The Potential of Historical Hydrology in Switzerland

Oliver Wetter[1]

[1]Oeschger Center for Climate Change Research (OCCR) and Institute of History, Section of Economic, Social and Environmental History (WSU), University of Bern, Bern, Switzerland.

Abstract

Historical hydrology bases on data derived from historical written-, pictorial and epigraphic documentary sources. It lies on 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 gained some 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 mentioned historical hydrological study serve now as basis for the currently running 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 Rhine River 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. 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 (e.g. Vischer, 2003) sheds light to more 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 outstandingly good due to several reasons. First it has to be mentioned that Switzerland was not involved in war activities anymore since 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 either were 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 accepted the handover of power to their previous subjects peacefully (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

1 systematically destroyed by French forces on their retreat. This military tactic complicated not only
2 the advance of the adverse forces but also significantly aggravates the reconstruction of many pre
3 instrumental flood events, because documentary pre instrumental flood evidence in many cases are
4 either directly or indirectly related to these architectures, which at certain locations survived ice
5 drifts and floods for several centuries before they were destroyed by the French. The second reason
6 why the historical documentary data availability is very good in Switzerland can be assigned to the
7 lack of major large scale natural disasters that compromised important cities (and thus also archives)
8 since the great and very destructive earthquake from 1356 that almost completely annihilated the
9 city of Basel. The destruction of Basel was not so much caused by the seismic shocks but more
10 importantly because of the outbreak of fire. After a foreshock taking place in the late afternoon,
11 most of the citizens fled to open fields, leaving the many fireplaces unguarded, which then where
12 destroyed during the main seismic shocks, causing an unprecedented town fire that lasted, according
13 to the chronicles, during eight days until the fire extinguished because there was nothing left that
14 could continue to nurture the flames (Meyer, 2006). Speaking of town fires, it has to be stated that
15 the third reason why the historical documentary data availability is good in Switzerland is caused by
16 several related facts that taken together significantly lower the vulnerability towards town fires as
17 well as towards other "natural" disasters. The Begin of the petrification process, especially of
18 important buildings, started quite early in Swiss towns and can, e.g. for Basel, be assigned to the 12th
19 Century, which is more or less true also for other major Swiss cities (D'Aujourd'hui, Lavicka, 1982).
20 Important and powerful people, groups and institutions were among the first who built expensive
21 and representative buildings in stone. The same political, religious and economic influential circles
22 produced the vast majority of historical documents which were archived in those comparably (to
23 wooden buildings) fire safe buildings. The inventories of the state archive of Basel include a huge
24 variety of archival materials (produced by the nobility, the church, guilds, city authorities and
25 important institutions) that are dated partly significantly earlier than the earthquake from 1356,
26 which demonstrates that these historical documents survived the destructive town fire caused by the
27 quake. Cities under normal-, non-cumulative disaster situation unlike as in 1356 or during war
28 activities, generally had the necessary organisational skills, the needed staff and the financial and
29 technical background to support effective measures against natural disasters (Fouquet, 1999) so
30 that, as a rule, single disasters such as town fires could be limited to a house, a street or a quarter
31 but did generally not burn down the settlement as a whole, which in those cases certainly anyhow
32 may have led to significant historical documentary losses, but they on the same time could not
33 destroy the majoritarian rest of the documents. To sum it up, the generally good historical data
34 availability in Swiss cities is founded on interrelated positive circumstances like the almost absence of
35 direct involvement of major war activities as well as the absence of cumulative natural disasters, the
36 early begin of petrification of important buildings and the existence of effective measures against
37 non-cumulative disasters such as town fires. These positive historic factors in combination with the
38 comparably recent prosperity of Switzerland, allowing the maintaining of relatively cost intensive
39 archives, provide an excellent opportunity for historians and historical climatologists to draw on a
40 very rich legacy of historical documents for their analysis. The Euro-Climhist- and the WSL databases,
41 a rich stock of relevant historical climatological and hydrological analysis in form of qualification
42 works (Seminar-, BA-, MA- and PhD thesis) originating mostly from the University of Bern as well as
43 some fundamental historical hydrological publications focussing on the situation in Switzerland (e.g.
44 Lanz-Lanz-Stauffer & Rommel, 1936; Nast, 2006; Pfister, 1998, 1999; 2006, 2009a; Röthlisberger,
45 1991; Schmocker-Fackel, P & Naef, F., 2010; Vischer, 2003; Wetter et al., 2011) significantly facilitate
46 the search for data and may even deskill further historical hydrological analysis.
47
48 According to Brázdil et al. (2005) historical documentary evidence about climate and single extreme
49 events like e.g. floods are to be distinguished – based on their manor of observation – between
50 *direct*- and *indirect data*. Direct narrative data directly describe the course of weather and climate or
51 extreme events like e.g. floods per se, while indirect data refer to (bio-) physically based phenomena
52 associated with weather and climate such as plant and animal life cycle events or ice and snow

1 seasonality features. With respect to the generation of historical documentary sources Pfister et al.
2 (2009b) differentiate between *individual-* and *institutional sources*. Individual sources are shaped by
3 the social background, the motivations and preferences of their authors and their temporal scope is
4 limited – at least the one in which they can be considered as contemporaries to the events they
5 describe – to the life time of the observer. Institutional sources on the other hand are produced by
6 governments or other bodies and institutions such as e.g. the church. These institutional bodies were
7 typically not interested in describing weather and climate or single extreme events, but kept records
8 in order to document their activities and in doing so, they indirectly recorded the before mentioned
9 climate related aspects. Their administrative routines generally involved a good standardisation in
10 the way records were kept which makes them highly homogeneous over periods of time far longer
11 than that of single human beings which is a very good prerequisite to create long term homogeneous
12 series of climate parameters. The following types of individual and institutional sources shall now be
13 described in more detail as they are crucial for historical hydrological analysis:

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

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

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

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

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

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

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

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

3.   Methodologies

3.1   Critique of sources

According to the great variety of documentary evidence accessible, a bunch of different methodologies exist to extract their inherent climatological and hydrological information. As we are dealing with historical sources it is an absolute prerequisite to critically evaluate their reliability and validity, before further methodologies and analysis should 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 style 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 to a, based on contemporary sources, already known event. Municipal accounts are seen as contemporary historical sources, as they "report" almost simultaneously to the "described" event. Same is generally true for newspaper- or early scientific expert reports. In case of 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 far away 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.

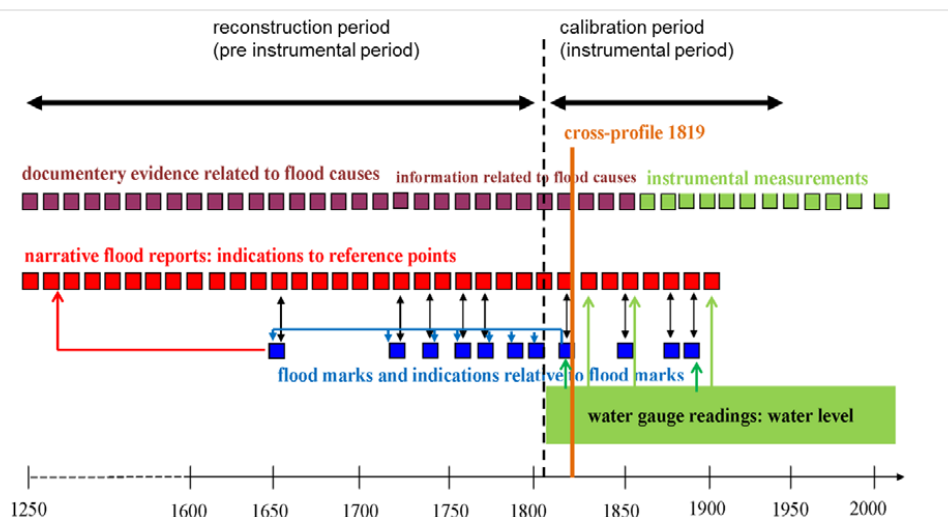
3.2.   Methodologies to reconstruct frequency, seasonality and magnitudes of pre instrumental hydrological (extreme-) events

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

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

27 **Figure 1:**   **Qualitative calibration; assigning gauges to pre instrumental "flood information systems"**
28   **(Wetter et al., 2011)**
29
30 The vertical punctuated line represents the differentiation between the pre instrumental- and the
31 instrumental period. In the instrumental period gauges were first determined by eye on a daily- and
32 around mid-nineteenth century on a sub daily or continuous level by instruments. Earlier societies
33 established different "flood information systems" like affixing flood marks or describing such events
34 as accurate and objective as possible with the goal of intergenerational risk communication (Pfister,
35 2011a). Many chroniclers and journalists described the magnitude of floods in the form of standard

1 narratives, referring to specific landmarks in the built (municipal) environment. References typically
2 were drawn on streets, alleys and town squares as well as on distinctive edifices like churches,
3 municipal wells or other public buildings like bridges or river-near city walls. These observers
4 generally tried to accurately describe the expansion of the flooding area as well as the depth of the
5 inundation at specific spots in the inundated area (Wetter, 2011). If long term gauge measurements
6 are at hand an overlap with narrative flood descriptions becomes likely, so that the landmarks that
7 were narratively referred to floods may be calibrated with the corresponding measured gauges (Fig.
8 1; bright green arrows). A very similar calibration can be done with existing flood marks (Fig 1; dark
9 green arrows). In the spirit of intergenerational risk communication, flood marks were commonly
10 affixed at buildings with good visibility for the public and thus were often attached at the very same
11 building. "Gauge" identification of pre instrumental flood marks (i.e. flood marks that are dated
12 earlier than the Begin of the instrumental period) in those cases are simple as they can be easily
13 calculated from a reference flood mark from the instrumental period (Fig. 1; blue arrows). Otherwise
14 they have to be reconstructed either by measurement or the flood marks altitude (asl) needs to be
15 reconstructed otherwise. Pre instrumental flood marks may also define the "gauge" of landmarks
16 that were mentioned in narrative pre instrumental flood descriptions but were not referred to in the
17 instrumental period (Fig. 1; black double arrows). According to typical local inundation sequences it
18 may very well be that certain landmarks were quite commonly narratively referred over the
19 centuries. If such a commonly referenced landmark could be calibrated e.g. with an instrumentally
20 measured gauge from the nineteenth century, this gauge can principally also be used for a flood
21 event that has taken place several centuries before (Fig. 1; red arrow). But, it imperatively has to be
22 taken into account that major architectural- and ground level changes may occur over time,
23 especially in urban areas. It thus has always to be double checked whether the referred landmark
24 really is the same- and was in earlier times in the same condition than it was during the instrumental
25 period when the calibration was carried out. In some cases qualitative calibration does not work
26 because – especially if discharge conditions changed significantly over time – certain landmarks may
27 have only be narratively referred to in the pre instrumental period so that calibration with measured
28 gauges is not possible. In those cases reconstructions of the corresponding landmarks, incorporating
29 the above mentioned possible architectonical and ground level changes over time, need to be
30 conducted. Recourse to archaeological- and architectural history studies to be able to adequately
31 reconstruct the condition of a landmark at the time the flood took place is therefore an absolute
32 prerequisite. Not taking into account these possible changes could lead to significantly distorted
33 results as especially in urban areas major changes, like e.g. ground level increases of up to several
34 meters, may occur over the centuries. Reconstructions of narrative references to landmarks
35 commonly require quite distinct investigative skills to transform them into flood water levels (in m
36 asl.) or discharges, as will be presented by an example of two Rhine river flood events in Basel: The
37 vicar Hieronymus Brilinger noted in his chronicle that the river Rhine rose so high that people could
38 wash their hands in the water while they were standing on the bridge, which Brilinger did himself
39 when he was a young boy (Hirzel, 1915). The sentence "quod ego ipse feci" (engl.: "which I did
40 myself") clearly reveals that Brilinger was an eyewitness of the 1480 flood event and his report can
41 thus be awarded the highest reliability. An anonymous addendum in a chronicle reporting about a
42 flood of river Rhine in 1424 uses a very similar wording as Brilinger, by mentioning that the Rhine
43 rose so high that three pillars of the bridge were destroyed and people washed their hands in the
44 Rhine (Hirzel, 1890). It is not really clear if people were on the bridge while they were washing their
45 hands in the Rhine but the really close semantic connection between the mentioning of the bridge
46 and the washing of hands supports the conclusion that people might have been standing on the
47 bridge while they washed their hands in the Rhine. This conclusion can be made even more plausible
48 by relating the further referred landmarks to the height of the bridge, as the anonymous addendum
49 additionally reported that boats needed to be boarded through the windows of the guild house of
50 the boatmen and that the Rhine entered the city through the city wall. Figure 2 demonstrates that
51 these references fit very well to each other and are (hydro-) logically meaningful. The yellow dotted
52 horizontal line on image a) (Fig. 2; a) shows that the windows of the guild house of the boatmen are

1 quite on the same height as the level of the bridge which both must have been more or less reached
2 by the water if people on the bridge could wash their hands (as we assumed) and boats needed to be
3 boarded through the window of the guild house (as was explicitly reported). The reference that the
4 water flooded the city behind the city wall supports the before made assumption that the water level
5 more or less must have reached the level of the bridge as well. The horizontal yellow dotted line on
6 image b) (Fig. 2) demonstrates that the city wall would have been submerged if the water had
7 reached the level of the bridge so that the reported flooding of the city right behind the wall is
8 plausible. Last not least it has to be mentioned that the townscape oeuvres of Büchel (Fig 2, a and b)
9 are known to feature good closeness to reality (Boerlin-Brodbeck, 2006).

12 **Figure 2:**   **Hydro-logical plausibility check of referenced landmarks in chronicler reports about the**
13   **Rhine river flood from 1424 and 1480.**
14
15   Image a)   Blick auf das linke Rheinufer, 1759; Artist Emanuel Büchel, StABS,
16   Collection Weber-Oeri, Topo 2.
17   Image b)   Blick vom Rheinsprung auf die Rheinbrücke und Kleinbasel mit Hinterland,
18   1767; Artist: Emanuel Büchel, StABS, Collection Weber-Oeri, Topo 2.
19
20
21 It has been shown before that the water level of the floods of 1424 and 1480 have more or less
22 reached the height of the bridge as well as the height of the windows of the guild house right
23 beneath the bridge. These references may be used to reconstruct the peak water levels of the two
24 flood events which was realised as presented in figure 3.

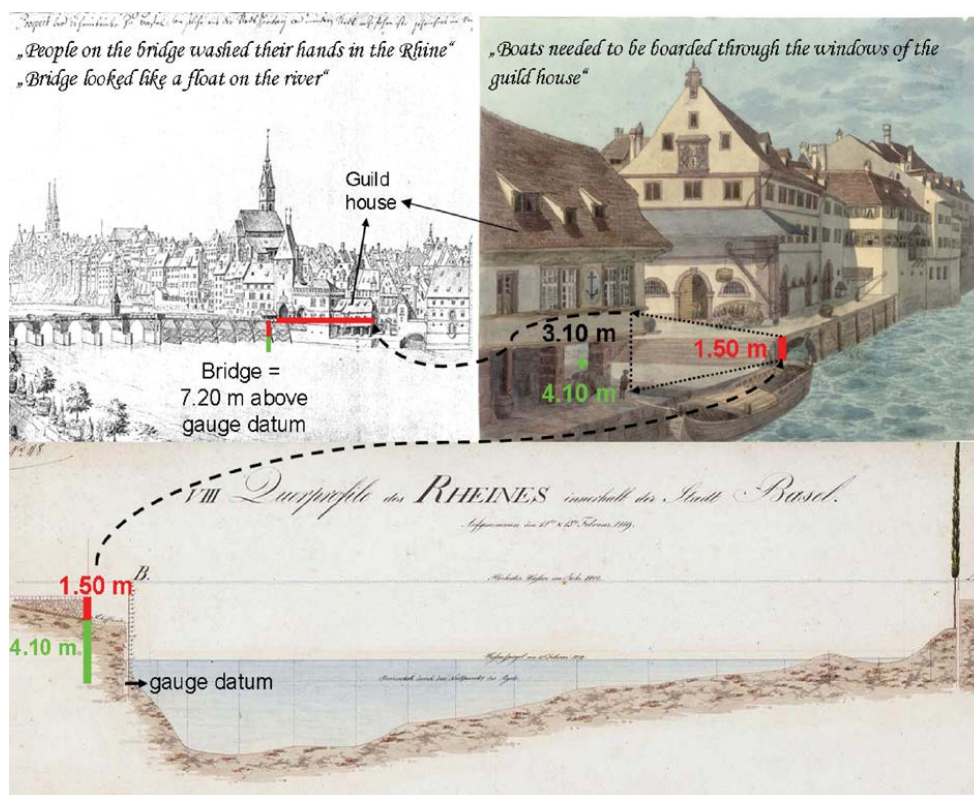



Figure 3: **Reconstruction of peak water levels of the 1424 and 1480 river Rhine flood events in Basel based on narrative landmark references (references = levels of the bridge and the windows of the guild house) in combination with a cross profile taken right on the spot of the referenced landmarks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

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 the difference between the two ground surfaces which 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 of the gauge, 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

1 m asl. The height of the windows of the guild house amounted thus approximately to 251.13 m asl.
2 (243.93 + 7.20). This reconstructed level serves now as the water level for the two flood events from
3 1424 and 1480 of Rhine River in Basel. The discharges of the two flood events may then be assessed
4 based on the reconstructed flood water levels (i.e. 251.13 m asl.) by applying e.g. a one-dimensional
5 (1D) hydraulic model that calculates the transient 1D flow integrated over the cross-sections of the
6 river systems based on the de-Saint Venant equations (Ven Te Chow, 1973). It has to be kept in mind
7 that discharge quantifications should only be calculated based on cross- and longitudinal profiles that
8 may be considered as representative for the runoff conditions during the concerning pre
9 instrumental flood events so that errors may be kept as small as possible. The cross- and longitudinal
10 profiles that were taken in 1819 along the river on the territory of the city of Basel satisfies the
11 before made statement as the most influencing local river engineering measures, like the
12 construction of river banks, were realised much later at the end of the nineteenth century. Pfister
13 and Wetter (2011b) demonstrated that the above exemplarily outlined approach can be successfully
14 transferred also to other sites in Switzerland, which so far was realised for pre instrumental Sihl- and
15 Limmat river flood events in Zürich (Wetter & Specker, 2015a; Näf-Huber et al., 2016) as well as for
16 Aare-, Saane- and Reuss rivers at different sites alongside the concerning water bodies (Wetter et al.,
17 2015b).
18
19
20 **3.2.3. Reconstruction of long term frequency and seasonality of minor pre instrumental flood**
21 **events**
22
23 City accounts belong to a source category with a very high potential for historical hydrological as well
24 as for historical climatological analysis, which is why they will now be described in more detail. A
25 special focus shall be laid on the books of weekly expenditures of the city of Basel
26 ("Wochenausgabenbücher der Stadt Basel"). These records were led from December 1401 to April
27 1799 in 84 volumes, each containing several years. Unfortunately some volumes are missing,
28 including the records for the years 1408-1409, 1434-1451 and 1619-1621. The records are dated on a
29 weekly basis, meaning that the date accuracy of the single records is somewhat distorted. The books
30 of weekly expenditures were first analysed by Fouquet (1999) who found recurring records of wage
31 expenditures for a squad of craftsmen that was called up onto the bridge of Rhine river with the task
32 to prevent it from being damaged by manoeuvring the drifting logs from the flood waters around the
33 vulnerable wooden pillars. Even-tough Fouquet's research interest did not have a historical
34 hydrological focus, he could proof a large number of river Rhine flood events which he concluded
35 from the before mentioned records. All in all he found 68 floods for the period from 1456 - 1542,
36 whereas chroniclers only recorded seven events during the same period. This ratio of almost 10:1
37 points to significantly sharper "observations skills" of the weekly records of expenditures towards
38 smaller flood events, which may be explained by the fact that bridges can be endangered by
39 relatively small events, whereas on the other hand it is known that chroniclers as well as journalists
40 were generally focussing on spectacular (i.e. extreme) flood events. A closer-, specifically historical
41 hydrological look at this source reveals that the "observation skills" towards small river Rhine flood
42 events is even much better than one could assume according to the findings by Fouquet (1999) and
43 that the weekly led records also include a vast number of expenditures (records) in context to further
44 local water bodies, like Wiese River and brook Birsig. These latter records are given in the form of
45 wages for gatekeepers to open the fence at the brooks entry into the city through the city wall with
46 the goal to prevent damming by floating debris during flood events. Sometimes these accounting
47 records even allow the assessment of flood durations, as they mention how many night wages for
48 the guarding of the bridge or the fences at the city wall were paid. The books of weekly expenditures
49 of Basel additionally include information about weather related damages in Basel's sphere of
50 influence or in regionally more far away befriended cities. In the following example from a record
51 dated on the 15th September in 1607 the council donated 2£ and 10β to two persons from its
52 confederate ally Lucerne, who suffered losses because of the water (i.e. flood). The weekly books of

1 expenditures furthermore contain expenditures for hay- and after-grass harvests at municipal
2 meadows. Spycher (2017), who compared these harvest dates with monthly resolved precipitation-
3 and temperature anomalies from Pfister (1998), found significant correlations between early and late
4 onsets of hay- and after-grass harvest dates and the preceding months with dry or moist weather
5 anomalies. According to her findings, above average moist or dry conditions in the period from April
6 to June (AMJ) correlate with late- (moist) or early (dry) hay harvests, whereas above average July-
7 August (JA) conditions result in late- (moist) or early (dry) after-grass harvests. Similar analysis by
8 Wetter (unpublished) revealed that hay harvest dates, if they are dated on a daily accuracy level
9 (unlike the hay- and after-grass harvest dates from the books of weekly expenditures), significantly
10 correlate with anticyclonic weather conditions if they are compared to a ± 3 day temporal context
11 around the corresponding hay harvest dates. This temporal correlation between hay harvest and
12 anticyclonic weather situations, which usually correlate with sunny weather, can be plausibly
13 explained, as the grass – after hay harvest – needed to be dried on the field, before it could be
14 collected and stored in the barn. Farmers were generally good interpreters and predictors of local
15 weather, as not only hay harvest but also many other agricultural activities directly depended on
16 these short term weather situations. The narrative information given from these accounting records
17 is in no means adequate enough, either to assess flood magnitudes by applying an index based
18 approach or to reconstruct flood water levels. Their strength instead lies in the detection of minor
19 and normal, so far not known, pre instrumental flood events and the ability to date them on a
20 weekly, monthly or seasonal resolution. They furthermore allow the definition of a minimum
21 discharge threshold when protection measures like the guarding of the bridge or the opening of the
22 gate usually was ordered and executed. The dating of the floods recorded in the books of weekly
23 expenditures of Basel is not as simple as one might think because the records are dated only on a
24 weekly basis which makes an exact assignment to a month in certain cases uncertain. This
25 uncertainty arises when, after the calendar correction has been executed, the weekly dated
26 expenditures (being a list of expenditures that is dated every Saturday) overlaps two months as in
27 these cases one cannot be certain in which month the recorded flood event actually took place. In
28 these cases we are dependent on likelihood estimations which we apply as explained by the
29 following example: If the calendar corrected date was Saturday 29th July, it is somewhat more likely
30 that the recorded flood took place in August than in July because there are 3 possible days of the
31 flood event in July (29th to 31st July) compared to 4 probable days in August (1st to 4th August). In this
32 special case the flood would thus be assigned to August. In other words the recorded flood events
33 will always be assigned to the month which has mathematically more potential for a flood event
34 (simply by having more possible days when the flood event could have taken place). Incorrect month
35 assignment cannot be excluded with this approach but on the long run these errors should abrogate
36 each other. Municipal accounts that are dated only on a half year level do not have this dating
37 accuracy problem as there are no overlaps between the two half year periods if the two periods
38 begin, as they usually do, on 1st January (1st half year period) and on 1st July (2nd half year period).
39 Some half year dated municipal accounts might start – according to another-, more to agricultural
40 interests related manor of dating – the first period on 1st March (1st period = 1st march to 31st August)
41 whereas the second period starts on 1st September but ends on 28 or 29th (leap years) February in
42 the next year. If there is no additional singular dating of records in the second period it is impossible
43 to disentangle whether the recorded floods from the second period did appear still in the "old" or
44 already in the "new" year. For future analysis I therefore strongly recommend to focus
45 predominantly on weekly led- and in second priority on half yearly led municipal accounts, where
46 both periods are in the same year.
47
48 **3.2.4.   Reconstruction of pre instrumental drought events**
49
50 Historical documentary sources including information about drought events are quite rare compared
51 to the numerous sources that provide information about flood events. This is explained by the fact
52 that meteorological droughts, being defined as a lack of precipitation over a large area and for an

1   extensive period of time (e.g.; Sheffield et al., 2012), do not occur as frequently in Central Europe as
2   flood events, which compared to droughts may be very local, are often spectacular and may cause in
3   a short time huge losses and destructions all of which is predestined to attract the attention of
4   contemporary chroniclers or journalists. Meteorological droughts on the other hand develop slowly,
5   are for a long time completely unspectacular and therefore in that phase generally not recognised by
6   most of the contemporaries. Only when the meteorological droughts gave rise to agricultural
7   droughts [being defined as insufficient soil moisture to support crops (Seneviratne et al., 2012)]
8   and/or socio-economic droughts [being defined as all sort of direct and indirect impacts on humans
9   and society (e.g. Heim, 2002)], chroniclers usually began to report; mainly about negative societal
10   and economic impacts, as the resilience of these pre-industrialized-, mainly agricultural- and often
11   rather regional-trade based societies probably were quite a bit weaker towards these, for Central
12   Europe, rather unusual hydrological extreme events, than towards much more routinely occurring
13   flood events. In case of severe drought events, like e.g. during the perennial heat and drought of
14   1540, many chroniclers were trying to describe the droughts severity as accurate as possible, by
15   objectivising their descriptions with observations about the impacts on the physical- and biological
16   environment. The contemporaries described very low water levels of waterbodies often in such a
17   way that they can be reconstructed. They furthermore made references to extreme soil desiccation
18   by describing the wideness and deepness of soil cracking or described the leaf fall of vines and trees
19   to objectivise the severity of the heat and dryness. Observations about unprecedented early vine
20   harvest allow to assess the magnitude of the mean spring-summer temperature anomaly, which in
21   the case of 1540 was assessed to have amounted to around + 6° Celsius (between 4.7 and 6.8 ° C)
22   compared to the 20th century mean (Wetter and Pfister, 2013). Several independent chroniclers were
23   reporting about the number of days with precipitation in 1540 which allows to assess the
24   precipitation amount on a seasonal and annual level as the number of days with precipitation (NDP)
25   and the seasonal- and annual precipitation amount (PA) are highly correlated. Reconstruction of low
26   water levels and the assessment of discharges do principally work very similar to flood
27   reconstructions. The principal methodology will be shown in the following example: the chronicler
28   Adelberg Meyer (Basler Chroniken, 1902) described the situation for Rhine River in Basel. He
29   referenced his description to the build environment like the bridge, the cathedral and the
30   confluences of rivers Birs and Rhine. Meyer reported that Wiese river was completely dry whereas
31   Birs- and Rhine river were very small. The right riverbank of the Rhine was dry up to the position of
32   the little chapel which was installed on the fourth pillar of the bridge (Fig. 4; yellow cross). The left
33   river bank was dry from the confluence of Birs- to Rhine river (more than 2 km upstream of the
34   bridge) up to the position of the cathedral, being less than 400 m upstream of the bridge. Including
35   the information given from downstream of the bridge the approximate 1540 river channel, where
36   water still was flowing, could be reconstructed as it is illustrated in Figure 4. The line of the reported
37   river channel is hydrologically consistent as the cross profiles from upstream the position of the
38   cathedral suggest a small dry left river side during extremely low water levels because of its steep-,
39   whereas the right river side should be largely dry because of its broad shallow shapes. Rhine River
40   takes a strong bend to the right after the position of the cathedral, which is why the water carved out
41   the profile there very deeply and explains why in this part the water was still flowing during the peak
42   of the 1540 low water level.

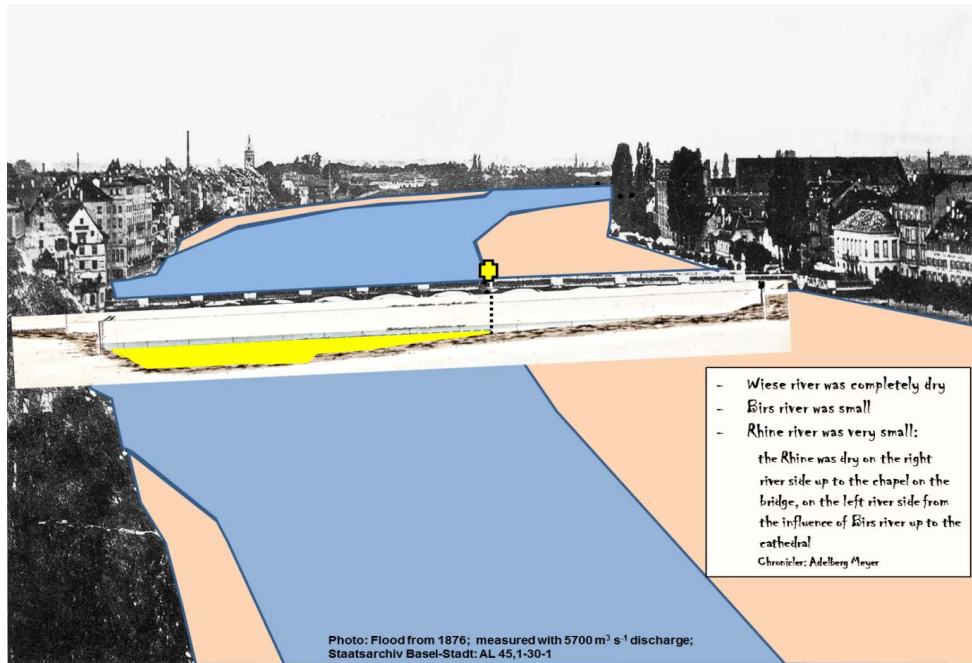



Figure 4:   **Reconstructed Rhine river channel during the peak of the perennial drought in 1540**

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 quite strait forward 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.

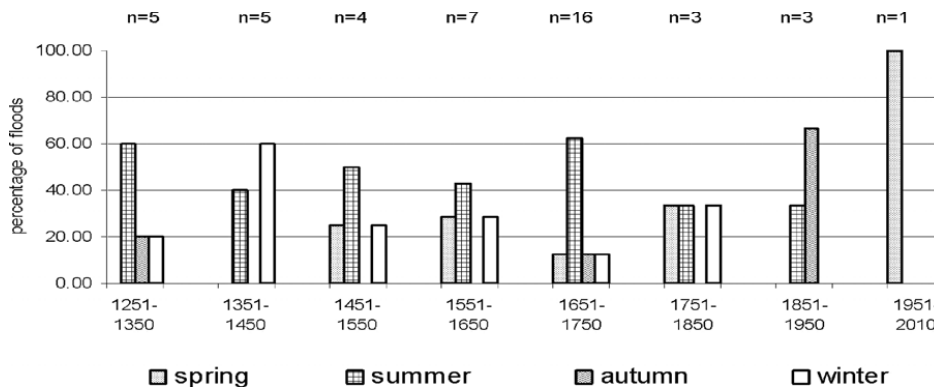
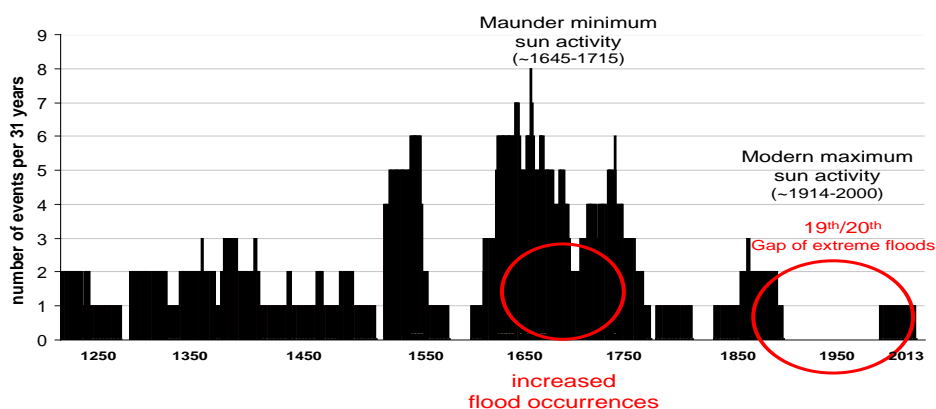



Figure 5:   **Seasonality of Rhine river flood events for the period 1250 – 2010 in Basel ≥ 5000 m^3 s^{-1}**
             (Wetter et al., 2011)

1 The definition of the seasonality resolution and sub periodisation is completely up to the analyser's
2 discretion. It can be realised as shown in the figure above including the 5000 m^3 s^{-1} threshold or e.g.
3 in a more binary approach that only distinguishes between flood and no flood or drought and no
4 drought (-evidence). Figure 6 visualises long term changes of Rhine River flood occurrences above a
5 discharge threshold of ≥ 4300 m^3 s^{-1} in Basel, showing an increase in the second half of the 17th
6 century and a significant gap of extreme events at the end of the 19th and almost during the whole
7 20th century.

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

12 Flood frequency changes like this, whatever the reason might be, do have significant consequences
13 on the assessment of recurring periods of extreme events. Figure 7 demonstrates the impact of the
14 inclusion of reconstructed flood events from the pre instrumental period on the result of flood
15 frequency analysis. First of all the inclusion of the reconstructed pre instrumental period flood events
16 significantly expands the reliable extrapolation range from a two hundred year- (based on the
17 instrumental period only) to a five hundred year flood event. Secondly, the discharge magnitudes e.g.
18 of two hundred year flood events significantly increase from less than 5000 m^3 s^{-1} to more than 6000
19 m^3 s^{-1}. It has to be stated that the discharge values have been included in the frequency analysis as
20 they were observed and reconstructed, which means that no adjustments of pre- and past river
21 regulated conditions have been established which very likely distorted the results of the increased
22 flood discharge magnitudes significantly. This point will be discussed later in detail in chapter 4.3.

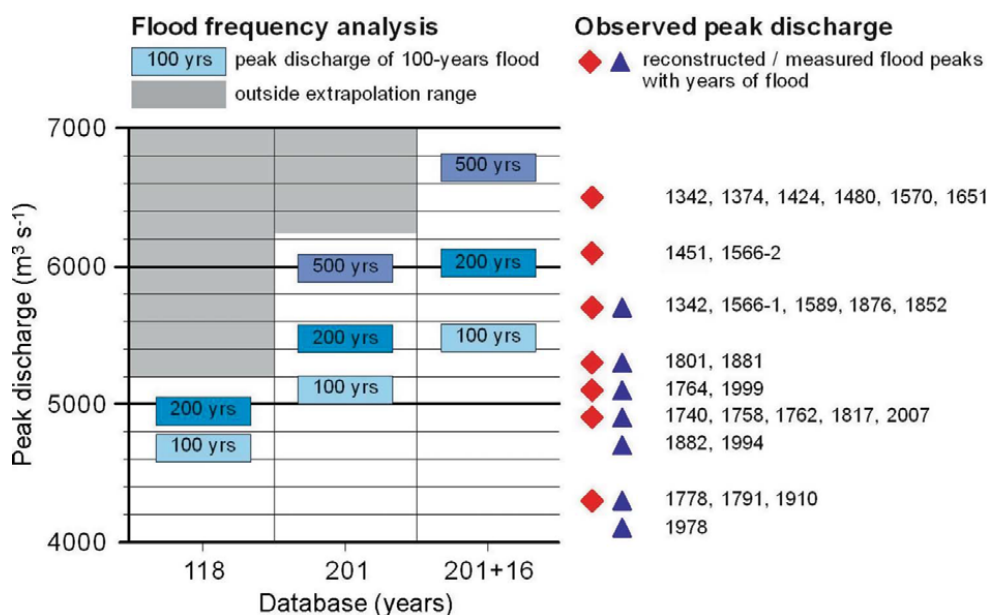
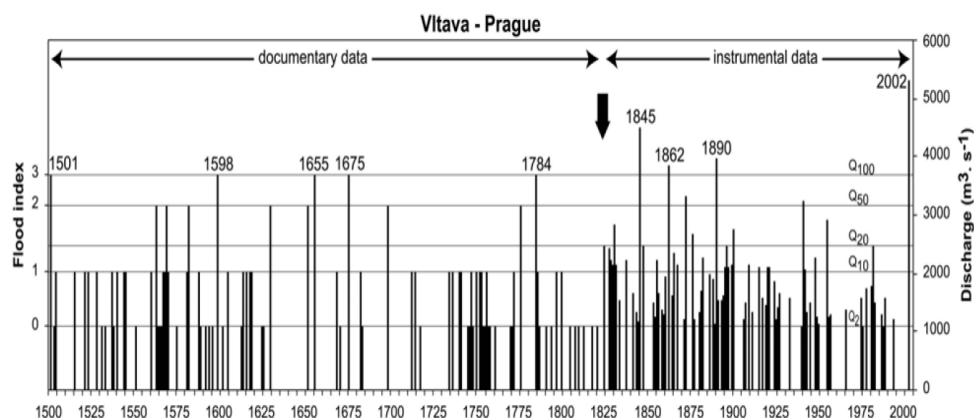
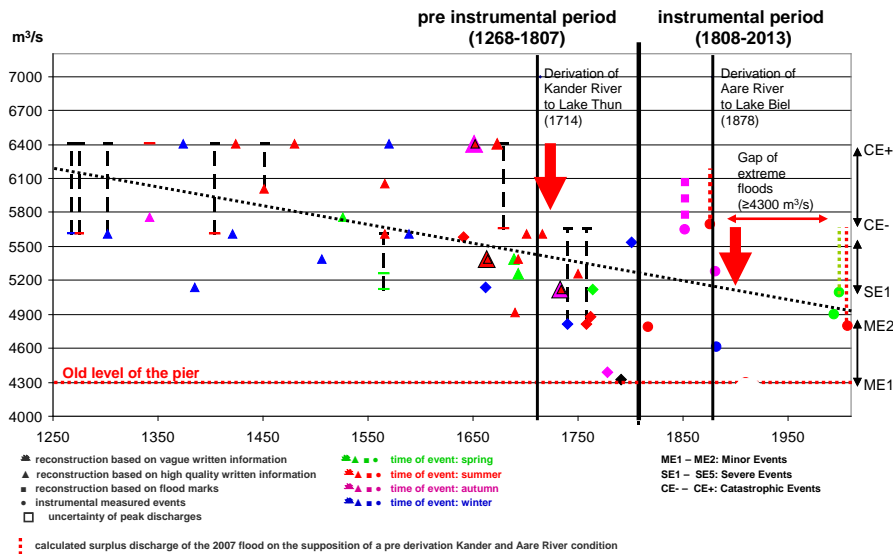



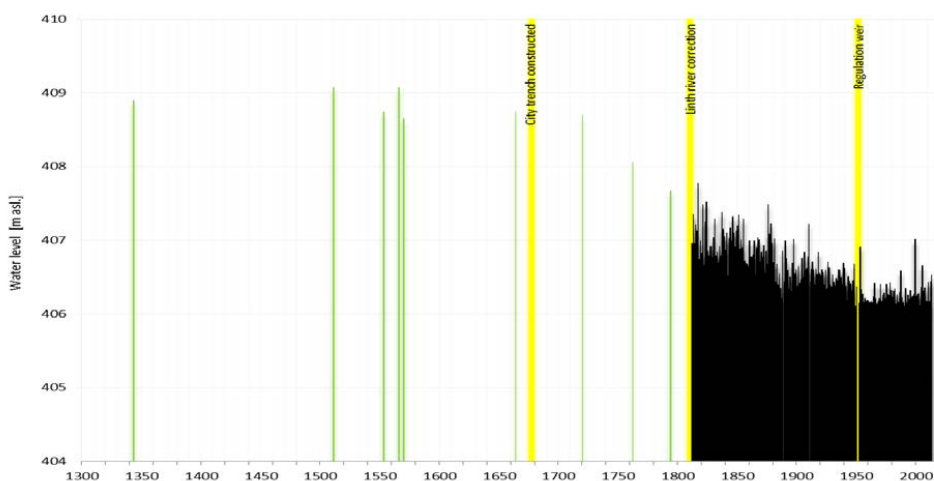
Figure 7: **Flood frequency analysis based on the official reference period (1891 – 2008), the full instrumental period (1808 – 2008) and the full instrumental period plus 16 reconstructed pre instrumental flood discharges for Rhine River in Basel**

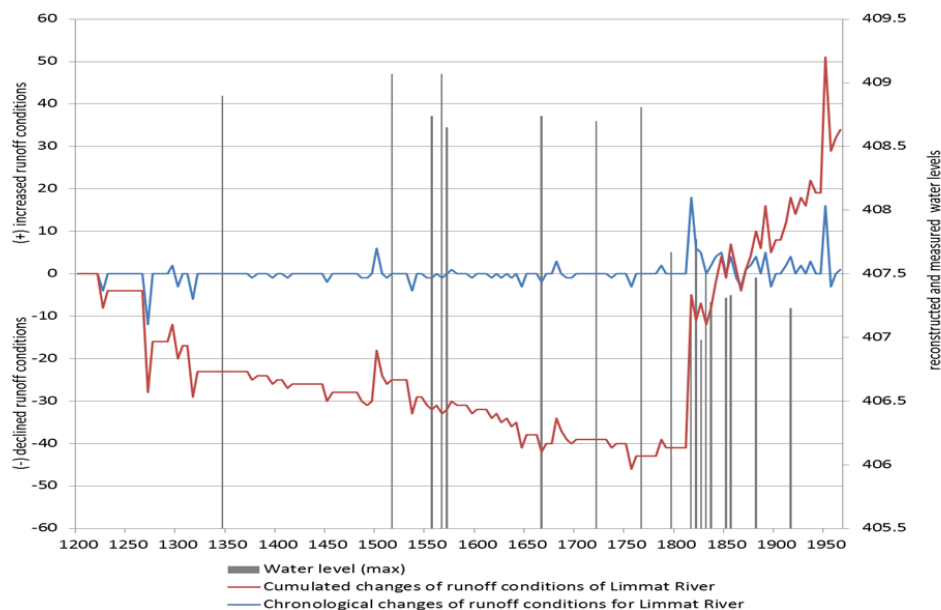
4.2. Index based magnitude reconstruction of extreme pre instrumental hydrological events

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 worth to step in this direction after the water level- and discharge reconstructions of major Swiss rivers will be completed, so that comparatively much more flood evidence may be included in long term hydrological analysis. Figure 8 shows an example of a 4 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.

2
3 **Figure 8:**   **Index based flood magnitude reconstruction for Vltava River in Prague (Brázdil et al., 2006)**
4
5 A similar kind of approach should be applicable for Switzerland as well. The goal will be to combine
6 indexed flood events, reconstructed flood levels and discharges as well as indirect flood data from
7 municipal accounts with observed flood events from the instrumental period. It is not possible to
8 reconstruct flood levels or discharges based on indirect flood data from municipal accounts but it is
9 indeed possible to assess a minimum discharge threshold by comparing the number of the municipal
10 account flood records with the instrumental observation series and calculate the ratio (on the
11 assumption that the flood frequency is comparable between the two series) from which the
12 minimum discharge or water level can finally be deduced from the instrumental series. This
13 minimum discharge seems to have been the threshold for the person in charge (i.e. the bridge-
14 master or gatekeeper) to take precautionary measures to protect the corresponding infrastructure
15 against possible flood damages which finally found its entry into the municipal accounts in form of
16 records about paid wages for the executive staff.
17
18
19 **4.3.**   **Water level or discharge based reconstruction of extreme pre instrumental hydrological**
20   **events**
21
22 Figure 9 visualises the results of the discharge reconstructions of Rhine River flood events in Basel
23 showing a significant trend of decreasing flood magnitudes since the beginning of the 18th century. A
24 more sophisticated analysis reveals that this "trend" is in truth a two-step decrease which was
25 caused by two major anthropogenic river engineering interventions in the large-scale catchment area
26 which significantly changed the discharge budget, especially in case of extreme flood events. The
27 timing of the redirections of river Kander to Lake Thun in 1714 (Vischer, 2003) and of river Aare to
28 Lake Biel in 1878 (Przegon, 1999) clearly correlates with the decreased flood magnitudes of River
29 Rhine in Basel. The additional retention capacities of the two lakes significantly decelerates the flood
30 waves which before the redirections just rushed through river Kander and Aare and finally reached
31 river Rhine in Basel without being significantly decreased before.

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

4 The two-step flood magnitude decrease for River Rhine at Basel is confirmed by other flood
5 reconstructions at other sites at Aare and Rhine River downstream of the two redirections, whereas
6 no long term change of flood magnitudes can be detected at Rhine River above the confluence with
7 Aare River. This result is plausible as Lake Constance as well as the corresponding section of the
8 Rhine River was never subject of river engineering measures that could have significantly influenced
9 the runoff characteristics. The difference of flood magnitudes at the different flood reconstruction
10 sites along the Aare and Rhine, on the other hand, are very well comparable with each other, which
11 should thus allow to assess the long term mean retention capacities of the two lakes (Lake Thun and
12 Biel) which finally will provide the opportunity to homogenise the pre redirection flood events to the
13 actual runoff regime (paper in progress). The influence of anthropogenic river engineering measures
14 on runoff conditions and flood water levels is very obvious for Lake Zürich and Limmat River as well.
15 Three steps of decreased flood water levels could be detected. The first step occurs after the works
16 at the city trench (Schanzengraben) were finished in 1677 which created, apart from Limmat River,
17 an additional run-off for Lake Zürich. The second step occurred after Linth River was redirected to
18 Lake Walen in 1816 which significantly decreased flood level magnitudes in Zürich. The last step
19 occurred in the early 1950's when the weir for power and regulation purposes was constructed. Note
20 that Figure 10, unlike Figure 9, demonstrates flood levels, as flood discharge calculations have not
21 been realised yet.

2
3   **Figure 10:**   **Three step decrease of flood magnitudes for Lake Zürich and River Limmat in Zürich (Näf et**
4   **al., 2016 and Wetter and Specker, 2015a)**

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

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

14   The numerous anthropogenic interventions, influencing the runoff conditions were quantified in a
15   semi-quantitative approach. The quantification bases on a twelve index levelled scale where - 6
16   stands for a very strong-, - 1 for a very weak declined runoff, whereas + 6 stands for a very strong-
17   and + 1 for a very weak increased runoff in Zürich. Figure 11 shows numerous anthropogenic

1 interventions causing each only very weak declined- (Fig. 11, blue graph) runoff conditions but taken
2 together (Fig. 11, red graph) declined the runoff conditions in the period from the 14th to the early
3 19th century significantly. The most significant increase of runoff conditions was realised in the
4 context of the Linth River correction in the early 19th century, when the main tributary of Limmat
5 River was redirected to Lake Walen and most river damming installations were withdrawn from
6 Limmat with the goal to increase the runoff in Zürich.

9 **Figure 12:** **Long term stationarity of Lake Lucerne and Reuss River extreme flood water levels (Wetter**
10 **et al., 2015b) or slow trend of decreasing flood magnitudes (?)**
11 **Green bars: reconstructed flood levels above sea level (asl.)**
12 **Black bars: measured flood levels asl.**
13 **Yellow bar: significant anthropogenic intervention in the discharge conditions**
14
15 Figure 12 demonstrates the flood level development of extreme events in Lucerne for Lake Lucerne
16 and Reuss River showing a weak trend towards slightly smaller flood levels of extreme Lake Lucerne
17 and Reuss River flood events if the extreme flood event from 1817 is excluded from the analysis.
18 1817 is by far the most extreme event in the last seven centuries which is also true for Lake
19 Constance. This correlation of the two most important Lakes right on the edge of the Swiss Alps is
20 not coincidental and is directly linked to the so called year without a summer from 1816 (e.g.
21 Luterbacher & Pfister, 2015). A significant cooling and change of precipitation patterns occurred in
22 1816 Europe mainly due to the large amounts of SO_2 emissions to the atmosphere caused by the
23 massive eruption of the Tambora volcano in the tropics. Precipitation (especially but not exclusively
24 in the Alpine region) fell as snow, sometimes even in summer and the stored snow masses from
25 winter 1815/1816 did not melt in the Alps due to the overall cool temperatures. The second layer of
26 snow, in chronological order, was added throughout the year 1816, due to snow- instead of rainfalls
27 in the Alpine region. The first two layers then were again superimposed by the 1816/1817 winter
28 snow precipitation. In spring and summer 1817 massive amounts of melting water accommodated in
29 Lake Lucerne and Constance due to three- instead of only one melting snow layer. The runoff
30 conditions of River Reuss in Lucerne did only marginally increase during the last seven centuries
31 which might explain the somewhat smaller flood levels since the construction of the Lake Lucerne
32 regulation weir in 1861, again not taking into account the 1817 event (Fig. 13).

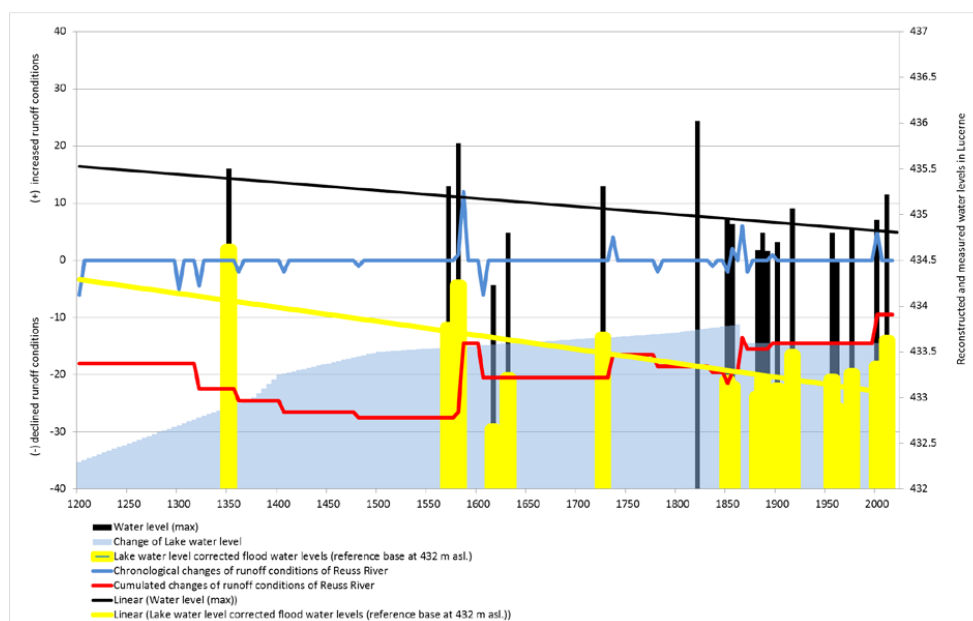



Figure 13: Significant increase of normal Lake Lucerne water level versus slight increase of Reuss river runoff conditions over the last seven centuries.

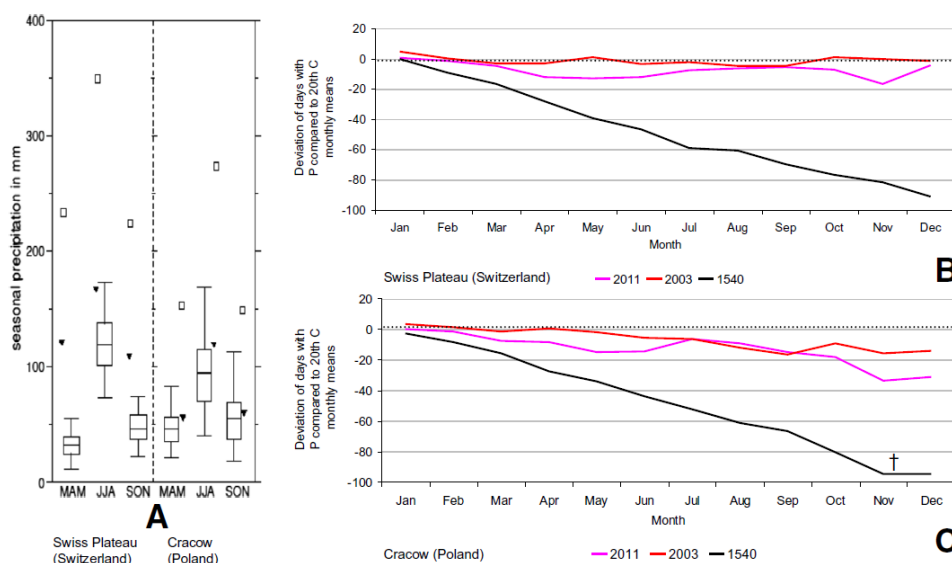
The decrease of flood magnitudes gets a bit more obvious if the dammed water level of Lake Lucerne is taken into account. According to Küng (2006) the norm water level of Lake Lucerne was intentionally dammed by a medieval weir to provide enough water to run the mills in the Reuss River. Since then this weir was gradually heightened to stand the pace of the increasing amount of water mills in the following centuries. Due to the constantly increased norm lake water level, later flood water levels did not need the same amount of water to reach the same water level as earlier flood events. In terms of figures this difference of the norm lake water levels can be corrected from the flood level which results in a more obvious decrease of flood magnitudes which 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 Reuss River in the nineteenth as well as due to the 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

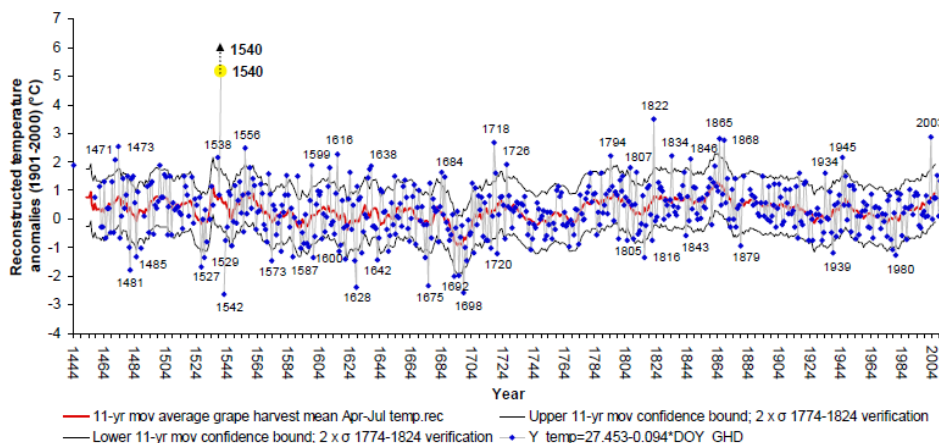
Climate parameters like Temperature and precipitation belong to the main drivers of extreme hydrological events (i.e. drought- and flood events). Chroniclers, reporting about these extreme events, mainly focus on the description of (material) losses, negative impacts on the economy and society and in 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 described comparably rare. If the events are extraordinarily extreme, science-oriented explanations are 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, being most probably the most extreme flood of Aare River in the last seven centuries (Pfister &

1   Wetter, 2011b) in the following, science-oriented manor: Three days and nights of uninterrupted
2   heavy rainfalls heralded the start of this extraordinary extreme flood event taking place on 1st August
3   1480. Schilling additionally provided important information about the "pre disposition" by stating
4   that there was a distinct warm phase in the forefront of the extreme precipitation event which
5   rapidly melted the glaciers and stored snow in the Alps. From other sources it is known that spring
6   and early summer were exceedingly wet and in the Alps rich in snow. By combining the information
7   we have enough contemporary and reliable evidence to conclude the trigger of the 1480 flood event.
8   In case of opposite hydrological extreme events, like e.g. the severe heat and drought in 1540,
9   chroniclers not only provided useful information on low water levels but also began to numerate the
10 very few days with precipitation in that year. Figure 14 presents the reconstructed number of days
11 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	rain								N/A												
26		snow											N/A											rain	
27	snow			rain			rain						N/A											rain	
28		rain		rain			rain						N/A											rain	
29		rain	rain				rain						N/A											rain	
30			rain										N/A												
31													N/A												

14 **Figure 14:**   **Number of days with precipitation (NPD) in Cracow (left) and Switzerland (right) derived**
15   **from the weather diary of Marcel Biem (left) and from chroniclers situated in Switzerland**
16   **and nearby Alsace and southern Germany (Wetter et al., 2014; supplementary material)**
17
18 The reconstructed NPD for Cracow and Switzerland are considerably lower than that of the 20th
19 century average and even below the successive absolute minima of spring, summer and autumn of
20 the instrumental period since 1864. Figure 15 demonstrates the cumulated deviation of NPD
21 compared to the 20th century mean (Fig. 15; B; dotted line = 20th century mean versus black line NPD
22 of 1540) which amounted to 81 % less days with precipitation in Switzerland. The precipitation
23 amount (PA) was calculated according to the methodology, developed and discussed in Wetter et al.
24 (2014) which, simplistically expressed, bases on the close correlation between NPD and PA (Fig. 15;
25 A). The calculated 1540 PA for Switzerland was significantly below the 100-year minimum levels
26 throughout spring (MAM), summer (JJA) and autumn (SON). No similar event is documented, where
27 all three seasons successively underbid the 100-year PA minima as well as the absolute minima of
28 NPD within the instrumental period in Switzerland. This finally caused the record breaking low water
29 level of Rhine River in Basel and other sites in Switzerland and Europe.

2 **Figure 15:**   Reconstructed seasonal precipitation amounts for spring, summer and autumn and
3   cumulative deviations of 1540 NPD compared to the 20th-century mean, 2011 and 2003 .a:
4   Median, upper and lower quartiles (boxes), 95 % uncertainties (whiskers) as well as 50 and
5   100 year minimum levels (box and triangle) of 20th century data for Swiss Plateau (northern
6   Switzerland) average (left) and Cracow(right), b: compares cumulative deviations of
7   NPD in Northern Switzerland in 2011, 2003 and 1540. NPD for 2003 and 2011 are taken from
8   Federal Office of Meteorology and Climatology, MeteoSwiss (NPD were averaged over
9   stations of Basel, Luzern, Schaffhausen and Zürich). Dotted line=20th-century mean of days
10   with Precipitation≥1 mm, c: compares cumulative deviations of NPD in Cracow, Poland in
11   2011, 2003 and 1540. NPD for 2003 and 2011 are taken from the Center for Poland's Climate
12   Monitoring. Dotted line=20th-century mean of days with Precipitation≥1 mm; † date of
13   death of Marcin Biem: 19th Nov 1540 (Wetter et al., 2014)

15 The extreme dryness throughout 1540 led to an – for Central Europe – extraordinary soil-moisture-
16 and evapotranspiration deficit which was prescribed by numerous chroniclers by referencing on
17 extreme soil cracking, the fail of wells, the fruitless digging for groundwater in dried out river beds
18 and leaf fall of trees and vines due to heat stress. In temperate climates, a considerable part of
19 incoming shortwave radiation is generally used for evapotranspiration (i.e. humidification of water
20 from vegetation, soils and water surface sources) which is called the latent heat flux. The remaining
21 sensible heat flux ultimately impacts air temperature. In case of a strong soil-moisture deficit the
22 share of sensible heat increases as the latent heat flux gets weaker due to decreasing moisture
23 sources which consequently leads to increasing air temperatures. Increased air temperature on the
24 other hand leads to a higher evaporative demand and thus to a potential increase in
25 evapotranspiration, leading to a further decrease in soil moisture until the total drying of the soil
26 when temperature increases cannot be dampened by further increases in evapotranspiration
27 anymore (Seneviratne et al., 2010). In these cases skyrocketing air temperatures result. Spring-
28 summer temperatures were assessed by calibrating grape harvest dates (GHD) with the monthly
29 anomalies from 1901 to 2000 mean of HISTALP temperature series which resulted in a linear
30 regression equation where GHD served as temperature proxies (Wetter & Pfister, 2013). GHD for
31 1540 is not available which is why it had to be deduced from full maturity of grapes and the temporal
32 difference between veraison and the usual begin of grape harvest. Based on the veraison date and
33 the full ripeness of the grape (both is known for 1540) GHD was assessed between 12th and 25th
34 August, marking the margins of fluctuation within full grape maturity, when under normal

1 circumstances grape harvest would have occurred (Wetter & Pfister, 2013). The so assessed
2 temperature anomaly for May-July temperatures amounted to + 4.7 °C and + 6.8 °C compared to the
3 20th century mean (Fig. 16).

5 **Figure 16:**   **Temperature anomalies compared to the 20th century based on grape harvest dates linear**
6   **regression calculations (Wetter & Pfister, 2013)**
7
8 In case no (agro-) phenological data (like GHD or grain harvest dates) is available it is still possible to
9 use weather descriptions which may refer to considerable phenological anomalies (like e.g.
10 blossoming of trees in winter), reference to the cryosphere (like e.g. the description of freezing over
11 of Lakes and rivers) or provide general descriptions about temperature and precipitation (e.g.
12 remarks about mild winter temperature or wet summer conditions) to assess the weather related
13 contexts of pre instrumental flood or drought events. Pfister (1999) developed a 7 step index (-3/-2/-
14 1/0/+1/+2/+3) to quantify such qualitative narrative information and was able to reconstruct a
15 monthly resolved temperature and precipitation series for the period 1496-1995. The following
16 chapter will demonstrate the very high potential of municipal accounts to significantly improve the
17 already existing precipitation reconstruction in Switzerland (Pfister, 1999).
18
19
20 **4.5. Reconstruction of long term seasonality of minor pre instrumental flood events based on**
21 **institutional sources**
22
23 The books of weekly expenditures of the city of Basel include, as mentioned earlier, records about
24 wage payments for craftsmen and guards who were engaged to protect the Rhine bridge and the
25 inlet fence of Birsig river at the city gates from possible destruction due to floating debris. Recently
26 the period from 1600 to 1650 was completely analysed (Spycher, 2017). All in all 70 Rhine- and 218
27 Birsig river flood events could be detected whereas chroniclers in the same period only reported on 3
28 Rhine- and 5 Birsig floods. This ratio of 23:1 for Rhine- and 44:1 for Birsig floods clearly demonstrates
29 the significantly sharper "observation skills" of the city accounts towards minor and much more
30 frequent flood events (flood return period ≤ 1 year). The quality and reliability of these historic
31 records was checked by comparing whether the monthly-, seasonal and half yearly distribution of the
32 historic flood events resemble the distribution during the instrumental period. As the historic records
33 in the municipal accounts do not provide information about the minimum discharge amount that
34 was needed to cause preventive protection measures, which would define the "flood" events in the
35 instrumental period, the flood definition was specified as follows: Under the assumption that both
36 series (historic and instrumental) were comparable, a simple ratio of the length of the historic series
37 to the length of the instrumental Rhine and Birsig series was calculated. This ratio defined the

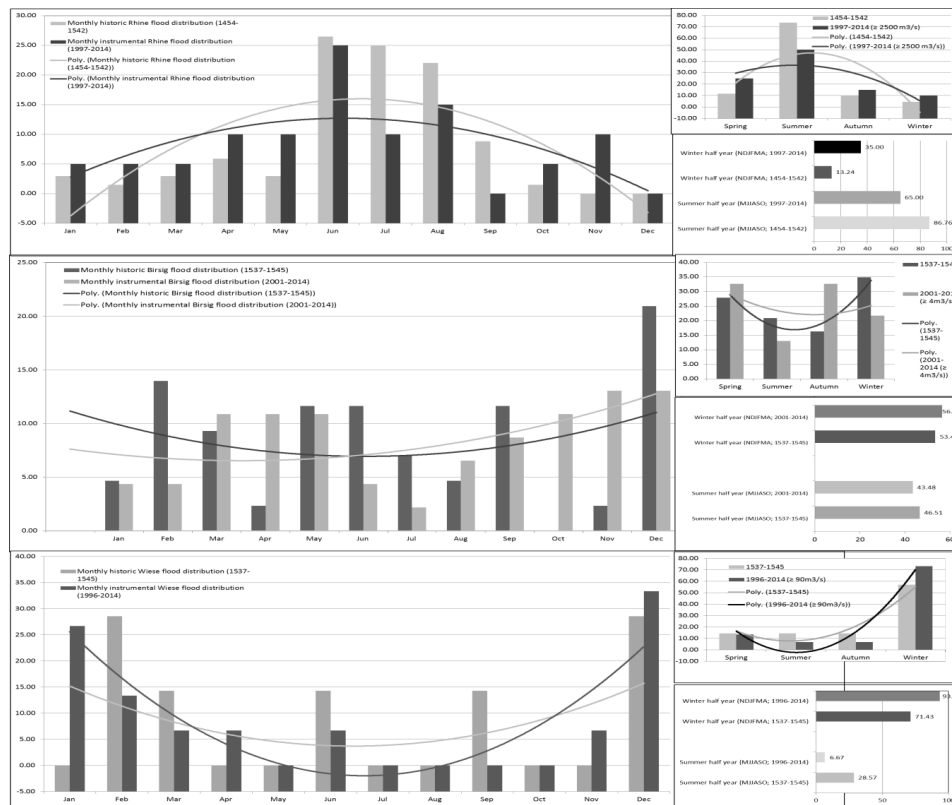
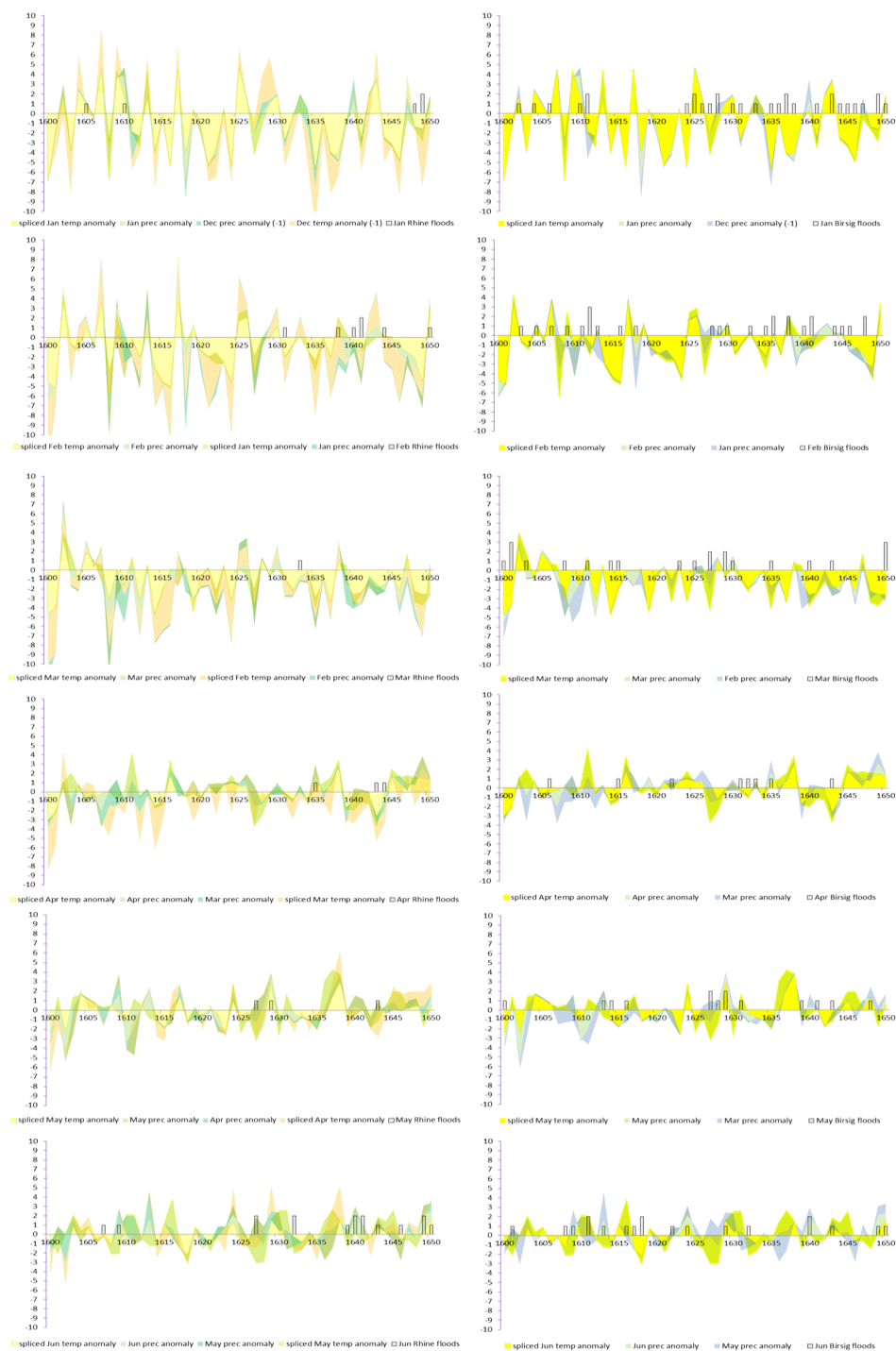
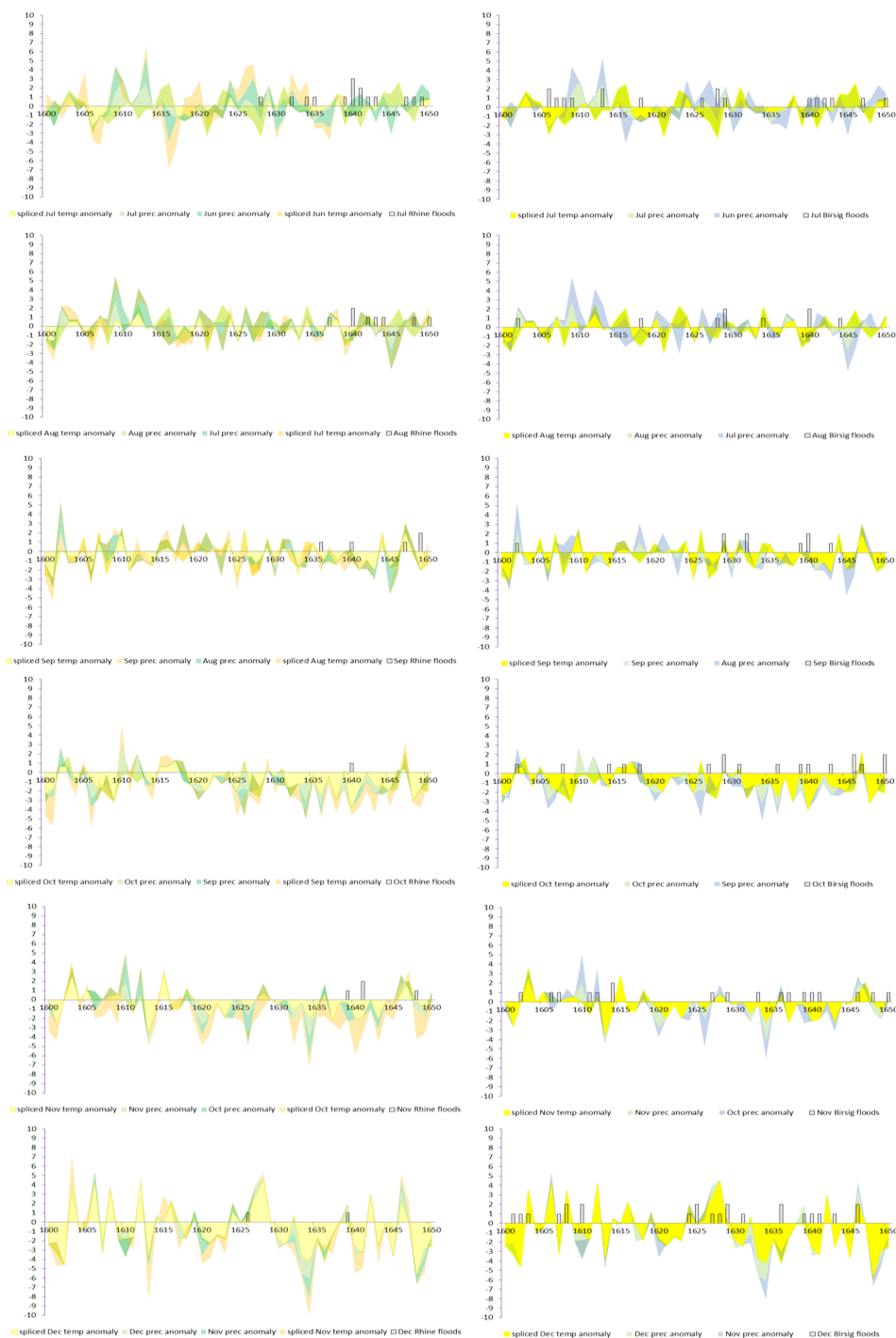
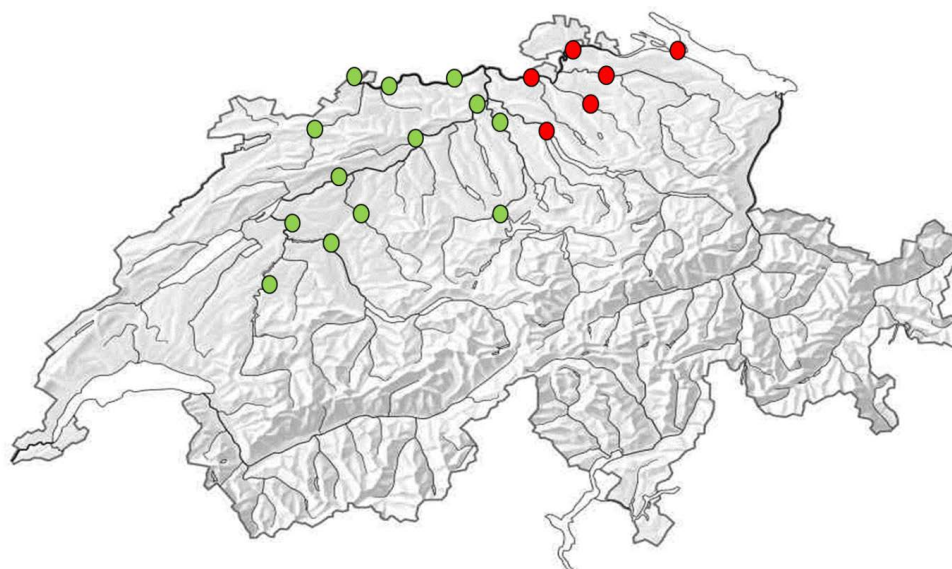
1 number of events that had to be considered in the instrumental period which in the same time also
2 defined the minimum discharge that probably was needed to cause preventive protection measures
3 in historic times. Figure 17 shows overall good visible correlations of the monthly and seasonal
4 distribution of flood events between the historic and the instrumental Rhine-, Birsig and Wiese flood
5 events. We thus are in good spirits that the indirect flood information from the municipal accounts is
6 a valid flood proxy. A closer look to the fully analysed 50 year period from 1600 – 1650, reveals that
7 our assumption about the good quality and reliability of this flood proxy seems to have been correct.
8 Figure 18 demonstrates the monthly distribution of Rhine and brook Birsig flood events in the
9 historic and the instrumental period. The overall correlation amounted to 0.81 for river Rhine and
10 0.47 for brook Birsig (pearson).

13 **Figure 17:**   **Distribution of historical and instrumental Rhine, Birsig and Wiese flood events in**
14   **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
brook Birsig is rather short and the measurement station is several kilometres upstream of the
historic flood information (above the inflow of some tributaries). It has to be further analysed, once
all flood proxies from the weekly books of expenditures will have been extracted (1401-1799),
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 points to pure flood proxies (see Fig. 17 and 18). Figures 19 and 20 demonstrate that several
Rhine River and brook Birsig 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 further astonishing as
currently available precipitation reconstructions are predominantly based on direct description 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 usually is significantly 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.

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

2   **Figure 20:**   **Monthly spliced temperature (Dobrovolný et al. 2009) and precipitation (Pfister, 1999)**
3   **reconstructions combined with Rhine- and Birsig river flood proxies from the weekly led**
4   **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, mainly because of interrelated positive circumstances like 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 data 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 the 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). It furthermore 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 every other Swiss town. These records usually start in the 14th, the 15th or the 16th 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. 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.

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

5 If, for example, the municipal accounts from Fribourg, Bern, Aarberg, Delémont, Solothurn, Burgdorf,
6 Olten, Lucerne, Laufenburg, Rheinfelden and Basel contained flood records (green dots in Fig. 21)
7 whereas accounts from eastern Switzerland (red dots in Fig. 21) remained silent, the conclusion
8 could be safely drawn that this specific flood event was primarily triggered by the catchments of Aare
9 River and its tributaries (namely by the rivers Saane-, Emme, Birs and Reuss), whereas the catchment
10 of the High Rhine, upstream of the influence of Aare, did not play a major role. The meteorological
11 trigger of this hypothetical flood event, according to the distribution of the contributing and non-
12 contributing rivers, therefore quite clearly points to a western based origin of the flood wave. The
13 books of weekly expenditures do also contain records about hay- and after-grass harvests. Spycher
14 (2017) compared these harvest dates with monthly resolved precipitation- and temperature
15 anomalies (Pfister, 1998) and found significant correlations between early and late onsets of hay-
16 and after-grass harvest dates and the preceding months with dry or moist weather anomalies. These
17 hay- and after-grass harvest data series are thus of great value for further historical climatological
18 analysis. They improve and (chronologically) expand the already existing temperature- and
19 precipitation series back in time and furthermore may help to shed light on weather conditions in
20 advance and during pre-instrumental flood events. It seems, as indicated in the abstract, that non-
21 scientific peer group interest in historical hydrological analysis, especially from responsible public
22 ministries- and local offices side, significantly increased in the last very few years in Switzerland. If
23 this interest is going to last this would initialise a huge potential for further historical hydrological
24 analysis partly in cooperation with private engineer companies and would help to significantly
25 improve flood risk analysis from which the public sector would certainly benefit as well. Further
26 historical hydrological research, especially based on municipal accounting records, is needed and
27 required as it promises highly valuable results of so far not yet reached quality.

29
30 *Acknowledgements.* I would like to thank Fiona Spycher, Dr. Beat von Scarpatetti and Daniel Tuttenuj
31 for transcribing the Books of weekly expenditures of the city of Basel. Thanks furthermore go to the
32 Swiss National Science Foundation (SNSF) for support. This paper is related to the SNSF project
33 153327 "Reconstruction of the genesis, process and impact of major pre-instrumental flood events of
34 major Swiss rivers including a peak discharge quantification".

1 References

Arnold, K.: Der wissenschaftliche Umgang mit Quellen, in: Hans-Jürgen Goertz (ed.): Geschichte. Ein Grundkurs, 2. Auflage, Hamburg, 42 – 58, 2001.

Basler Chroniken: Die Aufzeichnungen des Adelberg Meyers 374 – 1542, 6. Band, 1902.

Boerlin-Brodbeck, Y.: Büchel, Emanuel; SIKART Lexikon zur Kunst in der Schweiz; http://www.sikart.ch/KuenstlerInnen.aspx?id=4024279, 2006.

Brázdil, R., Pfister, C., Wanner, H., von Storch, H., Luterbacher, J.: Historical Climatology in Europe – State of the Art. Climatic Change, 70: 363–430, 2005.

Brázdil, R., Kundzewicz, Z.W. & Benito, G.: Historical hydrology for studying flood risk in Europe. Hydrological Sciences Journal, 51:5, 739-764, 2006.

Christian, S.: Die Helvetik als Revolution in Staat, Wirtschaft und Gesellschaft. In: Hans Werner Tobler (ed.), 1798/1998. Die Helvetik und ihre Folgen. Zürich, 49–72, 1998.

D'Aujourd'hui, R.; Lavicka, P.: Zusammenfassende Bemerkungen zu den Sondierungen in der mittelalterlichen Talstadt. In: Basler Zeitschrift für Geschichte und Altertumskunde, Band 82, Basel, 1982.

Dobrovolný, P, Moberg, A., Brázdil, R., Pfister, C., Glaser, R., Wilson, R., van Engelen, A., Limanówka, D., Kiss, A., Halíčkova, M., Macková, J., Riemann, D., Luterbacher, J., Böhm, R.: Monthly, seasonal and annual temperature reconstructions for Central Europe derived from documentary evidence and instrumental records since AD 1500, Climatic Change, 101:69, issue 1-2, 69-107, 2009.

Fouquet, G.: Der Zimmerer- und Brückenwerkmeister, in: Bauen für die Stadt. Finanzen, Organisation und Arbeit in kommunalen Baubetrieben des Spätmittelalters. Eine vergleichende Studie vornehmlich zwischen den Städten Basel und Marburg (Städteforschung: Reihe A, Darstellungen; Bd. 48). Köln, Weimar, Wien: Böhlau, 210-225, 1999.

Glaser, R., Riemann, D., Schönbein, J., Barriendos, M., Brázdil, R., Bertolin, C., Camuffo, D., Deutsch, M., Dobrovolný, P., van Engelen, A., Enzi, S., Halícková, M., König, S. J., Kotyza, O., Limanowka, D., Macková, J., Sghedoni, M., Martin, B. & Himmelsbach, I.: The variability of European floods since AD 1500. Climatic Change 101, 235-256, 2010.

Hirzel, S.: Anonyme Zusätze und Fortsetzungen zu Königshofen, nach der Abschrift Erhards von Appenwiler 1120-1454. In: Basler Chroniken (ed. by Historischen und Antiquarischen Gesellschaft in Basel). Band 4. Leipzig, 522 pp., 1890.

Hirzel, S.: Die Aufzeichnungen des Kaplans Hieronymus Brilinger. 1474-1525. In: Basler Chroniken (ed. by Historischen und Antiquarischen Gesellschaft in Basel). Band 7. Leipzig, 528 pp., 1915.

Heim, RR (2002) A review of twentieth-century drought indices used in the United States. Bull Am Meteorol Soc 83(8),1149–1165, 2002.

Küng, F.: Luzern. Bauen am Fluss. Archäologische Untersuchungen an der Kronengasse 6 – 10. Archäologische Schriften Luzern, 5-69, 2006.

Lanz-Stauffer, H. Rommel, C.: Rückversicherungsverband kantonal-schweizerischer feuerversicherungsanstalt, Bern, 1936.

Lehmann, C. S.: Spätmittelalterlicher Nationalismus: die Burgunderkriege am Oberrhein und in der Eidgenossenschaft. (Veröffentlichungen des Max-Planck-Instituts für Geschichte, 116). Vandenhoeck & Ruprecht, Göttingen, 488 pp., 1995.

Luterbacher, J. & Pfister, C.: The year without a summer. Nature Geoscience 8, 246-248, 2015.

Meyer, W.: Da verfiele Basel überall. Das Basler Erdbeben von 1356. Mit einem geologischen Beitrag von Hans Peter Laubscher. Schwabe, Basel, 230 pp., 2006.

Mudelsee, M., Börngen, M., Tetzlaff, G. & Grünewald, U.: Extreme floods in central Europe over the past 500 years: Role of cyclone pathway "Zugstrasse Vb", Journal of Geophysical Research 109, D23101, doi:10.1029/2004JD005034, 2004.

Näf-Huber, D., Scherrer, S., Wetter, O., Specker, T., Oplatka, M., Eisenhut, N.: Hochwasserschutz Zürich – Seestände und Abfluss. Heute mit dem Schiff ins Zürcher Fraumünster?! Wasser Energie Luft. 108. Jahrgang, Heft 2, Baden, 2016.

Nast, M.: überflutet – überlebt – überlistet. Die Geschichte der Juragewässerkorrektionen. Verein Schlossmuseum Nidau, 192 pp., 2006.

Paravacini, G.: Gestautes Wasser – Regulierter See. Geschichte, Bau und Betrieb der Reusswehranlage in Luzern. Kantonaler Lehrmittelvertrag Luzern, 191 pp., 2013.

Pfister, C.: Raum-zeitliche Rekonstruktion von Witterungsanomalien und Naturkatastrophen 1496-1995. (unter Mitarbeit von Daniel Brändli. Schlussbericht zum Projekt 4031-33198 des NFP 31) Hochschulverlag ETH, Zürich, 1998.

Pfister, C.: Wetternachhersage. 500 Jahre Klimavariationen und Naturkatastrophen (1496–1995).Verlag Paul Haupt, Bern, Stuttgart, Wien, 304 pp., 1999.

Pfister, C., Weingartner, R., Luterbacher, J., Hydrological winter droughts over the last 450 years in the Upper Rhine basin: a methodological approach, Hydrological Science Journal, Special Issue: Historical Hydrology, 51, 5, pp. 966 – 985, 2006.

Pfister, C.: Die Katastrophenlücke des 20. Jahrhunderts und der Verlust traditionalen Risikobewusstseins, in: GAIA Ecological Perspectives for Science and Society, 3, 18, 239-246, 2009a

Pfister, C., Luterbacher, J., Wanner, H., Wheeler, D., Brázdil, R., Ge, Q., Hao, Z., Moberg, A., Grab, S., and Rosario Del, P. M.: Documentary evidence as Climate Proxies. Proxy-specific White Paper produced from the PAGES/CLIVAR workshop, Trieste, 2009b

Pfister, C.: "The Monster Swallows You". Disaster Memory and Risk Culture in Western Europe, 1500-2000, Rachel Carson Center Perspectives 1/2011, 1-23, 2011a.

Pfister, C.; Wetter, O.: Das Jahrtausendhochwasser von 1480 an Aare und Rhein, Berner Zeitschrift für Geschichte, 74, 4, 41-49, 2011b.

Przegon, Wojczech: Jan Pawel Lelewels Generalplan zum Projekt der Trockenlegung der Sumpfgebiete des Seelandes (1834). In: Vermessung Photogrammetrie Kulturtechnik Heft 8, 432–434, 1999.

1   Remark, J.: Bruderzwist, nicht Brudermord. Der Schweizer Sonderbundkrieg von 1847. Orell Füssli, Zürich, 285 pp., 1997.
2   Röthlisberger, G.: Chronik der Unwetterschäden in der Schweiz. Berichte der Eidgenössischen Forschungsanstalt für Wald,
3   Schnee und Landschaft, 330, 123 pp., Birmensdorf, 1991.
4   Schmocker-Fackel, P., Naef, F.: Changes in flood frequencies in Switzerland since 1500. Hydrol. Earth Syst. Sci., 14, 1581-
5   1594, 2010.
6   Seneviratne, S. I., Corti, T., Davin, E. L., Hirschi, M., Jaeger, E. B., Lehner, I., Orlowsky, B., and Teuling, A. J.: Investigating soil
7   moisture-climate interactions in a changing climate: A review, Earth Sci. Rev., 99, 125–161, 2010.
8   Seneviratne SI, Nicholls D, Easterling CM, Goodess S, Kanae J, Kossin Y, Luo J, Marengo K, McInnes M, Rahimi M, Reichstein
9   A, Sorteberg, Vera C, Zhang X.: Changes in climate extremes and their impacts on the natural physical environment, in:
10   Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation [Field CB, V Barros, TF
11   Stocker, D Qin, DJ Dokken, KL Ebi, MDMastrandrea, KJ Mach, GK Plattner, SK Allen, M Tignor and P.M. Midgley (eds.)]. A
12   Special Report ofWorking Groups I and II of the Intergovernmental Panel on Climate Change, 109–230, 2012.
13 Sheffield, J., Wood, EF, Roderick, ML: Little Change in global drought over the past 60 years. Nature 49 1: 435-438. Doi:
14   10.1038/nature 11575, 2012.
15 Spycher, F.: Witterungsbedingte Ausgaben des Basler Rates. Eine Untersuchung der Basler- Wochenausgabenbücher 1600-
16   1650. MA-Thesis, Historisches Institut, Abteilung für Wirtschafts-, Sozial- und Umweltgeschichte (WSU), Universität Bern,
17   131 pp., 2017.
18 Sturm, K., Glaser, R., Jacobeit, J., Deutsch, M., Brázdil, R., Pfister, C., Luterbacher, J. & Wanner, H. (2001) Hochwasser in
19   Mitteleuropa seit 1500 und ihre Beziehung zur atmosphärischen Zirkulation. Petermanns Geographische Mitteilungen
20   145 (6), 14–23, 2001.
21 Ven te Chow: Open Chanel Hydraulics. New York: McGraw-Hill, 1973.
22 Vischer, D.: Die Geschichte des Hochwasserschutzes in der Schweiz. Von den Anfängen bis ins 19. Jahrhundert. Berichte des
23   BWG, Serie Wasser 5, 3-208, 2003.
24 Wetter, O., Pfister, C., Weingartner, J., Luterbacher, J., Reist, T. & Trösch, J.: The largest floods in the High Rhine basin since
25   1268 assessed from documentary and instrumental evidence. Hydrological Science Journal, 56:5, 733-758, 2011.
26 Wetter, O.: Hochwasser "Katastrophen" in Basel vom 13. bis 21. Jahrhundert: Rekonstruktion, Deutung und Lerneffekte, in:
27   Krisen – Crises. Ursachen, Deutungen, Folgen. Schweizerisches Jahrbuch für Wirtschafts- und Sozialgeschichte (ed. By
28   David, T., Mathieu, J., Schaufelbuehl, J.M., Straumann, T.), 27, 48 – 63, Chronos Verlag, Zürich, 2012.
29 Wetter, O., Pfister, C.: An underestimated record breaking event – why summer 1540 was likely warmer than
30   2003. Clim Past 9:41–56, 2013.
31 Wetter, O., Pfister, C., Werner, J.P., Zorita, E., Wagner, S., Seneviratne, I.S., Herget, J., Grünewald, U., Luterbacher, J.,
32   Alcoforado, M.-J., Barriendos, M., Bieber, U., Brázdil, R., Burmeister, K.H., Camenisch, C., Contino, A., Dobrovolný, P.,
33   Glaser, R., Himmelsbach, I., Kiss, A., Kotyza, O., Labbé, T., Limanová, D., Litzenburger, L., Nordli, Ø., Pribyl, K., Retsö, D.,
34   Riemann, D., Rohr, C., Siegfried, W., Söderberg, W., Spring, J.-L.: The year-long unprecedented European heat and
35   drought of 1540 – a worst case, Climatic Change, 125:365, 365-367, 2014.
36 Wetter, O., Specker, T.: HWS Sihl-Limmat. Schlussbericht Historische Studien. Nicht öffentlicher Untersuchungsbericht
37   zuhanden des Amtes für Wasser, Energie und Luft des Kantons Zürich (AWEL), 66 pp., 2015a.
38 Wetter, O., Tuttenuj, D., Longoni, R.: Rekonstruktion vorinstrumenteller Scheitelwasserstände der Aare – einschliesslich
39   ihrer wichtigsten Zubringer Saane, Emme, Reuss und Limmat inklusive einer Meteoumfeldanalyse für die extremsten
40   Hochwasser. Nicht öffentlicher Untersuchungsbericht zuhanden des Bundesamt für Umwelt (BAFU), 128 pp., 2015b.