von Basel. In: *Annalen und Chronik von Kolmar.* Nach der Ausgabe der Monumentia Germaniae. Leipzig.

Source S20: Vogelschauplan der Stadt Basel von Norden, 1615. Rechte Hälfte. Matthäus Merian d. Ä. Staatsarchiv Basel-Stadt: STABS Planarchiv Z 1,39.

Source S21: Der grosse Rhein den 18 September 1852. Louis Dubois Staatsarchiv Basel-Stadt: STABS Bild 13, 323.

Source S22: Rheinhochwasser 1876; Statsarchiv Basel-Stadt: STA AL 45,1-30-1.

Source S23: Billwiler, R. (1876) Die Niederschläge im Juni 1876 in der Schweiz. *Schweizerische Meteorologische Beobachtungen* **14**. Zürich.

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