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Historical flood reconstruction in a torrential alpine catchment and its implication for flood hazard assessments

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ABSTRACT

Flood marks and descriptions of past floods in archival records are valuable sources of information to complement the often short – and sometimes lacunary – systematic records provided by gauge stations, especially in mountain and smaller catchments for which the network of recording stations is still fragmentary. Yet, historical accounts of floods are only rarely used to calculate discharge during past floods and to complement estimates of flood frequency and magnitude. This is because the definition of flood types and the reconstruction of past topography of the now urbanized riverscapes is often challenging. Here, we employ an approach by which we combine (i) archival (1331–1965) and continuous gauge (1966–2020) records of past floods, (ii) information on past topography and mitigation measures found on topographic maps and contemporary documents specifying the dimensions of contemporary engineering plans and (iii) a hydraulic model to derive a c. 700-year history of flood activity and related discharges for the Saltina River, Brig-Glis (Valais, Swiss Alps). Periods of increased flood activity match with flood-rich episodes in the Rhone River and high lake levels at Lago Maggiore (Ticino), and the time series passes stationarity tests since at least 1828 CE. For a total of 32 floods occurring prior to the installation of the gauge station in 1966, we provide discharges following a descriptive classification, and demonstrate that major floods occurred in 1755 (~140 m^3s^{-1}), 1828 (~160 m^3s^{-1}), and 1921 (~120 m^3s^{-1}). We also evidence that the construction of mitigation measures has contributed to a reduction in flood frequency, but that the occurrence of extraordinary floods has again been on the rise since the early 21st century.

1. Introduction

Mountain rivers tend to flood with short concentration periods making forecasting and early warning difficult (Borga and Morin, 2014; Stoffel et al., 2016; Wohl, 2000). As riverscapes have been settled extensively during the 20th century (Hajdukiewicz et al., 2016; Spitalar et al., 2014; Wohl, 2006), people and their goods – often located on fans, terraces and close to channels – have become increasingly exposed, and/or vulnerable to extreme weather events and related flood disasters (Bubeck et al., 2017; IPCC, 2012). In the context of climate change and the greater water-holding capacity of an increasingly warmer atmosphere (IPCC, 2021), severe weather events and associated runoff are expected to increase in both frequency and magnitude (Bloschl et al., 2019; IPCC-SREX, 2012). Yet, most approaches based on downscaling of

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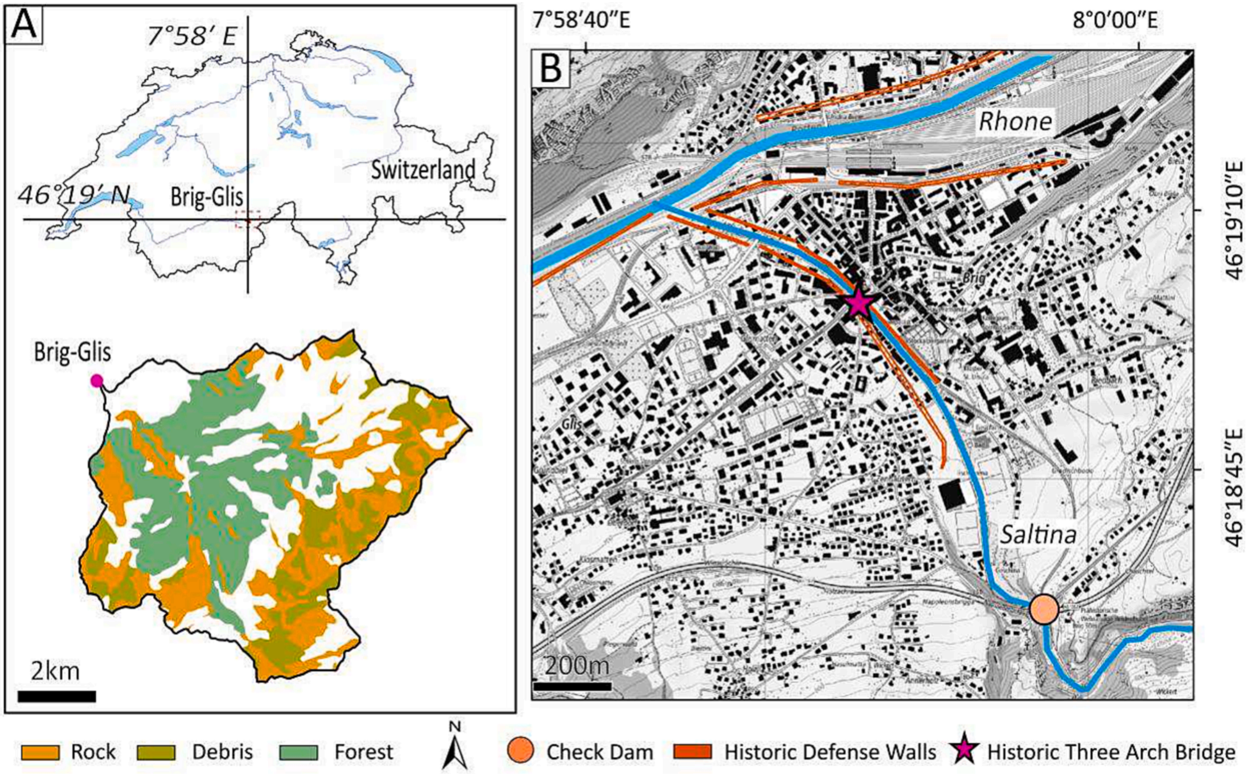

Fig. 1. Location of the study site: (A) Overview of the Saltina River and the settlement of Brig-Glis, Switzerland; (B) Land cover of the Saltina catchment; (C) Detailed view of the current channel of the Saltina River, and location of the historical three-arched bridges (star) and flood defense structures.

nested climate models with deterministic and statistical hydrological approaches produce uncertain results that are difficult to implement at the local scale (García et al., 2014). In this context, information from past floods represents a key source of information to place current flood activity in a longer-term context and to quantify links between the occurrence of extremes and natural climate variability that provide expectations of future climate change (Benito et al., 2021).

Likewise, the design of mitigation measures critically requires long-term flood records to better understand flood activity and to reduce uncertainties in flood quantiles assessments which are usually extrapolated from short instrumental records (Baker, 2006; Benito et al., 2015; Benito and Thorndycraft, 2007; Elleder, 2015; Wilhelm et al., 2018a). In Switzerland, for example, although the first national monitoring network was established in the 19th century (Brazdil et al., 2006), reliable observations of floods in the Alps span a century at best and are more often limited to a few decades. Moreover, the available data suffer from the fact that they also cover the “disaster gap”, a period—from 1882 to 1976—during which floods and their consequences for society were relatively exceptional in the Swiss Alps (Pfister, 2009). The relatively short periods covered by instrumental data also result in a series of floods containing only a few major events, making it difficult to estimate floods with return periods exceeding 100 years (Coles et al., 2001; Favier et al., 2016).

In regions with a long-standing urban configuration, historical sources (e.g., economic records, newspapers, annals, and chronicles; Brazdil et al. (2006) are often used in combination with flood marks to overcome this lack of data. Carved into bridge abutments, gates, churches or house walls, these marks recall extreme floods that occurred in major cities centuries ago (Bösmeier et al., 2022). They provide valuable information about the maximum flood water level at a particular location in a variety of ways, usually by means of a horizontal line accompanied by the year of the flood. Located at a river cross-section with a known water level-discharge relationship and a sufficient comparability with the historical situation, flood marks can be used to estimate flood peak discharge (Herget et al., 2014; Macdonald, 2007), provided careful interpretation and analysis of the source (Barriendos et al., 2003). In smaller towns, or mountainous contexts, flood marks are rarely installed and historical information on floods is scarce (Boisson et al., 2022) but even more critically needed as both measurement series tend to be shorter and response times faster in smaller catchments.

Over the last decades, large efforts have been undertaken to improve flood frequency analyses in ungauged or poorly gauged catchments. The main goals of these works were to (i) derive the shape of peak discharge distributions based on statistical properties of rainfall and assumptions on physical behaviors of watersheds (Eagleson, 1972; Gaume, 2006; Paquet et al., 2013; Rogger et al., 2013), and to (ii) integrate historical and paleoflood information through a “temporal extension” of timeseries (Hosking and Wallis, 1986, 1993; Merz and Blöschl, 2003; Neppel et al., 2010; Payrastre et al., 2011) or by merging datasets from homogeneous hydrological response regions through a “spatial extension” (El Adlouni et al., 2006; Fill and Stedinger, 1998; Halbert et al., 2016; Jones and Kjeldsen, 2009; Merz and Blöschl, 2003; Wallis et al., 2007). In recent years, the development of online databases and resources such as the “Chronology of British Hydrological Events” (CBHE, https://www.cbhe.hydrology.org.uk/index.php), the French–German “Observatoire Régional des Risques d’Inondation” (ORRION, https://orrion.fr/, Giacona et al., 2019) or the Swiss Euro-ClimHist (https://www.euroclimhist.unibe.ch/de/, Pfister and Rohr, 2015) datasets, have offered comprehensive historical information and therefore facilitated historical analysis of past floods, even if the development of such databases has been somewhat piecemeal, resulting in different forms of datasets (Wilhelm et al., 2018b). Therefore, in practical applications, unearthing extensive databases on historical extreme floods remains a formidable challenge, posing significant obstacles to conducting thorough flood frequency analysis at local and regional scales.

Here, we focus on the reconstruction of historical flood discharges in a torrential alpine catchment since the 14th century and to analyze the extension of a short instrumental timeseries of flood frequency and

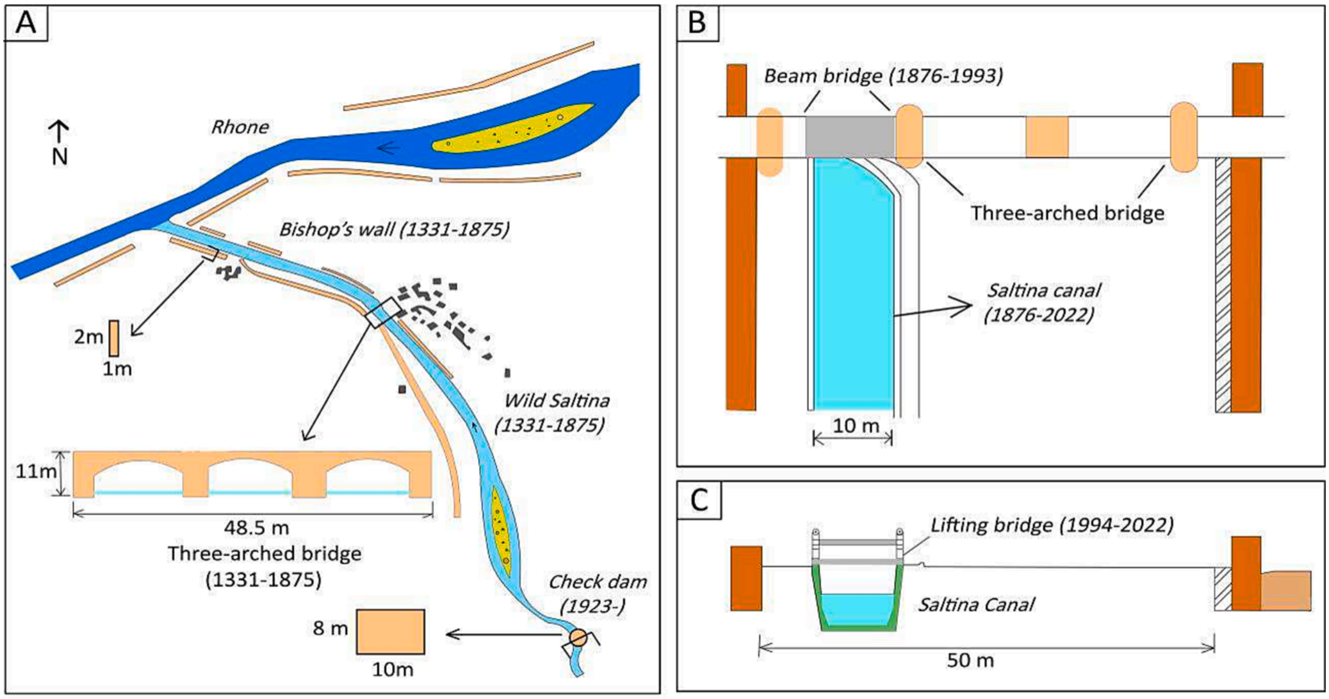

Fig. 2. A. Sketch of the Bishop's Wall and the three-arched bridge at the location of today's lifting bridge (inset; adapted from Meyer et al., 1997; Imboden, 1996); B. Riverbed and bankfull width area of the Saltina River above the city of Brig-Glis after 1875 (source: Imboden, 1996); C. Cross section of the "Saltina canal" and the lifting bridge.

discharge over several centuries. To this end, we (i) studied a large corpus of historical flood descriptions from this small river and classified historical data into catastrophic, extraordinary, and ordinary events based on the available flood description, (ii) performed 2D-hydraulic modeling to estimate flood magnitudes at different times (and with different riverscape settings), and (iii) applied flood-frequency analyses to define flood return periods. In addition, and thanks to the defense structures installed over time, we then discuss the role of human interventions on flood magnitudes. Despite some possible limitations inherent to historical quantitative hydrology (Benito et al., 2015), the transformation of known information of flow levels into discharge estimates has allowed provision of robust scenarios for the definition of flood quantiles, especially for events exceeding the 100-year return period flood.

2. Material and methods

2.1. A torrential alpine catchment

The Saltina river is a 12.2-km long tributary of the Rhone River and a torrential alpine catchment of the Swiss Alps. The catchment has an area of 76.5 km^2, with an elevation varying between 670 and 3,194 m asl. In terms of land occupation, approximately one-fourth each of the catchment is composed of bedrock (26 %) and forest (27 %), while grassland and pastures account for 31 %. In the headwaters, unconsolidated debris, including moraine deposits and talus predominate, accounting for 13 % of the entire catchment, whereas glaciers cover 3 % of the catchment area (Fig. 1A). Mean annual air temperature is 9.4 ℃, and annual precipitation is 596 mm. Most of the rain falls from May to August with 208 mm (MeteoSwiss, 2022). Intense rainfall and thunderstorms in summer and fall are one of the main triggering phenomena that modulates the extreme floods.

Historically, the Saltina river has recurrently flooded, causing damage to the cities of Brig and Glis. The first documented flood dates back to 1331 CE, where a Latin text paints a vivid picture of a flood: "… *land that lies desolate and covered with stones due to the flooding caused by a watercourse named Saltina*" (Imboden, 1996). In 1755 CE, a flood ravaged the village, causing substantial damage to all lands adjoining the Saltina. In September 24, 1993, a catastrophic flood deposited approximately 250,000 m^3 of mud, sand, and debris in urban areas (Fig S1). This debris flood event caused two fatalities and damages up to ca. 650 million Swiss Francs (Bezzola et al., 1994). Since 1966, there is a flow gauge station operating in the Saltina river (Federal Office for the Environment, 2023).

2.2. Historical changes in the catchment and reconstruction of digital elevation models

The "Bishop walls" were erected after the 1331 flood to protect the villages from floods in the Saltina river (Fig. 2A). These walls have an average width and height of 1 and 2 m, respectively, and were maintained regularly until 1875 when the three-arched bridge was replaced by a metal bridge crossing the newly channelized river (Fig. 2B). This means that the wild Saltina was forced into a rigid channel and its bed narrowed down from 50 to 10 m—known as the "Saltina canal". In 1923, a major check dam was built to retain sediments at the contact between the Saltina gorge and the much flatter fan. The check dam was raised to 8 m in 1927 (Fig. 1B). Whereas the geometry and the cross-section of the main bridge was not changed substantially over the first half of the 20th century, urbanization and the lack of major floods has resulted in its enlargement and the construction of parking spaces on the largely enlarged bridge. It was only after the major September 24, 1993 disaster that the bridge was removed and the channel walls reinforced. In addition to the construction of an autonomous lifting bridge (Meyer et al., 1997), new check dams have been constructed in the Saltina gorge to better dose sediment transport through the channel during floods. Although the floods of October 14–16, 2000 were larger than that of 1993, the new system managed to absorb both water and sediment without major damage. Based on this history of engineering measures realized in the Saltina river and the impact of channelization and check dam constructions on river flow behavior, we distinguish three "homogeneous" pre-instrumental episodes representing the periods

1331–1875, 1876–1923, and 1924–1965. In the following, we describe how historical topography and the extent and nature of the settlement(s) were assessed for each of the periods to adequately estimate past flood discharges. Reconstruction of past topography was based on the combination of the current digital elevation model (DEM)—at a resolution of 50 cm—with historical maps available from (Swiss Federal Office of Topography, 2023) and Lechevalier (2005). For each period, relevant spatial elements were digitized as shapefiles from old, georeferenced maps using ArcGIS 10.8.2 (ESRI, 2020). Special attention was given to defense walls, check dams and buildings, for which we also relied on historical descriptions (Imboden, 1996) and surviving cadastral and engineering plans available at the *Forschungsinstitut zur Geschichte des Alpenraums* in Brig. In the case of flood defense structures, we placed all objects at their exact location and used the effective dimensions of structures in the DEM. To integrate historic buildings into the current DEM, we defined them to be 3D objects. In the case of buildings, we defined an elevation of 10 m to each building from ground level using ArcGIS Raster Calculator tool (Kennedy, 2013). This specific procedure was chosen as it avoids flooding over-the-top of building features and thus optimizes the spatial propagation of the simulation of historical floods. Based on historical maps, descriptions, Medieval engravings, drawings and 19th-century engineering plans, we here assume that both the elevation and slope of the riverbed did not undergo substantial changes over time and the current characteristics of the Saltina River on the fan can be used for the three periods investigated. Hence, we defined the slope of the Saltina River to 2.6 % for the first 1.1 km of the fan (downstream of the check dam) and to 3.6 % from 1.1 to 1.8 km.

For the period 1924–1965, the geomorphic configuration of the fan has remained stable and we thus use the current DEM as a baseline. Buildings were added to the DEM according to their position on the topographic Siegfried map of 1933 (1:50,000; Imfeld and Leuzinger, 1935). Specific attention was given to the digitalization and implementation of the check dam, located at the fan apex. To adapt the DEM to the fan configuration of the period 1876–1923, we removed the check dam and also designed a riverbed section with the current slope. Buildings were digitized and embedded to the DEM using the Siegfried maps of 1881 and 1890 (1:50,000; Dufour (1881)).

Finally, for the period 1331–1875, we removed the channel and redesigned the riverbed. The characteristics of the riverbed and its cross-sections were interpreted from current fan geometry and historical documents such as the map designed by the Napoleonic troops in 1802 (Lechevalier, 2005; Reynard, 2009) and sketches of Brig showing the situation in the 14th and 17th centuries (Erpen, 1991). The riverbed was widened to reach up to 200 m in both the upper and lowermost sections of the fan. In addition, we modified the riverbanks of the Saltina River and digitized the Bishop's defense walls all along the Saltina. They were considered as 1-m thick and 2-m high features above the riverbed. The three-arch bridge—dismantled in 1875—was digitized at its historical location and considered with the following characteristics: 48-m long, 6-m wide and 11-m above the riverbed. Finally, buildings were digitized from the same historical documents mentioned above and then added to the DEM.

2.3. Historical flood classification

The flood records of the Saltina River comprise an instrumental series from 1966 to 2020 and non–continuous records from 1331 to 1966, available from local archives. All references to historical floods have been compiled by the *Forschungsinstitut zur Geschichte des Alpenraums* (FGA, 2022) and were published by Imboden (1996) and Zenhäusern (2022).

The extraction of scientifically reliable data from historical sources and its expression as quantitative data obviously is a difficult task (Glaser et al., 2010). To assess the magnitude of past floods of the Saltina, we employed a classification scheme proposed by Barriendos et al. (2003) where three classes are defined to account for the severity of the damage and the spatial dimension of the event: 1) *ordinary floods* causing overbank flows and temporary disruption of human activities; 2) *extraordinary floods* causing overbank flows of moderate intensity, with minor damage to crops, houses, and river dykes (0–1.5 m depth); as well as 3) *catastrophic floods* causing extensive overflow with significant damage to agriculture, mills, and/or the destruction of houses and infrastructures (>1.5 m depth). More details are provided in Table 1, by way of example, for the 1755 catastrophic, 1834 extraordinary and 1866 ordinary floods, whereas Table S1 presents the classification of all 32 floods recorded between 1331 and 1965.

Table 1
Flood type definition based on historical documentary description.

Flood Type	Year	Description
Catastrophic	1755	1.The Saltina overflows all bordering land such as e.g., "Sandmatten", "Englisch Gruss". 2. All lands bordering the Saltina suffered considerable damage. 3.1755 was an unfortunate year, it ruined land with an extraordinarily large amount of water. 4. Terrible weather, which we have not had since times immemorial.
Extraordinary	1834	1.The Saltina carries large masses of wood and solid material. 2. The Saltina rises above its banks, and overflows parts of the land in Glis and Brig. 3. Damage: 20 000, old currency
Ordinary	1866	1. The Saltina did not rise above its banks. 2. A person fell into the torrent and drowned.

2.4. Hydraulic modeling

Historical flood water levels can be derived either from (i) landmarks or observed flow depths measured at sites reached by the flow (e.g., monasteries, bridges, chapels), (ii) descriptions of flooded areas (e.g., sectors of the floodplain, orchards or mills that have been affected), (iii) mentions of non–flooded areas, or (iv) relative flood levels of subsequent historical floods (e.g., flood level reached was less than during a previous flood; (Herget et al., 2014). Here, the documented flood evidence for the Saltina River was used to estimate the interval magnitude of each historical flood.

Discharge of individual floods was estimated with the hydrodynamic module of the IBER model based on the calculation of depth-averaged two-dimensional shallow water equations (2D Saint-Venant Equations) (Gómez et al., 2019). The module uses a finite–volume scheme and a non-structured mesh of triangular and quadrilateral elements whose spatial resolution was set at 2 m for the Saltina channel and 4 m for the floodplain. Manning's n values were assigned to different land-cover classes based on contemporary and historic maps following the National Flood Inundation Hazard Map (Chow, 1959; USGS, 1989). The hydraulic model was calibrated against recent floods using flow discharge and stage records at the local gauging station. We fixed Manning's n values of the Saltina River to 0.02 for low–medium discharge (i.e., 40–80 m^3/s) and 0.025 for medium–high discharge (i.e., >80 m^3/s) after comparing relative errors of water depths. As shown in Table 2, the relative error of water depths between model outputs and systematic observations was found to be well below 10 %, except for the September 24, 1993 flood which must be considered exceptional due to the clogging of the Saltina bridge with wood and sediment.

2.5. Observation-based estimation of flood return periods

In a next step, we combined the historical (1331–1965) with the systematic (1966–2020) records in a single flood frequency analysis. To this end, we first tested stationarity of the historical flood reconstruction using Lang's test (Lang, 1999) assuming that flood records follow a homogenous Poisson process at the 95 % tolerance interval. Flood series

Table 2
Calibration of roughness based on observed and modeled flood depths.

Year	Discharge ($m^3 s^{-1}$)	Observed elevation(m)	Water depth(m)	$n = 0.02$ (Saltina)			$n = 0.025$ (Saltina)		
				Modeled elevation(m)	Error(m)	Relative error	Modeled elevation(m)	Error(m)	Relative error
1999	43.3	678.25	1.25	678.24	–0.01	–0.8 %	678.23	–0.02	–1.6 %
2004	53.1	678.45	1.45	678.40	–0.05	–3.4 %	678.37	–0.08	–5.5 %
2008	61.9	678.63	1.63	678.50	–0.13	–8.0 %	678.52	–0.11	–6.7 %
1993	99.7	679.26	2.26	678.89	–0.37	–16.4 %	678.91	–0.35	–15.5 %
2000	123.5	679.42	2.42	679.20	–0.22	–9.1 %	679.21	–0.21	–8.7 %

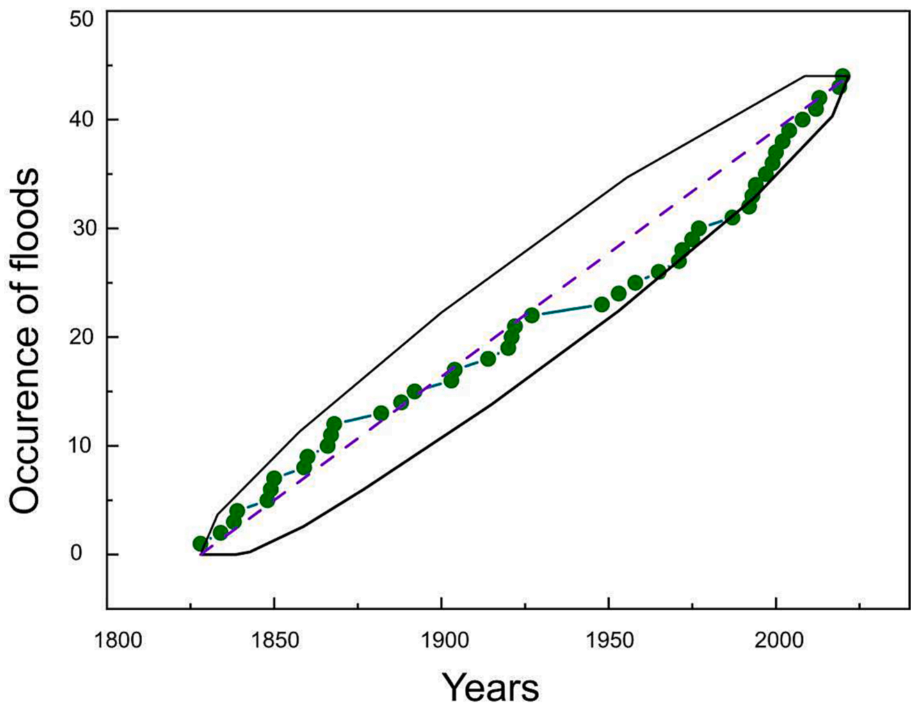

Fig. 3. The Lang test evidences stationarity in the frequency of ordinary floods between 1828 and 2020.

are thereby defined as stationary if they remain within the 95 % tolerance interval. Next, we estimated flood frequencies from historical and systematic records using U.S. National Flood Frequency Guideline Bulletin 17C (England, 2019). We then used Peak FQ (version 7.3; Veilleux et al. (2014)) as it estimates the parameters of the log-Pearson Type III frequency distribution from logarithmic sample moments (mean, standard deviation, and coefficient of skewness) of the record of flows, with adjustments for low outliers, high outliers, historic peaks, and generalized peak skew. The parameter values were then used to obtain quantiles of the log-Pearson Type III distribution for selected exceedance probabilities (Cohn et al., 2001; Flynn et al., 2006). As low annual discharge values may excessively influence the estimated frequency of large floods, we performed Multiple Grubbs–Beck statistics to identify Potential Influential Flows (PLFs) in existing records (Cohn et al., 2013). We also used perception thresholds to assure temporal continuity of the records (Benito et al., 2004; Benito and Thorndycraft, 2007). These thresholds were set on the basis of flood magnitudes spilling over the channel into the urban areas where they are likely to disrupt human activities and/or to produce damage (Benito et al., 2021). In this paper, perception thresholds for the period 1331–1965 were set close to the relative bankfull discharge and combined with settlement density. As such, they were defined as the lower limit of an ordinary flood.

3. Results and discussion

3.1. Historical flood reconstruction of the Saltina River

Historical archives contain descriptions of 32 floods between 1331 and 1965, of which most (i.e., 26) occurred after the mid–18th century, which means that only six floods were recorded between 1331 and 1756. Also, during the 19th century, the number of documented floods was considerably higher (15 floods) than in previous and subsequent periods. During the 20th century, and before systematic measurements started in 1966, 11 floods were documented in historical records. The use of long historical records for flood frequency analysis rely on an assumption of stationarity (Barriendos et al., 2003). Yet, and besides climate, the occurrence of floods can be affected by changing land-use conditions. In our case, the flood records fulfill the stationarity requirements and pass the Lang test with a 95 % confidence interval since 1828 when floods started to be registered systematically for the Saltina River (Fig. 3).

As usual for proxy data, we cannot obviously rule out the possibility of some unregistered floods, especially before 1828. In addition, some sources may have been lost over the centuries or information on past events forgotten due to the lack of transmission (e.g., end of oral tradition). This is probably also one of the reasons why the increase in flood records documented in this study is not constant over time. In addition, according to the large proportion of non-damaging flooding after 1828, we also believe that the records for the earlier

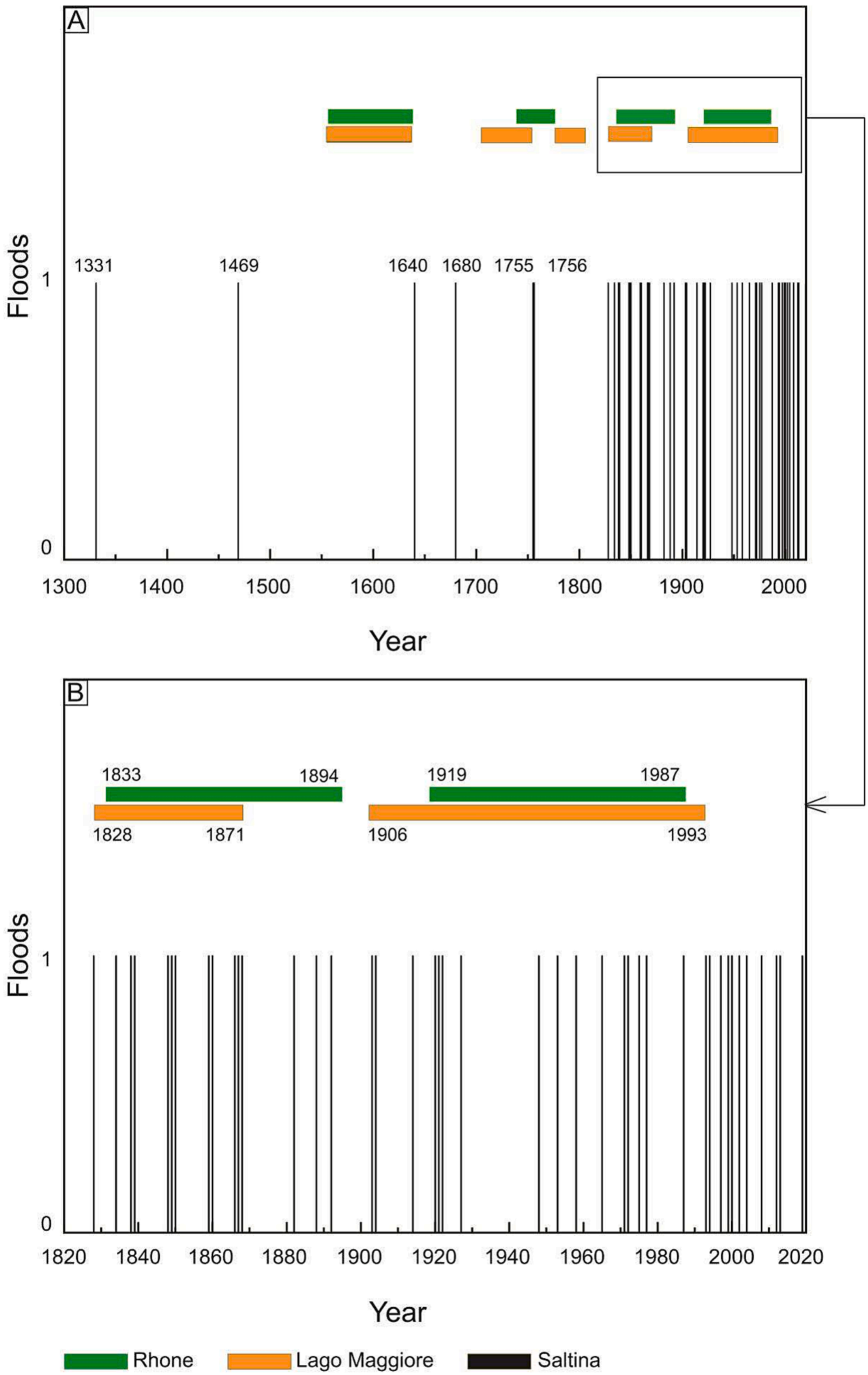

Fig. 4. A. Saltina flood records (1331–2020) as retrieved from historical archives and systematic gauge records compared with reconstructed floods in different larger neighboring catchments affected by comparable synoptic situations during floods. B: Detailed 1828–2020 view of flood occurrences in the Saltina River and reconstructed flood histories from the sites used in panel A.

Table 3
Estimated peak discharge intervals and perception thresholds for floods that occurred between 1331 and 2020 as obtained from hydraulic modeling with IBER and different topographies.

Type	Period	Ordinary floodrange (m3.s^{-1})	Extraordinary floodrange (m^3.s^{-1})	Catastrophic floodrange (m^3.s^{-1})	Perceptionmagnitude (m^3. s^{-1})
Historical	1331–1875	70–90	90–130	>130	70
	1876–1923	50–80	80–120	>120	50
	1924–1965	40–70	70–110	>110	40
Instrumental	1966–2020	30–50	50–70	>70	30

period—generally reporting harmful and large floods—was limited to the most devastating events whereas smaller floods were not reported in surviving documents.

Looking at floods across larger spatial scales, Blöschl et al. (2020) investigated period that were rich and others that were poor in flood occurrences, either regarding the extent or the magnitude of events. In the case of the Saltina River, it is possible to distinguish flood-rich from flood-poor period, and to compare these with comparable records from neighboring, but much larger catchments. To this end, we compared our flood chronology to those of the Rhone River and to Lago Maggiore (Pfister, 1999). The Saltina River is part of upper Rhone River basin and both are located within the same inner alpine valley. Lago Maggiore is located south of the main Alpine divide but is often affected by floods in fall when low-pressure systems transport large masses of humid air to the main alpine divide. The same rainfall events are often at the origin of floods in the Saltine River (Bezzola et al., 1994; Imboden, 1996; Stoffel et al., 2005). Fig. 4A provides an overview of flood-rich periods in the three catchments. In Fig. 4B, flood-rich periods have been identified for the Saltina River for 1839–1843, 1850–1857, 1866–1875, 1921–1930, 1972–1981, and in 1993/4. All six periods found in the Saltina River are also considered flood-rich periods in the Rhone River and at Lago Maggiore, even if periods in these larger catchments are sometimes longer in duration that at the much smaller Saltina River. This agreement provides further, independent evidence for the rather accurate and fairly complete record of past floods at the study site.

3.2. Significance of past events in flood frequency analysis

In a next step, we estimated flood types (i.e., ordinary, extraordinary, and catastrophic floods) and peak discharges for historical floods of the past c. 700 years based on flooded area, water depth and damage to infrastructure, using the three DEM that have been constructed for the periods 1331–1875, 1876–1923, and 1924–1965. These periods were complemented by the systematic records covering the period 1966–2020. Based on the information obtained, we considered floods as ordinary when discharge was 70–90 m^3/s for the period 1331–1875, 50–80 m^3/s for the period 1876–1923, 40–70 m^3/s for the period 1924–1965, and 30–50 m^3/s for the period 1966–2022. In the case of extraordinary floods, peak discharges were estimated at 90–130 m^3/s (1331–1875), 80–120 m^3/s (1876–1923), and 70–110 m^3/s (1924–1965), and 50–70 m^3/s (1966–2020). Floods were considered catastrophic when estimated peak discharges exceeded 130 m^3/s

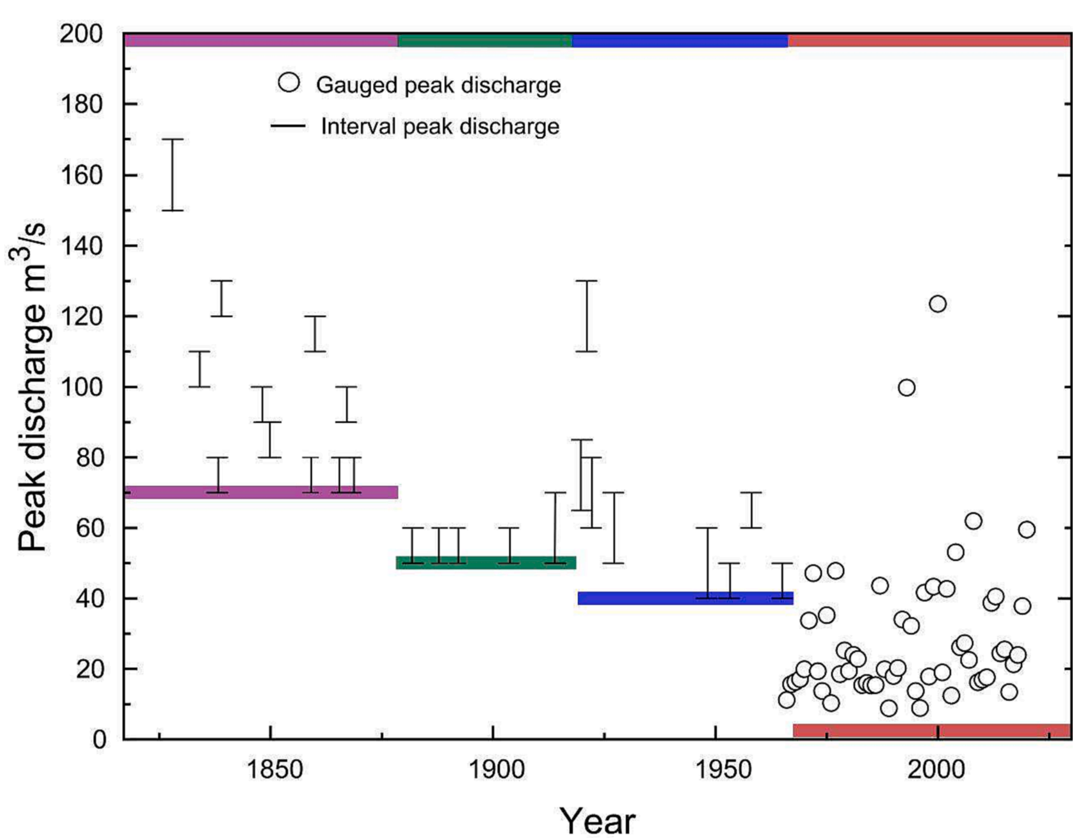

Fig. 5. Composite chronicle of reconstructed (historical) and systematic (gauged) peak discharges of past floods in the Saltina River with changes in perception thresholds (colored horizontal bars).

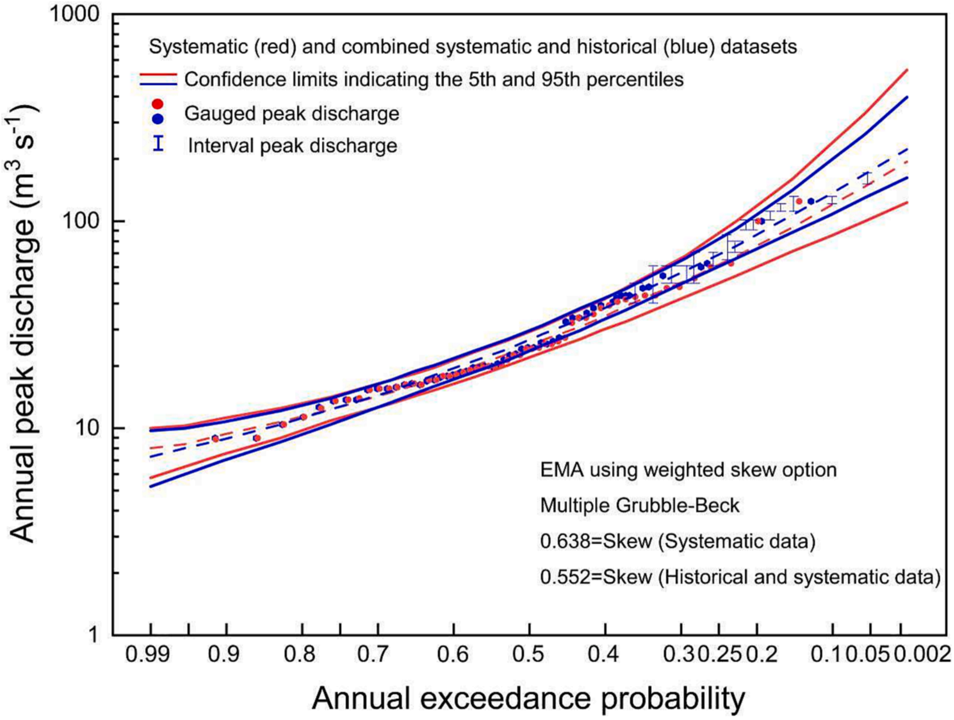

Fig. 6. Flood frequency analysis with and without historical records.

Table 4
Peak flow quantiles in cubic meters per second (m^3/s) based on FFA using EMA and multiple Grubbs–Beck tests. The variance of estimates is shown in log space (OS: only systematic records; IH: including historical records; DD: difference of discharge).

Return period (year)	EMA estimate ($m^3.s$–1) with regional Skew			Variance of estimate		Lower 2.5 % confidence limit (m^3 s^{-1})			Upper 97.5 % confidence limit (m^3 s^{-1})			The absolute value of uncertainty reduction ($m^3.s^{-1}$)	Percentage of uncertainty reduction ration
	OS	IH	DD	OS	IH	OS	IH	DD	OS	IH	DD		
2	23	24	1	0.0012	0.0009	20	21	1	26	27	1	1	12.7 %
5	38	42	4	0.0021	0.0009	32	37	4	46	47	0	4	30.2 %
10	51	57	6	0.0033	0.0012	43	50	8	68	66	–2	10	38.9 %
25	73	82	9	0.0061	0.0021	57	70	13	110	101	–9	22	41.7 %
50	93	106	13	0.0092	0.0034	70	88	18	159	140	–20	37	41.9 %
100	117	134	17	0.0133	0.0052	84	107	23	229	191	–38	61	41.9 %
200	145	167	22	0.0183	0.0075	99	128	29	329	261	–68	97	42.1 %
500	192	221	30	0.0267	0.0117	122	160	38	530	392	–138	176	43.2 %

(1331–1875), 120 m^3/s (1876–1923), 110 m^3/s (1923–1965), and 70 m^3/s (1966–2020) (Table 3). The threshold values for ordinary, extraordinary, and catastrophic floods, as well as the perception thresholds are not static but vary with changing river morphologies (i.e., changes to the riverscape and channel width) and hydraulic flood mitigation measures—e.g., channelization, dykes, check dams, changing bridge geometry (Barriendos et al., 2003; Stamataki and Kjeldsen, 2021).

Discharges of the 32 floods for which information was available between 1331 and 1965 were assessed catastrophic in four, extraordinary in eight and ordinary in twenty cases. Over the past four centuries, the most damaging floods occurred in 1755 (130–150 m^3/s), 1828 (150–170 m^3/s), 1921 (110–130 m^3/s), and 1993 (c. 100 m^3/s) based on descriptions and estimates. Fig. 5 shows the resulting composite chronicle of reconstructed (historical) and systematic peak discharges of the Saltina River from 1828 to 2020, that is for the period during which conditions can be considered as stationary.

The inclusion of historical data in flood frequency analysis also yields a more realistic picture of flood quantiles. Fig. 6 provides a dataset of past floods fitted with an LP3 distribution (Table 4) and shows quite clearly that discharge at a given probability will be underestimated if analyses are based on systematic measurements alone. In other words, incorporating historical data into the FFA will not only reduce the variance of estimated discharges but also result in a slight increase of flood quantiles (marked with a solid line in Fig. 6) compared to values derived exclusively from systematic records (Table 4). For example, if all historical floods found in archives are added (i.e., dashed line in Fig. 6), the magnitude of a 100-year return period flood rises from 117 m^3/s to 134 m^3/s. It is also noticeable that the uncertainty of discharge estimations at a specific return period decrease drastically after inclusion of historical records. In the case of the 100-yr return period flood, the 95 % (2.5–97.5 %) confidence interval can be reduced from 145 m^3/s (84–229 m^3/s) to 85 m^3/s(107–191 $m^3.s^{-1}$) or –41.9 % when adding historical data to the systematic record. Uncertainty can be reduced even more substantially in terms of absolute value and ratio reduction for the largest floods (i.e., 97 m^3/s or 42.1 % for a 200-yr and 176 m^3/s or 43.2

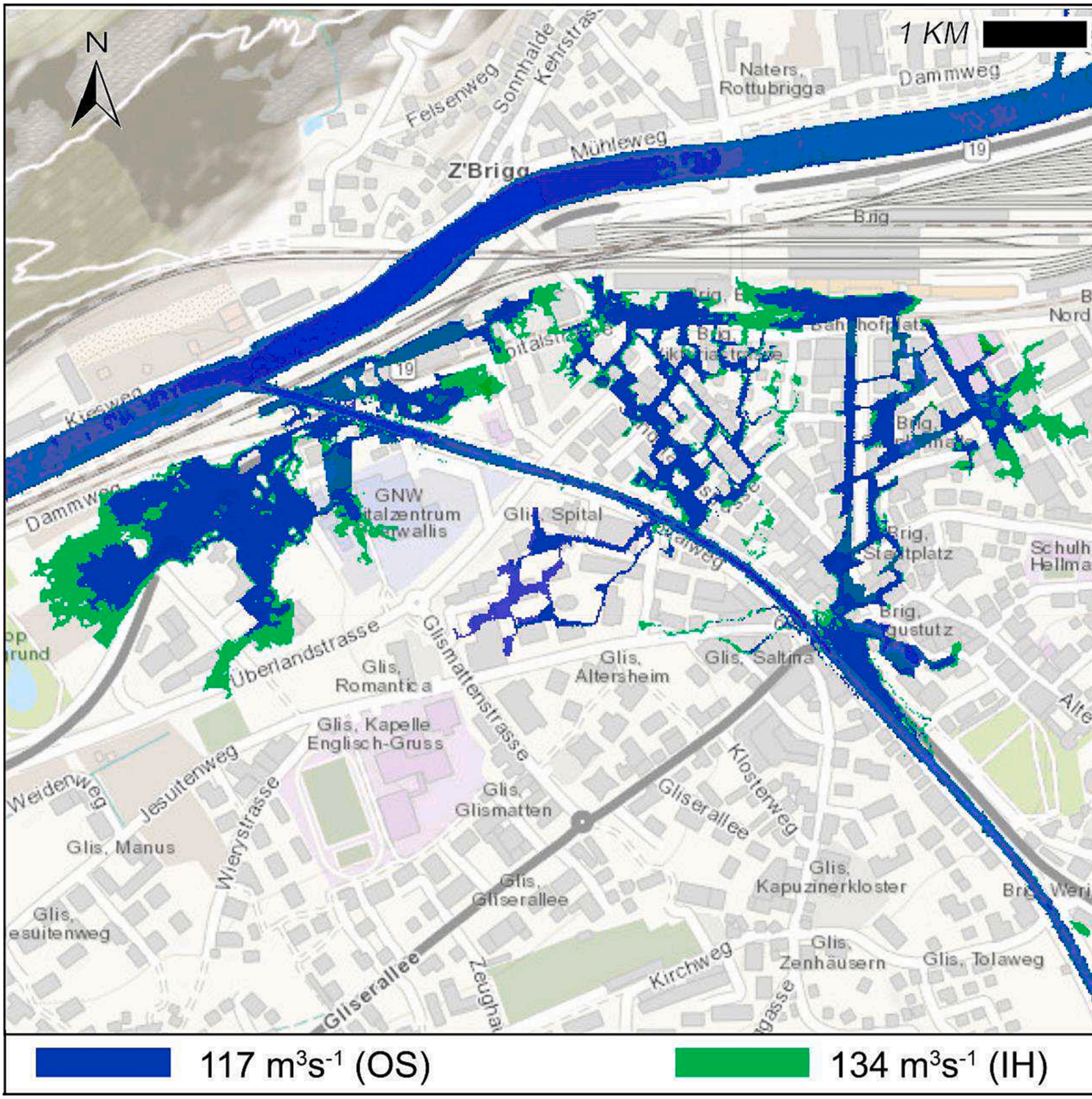

Fig. 7. Flood depths as obtained with hydraulic modeling for tje 100–year return period flood in the Saltina River (Brig-Glis) with flood-affected areas as obtained with (A) systematic records only (117 m^3. s^{-1}) as well as (B) systematic and historical records (134 m^3. s^{-1}).

Table 5
Inundation scenarios under 1% AEP flooding magnitudes (historical and systematic).

Type	Mean water depth (m)	Inundation boundary (m)	Inundation area (m^2)	Inundation total volume (m^3)	Peak discharge (m^3)
OS	0.12	26,900	108,600	6,600	117
IH	0.16	31,500	133,800	21,400	133
Increase percentage	33 %	17 %	19 %	224 %	14 %

% for a 500-yr return period flood).

We then modelled a 100-yr flood discharge to define inundation extent by using 117 m^3/s vs 134 m^3s^{-1}. Results are shown in Fig. 7 with a summary of key features in Table 5. The different discharges considered for the 100-year return period flood result in an increase in mean water depths in the city by 33 %, whereas boundaries of areas inundated (m^2) and inundation volume (m^3) increase by 17 % and 224 %, respectively (Fig. 8).

3.3. Impacts of mitigation structures along the Saltina River on flood magnitude

We studied four periods (1828–1877, 1878–1927, 1928–1997 and 1998–2020) during which the Saltina River flowed over the fan in different configurations. The first period is characterized by a near-natural environment without major lateral restrictions and a three-arched bridge. This is followed by a first phase of engineering works, at the end of the 18th century, during which the riverbed was channeled

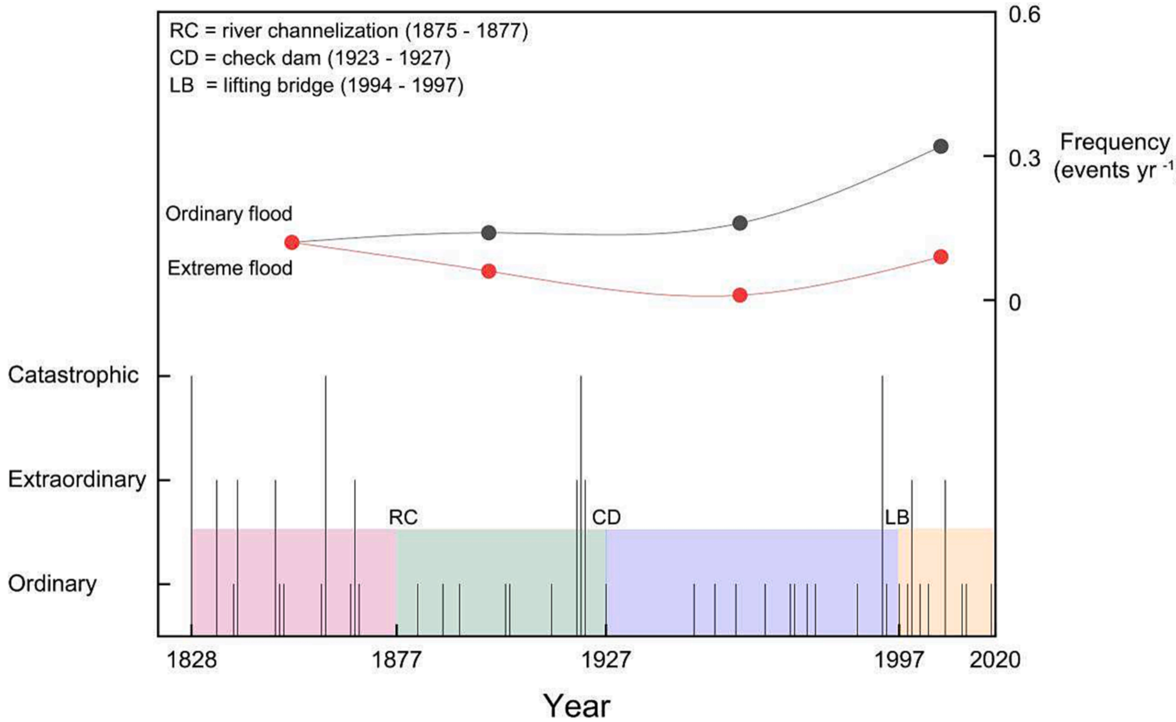

Fig. 8. Flood occurrence rate and changes from 1828 to 2020 with historical and systematic records considering the channelization of the Saltina River and smaller bridge, check dam construction, and the new lifting bridge (light orange: the period from 1828 to 1877, prior to river channelization, green: the period from 1878 to 1927, between river channelization and construction of check dam, blue: the period from 1928 to 19,977 after check dam built but before lifting bridge, orange: the period from 1998 to 2020, after lifting bridge). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 6
Value of flood occurrence rates before and after primary protective measures (Nb: number; Freq: frequency; Prec. Total: Percentage total).

Period	Engineering measures	Items	Ordinary	Extraordinary	Catastrophic	Total
1828–1877	–	Nb	6	5	1	12
		Freq	0.12	0.10	0.02	0.24
		Perc. Tot (%)	50	42	8	100
1878–1927	River channelization	Nb	7	2	1	10
		Freq	0.14	0.04	0.02	0.2
		Perc. Tot (%)	70	20	10	100
1928–1997	Check dam	Nb	11	0	1	12
		Freq	0.16	0.00	0.01	0.17
		Perc. Tot (%)	92	0	8	100
1998–2020	Lifting bridge	Nb	7	2	0	9
		Freq	0.32	0.09	0.00	0.41
		Perc. Tot (%)	78	22	0	100

*The term "extreme flood" groups extraordinary and catastrophic floods.

and the cross-section reduced. The third period includes the construction of dams (1923–1927) at the contact of the Saltina river gorge with the fan. Finally, the last period begins after the construction of a lifting bridge (1996/7) and other sediment control measures in the Saltina gorge. The findings are presented in Fig. 8, accompanied by a summary in Table 6. The implementation of mitigation measures did not lead to a clear reduction in the frequency of reported floods, which remained stable during the first three periods (0.17–0.24 events yr^{-1}). In contrast, the magnitude of floods shows a rapid and significant decrease after the channelization of the river and especially after the installation of the check dams. The proportion of extraordinary and catastrophic floods ($n = 6$), which represented 50 % of the reported floods ($n = 12$) before 1878, decreased to 30 % (3 out of 10 events) and to 8 % (1 in 12 events) for the periods 1878–1927 and 1928–1997, respectively. Interestingly, and despite the installation of the lifting bridge, both the frequency (0.41 events yr^{-1} since 1998) and the magnitude (2 extraordinary events in 2000 and 2008) have increased again since the turn of the 21st century.

4. Conclusions

In this study, we successfully derived peak discharge estimates from historical descriptions of floods in the now urban area of Brig-Glis by systematically screening local archives and by developing different generations of digital terrain models representing the contemporary conditions in terms of the riverscape, urban development and structural flood mitigation measures. Our key findings are:

- Discharges of the 32 historical floods for which documents exist between 1331 and 1965 were assessed as catastrophic in four, extraordinary in eight and ordinary in twenty cases. Over the past four centuries, the most damaging floods occurred in 1755 (130–150 m^3/s), 1828 (150–170 m^3/s), 1921 (110–130 m^3/s), and 1993 (c. 100 m^3/s) based on descriptions and estimates. The composite

chronicle of peak discharges from 1828 to 2020 can be considered as stationary.
- Flood-rich periods have been identified for the Saltina River for 1839–1843, 1850–1857, 1866–1875, 1921–1930, 1972–1981. Flood-rich period and major events match with nearby major catchments, such as the Rhone River and Lago Maggiore catchments.
- The uncertainty of discharge estimations for specific return periods decreases drastically after inclusion of historical records. In the case of the 100-yr return period flood, the estimated discharge can be reduced by 41.9 % when adding historical data to the systematic record. Uncertainty can be reduced even more substantially in terms of absolute value and ratio reduction for the largest floods (i.e., 97 m^3/s or 42.1 % for a 200-yr and 176 m^3/s or 43.2 % for a 500-yr return period flood).
- Mitigation measures realized between 1828 and 1927 did not clearly result in a reduced flood frequency, which stayed stable at 0.17–0.24 events yr^{-1}. In contrast, after the river channelization and construction of check dams, the flood magnitude dropped significantly. The occurrence of extreme floods dropped from 50 % pre-1878, to 30 % between 1878 and 1927, and 8 % during the period 1928–1997. Despite the implementation of a lifting bridge in 1994, flood frequency and magnitude have increased again in 1998–2020.

Our results are based on existing and reconstructed datasets. We assume that the multi-century extreme flood distribution documented here can be used to constrain future extreme floods. Including the effect of climate change could have an impact on the flood frequency estimation, but current climate modelling frameworks present significant uncertainties, especially at the local scale. Here, the long-term reconstructed peak discharges exceed the duration of modes of natural climate variability, and thus provide an opportunity to compare past, recent and future floods using different climate scenarios (Benito et al., 2023). The gathered information in this study also holds implications for the management of local flood risk. Ultimately, this research can serve as a model for the exploration of shifts in flood activity in regions with abundant historical records and well-documented floodplain evolution.

CRediT authorship contribution statement

Yihua Zhong: Conceptualization, Resources, Formal analysis, Writing – original draft, Writing – review & editing. **Juan Antonio Ballesteros–Cánovas:** Conceptualization, Resources, Formal analysis. **Adrien Favillier:** Resources, Formal analysis. **Christophe Corona:** Formal analysis, Writing – review & editing. **Gregor Zenhäusern:** Resources. **Alberto Munoz Torrero Manchado:** Formal analysis. **Sebastien Guillet:** Conceptualization. **Florie Giacona:** Resources, Conceptualization. **Nicolas Eckert:** Conceptualization. **Jiazhi Qie:** Formal analysis. **Georges Tscherrig:** Conceptualization, Resources. **Markus Stoffel:** Conceptualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2023.130547.

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