The Potential of Historical Hydrology in Switzerland

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Abstract

Historical hydrology is based on data derived from historical written-, pictorial and epigraphic documentary sources. It lies at the interface between hydrology and environmental history using methodologies from both disciplines basically with the goal to significantly extend the instrumental measurement period with the experience from the pre instrumental past. Recently this field of research has gained increased recognition as a tool to improve current flood risk estimations when EU guidelines regulated by law the quantitative consideration of previous floods.[1] The awareness to consider pre instrumental experience in flood risk analysis seems to have risen at the level of local- and federal authorities in Switzerland as well. The 2011 Fukushima catastrophe probably fostered this rethinking process, when pressure from the media, society and politics as well as the regulations of the International Atomic Energy Agency (IAEA), forced the authorities to reassess the current flood risk analysis for Swiss nuclear power plants. In 2015 a historical hydrological study was commissioned by the Federal Office for Environment (FOEN) to assess the magnitudes of pre instrumental Aare river flood discharges including the most important tributaries (Saane-, Emme-, Reuss and Limmat river). The results of the historical hydrological study serve now as basis for the main study EXAR [commissioned under the lead of FOEN in cooperation with the Swiss Nuclear Safety Inspectorate (ENSI), Swiss Federal Office of Energy (SFOE), Federal Office for civil protection (FOCP), Federal Office of Meteorology and Climatology (MeteoSwiss)] which combines historical- and climatological analysis with statistical approaches and mathematical models with the goal to better understand the hazards and possible interactions that can be caused by extreme flood events. In a second phase the catchment of the River Rhine will be targeted as well. More recently several local historical hydrological studies of smaller catchments have been requested by responsible local authorities. The course for further publicly requested historical hydrological analysis seems thus to have been set. This paper therefore intends to discuss the potential of historical hydrological analysis with a focus on the specific situation in Switzerland.

1 EU: Richtlinie 2007/60/EG des Europäischen Parlamentes und des Rates vom 23. Oktober 2007 über die Bewertung und das Management von Hochwasserrisiken, Amtsblatt der Europäischen Union, L 288, 27–34, Brussels, 2007.

1. Introduction

This paper aims to describe the potential of historical hydrology in Switzerland in terms of data availability, methodologies, reconstruction capabilities and usefulness for the scientific- and practical communities like Federal or Cantonal Agencies and private engineering companies by adding a longer term historical perspective to the spectrum of already existing risk and vulnerability assessments. The concept of historical hydrology is – not by its definition but by its specific application – quite often used as an equivalent to analysis of – mostly – extreme pre instrumental or early instrumental flood events even though the research interest of historical climatology is more heterogeneous. The analysis of the vulnerability of past societies to extreme hydrological events (e.g. Pfister, 2011a) can be seen as the most “classical” historian approach in the field of Historical Hydrology, whereas the reconstruction of anthropogenic influence on runoff conditions due to flood protection and river regulation constructions [Vischer, 2003, Salvisberg, 2017, Longoni, 2017, Longoni & Wetter (in prep)] sheds light on hydrological and hydraulic research questions. The reconstruction of temporal and spatial patterns of floods (e.g. Glaser et al., 2010), or the analysis for meteorological triggers of particular flood events (e.g. Mudelsee et al., 2004) however, do have a more climatological research focus. In this paper the almost complete spectrum of historical hydrology shall be applied, meaning that all kind of pre instrumental hydrological events like floods or droughts as well as precedent meteorological causes of such events or the anthropogenic influence on discharge conditions are meant, when the term historical hydrology is used. The focus will be primarily laid on obtaining quantitative hydrological and meteorological information from all kind of documentary sources (written, pictorial, epigraphic) with the goal – whenever possible – to analyse pre instrumental historical hydrological events holistically in the sense of the definition of historical hydrology. Solely the society and vulnerability aspect does not stay in the forefront of interest in this paper unless anthropogenic interventions significantly influenced the hydrological system. The specific targets are (1) to describe the strengths and weaknesses of the available historical hydrological documentary evidence, (2) to shed light on the existing basic methodologies leading to long-term frequency, seasonality and magnitude reconstructions of pre instrumental hydrological events, (3) to discuss the comparability of reconstructed pre instrumental flood events compared to current events and (4) to provide an outlook of future analysis which (in some cases) might be unique for Switzerland.

2. Data

The general historical documentary data availability in Switzerland is good due to several reasons. First it has to be mentioned that Switzerland was not involved in war activities anymore after the Sonderbund War in 1847 (a very short term civil war causing approximately 150 casualties and around 400 wounded) (Remark, 1997) which could have led to significant losses of archives and historical documents. Confederate troops from the Old Swiss Confederacy (~ 13th Century to 1798) gained an aura of invincibility because of their tactics and combat strength in open field battles, latest after they devastatingly defeated the Burgundian Forces three times in a row during the Burgundian Wars (1474 – 1477), which – with their outstanding artillery and heavy cavalry – was a military superpower at that time (Lehmann, 1995). Confederate troops, on the other hand lacked adequate besieging technologies and tactics to successfully take over bastioned cities. This fact might be the reason why, generally spoken, Swiss cities (and thus archives) where not too negatively affected during Old Swiss Confederacy war activities, because the battles were either fought in open fields, besieging most of the time was not successful or cities surrendered peacefully. When Napoleonic military forces invaded Swiss territory, resulting in the Helvetic Republic (1798 – 1803) and the Mediation period (1803 – 1813) authorities from important Old Swiss Confederate Powers like e.g. Basel, Freiburg, Bern, Solothurn, Schaffhausen and Zürich either resigned or peacefully accepted the handover of power (Christian, 1998). Again Swiss archives and thus important historical documents were thus luckily not destroyed during the Napoleonic influenced era. This unfortunately is not true for most of the bridges, which were systematically destroyed by French forces on their retreat. This military tactic complicated not only the advance of the opposing forces, but also significantly aggravates the reconstruction of many pre instrumental flood events, because documentary pre instrumental flood evidence in many cases are either directly or indirectly related to these infrastructures, which at certain locations survived ice drifts and floods for several centuries before they were destroyed by the French. The second reason why the historical documentary data availability is good in Switzerland can be assigned to the lack of major large scale natural disasters that compromised important cities (and thus also archives) since the great and destructive earthquake from 1356 that almost completely annihilated the city of Basel. The destruction of Basel was not so much caused by the seismic shocks, but more importantly because of the outbreak of fire. After a foreshock taking place in the late afternoon, most of the citizens fled to open fields, leaving the many fireplaces unguarded, which then where destroyed during the main seismic shocks, causing an unprecedented town fire that lasted, according to the chronicles, eight days until the fire was extinguished because there was nothing left that could continue to nurture the flames (Meyer, 2006). Speaking of town fires, it has to be stated that the third reason why the historical documentary data availability is good in Switzerland is caused by several related facts that taken together significantly lower the vulnerability towards town fires as well as towards other “natural” disasters. The Begin of the petrification process, especially of important buildings, started quite early in Swiss towns and can, e.g. for Basel, be assigned to the 12^{th} Century, which is more or less true also for other major Swiss cities (D’Aujourd’hui, Lavicka, 1982). Important and powerful people, groups and institutions were among the first who built expensive and representative buildings in stone. The same political, religious and economic influential circles produced the vast majority of historical documents which were archived in those comparably (to wooden buildings) fire safe buildings. The inventories of the state archive of Basel include a huge variety of archival materials (produced by the nobility, the church, guilds, city authorities and important institutions) that pre date the earthquake of 1356, which demonstrates that these historical documents survived the destructive town fire caused by the quake. Cities under normal-, non-cumulative disaster situation or during war activities, generally had the necessary organisational skills, staff and the financial and technical background to support effective measures against natural disasters (Fouquet, 1999) so that, as a rule, disasters such as town fires could be limited to a house, a street or a quarter but did generally not burn down the settlement as a whole, which in those cases certainly anyhow may have led to significant historical documentary losses, but they on the same time could not destroy the majoritarian rest of the documents. To sum it up, the generally good historical data availability in Swiss cities is founded on interrelated positive circumstances like the almost absence of direct involvement of major war activities as well as the absence of cumulative natural disasters, the early begin of petrification of important buildings and the existence of effective measures against non-cumulative disasters such as town fires. These positive historic factors in combination with the comparably recent prosperity of Switzerland, allowing the maintaining of relatively cost intensive archives, provide an excellent opportunity for historians and historical climatologists to draw on a rich legacy of historical documents for their analysis. The Euro-Climhist- and the WSL databases, a rich stock of relevant historical climatological and hydrological analysis in form of qualification works (Seminar-, BA-, MA- and PhD thesis) originating mostly from the University of Bern as well as some fundamental historical hydrological publications focussing on the situation in Switzerland (e.g. Lanz-Lanz-Stauffer & Rommel, 1936; Nast, 2006; Pfister, 1998, 1999; 2006, 2009a; Röthlisberger, 1991; Schmocker-Fackel, P & Naef, F., 2010; Vischer, 2003; Wetter et al., 2011) significantly facilitate the search for data and may even deskill further historical hydrological analysis.

According to Brázdil et al. (2005) historical documentary evidence about climate and single extreme events like e.g. floods are to be distinguished – based on their manner of observation – between *direct-* and *indirect data*. Direct narrative data directly describe the course of weather and climate or extreme events like e.g. floods per se, while indirect data refer to (bio-) physically based phenomena associated with weather and climate such as plant and animal life cycle events or ice and snow seasonality features. With respect to the generation of historical documentary sources Pfister et al. (2009b) differentiate between individual- and institutional sources. Individual sources are shaped by the social background, the motivations and preferences of their authors and their temporal scope is limited – at least the one in which they can be considered as contemporaries to the events they describe – to the life time of the observer. Institutional sources on the other hand are produced by governments or other bodies and institutions such as e.g. the church. These institutional bodies were typically not interested in describing weather and climate or single extreme events, but kept records in order to document their activities and in doing so, they indirectly recorded the before mentioned climate related aspects. Their administrative routines generally involved a good level of standardisation in the way records were kept, which makes them highly homogeneous over periods of time far longer than that of single human lifespan which is a good prerequisite to create long term homogeneous series of climate parameters. The following types of individual and institutional sources shall now be described in more detail, as they are crucial for historical hydrological analysis:

Annals, chronicles, memorial books or memoirs are narrative sources that may contain descriptions of weather and related phenomena like floods with varying degrees of detail, allowing the assessment of the intensity of climate parameters (like e.g. temperature or precipitation) or the magnitude of weather-related extreme events (like e.g. droughts or floods).

Newspapers and **journals** contain similar content as the narrative sources described previously, descriptions of unusual weather or weather-related extremes, often including information about causes and consequences and may sometimes even include (early) instrumental measurements.

Pictorial sources like paintings, etchings, photographs or Ex-votos may represent weather-related phenomena like droughts or floods or include specific built landscapes which – in combination with narrative sources describing such events – may be helpful for the reconstruction of flood- or low water levels. Caution needs to be taken concerning the reliability, especially with pre eighteenth century paintings which are often more imaginative than true-to-detail.

Early scientific papers and **expert reports** often contain valuable information about weather and weather related extreme events and mostly also provide additional scientific information about their occurrences, causes and impacts.

Epigraphic sources like water marks, consisting of marks or comments usually chiselled into stones of bridges, gates or houses, indicate (extraordinarily) high or low river- or lake water levels, may in most cases be regarded as valid sources that usually come closest to the accuracy of instrumental measurements. However, it has to be taken into account that this source may indeed also inherit wrong information like the incorrect dating or indication of false water levels, either caused by a phenomenon called capillary effect or by a dislocation of the mark to another place due to constructional changes.

Gauge readings, early instrumental measurements, early river profiles and official hydrological records. Gauge readings and early instrumental measurements are of great value for the comparison and validation of reconstructed pre instrumental water levels with those that have been measured in the instrumental period. Early river profiles on the other hand allow the assessment of pre instrumental discharges, if they have been proofed to be representative for the situation of the pre instrumental period. Official hydrological records often contain additional information e.g. about the stability of river profiles, local river engineering measures or sediment transport and alike.

Accounting books can clearly be attributed to so-called institutional sources. They record recurrent activities that generated income or cost in money or kind. These records are usually dated and provide short and crisp information about diverse activities the respective institution was involved.

Dated wage payment for agricultural labourers for hay-, grain- or grape harvest, expenditures for food and drinks as well as wages for the members of craftsmen that were ordered to guard a bridge from floating debris during a flood or recurring expenditures for the gatekeepers to open the fence at the entry of a brook into a town to prevent damming caused by floating debris may be found in this kind of source.

3. Methodologies

3.1 Critique of sources

According to the great variety of documentary evidence accessible, a range of different methodologies exist to extract their inherent climatological and hydrological information. When dealing with historical sources it is an absolute prerequisite to critically evaluate their reliability and validity, before further methodologies and analysis can be applied. The exercise of historical critique of sources (e.g. Arnold, 2001) in the context of historical climatological and historical hydrological purpose includes the correction of calendar from Julian to the Gregorian calendar as well as the distinction between contemporary and non-contemporary sources. Non contemporary sources generally need to be treated as sources of substantial lower reliability and should only be included for analysis if they provide additional and coherent information of an, based on contemporary sources, already known event. Municipal accounts are seen as contemporary historical sources, as they "report" almost simultaneously to the "described" event. Newspapers- or early scientific expert reports also provide contemporary accounts and details. Chronicles, annals or memorial books contemporariness is somewhat more complicated to decide. Usually the contents of chronicles or annals can be differentiated between a non-contemporary part in the Begin reporting about earlier events (either basing on the authors own historical research or simply on copying from earlier oeuvres) and a contemporary part at the End, where the authors own observations are reported. The contemporariness of the reported events, as a rule of thumb, can therefore be attributed more or less to the lifetime of the oeuvres author. A further differentiation concerning the reliability should be undertaken between distant events that only were reported to- and local events that were personally witnessed by the author. This is also-, or even more, true for pictorial sources. If the depicted motive is non-contemporary or only known by the artist from a narrative, the reliability usually becomes, similar as many pre eighteenth century paintings, much more imaginative than true-to-detail. Art-historical evaluations therefore urgently need to be undertaken if historical hydrological analysis base on such kind of evidences.

3.2. Methodologies to reconstruct frequency, seasonality and magnitudes of pre instrumental hydrological (extreme-) events

3.2.1. Reconstruction of frequency and seasonality of pre instrumental flood events

The methodology to reconstruct pre instrumental flood events depends on the kind of historical source and the narrative description quality the reconstruction is based on. If the narrative description quality is low (usually existing of a date and the term "flood") the corresponding flood evidence can obviously not be used for magnitude- but rather for long term flood frequency- or flood seasonality analysis.

3.2.2. Reconstruction of pre instrumental flood magnitudes

If the description quality is abundant, but still not good enough to transform the given narrative information into quantified values like peak water levels or peak discharges, the flood magnitude may be qualitatively quantified by applying an appropriate flood magnitude index. Pre instrumental flood events are most commonly classified into three- four- or rather rarely even into more categories. The number of category levels mainly depends on the overall informative content of common narrative concerning the flood evidence and the analyser's discretion. The documentary flood evidence across Switzerland can be rated as very satisfying or good. More important cities generally provide multiple municipal chronicles and newspapers covering together the last five- to six centuries more or less comprehensively. Smaller municipal bodies are usually not that well covered with chronicles but frequently possess long term municipal accounts, council minutes, one or two local chronicles and probably some flood marks. Taken together these sources usually provide valid information about local- and supra-regional flood events on the corresponding sites. According to this commonly good and regionally well distributed documentary flood evidence it is recommendable to apply a four level flood index as it was developed by Sturm et al. (2001) especially in case of an overview analysis that takes into account more than only one investigation site. This four level index categorises the narrative flood information in accordance with the following criteria: regional expansion, level of damage and losses as well as flood duration. The narrative description quality is comparatively to the overall evidence in rather rare cases adequate enough for the reconstruction of peak water levels. In major Swiss cities, sources with qualitatively dense descriptions roughly allow between ten and twenty peak water level reconstructions, covering the past five or seven centuries. In smaller municipal bodies with much less chronicle and newspaper coverage either none or only some individual floods may be deduced from narrative sources. The development of the principal methodology to reconstruct peak water levels based on narrative flood evidence in Switzerland was first realised for the situation in Basel (Wetter et al., 2011). This methodology basically combines the inherent information of narrative documentary-, epigraphic-, pictorial- and (early) instrumental flood evidence. Figure 1 demonstrates the functional principle of the qualitative calibration approach.

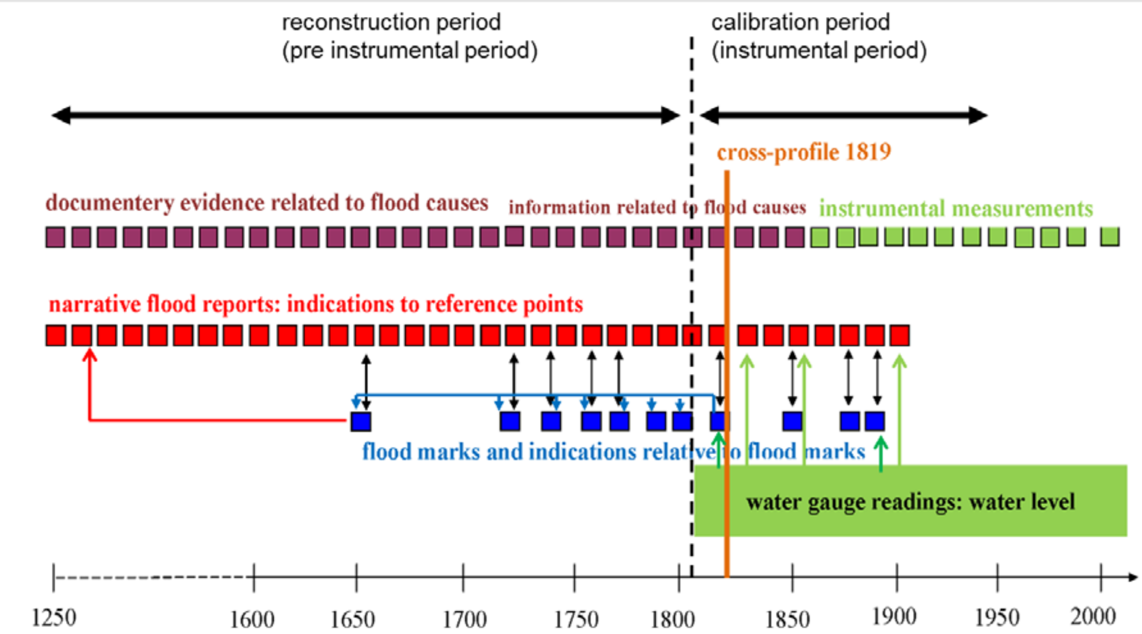

Figure 1: **Qualitative calibration; assigning gauges to pre instrumental "flood information systems" (Wetter et al., 2011)**

The vertical punctuated line represents the differentiation between the pre instrumental- and the instrumental period. In the instrumental period gauges were first determined by eye on a daily- and around mid-nineteenth century on a sub daily or continuous level by instruments. Earlier societies established different "flood information systems" like affixing flood marks or describing such events as accurate and objective as possible with the goal of intergenerational risk communication (Pfister, 2011a). Many chroniclers and journalists described the magnitude of floods in the form of standard narratives, referring to specific landmarks in the built (municipal) environment. References typically were drawn on streets, alleys and town squares as well as on distinctive edifices like churches, municipal wells or other public buildings like bridges or city walls adjacent to the river. These observers generally tried to accurately describe the expansion of the flooded area as well as the depth of the inundation at specific spots in the inundated area (Wetter, 2011). If long term gauge measurements are at hand an overlap with narrative flood descriptions becomes likely, so that the landmarks that were narratively referred to floods may be calibrated with the corresponding measured gauges (Fig. 1; bright green arrows). A similar calibration can be undertaken with existing flood marks (Fig 1; dark green arrows). In the spirit of intergenerational risk communication, flood marks were commonly affixed at buildings with good visibility for the public and thus were often attached at the very same building. “Gauge” identification of pre instrumental flood marks (i.e. flood marks that are dated earlier than the start of the instrumental period) is simple as they can be easily calculated from a reference flood mark from the instrumental period (Fig. 1; blue arrows). Otherwise the flood marks altitudes (asl.) have to be reconstructed by measurement. Pre instrumental flood marks may also define the “gauge” of landmarks that were mentioned in pre instrumental flood descriptions but were not referred to in the instrumental period (Fig. 1; black double arrows). According to typical local inundations it may be that certain landmarks were quite commonly referred to over the centuries. If such a commonly referenced landmark could be calibrated e.g. with an instrumentally measured gauge from the nineteenth century, this gauge can also be used for a flood event that has taken place several centuries before (Fig. 1; red arrow). But, it imperatively has to be taken into account that major architectural- and ground level changes may occur over time, especially in urban areas. It thus has always to be double checked whether the referred landmark really is the same- and was in earlier times in the same condition than it was during the instrumental period when the calibration was carried out. In some cases qualitative calibration does not work because – especially if discharge conditions changed significantly over time – certain landmarks may have only be narratively referred to in the pre instrumental period so that calibration with measured gauges is not possible. In those cases reconstructions of the corresponding landmarks, incorporating possible architectonical and ground level changes over time, need to be conducted. Recourse to archaeological- and architectural history studies is required to adequately reconstruct the condition of a landmark at the time the flood took place is prerequisite. Not taking into account possible changes could lead to significantly distorted results, especially in urban areas where e.g. ground level increases of up to several meters may occur over the centuries. Reconstructions of narrative references to landmarks commonly require quite distinct investigative skills to transform them into flood water levels (in m asl.) or discharges, as presented for two Rhine river flood events in Basel: The vicar Hieronymus Brilinger noted in his chronicle that the River Rhine rose so high that people could wash their hands in the water, while they were standing on the bridge, which Brilinger did himself when he was a young boy (Hirzel, 1915). The sentence “quod ego ipse feci” (engl.: “which I did myself”) clearly reveals that Brilinger was an eyewitness of the 1480 flood event and his report can thus be awarded the highest reliability. An anonymous addendum in a chronicle reporting about a flood of river Rhine in 1424 uses a very similar wording as Brilinger, by mentioning that the Rhine rose so high that three pillars of the bridge were destroyed and people washed their hands in the Rhine (Hirzel, 1890). It is not clear if people were on the bridge while they were washing their hands in the Rhine but the close semantic connection between the mentioning of the bridge and the washing of hands supports the conclusion that people may have been standing on the bridge while they washed their hands in the Rhine. This conclusion can be made even more plausible by relating the further referred landmarks to the height of the bridge, as the anonymous addendum additionally reported that boats needed to be boarded through the windows of the guild house of the boatmen and that the Rhine entered the city through the city wall. Figure 2 demonstrates that these references fit well to each other and are (hydro-) logically meaningful. The yellow dotted horizontal line on image a) (Fig. 2; a) shows that the windows of the guild house of the boatmen is of similar height as the level of the bridge which both must have been more or less reached by the water if people on the bridge could wash their hands (as we assumed) and boats needed to be boarded through the window of the guild house (as was explicitly reported). The reference that the water flooded the city behind the city wall supports the assumption that the water level more or less must have reached the level of the bridge as well. The horizontal yellow dotted line on image b) (Fig. 2) demonstrates that the city wall would have been submerged if the water had reached the level of the bridge so that the reported flooding of the city right behind the wall is plausible. Finally the townscape oeuvres of Büchel in Figure 2, a and b are known to feature good closeness to reality (Boerlin-Brodbeck, 2006).

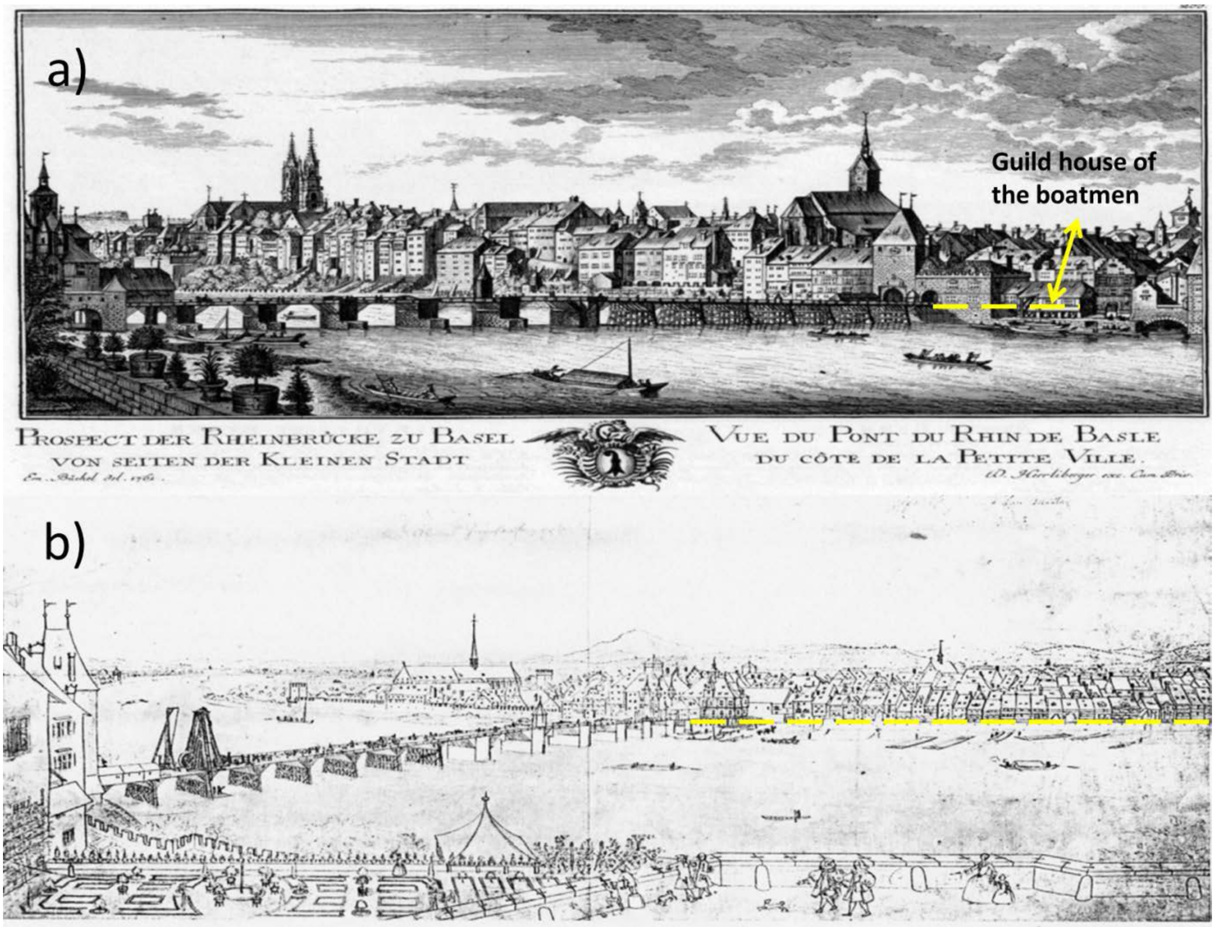

Figure 2: **Hydro-logical plausibility check of referenced landmarks in chronicler reports about the Rhine river flood from 1424 and 1480.**

Image a) Blick auf das linke Rheinufer, 1759; Artist Emanuel Büchel, StABS, Collection Weber-Oeri, Topo 2.

Image b) Blick vom Rheinsprung auf die Rheinbrücke und Kleinbasel mit Hinterland, 1767; Artist: Emanuel Büchel, StABS, Collection Weber-Oeri, Topo 2.

It has been shown that the water level of the floods of 1424 and 1480 have more or less reached the height of the bridge, as well as the height of the windows of the guild house right beneath the bridge. These references may be used to reconstruct the peak water levels of the two flood events which was realised as presented in figure 3.

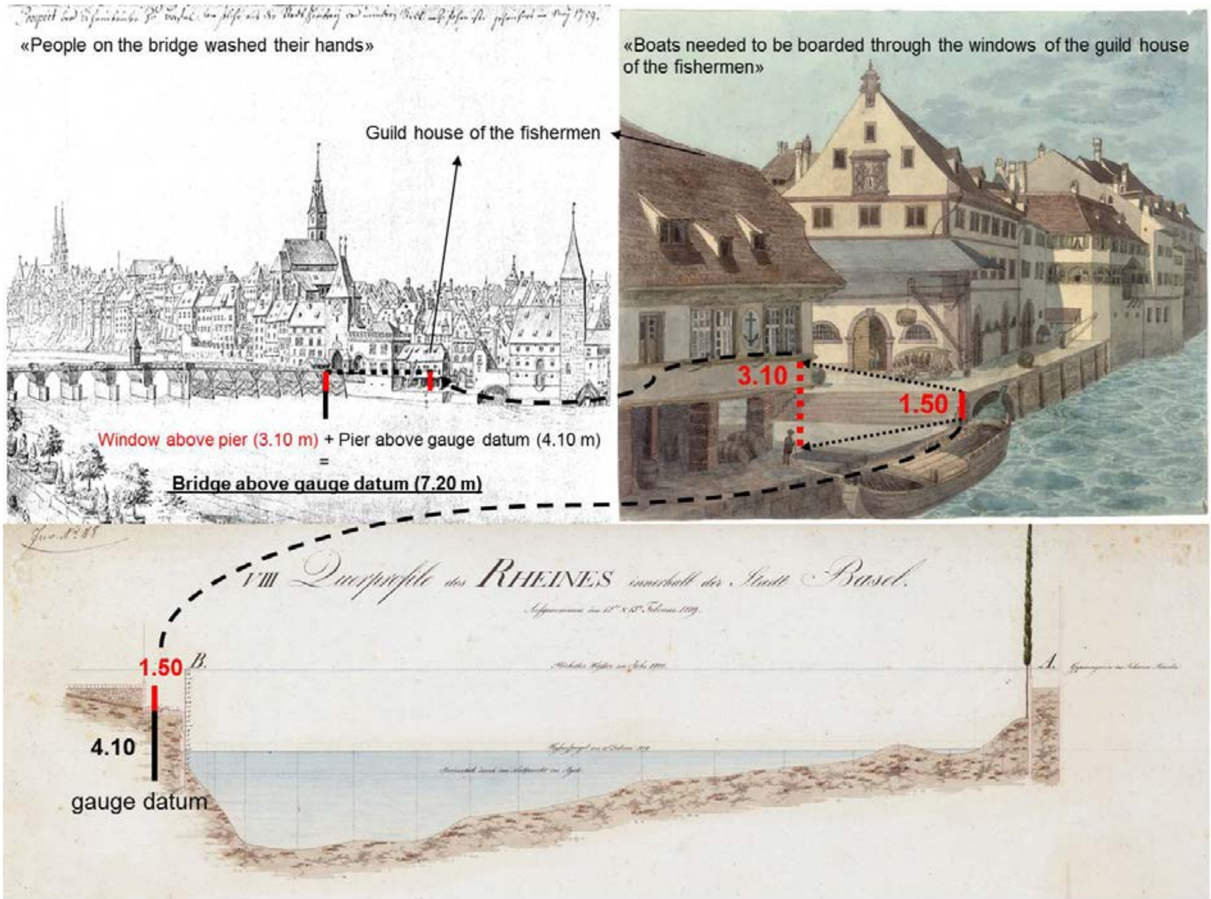

Figure 3: Reconstruction of peak water levels of the 1424 and 1480 river Rhine flood events in Basel based on narrative landmark references (references = levels of the bridge and the windows of the guild house) in combination with a cross profile taken in 1819, right on the spot of the referenced landmarks.

Left image: Blick auf das linke Rheinufer, 1759; Artist Emanuel Büchel, StABS, Collection Weber-Oeri, Topo 2.

Right image: Blick von der Rheinbrücke auf das Schiffleuten-Zunfthaus; Artist unknown, StABS, I 537.

Below: Querprofile des Rheines innerhalb der Stadt Basel. Aufgenommen den 12. & 13. Februar 1819, StABS, Planarchiv A6, 8.

The height of the windows of the guild house being on the same level as the bridge (as demonstrated on the left image; Fig. 3, left image) can be reconstructed in meter above sea level (m asl.) based on the gauge being depicted on the cross profile from 1819 (Fig. 3 below on the left). From the depicted gauge we are able to deduce that the difference between the two ground surfaces amounts to 1.50 m. The two ground surfaces are also depicted on the image on the right, showing the landing pier ("Schifflände") seen from the bridge (Fig. 3, right image). As we know the difference between the two ground surfaces, we are now able to assess the height of the window above the lower ground surface by a trigonometric calculation which amounts to 3.10 m (Fig. 3, right image). Based on the cross profile we furthermore know the difference from the lower ground surface to the gauge datum which amounts to 4.10 m (Fig. 3, below on the left). By adding the difference of the lower ground level to the gauge datum (4.10 m) to the assessed height of the window above the lower ground level (3.10 m) we finally obtain the height of the window above the gauge datum, which amounts to 7.20 m. The gauge datum, which was installed in 1808 right downstream of the bridge at the landing pier only some meters upstream of the guild house, is known and amounts to 243.93 m asl. The height of the windows of the guild house amounted thus approximately to 251.13 m asl. (243.93 + 7.20). This reconstructed level serves now as the water level for the two flood events from 1424 and

1480 of Rhine River in Basel. The discharges of the two flood events may then be assessed based on the reconstructed flood water levels (i.e. 251.13 m asl.) by applying e.g. a one-dimensional (1D) hydraulic model that calculates the transient 1D flow integrated over the cross-sections of the river systems based on the de-Saint Venant equations (Ven Te Chow, 1973). Discharge quantifications should only be calculated based on cross- and longitudinal profiles that may be considered as representative for the runoff conditions during the concerning pre instrumental flood events, so that errors may be kept as small as possible. The cross- and longitudinal profiles that were taken in 1819 along the river on the territory of the City of Basel satisfies the before made statement as the most influencing local river engineering measures, like the construction of river banks, were realised much later at the end of the nineteenth century. Pfister and Wetter (2011b) demonstrated that the above exemplarily outlined approach can be successfully transferred to other sites in Switzerland, which so far was realised for pre instrumental Sihl- and Limmat river flood events in Zürich (Wetter & Specker, 2015a; Näf-Huber et al., 2016) as well as for Aare-, Saane- and Reuss rivers at different sites alongside the concerning water bodies (Wetter et al., 2015b).

3.2.3. Reconstruction of long term frequency and seasonality of minor pre instrumental flood events

City accounts belong to a source category with a very high potential for historical hydrological as well as for historical climatological analysis, which is why they will now be described in more detail. A special focus shall be laid on the books of weekly expenditures of the City of Basel (“Wochenausgabenbücher der Stadt Basel”). These records were led from December 1401 to April 1799 in 84 volumes. Unfortunately some volumes are missing, including the records for the years 1408-1409, 1434-1451 and 1619-1621. The records are dated on a weekly basis, meaning that the date accuracy of the single records is somewhat distorted. The books of weekly expenditures were first analysed by Fouquet (1999) who found recurring records of wage expenditures for a squad of craftsmen that was called up onto the bridge of Rhine river with the task to prevent it from being damaged by manoeuvring the drifting logs from the flood waters around the vulnerable wooden pillars. Even-tough Fouquet’s research interest did not have a historical hydrological focus, he could evidence a large number of River Rhine flood events. 68 floods for the period from 1456 – 1542 were identified, whereas chroniclers only recorded seven events during the same period. This ratio of almost 10:1 points to significantly sharper “observations skills” of the weekly records of expenditures towards smaller flood events, which may be explained by the fact that bridges can be endangered by relatively small events, whereas on the other hand it is known that chroniclers as well as journalists generally focus on the spectacular (i.e. extreme) flood events. A closer-, specifically historical hydrological examination of this source reveals that the “observation skills” towards small River Rhine flood events is even much better than one could assume, according to the findings by Fouquet (1999) and that the weekly led records also include a vast number of expenditures (records) in context to further local water bodies, like Wiese River and the Birsig brook. These latter records are given in the form of wages for gatekeepers to open the fence at the brooks entry into the city through the city wall with the goal to prevent damming by floating debris during flood events. Sometimes these accounting records even allow the assessment of flood durations, as they mention how many day and night wages for the guarding of the bridge or the fences at the city wall were paid. The books of weekly expenditures of Basel additionally include information about weather related damages in Basel’s sphere of influence or even in further away locations of importance. In the following example from a record dated on the 15th September in 1607 the council donated 2£ and 10β to two persons from its confederate ally Lucerne, who suffered losses because of the water (i.e. flood). The weekly books of expenditures furthermore contain expenditures for hay- and after-grass harvests at municipal meadows. Spycher (2017), who compared these harvest dates with monthly resolved precipitation- and temperature anomalies from Pfister (1998), found significant correlations between early and late onsets of hay- and after-grass harvest dates and the preceding months with dry or moist weather anomalies. According to her findings, above average moist or dry conditions in the period from April to June (AMJ) correlate with late- (moist) or early (dry) hay harvests, whereas above average July-August (JA) conditions result in late- (moist) or early (dry) after-grass harvests. Similar analysis by Wetter (unpublished) revealed that hay harvest dates, if they are dated on a daily accuracy level (unlike the hay- and after-grass harvest dates from the books of weekly expenditures), significantly correlate with anticyclonic weather conditions if they are compared to a ± 3 day temporal context around the corresponding hay harvest dates. This temporal correlation between hay harvest and anticyclonic weather situations, which usually correlate with sunny weather, can be plausibly explained, as the grass – after hay harvest – needed to be dried on the field, before it could be collected and stored in the barn. Farmers were generally good interpreters and predictors of local weather, as not only hay harvest but also many other agricultural activities directly depended on these short term weather situations. The narrative information given from these accounting records is in no means adequate enough, either to assess flood magnitudes by applying an index based approach or to reconstruct flood water levels. Their strength instead lies in the detection of minor and normal, so far unknown, pre instrumental flood events and the ability to date them on a weekly, monthly or seasonal resolution. They furthermore allow the definition of a minimum discharge threshold when protection measures like the guarding of the bridge or the opening of the gate usually was ordered and executed. The dating of the floods recorded in the books of weekly expenditures of Basel is not as simple as one might think because the records are dated only on a weekly basis which makes an exact assignment to a month in certain cases uncertain. This uncertainty arises when, after the calendar correction has been executed, the weekly dated expenditures (being a list of expenditures that is dated every Saturday) overlaps two months as in these cases one cannot be certain in which month the recorded flood event actually took place. In these cases we are dependent on likelihood estimations which we apply as explained by the following example: If the calendar corrected date was Saturday 29th July, it is somewhat more likely that the recorded flood took place in August than in July because there are 3 possible days of the flood event in July (29th to 31st July) compared to 4 probable days in August (1st to 4th August). In this special case the flood would thus be assigned to August. In other words the recorded flood events will always be assigned to the month which has mathematically more potential for a flood event (simply by having more possible days when the flood event could have taken place). Incorrect month assignment cannot be excluded with this approach but on the long run these errors should abrogate each other. Municipal accounts that are dated only on a half year level do not have this dating accuracy problem as there are no overlaps between the two half year periods if the two periods begin, as they usually do, on 1st January (1st half year period) and on 1st July (2nd half year period). Some half year dated municipal accounts might start – according to another-, more to agricultural interests related manner of dating – the first period on 1st March (1st period = 1st march to 31st August) whereas the second period starts on 1st September but ends on 28 or 29th (leap years) February in the next year. If there is no additional singular dating of records in the second period it is impossible to disentangle whether the recorded floods from the second period did appear still in the “old” or already in the “new” year. For future analysis it is therefore strongly recommended to focus predominantly on weekly led- and in second priority on half yearly led municipal accounts, where both periods are in the same year.

3.2.4. Reconstruction of pre instrumental drought events

Historical documentary sources including information about drought events are quite rare compared to the numerous sources that provide information about flood events. This is explained by the fact that meteorological droughts, being defined as a lack of precipitation over a large area and for an extensive period of time (e.g.; Sheffield et al., 2012), do not occur as frequently in Central Europe as flood events, which compared to droughts may be local, are often spectacular and may cause in a short time considerable loss and destruction all of which is predestined to attract the attention of contemporary chroniclers or journalists. Meteorological droughts on the other hand develop slowly, are for a long time completely unspectacular and therefore in that phase generally not recognised by most of the contemporaries. Only when the meteorological droughts gave rise to agricultural droughts [being defined as insufficient soil moisture to support crops (Seneviratne et al., 2012)] and/or socio-economic droughts [being defined as all sort of direct and indirect impacts on humans and society (e.g. Heim, 2002)], chroniclers usually began to report; mainly about negative societal and economic impacts, as the resilience of these pre-industrialized-, mainly agricultural- and often rather regional-trade based societies probably were quite a bit weaker towards these, for Central Europe, rather unusual hydrological extreme events, than towards much more routinely occurring flood events. In cases of severe drought events, like e.g. during the perennial heat and drought of 1540, many chroniclers were trying to describe the droughts severity as accurately as possible, by objectivising their descriptions with observations about the impacts on the physical- and biological environment. Contemporaries described very low water levels of waterbodies often in such a way that they can be reconstructed. They furthermore made reference to extreme soil desiccation by describing the wideness and deepness of soil cracking or described the leaf fall of vines and trees to objectivise the severity of the heat and dryness. Observations about unprecedented early vine harvest allow the assessment of the magnitude of the mean spring-summer temperature anomaly, which in the case of 1540 was assessed to have amounted to around + 6° Celsius (between 4.7 and 6.8 ° C) compared to the 20th century mean (Wetter and Pfister, 2013). Several independent chroniclers were reporting about the number of days with precipitation in 1540 which permits the assessment of the precipitation amount on a seasonal and annual level as the number of days with precipitation (NDP) and the seasonal- and annual precipitation amount (PA) are highly correlated. Reconstruction of low water levels and the assessment of discharges in principal work similarly to flood reconstructions. The principal methodology will be shown in the following example: the chronicler Adelberg Meyer (Basler Chroniken, 1902) described the situation for Rhine River in Basel. He referenced his description to the built environment like the bridge, the cathedral and the confluences of rivers Birs and Rhine. Meyer reported that the Wiese River was completely dry whereas the Birs- and Rhine River were very small. The right riverbank of the Rhine was dry up to the position of the little chapel, which was installed on the fourth pillar of the bridge (Fig. 4; yellow cross). The left river bank was dry from the confluence of Birs- to Rhine River (more than 2 km upstream of the bridge) up to the position of the cathedral, being less than 400 m upstream of the bridge. Including the information given from downstream of the bridge, the approximate 1540 river channel, where water still was flowing, could be reconstructed as it is illustrated in Figure 4. The line of the reported river channel is hydrologically consistent as the cross profiles from upstream of the position of the cathedral suggest a small dry left river side during extremely low water levels because of its steepness, whereas the right river side should be largely dry because of its broad shallow shapes. The Rhine River takes a strong bend to the right after the position of the cathedral, which is why the water carved out the profile there deeply and explains why in this part the river was still flowing during the peak of the 1540 low water level.

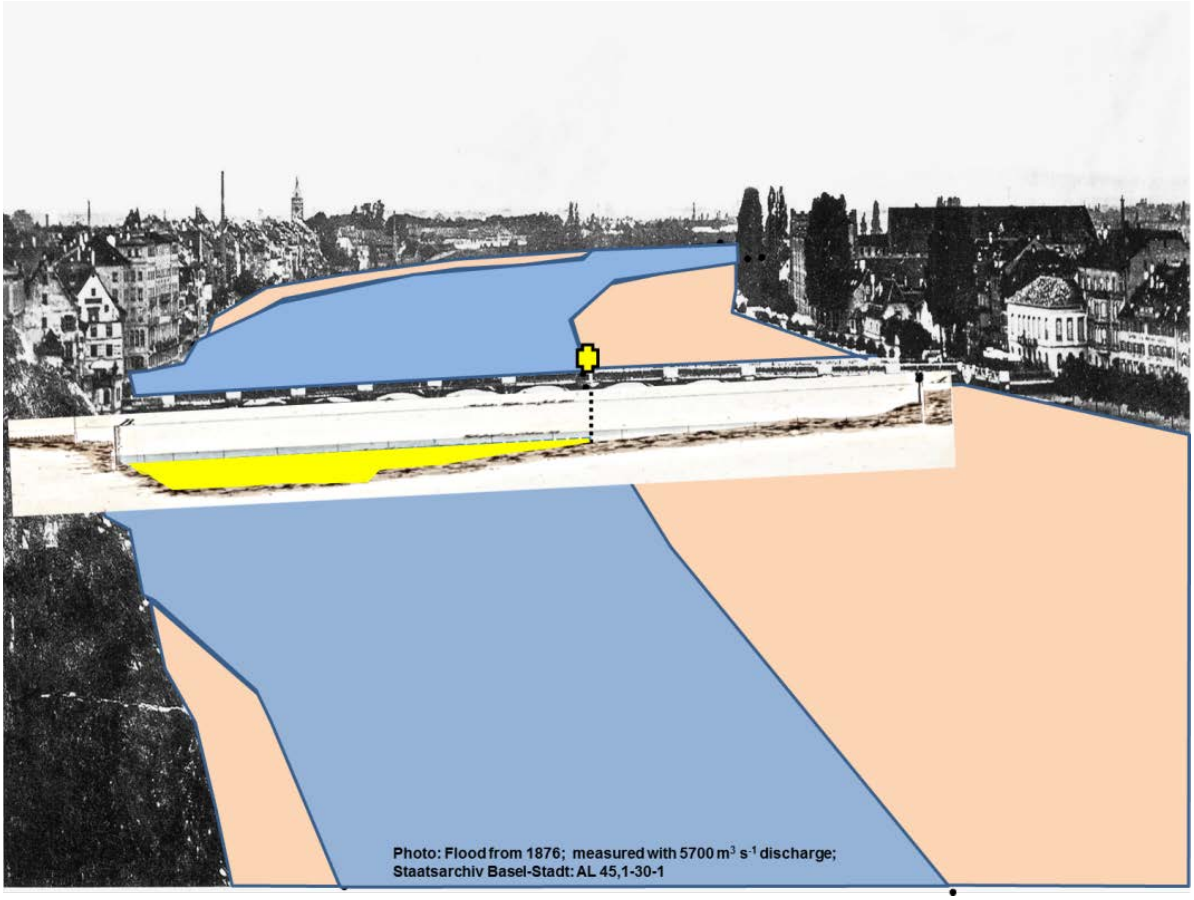

Figure 4: **Reconstructed Rhine River channel during the peak of the perennial drought in 1540**

The reconstructed low water river channel of the 1540 flood then was rendered to the cross profiles that were taken in 1819 from which finally the discharge could be deduced (Fig. 4; yellow array in the cross profile).

4. Results

4.1. Reconstruction of long term frequency and seasonality of hydrological extreme events

Long term frequency and seasonality reconstructions of hydrological extreme events can be conducted after necessary calendar style corrections have been realised. Figure 5 demonstrates the seasonality of Rhine river flood events in Basel ≥ 5000 $m^3 s^{-1}$ discharge.

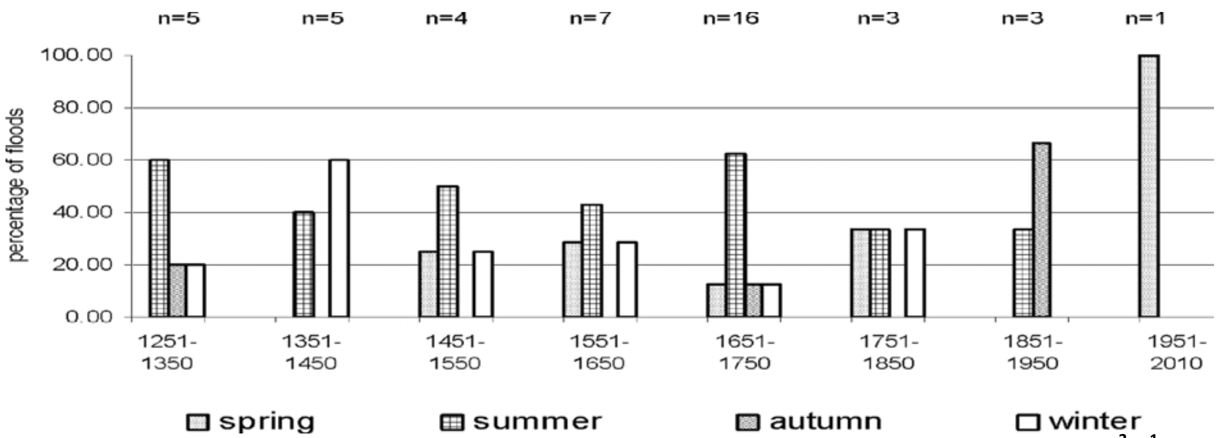

Figure 5: **Seasonality of Rhine river flood events for the period 1250 – 2010 in Basel ≥ 5000 $m^3 s^{-1}$ (Wetter et al., 2011)**

The definition of the seasonality resolution and sub periodisation is completely up to the analyser's discretion. It can be realised as shown in the figure above, including the 5000 $m^3 s^{-1}$ threshold or e.g. in a more binary approach that only distinguishes between flood and no flood or drought and no drought (-evidence). Figure 6 visualises long term changes of the Rhine River flood occurrences above a discharge threshold of ≥ 4300 $m^3 s^{-1}$ in Basel, showing an increase in the second half of the 17th century and a significant gap of extreme events at the end of the 19th and almost during the whole 20th century.

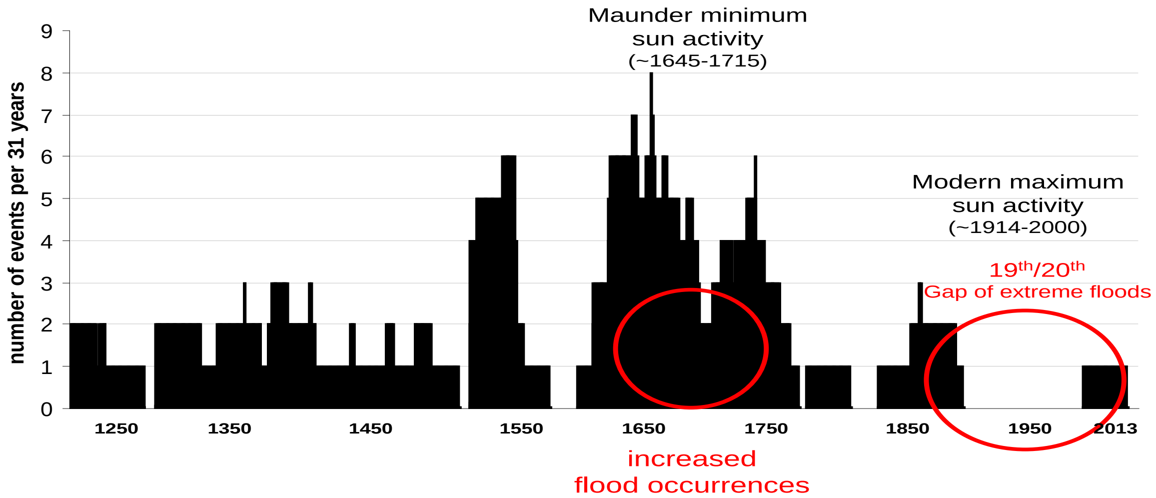

Figure 6: **31-year running mean of extreme Rhine river flood events (≥ 4300 $m^3 s^{-1}$) in Basel**

Flood frequency changes like this, whatever the reason might be, do have significant consequences on the assessment of recurring periods of extreme events. A well-known consequence of the extrapolation from short (instrumental) series is the high level of uncertainty associated with estimates of design floods with large return periods. For example, estimating the 100-year design flood peak from a 24-year record Stedinger and Griffis (2011) reported a factor of 4-to-1 between the upper and lower bounds of the 90% confidence interval. Figure 7 demonstrates the impact of the inclusion of reconstructed flood events from the pre instrumental period on the result of flood frequency analysis. First of all the inclusion of the reconstructed pre instrumental period flood events significantly expands the reliable extrapolation range from a two hundred year- (based on the instrumental period only) to a five hundred year flood event. Secondly, the discharge magnitudes e.g. of two hundred year flood events significantly increase from less than 5000 $m^3 s^{-1}$ to more than 6000 $m^3 s^{-1}$. It has to be stated that the discharge values have been included in the frequency analysis as they were observed and reconstructed, which means that no adjustments of pre- and past river regulated conditions have been established, which very likely distorted the results of the increased flood discharge magnitudes significantly. This point will be discussed later in detail in section 4.3.

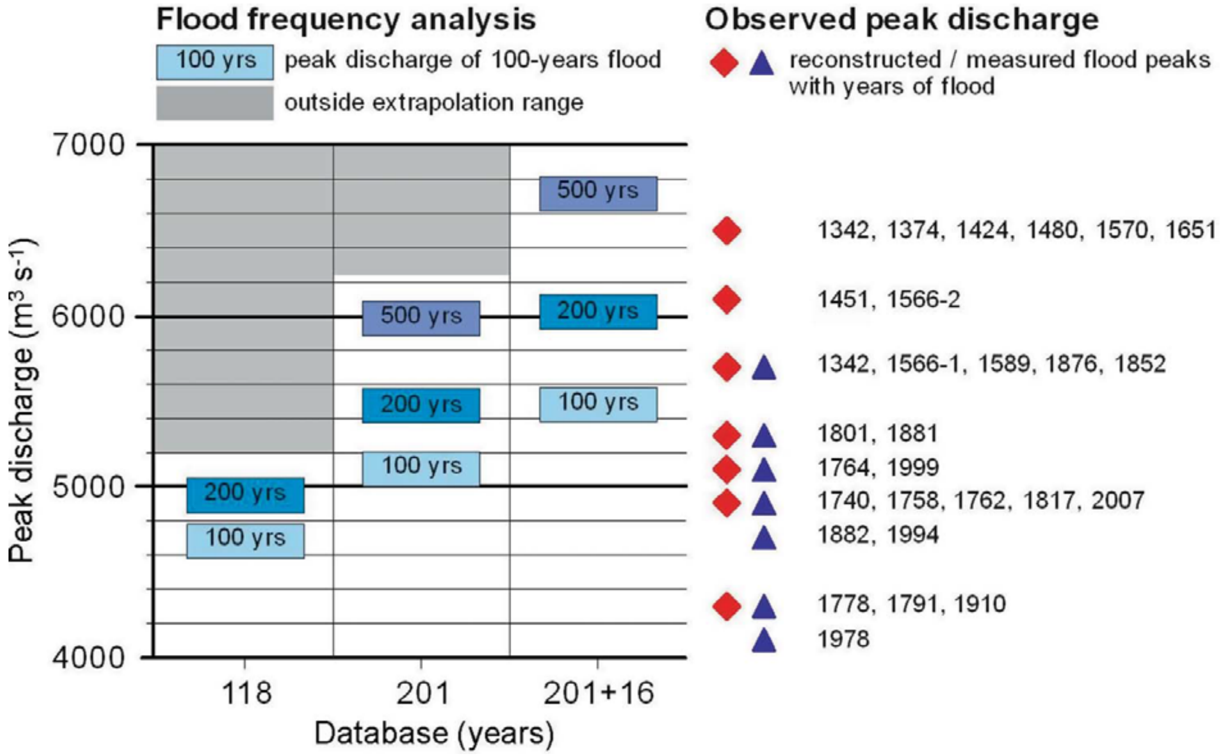

Figure 7: **Flood frequency analysis based on the official reference period (1891 – 2008), the full instrumental period (1808 – 2008) and the full instrumental period plus 16 reconstructed pre instrumental flood discharges for Rhine River in Basel**

4.2. Index based magnitude reconstruction of extreme pre instrumental hydrological events

So far the approach of the ongoing historical hydrological research (Swiss National Science Foundation project, 2014-2017)[2] was not focussed on index based flood magnitude reconstructions but it will definitely be considered after the water level- and discharge reconstructions of major Swiss rivers are completed, so comparatively much more flood evidence may be included in long term hydrological analysis. According to Kjeldsen et al. (2014) indexed pre instrumental flood events are a useful tool for categorising and visualising flood magnitude, but the approach has yet to be useful in the estimation of flood frequency as it removes individual event information and groups the events, thereby reducing the potential value of the data. By combining indexed flood events with observed discharges this handicap can partially be overcome. Figure 8 shows an example of a four step index flood magnitude reconstruction for Vltava River in Prague (Brázdil et al., 2006). This approach combines indices with observed discharges and assumes, based on informed expert judgement, that the thresholds of flood indices 0, 1, 2, 3 correspond to floods with a two- (Q_2), a ten- (Q_{10}), a fifty (Q_{50}) and a hundred year return period (Q_{100}).

2 SNF project 153327: Reconstruction of the genesis, process and impact of major flood events of major Swiss rivers including a peak discharge quantification.

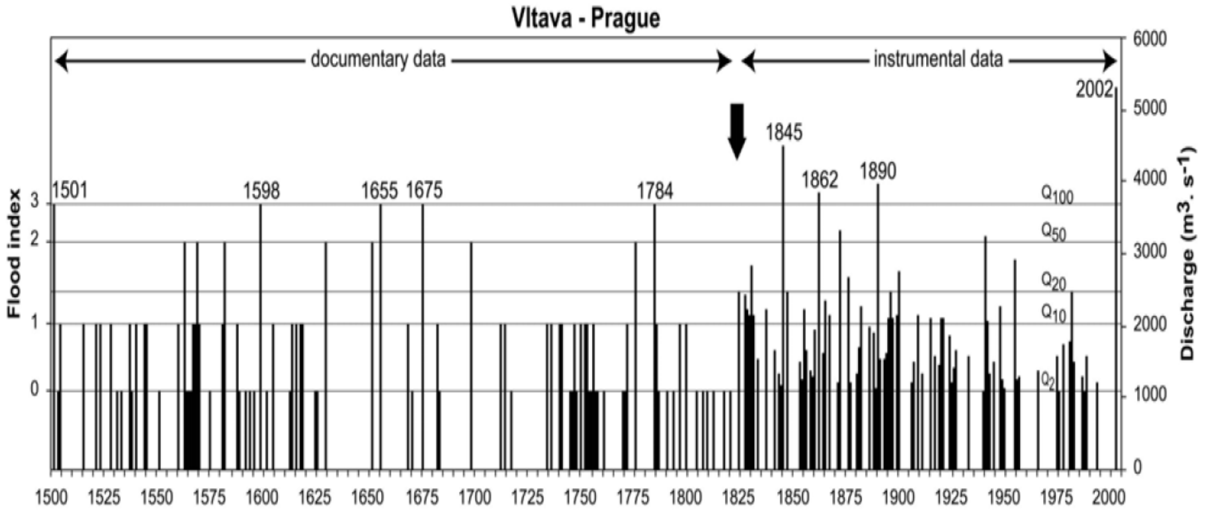

Figure 8: Index based flood magnitude reconstruction for Vltava River in Prague (Brázdil et al., 2006)

A similar kind of approach should be applicable for Switzerland as well. The goal will be to combine indexed flood events, reconstructed flood levels and discharges, as well as indirect flood data from municipal accounts with observed flood events from the instrumental period. It is not possible to reconstruct flood levels or discharges based on indirect flood data from municipal accounts, but it is indeed possible to assess a minimum discharge threshold by comparing the number of the municipal account flood records with the instrumental observation series and calculate the ratio (on the assumption that the flood frequency is comparable between the two series) from which the minimum discharge or water level can finally be deduced from the instrumental series. This minimum discharge seems to have been the threshold for the person in charge (i.e. the bridge-master or gatekeeper) to take precautionary measures to protect the corresponding infrastructure against possible flood damages, which finally found its entry into the municipal accounts in form of records about paid wages for the executive staff.

4.3. Water level or discharge based reconstruction of extreme pre instrumental hydrological events

Figure 9 visualises the results of the discharge reconstructions of the Rhine River flood events in Basel, showing a significant trend of decreasing flood magnitudes since the beginning of the 18th century. A more sophisticated analysis reveals that this “trend” is in truth a two-step decrease which was caused by two major anthropogenic river engineering interventions in the large-scale catchment area, which significantly changed the discharge budget, especially in case of extreme flood events. The timing of the redirections of River Kander to Lake Thun in 1714 (Vischer, 2003) and of River Aare to Lake Biel in 1878 (Przegon, 1999) clearly correlates with the decreased flood magnitudes of River Rhine in Basel. The additional retention capacities of the two lakes significantly decelerates the flood waves which before the redirections just rushed through river Kander and Aare and finally reached river Rhine in Basel without being significantly decreased before.

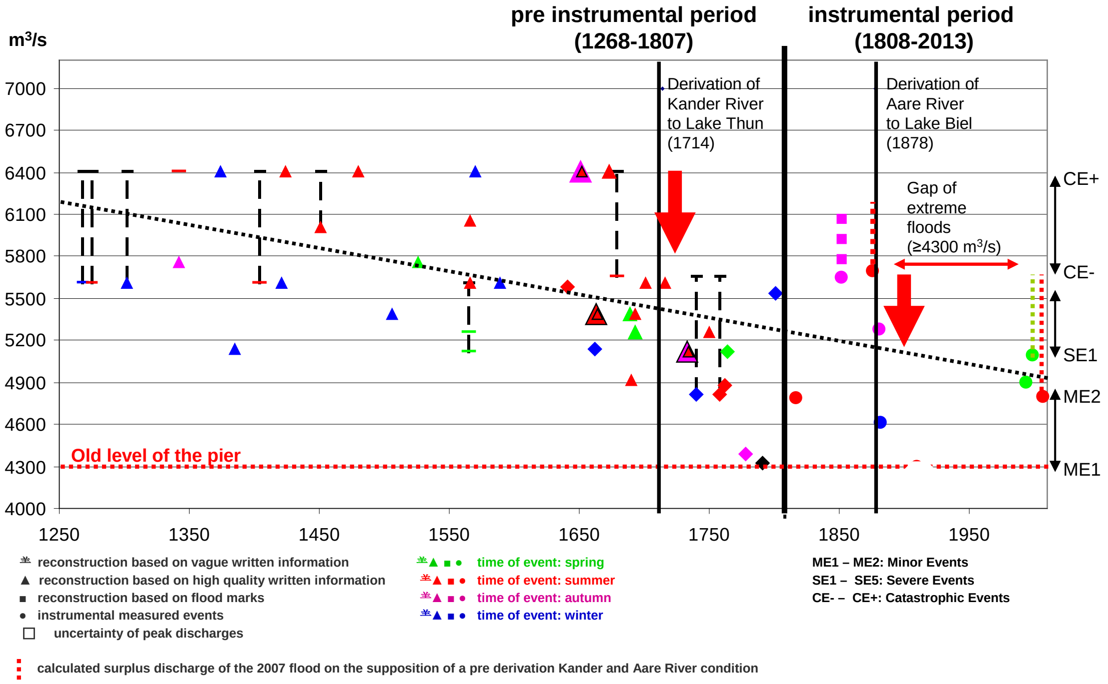

Figure 9: **River Rhine discharges in Basel for the period 1250 – 2010 (Wetter et al., 2011)**

The two-step flood magnitude decrease for the River Rhine at Basel is confirmed by other flood reconstructions at sites at Aare and Rhine River downstream of the two redirections, whereas no long term change of flood magnitudes can be detected at Rhine River above the confluence with the Aare River. This result is plausible as Lake Constance as well as the corresponding section of the Rhine River was never subject of river engineering measures that could have significantly influenced the runoff characteristics. The difference of flood magnitudes at the different flood reconstruction sites along the Aare and Rhine, on the other hand, are comparable with each other, which should thus allow an assessment of the long term mean retention capacities of the two lakes (Lake Thun and Biel), which provide the opportunity to homogenise the pre redirection flood events (i.e. the floods that took place in the period before the Rivers Kander and Aare were redirected to the Lakes Thun and Biel) to the actual runoff regime (paper in progress). The influence of anthropogenic river engineering measures on runoff conditions and flood water levels is obvious for Lake Zürich and the Limmat River as well, with three steps of decreased flood water levels. The first step occurs after the works at the city trench (Schanzengraben) were finished in 1677 which created, apart from Limmat River, an additional run-off for Lake Zürich. The second step occurred after Linth River was redirected to Lake Walen in 1816, which significantly decreased flood level magnitudes in Zürich due to the retention capacity of Lake Walen. The last step occurred in the early 1950's when the weir for power and regulation purposes was constructed. Note that Figure 10, unlike Figure 9, demonstrates flood levels.

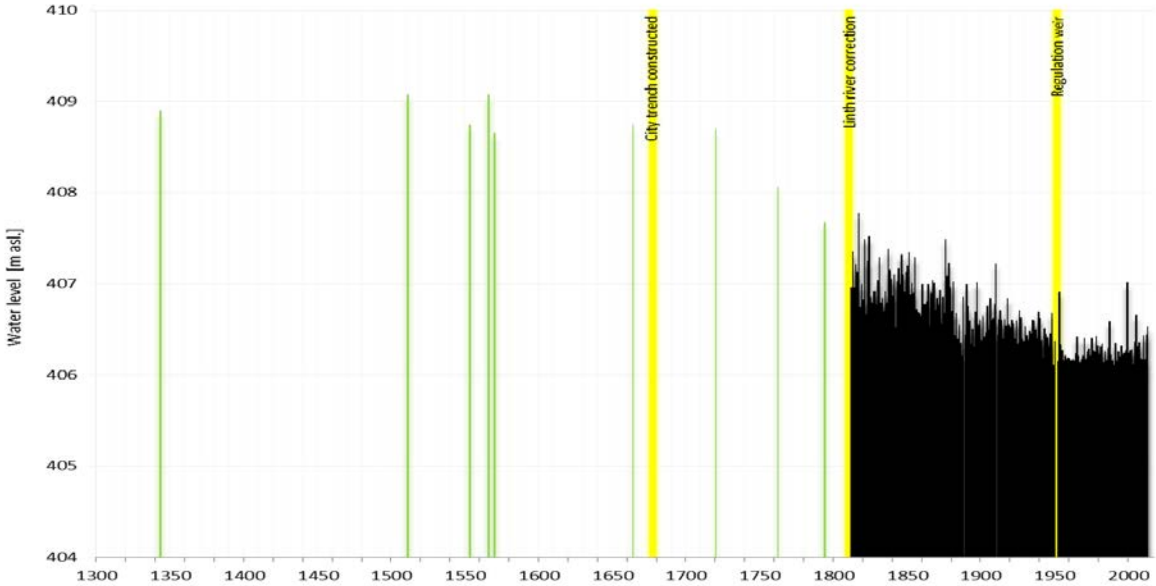

Figure 10: **Three step decrease of flood magnitudes for Lake Zürich and River Limmat in Zürich (Näf et al., 2016 and Wetter and Specker, 2015a)**

Figure 11 demonstrates the assessment of the long term changes of runoff conditions of Limmat River in Zürich, taking into account all (reconstructable) local- and regional anthropogenic interventions influencing the runoff conditions.

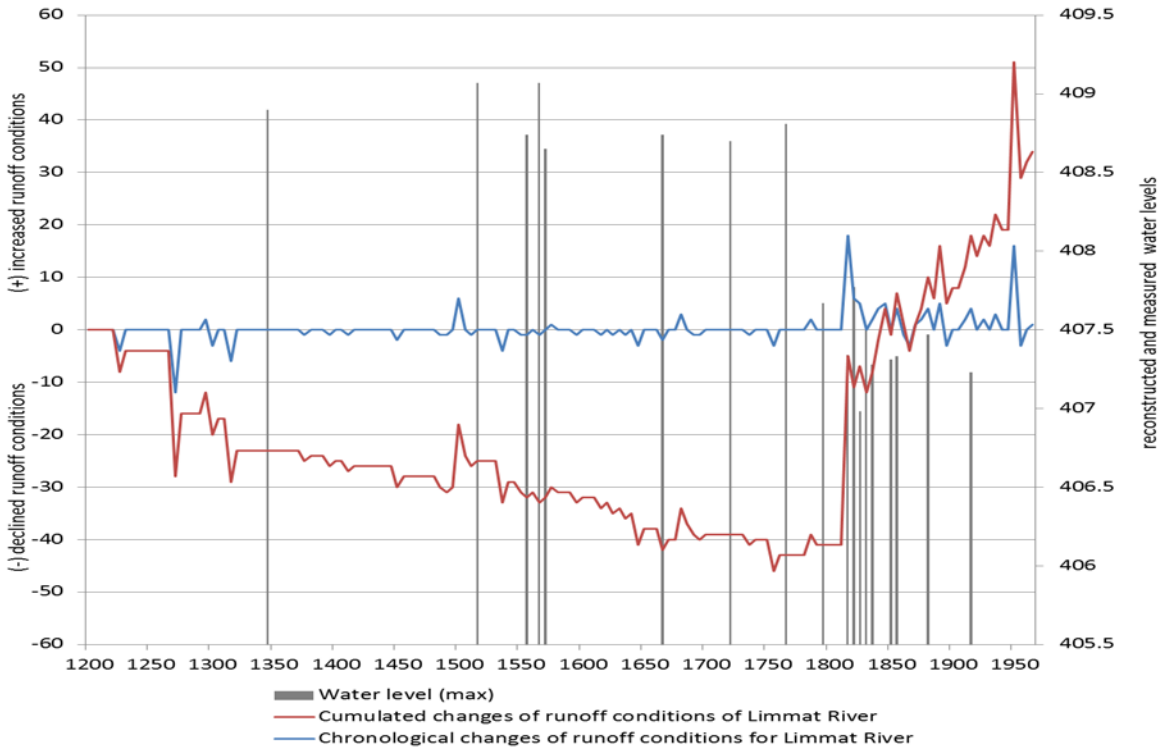

Figure 11: **Changes of runoff conditions of Limmat River in Zürich**

The numerous anthropogenic interventions, influencing the runoff conditions were quantified in a semi-quantitative approach. The quantification is based on a twelve point index scale, where - 6 stands for a very strong-, - 1 for a very weak declined runoff, whereas + 6 stands for a very strong- and + 1 for a very weak increased runoff at Zürich. Figure 11 shows numerous anthropogenic interventions, each causing only very weak declined- (Fig. 11, blue graph) runoff conditions, but taken together (Fig. 11, red graph) declined the runoff conditions in the period from the 14^{th} to the early 19^{th} century significant. The most significant increase of runoff conditions was realised in the context of the Linth River correction in the early 19^{th} century, when the main tributary of Limmat River was redirected to Lake Walen and most river damming installations in Zürich were withdrawn from Limmat River.

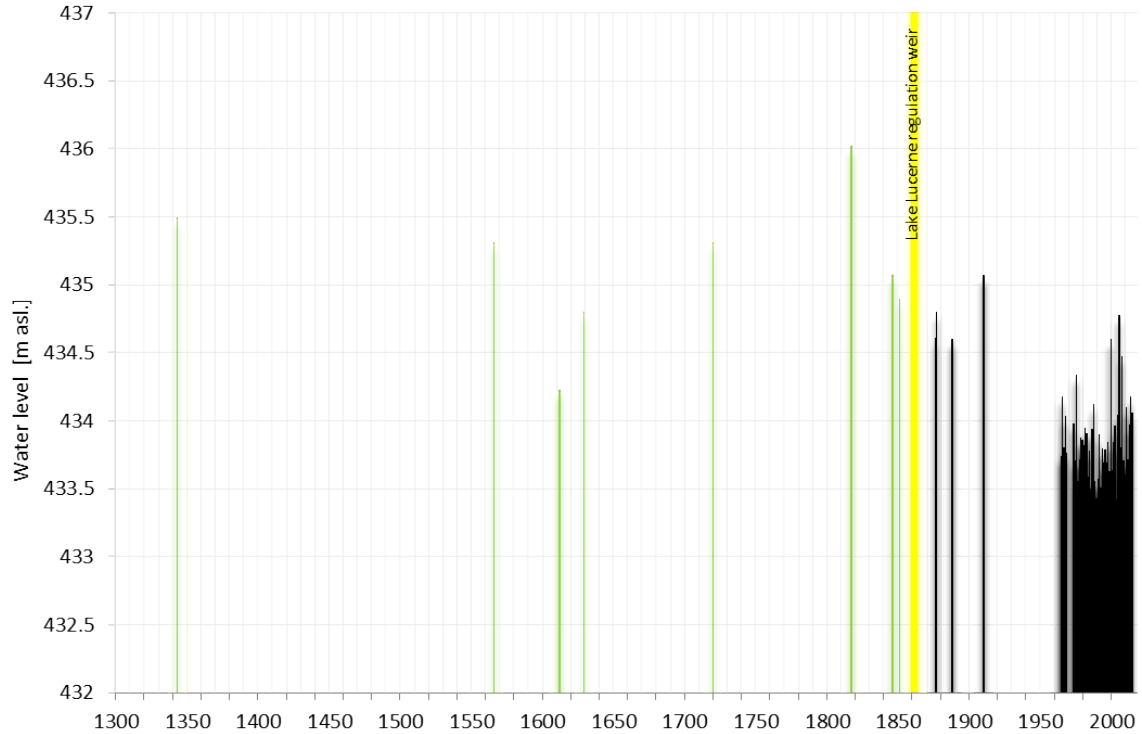

Figure 12: **Long term stationarity of Lake Lucerne and Reuss River extreme flood water levels (Wetter et al., 2015b) or slow trend of decreasing flood magnitudes (?)**
Green bars: reconstructed flood levels above sea level (asl.)
Black bars: measured flood levels asl.
Yellow bar: significant anthropogenic intervention in the discharge conditions

Figure 12 demonstrates the flood level development of extreme events in Lucerne for Lake Lucerne and Reuss River showing either a weak trend towards slightly smaller flood levels or simply a poor period of extreme floods, if the flood event from 1817 is excluded from the analysis. 1817 is by far the most extreme event in the last seven centuries which is also true for Lake Constance. This correlation of the two most important lakes right on the edge of the Swiss Alps is not coincidental and is directly linked to the so called year without a summer from 1816 (e.g. Luterbacher & Pfister, 2015). A significant cooling and change of precipitation patterns occurred in 1816 Europe mainly due to the large amounts of SO_2 emissions to the atmosphere caused by the massive eruption of the Tambora volcano in the tropics (Luterbacher & Pfister, 2015). Precipitation (especially but not exclusively in the Alpine region) fell as snow, sometimes even in summer and the stored snow masses from winter 1815/1816 did not melt in the Alps due to the overall cool temperatures. The second layer of snow, in chronological order, was added throughout the year 1816, due to snow- instead of rainfalls in the Alpine region. The first two layers then were again superimposed by the 1816/1817 winter snow precipitation. In spring and summer 1817 massive amounts of melting water accommodated in Lake Lucerne and Constance due to three- instead of only one melting snow layer. The runoff conditions of River Reuss in Lucerne did only marginally increase during the last seven centuries which might explain the somewhat smaller flood levels since the construction of the Lake Lucerne regulation weir in 1861, again not taking into account the 1817 event (Fig. 13).

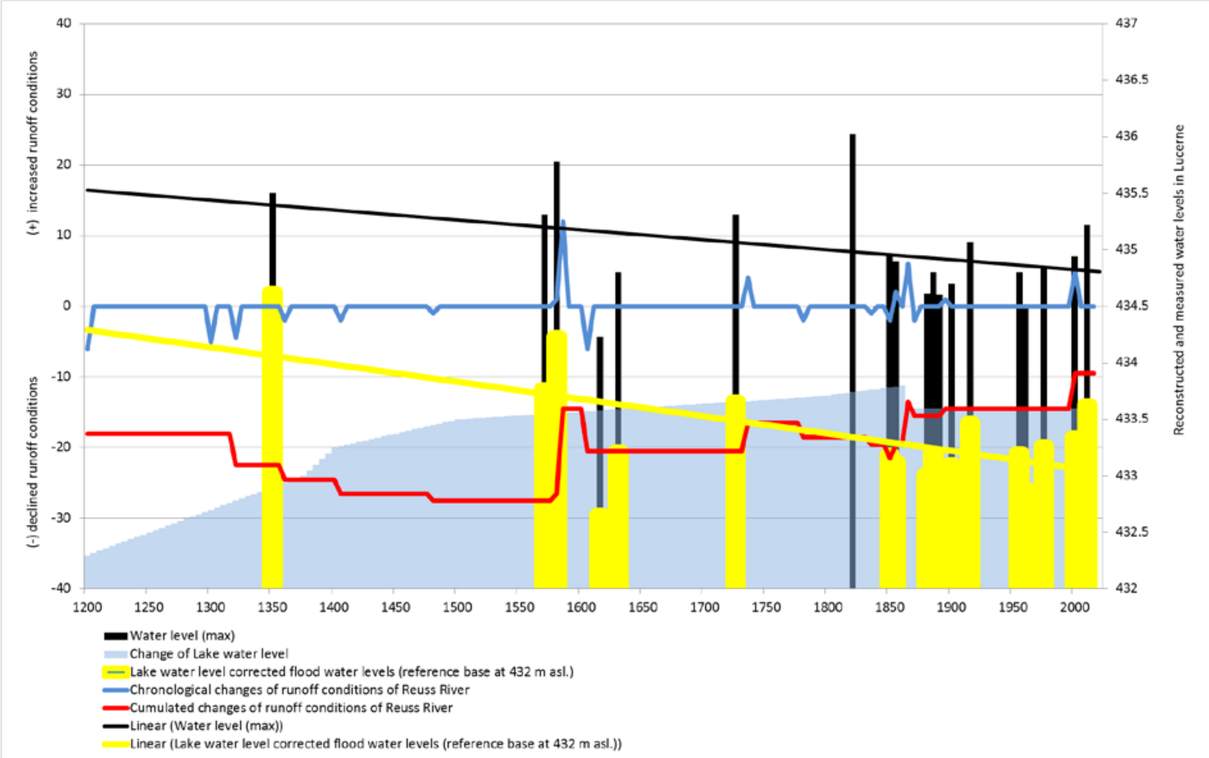

Figure 13: **Significant increase of normal Lake Lucerne water level versus slight increase of Reuss river runoff conditions over the last seven centuries.**

The decrease of flood magnitudes gets a bit more obvious if the dammed water level of Lake Lucerne is taken into account. According to Küng (2006) the norm water level of Lake Lucerne was intentionally dammed by a medieval weir to provide enough water to run the mills on the Reuss River. Since then this weir was gradually heightened to stand the pace of the increasing amount of water required by the mills in the following centuries. Due to the constantly increased lake water level, subsequent floods needed less water to reach the same water level as earlier flood events. In terms of figures this difference of the normal lake water levels can be corrected from the flood level, which results in a more obvious decrease of flood magnitudes. This was most probably caused by a more sophisticated lake water level regulation technique since the construction of the regulation weir and the removal of mills from the Reuss River in the nineteenth coupled with excavation of the river bed in the twenty-first century (Paravacini, 2013). No major river engineering interventions, except the construction of dams in the Alps, were realised in the upstream Reuss River catchment that could have significantly changed the regional and local runoff conditions in Lucerne. Note that so far only flood water levels are at hand as discharge calculations could not yet be realised.

4.4. Precipitation and temperature reconstruction to evaluate important drivers of extreme hydrological events

Climate parameters like temperature and precipitation are the main drivers of extreme hydrological events (i.e. drought- and flood events). Chroniclers, reporting events, mainly focus on the description of (material) losses, negative impacts on the economy and society and in case of floods quite often on the magnitude of the event (i.e. references to the water level and submerged area), whereas triggers of extreme hydrological events are rarely described. If the events are extraordinarily extreme, science-oriented explanation may be provided comparably more often, and mostly in a quite useful, substantial and informative quality. The Bernese chronicler Diebold Schilling (1445-1486) described the triggers of the 1480 flood event, probably the most extreme flood of Aare River in the last seven centuries (Pfister & Wetter, 2011b) in the following, science-oriented manner: Three days and nights of uninterrupted heavy rainfalls heralded the start of this extraordinary extreme flood event taking place on 1st August 1480. Schilling additionally provided important information about the “pre disposition” by stating that there was a distinct warm phase in the forefront of the extreme precipitation event, which rapidly melted the glaciers and stored snow in the Alps. From other sources it is known that spring and early summer were exceedingly wet and in the Alps rich in snow. By combining the information we have enough contemporary and reliable evidence to conclude that the trigger of the 1480 flood event was warm weather, snowmelt combined with 72 hours of uninterrupted heavy rainfalls. In case of opposite hydrological extreme events, like e.g. the severe heat and drought in 1540, chroniclers not only provided useful information on low water levels but also began to numerate the few days with precipitation in that year. Figure 14 presents the reconstructed number of days with precipitation (NPD) in 1540 for Cracow (Poland) on the left and Switzerland on the right.

DAY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	snow				rain								N/A											
2	snow												N/A											
3	snow					rain	rain						N/A											
4	snow								rain				N/A											
5	snow				rain			rain	rain				N/A											
6	snow												N/A											
7	snow										snow		N/A							rain				
8	snow												N/A							rain				
9	snow	snow			rain			rain					N/A							rain		rain		
10	rain	snow				rain		rain					N/A		rain					rain		rain		
11	rain	snow	snow	rain		rain							N/A		rain					rain				rain
12	rain		snow		rain				rain				N/A		rain					rain				
13					rain			rain tempest					N/A							rain				
14						rain		rain tempest					N/A							rain				
15													N/A							rain				
16													N/A							rain				
17		snow							rain				N/A											
18		snow					rain		rain				N/A					rain						
19							rain				†		N/A					rain						
20													N/A				rain	rain						
21			rain			rain							N/A					rain						
22			snow		rain								N/A					rain					rain	
23							rain						N/A											
24		snow			rain		rain						N/A								rain			
25		snow	rain				rain						N/A											
26		snow											N/A										rain	
27	snow				rain				rain				N/A										rain	
28			rain						rain				N/A										rain	
29			rain		rain				rain				N/A										rain	
30				rain									N/A											
31													N/A											

Figure 14: Number of days with precipitation (NPD) in Cracow (left) and Switzerland (right) derived from the weather diary of Marcel Biem (left) and from chroniclers situated in Switzerland and nearby Alsace and southern Germany (Wetter et al., 2014; supplementary material)

The reconstructed NPD for Cracow and Switzerland are considerably lower than that of the 20th century average and even below the successive absolute minima of spring, summer and autumn of the instrumental period since 1864. Figure 15 demonstrates the cumulated deviation of NPD compared to the 20th century mean (Fig. 15; B; dotted line = 20th century mean versus black line NPD of 1540) which amounted to 81 % less days with precipitation in Switzerland. The precipitation amount (PA) was calculated according to the methodology, developed and discussed in Wetter et al. (2014) which, simplistically expressed, is based on the close correlation between NPD and PA (Fig. 15; A). The calculated 1540 PA for Switzerland was significantly below the 100-year minimum levels throughout spring (MAM), summer (JJA) and autumn (SON). No similar event is documented, where all three seasons successively underbid the 100-year PA minima as well as the absolute minima of NPD within the instrumental period in Switzerland. This finally caused the record breaking low water level of Rhine River in Basel and other sites in Switzerland and Europe.

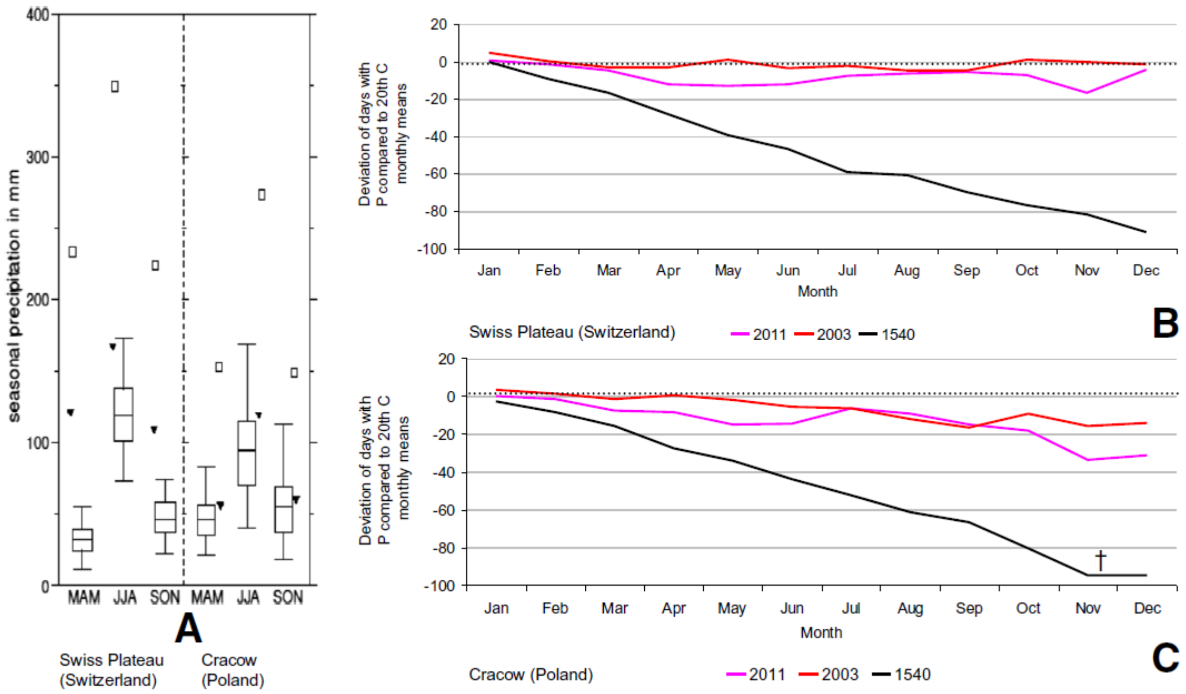

Figure 15: **Reconstructed seasonal precipitation amounts for spring, summer and autumn and cumulative deviations of 1540 NPD compared to the 20th-century mean, 2011 and 2003 .a: Median, upper and lower quartiles (boxes), 95 % uncertainties (whiskers) as well as 50 and 100 year minimum levels (box and triangle) of 20th century data for Swiss Plateau (northern Switzerland) average (left) and Cracow(right), b: compares cumulative deviations of NPD in Northern Switzerland in 2011, 2003 and 1540. NPD for 2003 and 2011 are taken from Federal Office of Meteorology and Climatology, MeteoSwiss (NPD were averaged over stations of Basel, Luzern, Schaffhausen and Zürich). Dotted line=20th-century mean of days with Precipitation≥1 mm, c: compares cumulative deviations of NPD in Cracow, Poland in 2011, 2003 and 1540. NPD for 2003 and 2011 are taken from the Center for Poland's Climate Monitoring. Dotted line=20th-century mean of days with Precipitation≥1 mm; † date of death of Marcin Biem: 19th Nov 1540 (Wetter et al., 2014)**

The extreme dryness throughout 1540 across Central Europe led to an extraordinary soil-moisture- and evapotranspiration deficit, which was prescribed by numerous chroniclers reference to extreme soil cracking, the failure of wells, fruitless digging for groundwater in dried out river beds and leaf fall of trees and vines due to heat stress. In temperate climates, a considerable part of incoming shortwave radiation is generally used for evapotranspiration (i.e. humidification of water from vegetation, soils and water surface sources) which is called the latent heat flux. The remaining sensible heat flux ultimately impacts air temperature. In case of a strong soil-moisture deficit the share of sensible heat increases as the latent heat flux gets weaker due to decreasing moisture sources which consequently leads to increasing air temperatures. Increased air temperature on the other hand leads to a higher evaporative demand and thus to a potential increase in evapotranspiration, leading to a further decrease in soil moisture until the total drying of the soil when temperature increases cannot be dampened by further increases in evapotranspiration anymore (Seneviratne et al., 2010). In these cases rapid and extreme increases in temperatures are observed. Spring-summer temperatures were assessed by calibrating grape harvest dates (GHD) with the monthly anomalies from 1901 to 2000 mean of HISTALP temperature series, which resulted in a linear regression equation where GHD served as temperature proxies (Wetter & Pfister, 2013). GHD for 1540 is not available which is why it had to be deduced from full maturity of grapes and the temporal difference between veraison and the usual beginning of the grape harvest. Based on the veraison date and the full ripeness of the grape (both are known for 1540) GHD was assessed between 12th and 25th August, marking the margins of fluctuation within full grape maturity, when under normal circumstances grape harvest would have occurred (Wetter & Pfister, 2013). The so assessed temperature anomaly for May-July temperatures amounted to + 4.7 °C and + 6.8 °C compared to the 20th century mean (Fig. 16).

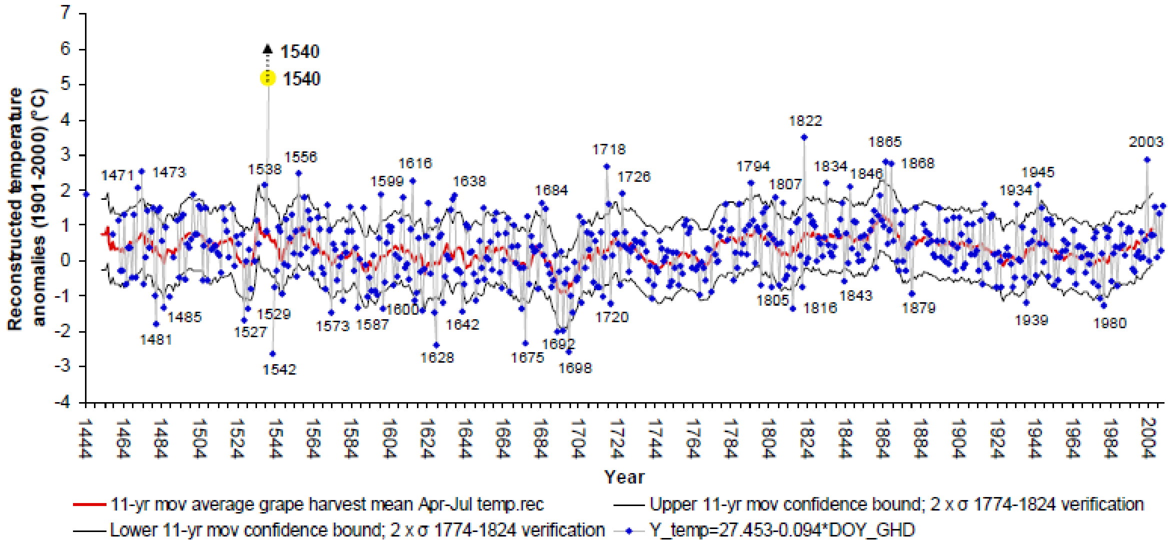

Figure 16: **Temperature anomalies compared to the 20th century based on grape harvest dates linear regression calculations (Wetter & Pfister, 2013)**

In case no (agro-) phenological data (like GHD or grain harvest dates) is available it is still possible to use weather descriptions, which may refer to considerable phenological anomalies (like e.g. blossoming of trees in winter), reference to the cryosphere (like e.g. the description of freezing over of lakes and rivers) or provide general descriptions about temperature and precipitation (e.g. remarks about mild winter temperature or wet summer conditions) to assess the weather related contexts of pre instrumental flood or drought events. Pfister (1999) developed a seven step index (-3/-2/-1/0/+1/+2/+3) to quantify such qualitative narrative information and was able to reconstruct a monthly resolved temperature and precipitation series for the period 1496-1995. The following section will demonstrate the very high potential of municipal accounts to significantly improve the already existing precipitation reconstruction in Switzerland (Pfister, 1999).

4.5. Reconstruction of long term seasonality of minor pre instrumental flood events based on institutional sources

The books of weekly expenditures of the City of Basel include records concerning wage payments for craftsmen and guards who were engaged to protect the Rhine bridge and the inlet fence of Birsig river at the city gates from possible destruction due to floating debris. Recently the period from 1600 to 1650 was completely analysed (Spycher, 2017), 70 Rhine- and 218 Birsig river flood events were detected, whereas chroniclers in the same period only reported on 3 Rhine- and 5 Birsig floods. This ratio of 23:1 for Rhine- and 44:1 for Birsig floods clearly demonstrates the significantly sharper "observation skills" of the city accounts towards minor and much more frequent flood events (flood return period ≤ 1 year). The quality and reliability of these historic records was checked by comparing whether the monthly-, seasonal and half yearly distribution of the historic flood events resemble the distribution during the instrumental period. As the historic records in the municipal accounts do not provide information about the minimum discharge amount that was needed to cause preventive protection measures, which would define the "flood" events in the instrumental period, the flood definition was specified as follows: Under the assumption that both series (historic and instrumental) were comparable, a simple ratio of the length of the historic series to the length of the instrumental Rhine and Birsig series was calculated. This ratio defined the number of events that had to be considered in the instrumental period which in the same time also defined the minimum discharge that probably was needed to cause preventive protection measures in historic times. Figure 17 shows overall good visible correlations of the monthly and seasonal distribution of flood events between the historic and the instrumental Rhine-, Birsig and Wiese flood events enhancing our confidence that the indirect flood information from the municipal accounts is a valid flood proxy. A closer examination of the analysed 50 year period from 1600 – 1650, reveals that our assumption about the good quality and reliability of this flood proxy seems to have been correct. Figure 18 demonstrates the monthly distribution of Rhine and Birsig brook flood events in the historic and the instrumental period. The overall correlation amounted to 0.81 for River Rhine and 0.47 for Birsig brook (pearson).

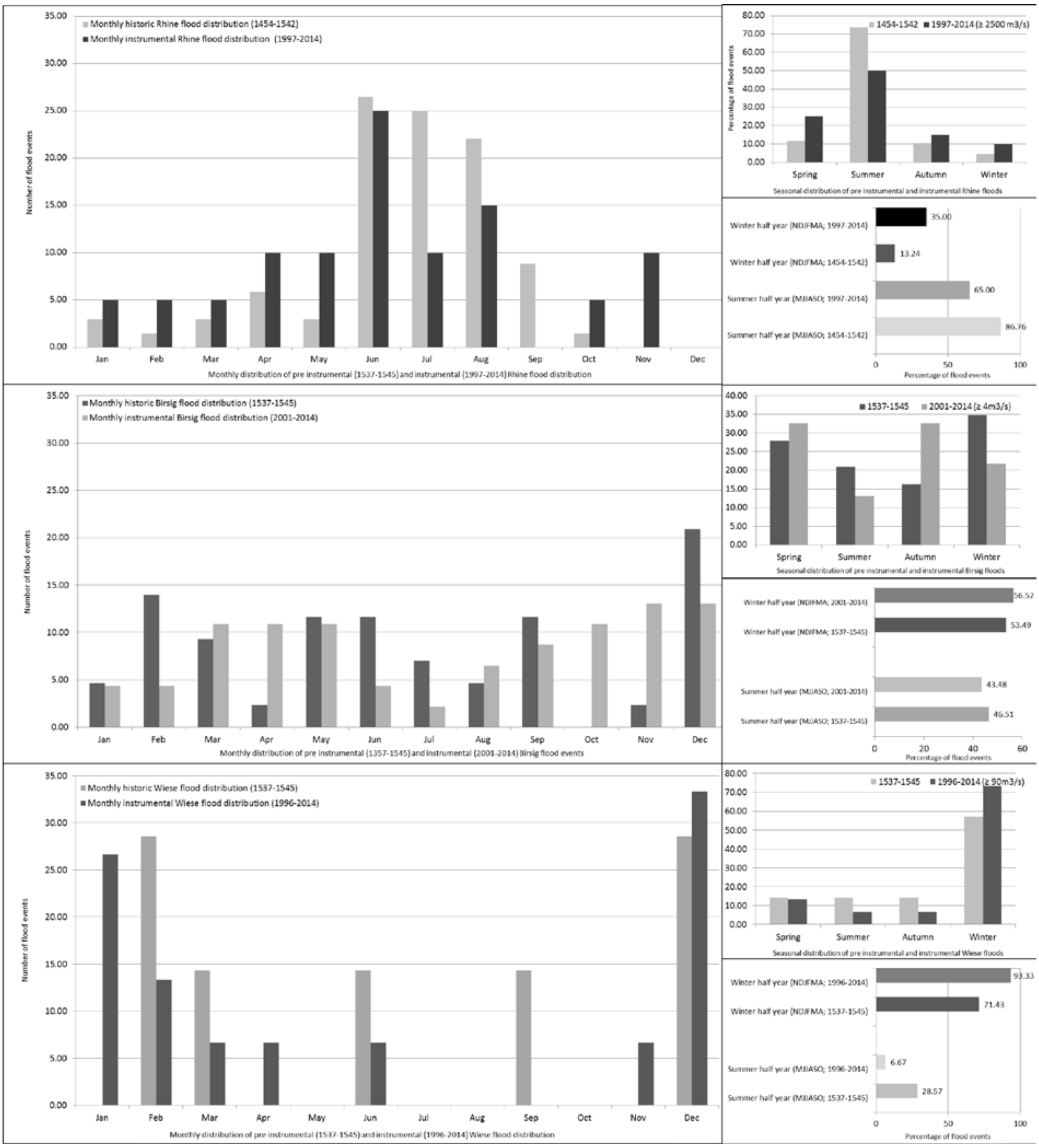

Figure 17: **Distribution of historical and instrumental Rhine, Birsig and Wiese flood events in comparison**

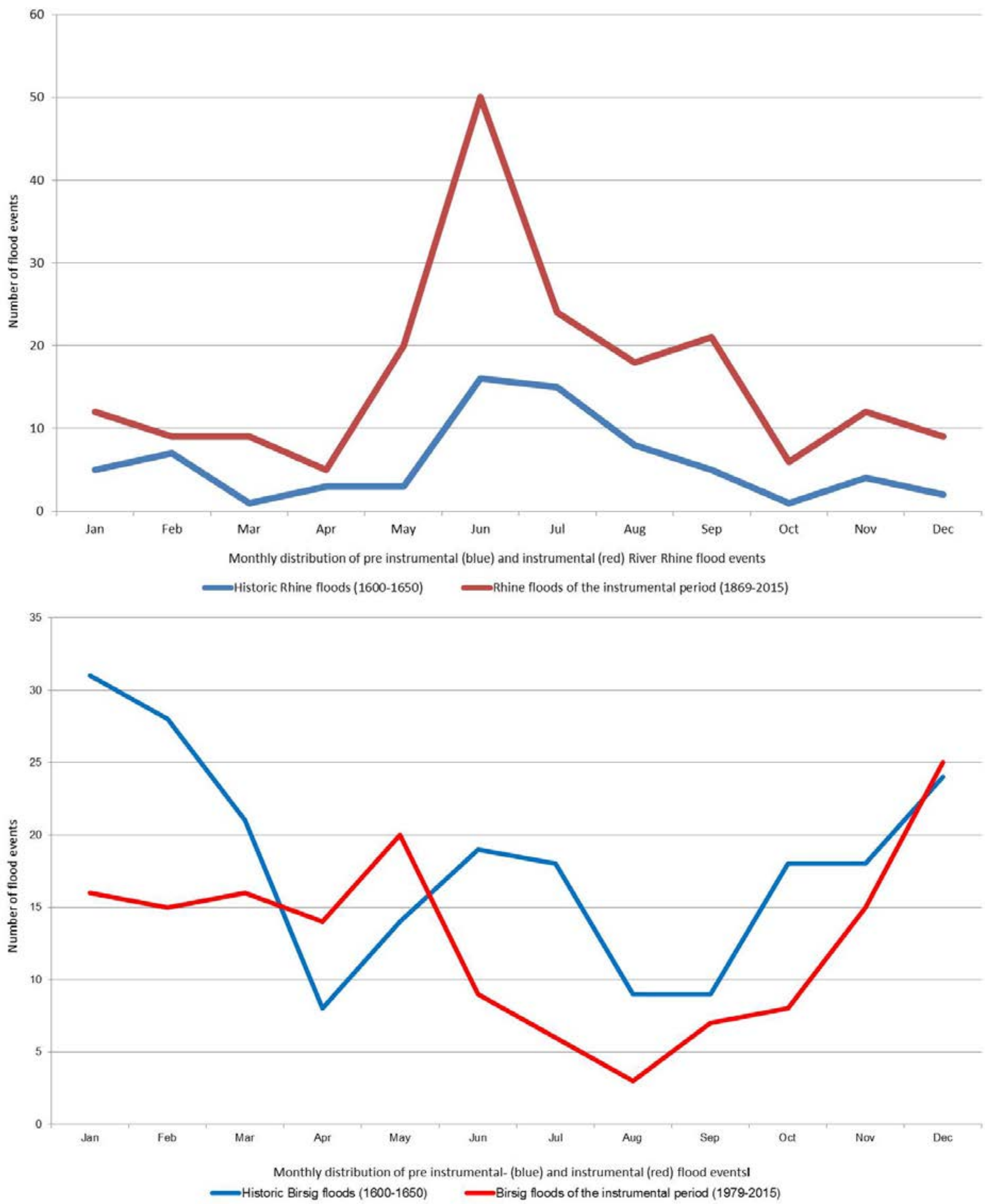

Figure 18: **Distribution of historical and instrumental Rhine and Birsig flood events in comparison**

The latter, relatively weak, correlation can be explained by the fact that the instrumental period of Birsig brook is rather short and the measurement station is several kilometres upstream of the historic flood information (above the inflow of some tributaries). Further analyse is required once all flood proxies from the weekly books of expenditures have been extracted (1401-1799) to ascertain whether the significant accumulation of historical Birsig "floods" in January and February might have been triggered by a climatic anomaly (LIA?) or whether the winter months (DJF) might in fact contain mixed information of floods on the one hand and ice on the other hand. An icebound river can in fact be a potential threat to the infrastructure and may cause severe flooding which might have justified the extra watches. The second explanation (mixed signals) is probably the more plausible. All other months (MAMJJASOND) are more or less in agreement with the instrumental measurement period, which implies that they might represent undisturbed flood proxies (see Fig. 17 and 18). Figures 19 and 20 demonstrate that several Rhine River and Birsig brook flood events, like e.g. in 1640 (12 Birsig- and 10 Rhine flood event records), cannot be explained by preceding and actual reconstructed temperature- (Dobrovolný et al. 2009) and precipitation (Pfister, 1999) reconstructions, which suggests that especially the precipitation reconstruction is not yet as good as it could be. This is not unexpected as currently available precipitation reconstructions are predominantly based on direct descriptions of wet or dry conditions or on reported flood events by chroniclers. The problem is that chroniclers tend to describe extreme events only, be it floods, temperature or precipitation, so that information about normal events are usually underrepresented. The flood proxies extracted from institutional sources, like the weekly books of expenditures of the City of Basel, do have a much "lower observation threshold" and include therefore also normal events, which makes them highly valid to be used to significantly improve existing precipitation reconstructions. The fact that the city accounts simultaneously record intensified flood occurrence for both "catchments", the local (Birsig) and the supra-regional (Rhine), beginning in June 1640, supports their mutual credibility. The simultaneousness of the intensified flood records in the two catchments makes it implausible that the intensified Rhine bridge- and Birsig fence watches were executed out of other reasons, like e.g. reparation works.

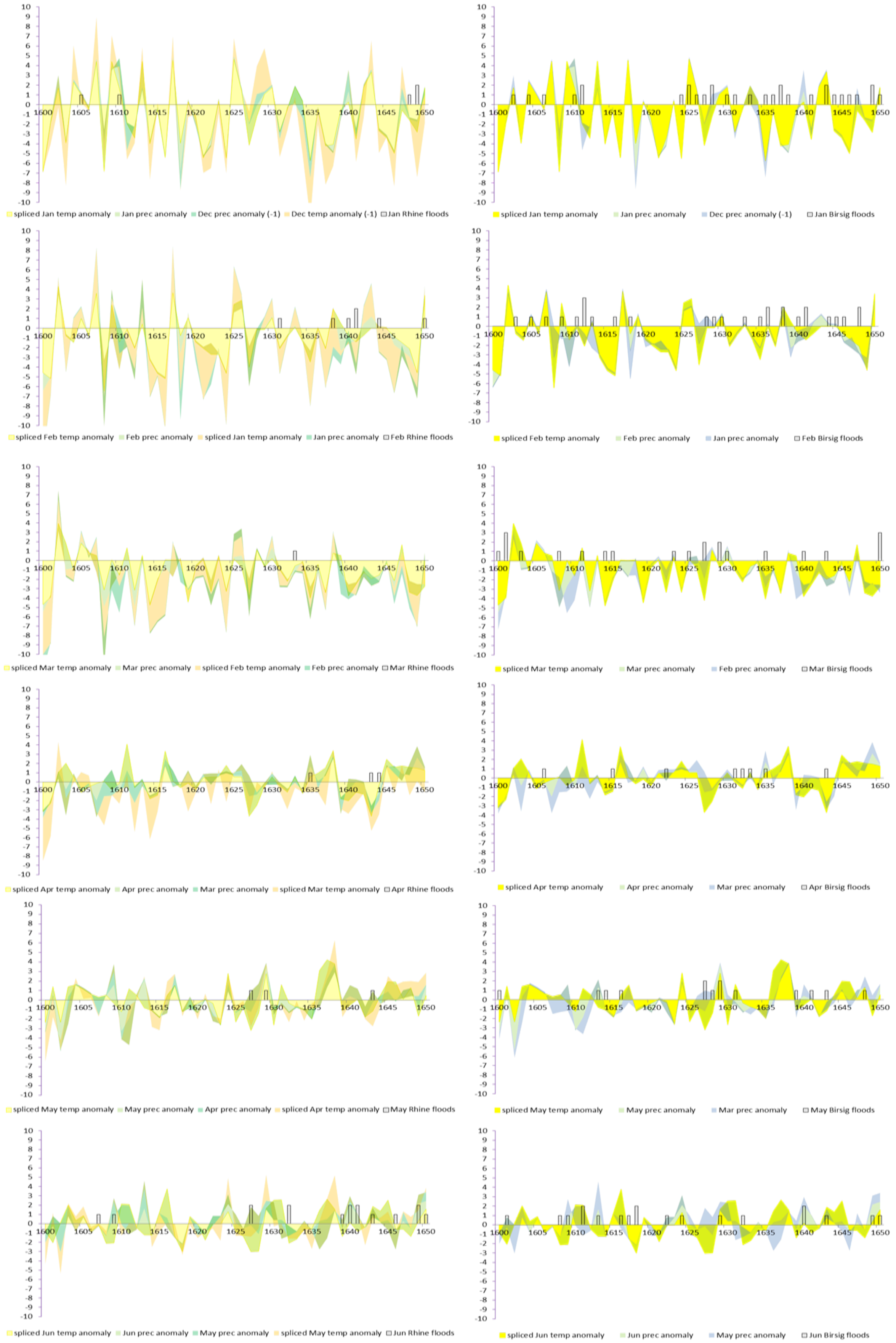

Figure 19: **Monthly spliced temperature (Dobrovolný et al. 2009) and precipitation (Pfister, 1999) reconstructions combined with Rhine- and Birsig river flood proxies from the weekly led books of expenditures from the city of Basel – January to June**

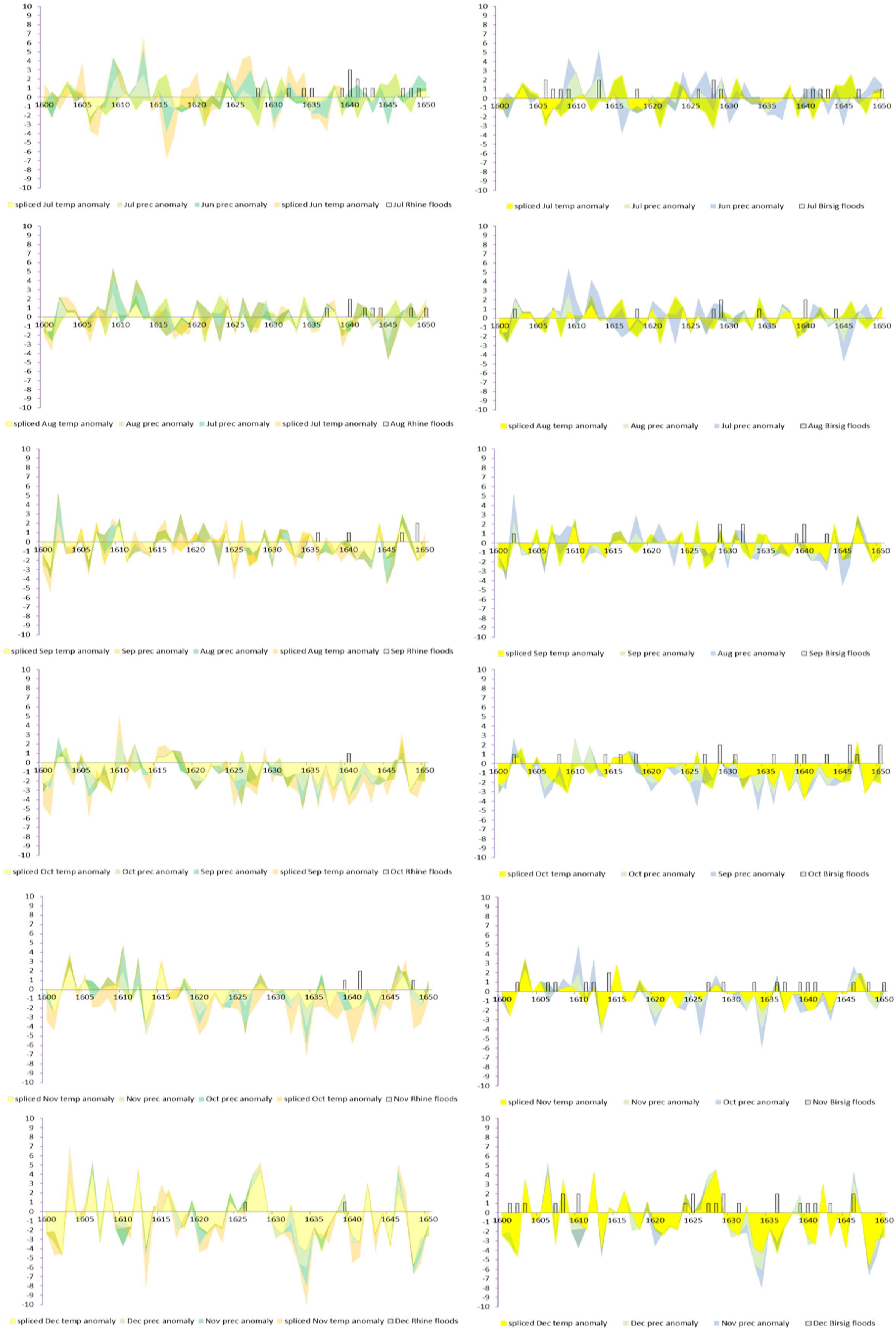

Figure 20: **Monthly spliced temperature (Dobrovolný et al. 2009) and precipitation (Pfister, 1999) reconstructions combined with Rhine- and Birsig river flood proxies from the weekly led books of expenditures from the city of Basel – July to December**

5. Conclusion and outlook

It has been demonstrated that the historical documentary evidence situation, allowing to reconstruct and assess climatic parameters (e.g. temperature or precipitation) as well as hydrological events, is remarkably strong in Switzerland. A number of factors have led to good record preservation including the almost absence of direct involvement in major destructive war activities of Swiss cities, the absence of cumulative natural disasters and the existence of effective municipal measures against non-cumulative disasters, as well as the more recent economic wealth and its positive aspects towards the support of countless state and local municipal archives. Existing historical documentary evidence as well as basic methodologies to reconstruct long-term frequency, seasonality and magnitudes of pre instrumental hydrological events have been introduced and their strengths and weaknesses have been briefly discussed. Prospects are good that reconstructed pre instrumental flood magnitudes (in water level or discharge) may be homogenised to actual runoff conditions, so that floods of pre-anthropogenic river engineering measures may be compared to the more recent floods under the actual anthropogenic influenced runoff conditions (paper in preparation). Furthermore it has been shown that the analysis of the books of weekly expenditures of the City of Basel provide significantly improved “observation skills” toward small- and normal flood events which are usually not recorded by chroniclers or journalists. In the fully analysed 50 year period between 1600 and 1650 the ratio between flood evidence from chroniclers and municipal accounting records amounts to 1:23 in the case of Rhine- and 1:44 of brook Birsig flood events. Preliminary investigation revealed that analogue institutional sources like the books of weekly expenditures of the City of Basel do exist in almost evry other Swiss town. These records usually start in the 14^{th}, the 15^{th} or the 16^{th} century. They are mostly labelled as “Säckelmeisterrechnungen”, which is the late medieval term for the chief officer of the cash receipts, or simply as “Stadtrechnungen” (city accounts). Even though many of these municipal account books are led on a six-monthly level only, making dating of flood events less accurate, we have good reason to assume that their observation skills towards small- and normal flood events is comparable to those in Basel, because bridges and fences were basically subject to the same threats and the system of guarding and protecting them was principally the same. The reconstruction of long term seasonality and frequency of small and normal pre instrumental flood events should therefore be possible for countless rivers and brooks at different sites in Switzerland. A complete analysis would expand the experience base about small and normal flood events, which so far is strictly limited to the instrumental period, for several centuries into the pre instrumental past, as, unlike for extreme flood events, no historical hydrological reconstructions are available yet in Switzerland. Reconstructions like this, once analysis will have been expanded to neuralgic other sites, would furthermore significantly deepen our understanding of the genesis of particular flood events and drawing of some principal conclusion about meteorological triggers – by analysing the contribution and non-contribution of rivers – would be possible.

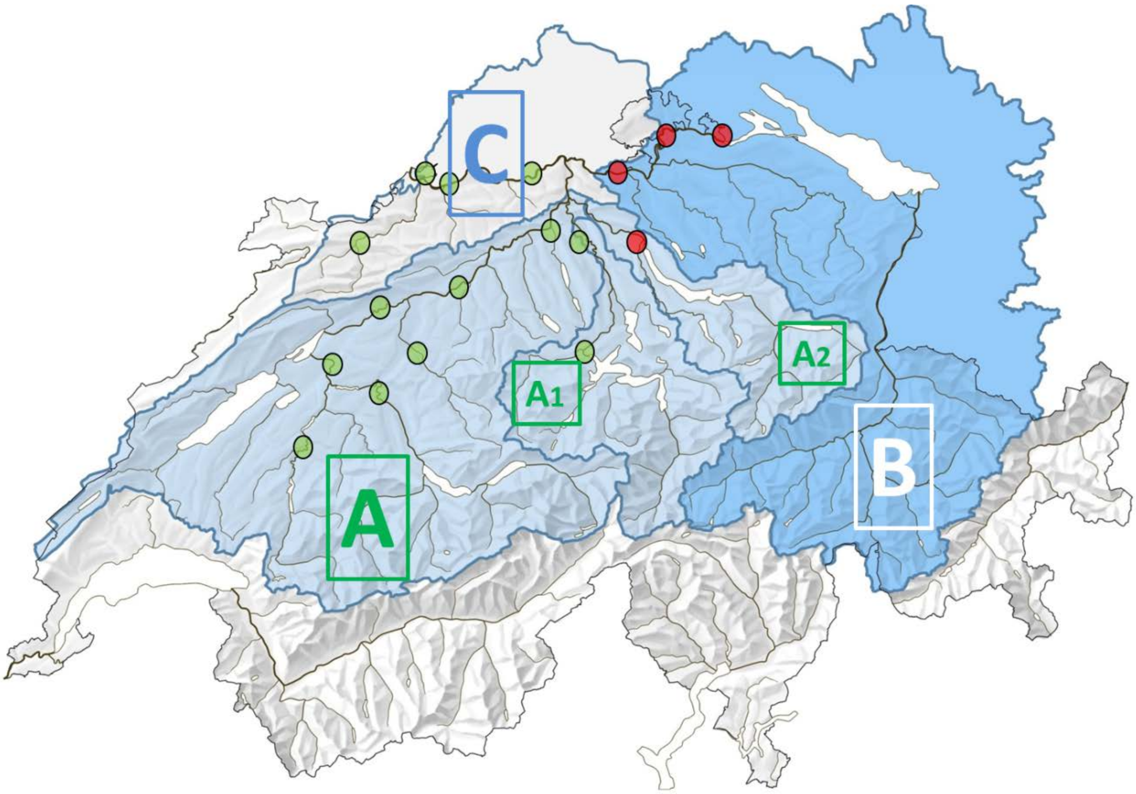

Figure 21: **Contribution (green dots) and non-contribution (red dots) of rivers to particular pre instrumental minor flood events.**

A: **Aare catchment**
A1: **Reuss catchment**
A2: **Limmat catchment**
B: **High Rhine catchment**
C: **Jura catchment**

If, for example, the municipal accounts from Fribourg, Bern, Aarberg, Delémont, Solothurn, Burgdorf, Olten, Lucerne, Laufenburg, Rheinfelden and Basel contained flood records (green dots in Fig. 21) whereas accounts from eastern Switzerland (red dots in Fig. 21) remained silent, the conclusion could be safely drawn that this specific flood event was primarily triggered by the catchments of Aare River and its tributaries (namely by the rivers Saane-, Emme, Birs and Reuss), whereas the catchment of the High Rhine, upstream of the influence of Aare, did not play a major role. The meteorological trigger of this hypothetical flood event, according to the distribution of the contributing and non-contributing rivers, therefore quite clearly points to a western based origin of the flood wave. The books of weekly expenditures do also contain records about hay- and after-grass harvests. Spycher (2017) compared these harvest dates with monthly resolved precipitation- and temperature anomalies (Pfister, 1998) and found significant correlations between early and late onsets of hay- and after-grass harvest dates and the preceding months with dry or moist weather anomalies. These hay- and after-grass harvest data series are thus of great value for further historical climatological analysis. They improve and (chronologically) expand the already existing temperature- and precipitation series back in time and furthermore may help to shed light on weather conditions in advance and during pre-instrumental flood events. It seems, as indicated in the abstract, that non-scientific peer group interest in historical hydrological analysis, especially from responsible public ministries- and local offices side, significantly increased in the last few years in Switzerland. If this interest is going to last this would initialise a huge potential for further historical hydrological analysis partly in cooperation with private engineer companies and would help to significantly improve flood risk analysis from which the public sector would certainly benefit as well. Further historical hydrological research, especially based on municipal accounting records, is needed and required as it promises highly valuable results of so far not yet reached quality.

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