The effect of the Tambora eruption on Swiss flood generation in 1816/1817

Ole Rössler*, Stefan Brönnimann

Institute of Geography, Oeschger Centre for Climate Change Research, University of Bern, Hallerstrasse 12, 3012 Bern, Switzerland

*corresponding author: ole.roessler@giub.unibe.ch

Abstract

The Tambora volcano erupted in April 1815ccaused many direct and indirect impacts on the climate system, as well as ecosystems and societies around the world. In Switzerland, the eruption contributed to the 1816 "Year Without a Summer", which is considered to be a key factor in generating the highest flooding ever documented of the Lake Constance (7th July 1817) and the flood of the Rhine in Basel. Snow was reported to remain during the summer of 1816, which laid the basis for a massive snow accumulation in the spring of 1817. The meltwater together with a triggering event led to the reported flooding. We aim to create a hydro-meteorological reconstruction of the 1816/1817 period in Switzerland to verify and quantify the historical sources and place them into present-day context. We used an analogue method that was based on historical measurements to generate temperature and precipitation fields for 1816/1817. These data drove a hydrological model that covers the Rhine Basin to Basel.

We reproduced the reported features of the hydroclimate, especially in regards to the temperature and snow storage. We showed that the snow storage in spring 1816 and 1817 was substantial and attained the magnitude of a recent extreme, snow-rich winter (1999). However, simulations suggest that the snowfall alone in the spring of 1817, rather than the enduring snow from 1815/1816, led to the meltwater produced from the snow pack that contributed to the flooding in Lake Constance and Basel. These events were strongly underestimated, as the triggering rainfall event was reconstructed too weak. Artificial scenarios reveal that a precipitation amount with a magnitude higher than the largest recent flood (2005) was necessary to generate the documented flood levels. We conclude that these Tambora-following flood events were a product of an adverse combination of extreme weather with an extreme climate.

Introduction

In April 1815, the volcano Tambora erupted and devastated the Indonesian archipelago. It also affected the global climate by releasing 60-80 megatons of sulphur dioxide into the stratosphere that spread within weeks around the globe, oxidised to sulphur aerosol that in turn dimmed the sunlight. A direct effect of the radiation decrease was a drop in global mean temperature by 0.5 – 1 °C over the next year or two. This decrease in turn lead indirectly to an increase of precipitation over south-central Europe, as outlined by Wegmann et al. (2014) based on model simulations: Less radiation leads to cooler land-masses and a weakening of monsoons. The weakening of the convection over the Sahel-Sudanese region induces a weaker local Hadley-cell and thus a weaker subtropical high. This enables a more southerly track of low-pressure systems over the Atlantic-European region. As a consequence, weather system pass more frequently over south-central Europe and lead to increased precipitation. In the case of the Tambora eruption, this mechanism arguably contributed to the "Year Without a Summer" of 1816 over Europe and North America, although random atmospheric variability also contributed or even dominated. This cold and rainy climate anomaly and subsequent impacts have been intensely investigated (e.g. Luterbacher and Pfister, 2015; Raible et al., 2016, Brönnimann and Krämer, 2016). Thereby, Switzerland is regarded to be one of the regions most strongly indirectly affected.

Two hundred years ago in 1817, Switzerland suffered from the consequences of the 1816 "Year Without a Summer", which had brought forth crop failures and famine and was partially the consequence of the

Tambora volcanic eruption in April 1815. In 1816, cold and wet weather was present in Switzerland during the entire summer, as the following measurements (Auchmann et al., 2012) and reports from contemporary witnesses have indicated: *"The rain continues, there is no day without rain. The misery is indescribable. This is the worst time in my memory."* (Hoffmann 1816 in Brönnimann and Krämer, 2016). Today, we know that the colder (-3.2 °C) climate was an effect of the eruption and also largely related to climate variability (Auchmann et al., 2013). Still, the impacts of this adverse combination were tremendous, causing the last famine in Switzerland (Flückiger et al., 2017; Krämer, 2015; Pfister, 1999). The colder and moister climate conditions also led to constant snowfall in the higher elevations of Switzerland. P. Robbi from the southeastern mountain areas reported that *"cattle couldn't find grass to graze from anymore - neither pasture or meadow. Some pastures on the Alps were covered by snow all summer long"* (Robbi in Pfister, 1999). It was summarized that the Year Without a Summer was followed by a snow-rich winter, which enabled the snow to endure during the summer of 1816. This snowpack was further increased during the spring 1817, which was colder and moister. According to the review, the resulting amount of snow for the first 1 ½ years after the eruption did not finally melt until the late spring of 1817, which caused a major flood event on the 6th of July in the Rhine in Basel and flooding one day later at Lake Constance. It was the highest flood level ever recorded at Lake Constance, and the 6th highest of the Rhine at Basel since 1805 (Amt für Wasserwirtschaft, 1926).

The causes of these floods are considered to be a combination of the massive snowmelt and several days of massive rainfall, which triggered the event during the first week of July 1817. Several qualitative, historical sources from the Swiss lowlands, namely, St. Gallen (observer: Daniel Meyer, Vadianische Sammlung, Kantonsbibliothek St. Gallen), Aarau (observer: Heinrich Zschokke, Staatsarchiv Aargau), Einsiedeln (observer: Bernhard Foresti; Klosterarchiv Einsiedeln), Schaffhausen (observer: Johann Christoph Schalch; Schweizerisches Bundesarchiv), and Marschlins (observer: Johann Rudolf von Salis; Staatsarchiv Graubünden) reported strong thunderstorms and enduring rainfall along the northern mountain chain, with intensification on the 4^{th}, 5^{th} and 7^{th} of July 1817. Interestingly, this course resembles the situation in May 1999, which was the third largest flood of Lake Constance and the 4th highest flood peak for the Rhine at Basel. The 1999 flood was similar to that which occurred in 1817, following a snow-rich winter in 1999 (Laternser and Schneebeli, 2003) and was additionally triggered by heavy rainfall (Froidevaux et al., 2015).

To better understand the hydro-meteorological conditions during 1816 and 1817 that led to these floods, we aimed to reconstruct the historic situation following the Tambora eruption. We used the recently published analogue method to reconstruct the daily fields of temperature and precipitation during 1816 and 1817 in the Rhine Basin (Flückiger et al., 2017). The resulting historic weather data were used to drive a hydrological model that was calibrated under present conditions but used the same meteorological fields that serve as the basis of the analogue method. A simulated time series of discharge, lake levels and spatial distributions of snow are obtained from historical reports and measurements from 1816 and 1817, which validated the ability of the approach to reproduce the hydro-meteorological conditions. The simulated results are analysed and compared to the present normal period and the extreme snow year of 1999 to set this historical event into the present context.

Data and Methods

The study region: the Rhine River to Basel in Switzerland

The region of interest within this reconstruction study is the upper part of the Rhine River up to the city of Basel (Figure 1). The catchment area is 35878 km^2, which covers an elevation gradient from 246 m to 4158 m (Jungfrau). This catchment discharges all of the water from north of the Alpine chain in Switzerland, as well as from the northwestern part of Austria (Vorarlberg) and some smaller areas of southwestern Germany. Upstream, 60 km of the gauge in Basel, the river splits into two major tributaries: the Aare and Rhine, of which Lake Constance is a part. Lake Constance in turn is the largest northern alpine lake, which covers an area of 529 km^2 (Jöhnk et al. 2004) and is one of the few still unregulated lakes in Switzerland. The seasonal course of both rivers and lake levels are characterized by the mostly alpine origins of the water flows: summer high levels are due to snowmelt and summer precipitation peaks alternate with winter low flows due to snow accumulation. The climate of (northern) Switzerland, which has annual temperatures of 6.5 °C and a mean annual precipitation of 1410 mm (both values are for the normal period of 1981-2009), is primarily influenced by the Atlantic Ocean. This results in a cooling effect in the summer and a warming effect during the winter.

Analogue method for reconstructing the 1816/1817 weather

The weather reconstruction for Switzerland follows the approach of Flückiger et al. (2017). We have outlined this method here that is also depicted in Appendix A1: the reconstruction is based on early sub-daily observations from Geneva (Auchmann et al., 2012; Schüepp, 1961) and Hohenpeissenberg (southwest of Munich, Winkler, 2009) that include temperature, precipitation, pressure, and wind direction data, among others. In addition, daily measurements from Délémont (near Basel, Bider et al., 1959) for temperature and pressure were used. Analogues of these historical measurements were searched for in the daily gridded time series (see description below) from 1961 onwards. The procedure of this approach consisted of three steps:

First, historical and present-day time series of meteorological variables were transformed into a time series of anomalies as the reference climatology. For the 1816 and 1817 data, a climatology from 1800-1820 was established, with the exception of the volcanically influenced years of 1809-1811 and 1816-1817 (in line with Auchmann et al., 2012). Data from 1982-2009 served as the present-day climatology. All data were additionally deseasonalized. Moreover, temperatures within the present-day period were linearly detrended. Second, to ensure that the historic and present-day values agreed on the synoptic weather characteristics, we restricted the sample of possible analogue days to those that share the same weather type. Here, we used a weather type classification after Auchmann et al. (2012) that uses pressure, pressure tendency, and wind direction.

Third, the analogue days are computed using the anomalies of all meteorological variables derived in step one by searching for the nearest present-day records in a Euclidean matrix. This search was restricted to a search window of +/- 30 calendar days apart from the target day and the same weather type, which was derived in the second step.

For the closest analogue day, we extracted temperature and precipitation from the meteorological fields in the Swiss national 2×2 km gridded dataset (Frei et al., 2006; MeteoSwiss, 2013), as well as from the E-OBS dataset (Haylock et al., 2008). These two products were combined with the Swiss grid, which represents Switzerland, and E-OBS, which represents the non-Swiss parts of the basin. Finally, the temperature difference between the historical and present-day climatology was subtracted from the combined fields for each day. For precipitation, no difference was found between the climatologies, and hence, no adjustment was made. For a more detailed description of the analogue method as well as the validation results, please see Flückiger et al. (2017).

Hydrological modelling

The physics-based, distributed hydrological model WaSiM-ETH (Schulla, 1997, 2015), Richards-equation version 9.05, was set up at a 1 km spatial resolution with a daily time-step for the Rhine catchment up to Basel. As only temperature and precipitation fields were available to drive the model, we chose less complex model routines. For instance, we used the Hamon instead of Penman-Monteith approach to calculate potential evapotranspiration, as well as the day-degree-factor instead of the energy-balance-based algorithms to simulate snowmelt. A further simplification for the model was the consideration of present-day land use, glacial extent, and river networks, with the exception of the Jura-waters-correction. There are several lakes situated within the Rhine catchment that are partly regulated. We estimated their respective discharge characteristics by calculating empirical volume-discharge functions based on observations of both lake level and amount of discharge at the downstream river for 1980-2010. Seasonal and sub-seasonal differentiations of this function were neglected. A special case is the so-called Jura-water-correction. Biel Lake and Neuenburg Lake, as well as their smaller companion Lake Murten, are situated at the foothills of the Jura Mountains (cp. Figure 1) and were artificially connected in either direction to regulate the water of the Aare River, which was redistributed into Lake Biel (cp. black (correction) and red (pre-correction) arrows, Figure 1). This correction was accomplished in 1878 and thus occurred after the intended simulation years of 1816 and 1817. In this study, we applied the uncorrected river network (red arrow, Figure 1). The applied river network considers the inflow from tributaries of the three lakes, without considering the retention effects of Biel, Neuenburg, and Murten Lakes. This simplification was necessary, as the volume-discharge-relationship is unknown between the lakes and the former discharging Zihl River in 1816/1817. In contrast, the application of present-day river and lake networks would affect the generation of flood peaks, as the additional retention in a flood situation was the reason behind the Jura-water-correction. We are aware that the applied lake-river-network with respect to the Jura-water-correction (Figure 1) is a simplification; however, because the model performances upstream (Aare, Bern) and downstream (Aare, Untersiggenthal) of this region were good (Table 1), we assumed that this simplification was sufficient to reproduce the effects of the Tambora eruption on the discharge of the Rhine at Basel and Lake Constance. The river network simplification was applied to both time periods to ensure comparability. As a second simplification, we applied present-day glacial extents for both simulations. This is justified by the small fraction of glacial extent in the Swiss Rhine Basin (1.2 %) and the rather small effect of melting glaciers during the cold and wet years. Furthermore, Stahl et al. (2016) showed that the glacial meltwater contribution during the past 100 years was at a similar level due to a trade-off between the decreasing glacial extent and increasing temperatures.

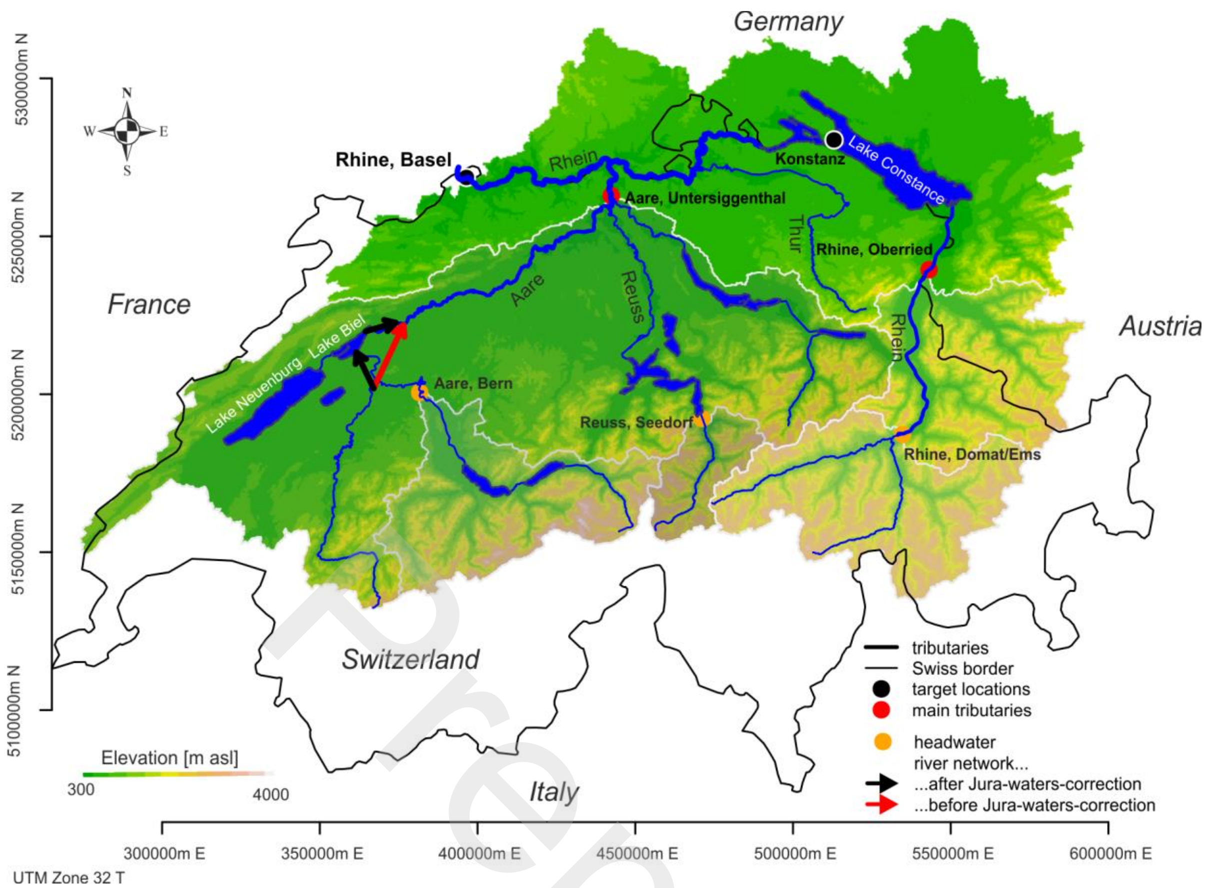


Figure 1: The river Rhine network up to the gauge in Basel that divides into the Aare, and the Alpine Rhine, with major headwater catchments (white outline). The Alpine Rhine enters Lake Constance, for which a flood on 7th July 1817 at the city of Konstanz is documented. The river network was simplified with respect to the Jura-waters-correction: In 1878 the river Aare was rechannelled into the Lake Biel ("black arrows"), that is connected with the Lake Neuenburg and the Lake Murten to increase the retention capacity during flood events. For all simulations the old river system ("red arrow") was applied considering all tributaries entering the three lakes.

The hydrological model was calibrated against the streamflow of the Rhine at Basel for the time period of 1993-1999 and validated against streamflow from 1981-2010. We also checked on the representation of streamflow in the sub-catchments, as well as simulation of the Lake Constance water level. Finally, we validated the model performance in terms of snow cover representation by comparing the modelled snow cover extent to the MODIS snow cover data (Hall et al., 2006) between March 2000 and December

2010. To ensure an accurate observational dataset, we used only images of days with more than 40 % positively classified pixels for the validation of simulated snow cover. The agreement was expressed by Pearson's R^2 and mean absolute error (MAE) measurements.

We considered the snow-rain temperature to be a crucial parameter in this study, as it influences the snowline and hence, the snow cover extent and amount of snow storage. Accordingly, we ran several model versions comprising different snow-rain threshold temperatures (T0R). Table 1 summarizes the performance measures for streamflow, water level of Lake Constance, and snow extent in the Rhine catchment. In terms of streamflow, we evaluated the simulated discharge for the entire basin (Rhine at Basel), the two major tributaries (Aare and Rhein), and the three alpine headwater catchments (Aare to Bern, Reuss to Seedorf, and Rhein at Domat). The three model versions are very similar in terms of goodness-of-fit criteria for discharge, lake level and snow coverage. The Alpine Rhine (Aare-Oberried) and its subcatchment (Rhein at Domat), with its mouth flowing into Lake Constance, show much lower performance values than the Aare tributary and its headwaters (Aare and Reuss). This is at least partly related to the strong anthropogenically regulated discharges (hydro power) that have not been considered in the hydrological model. To avoid misleading results, we simulated and analysed the discharge, lake levels and snow distribution for 1816 and 1817 with all three model versions (T0R 0.0, T0R 1.2, T0R 2.0). As initial conditions, especially the snow storage volume, prior to 1816 are unknown and yet, these data are essential to the simulation results. Thus, we assumed present-day conditions to reflect the spectrum of possible conditions. Hence, the present-day simulations (1981-2009) served as initial conditions, and therefore, each historic simulation of 1816 / 1817 comprised an ensemble of 28 runs, each of which was initialized with the conditions of two consecutive years of the present-day normal period (1981-2010).

Table 1: Comparison of model versions with alternating snow-rain-temperature (T0R) in terms of discharge, lake level, and snow extent (1981-2009). NSE: Nash-Sutcliff-Efficiency. MAE: mean absolute error; R^2: coefficient of determination. For the location of validated catchments, refer to Figure 1.

	discharge [m³/s]				lake level	snow	
	Rhine at Basel	Aare at Unter-siegenthal	Rhein at Oberried	selected headwater (Aare-Bern; Reuss-Seedorf; Rhein - Domat)	Lake Constance	snow extent Rhine basin (%)	
performance measure	NSE	NSE	NSE	NSE	NSE	R^2	MAE
version T0R 0.0	0.88	0.82	0.51	0.83; 0.78; 0.35	0.79	0.86	0.086
version T0R 1.2	0.89	0.89	0.57	0.84; 0.78; 0.4	0.78	0.87	0.075
version T0R 2.0	0.89	0.88	0.59	0.84; 0.77; 0.42	0.78	0.9	0.057

Results

Reproducing the meteorological conditions

Before beginning to analyse the simulated discharge, lake level, and snow developments, we tested the effectiveness of the described analogue approach at reproducing the meteorological conditions that were reported and measured in 1816/1817. This is shown by comparing the hydro-meteorological situation in 1816 and 1817 to the present normal period of 1981-2009 (Table 2), for both the basin average and the city of Bern. Clearly, the temperature during both years (-2.6 °C and -1.4 °C, resp.) and especially during the summers of 1816 (-3.4 °C) and 1817 (-0.5 °C) were below the present-day norm, and these areas received more rainfall (+5-+10 %) and 10 % wetter days. For the temperature, these values are in line with measurements (Auchmann et al. 2012).

We additionally evaluated the reconstruction performance in terms of precipitation and temperature, by directly comparing the reconstructed values to observations at the meteorological station Geneva (precipitation: Figure 2). Seasonal mean anomalies of temperature and precipitation were found to perform well with a tendency to underestimate temperature values (Flückiger et al. 2014). On a daily basis, correlation between observed and reconstructed time series reveal reasonable performance quality both for precipitation (0.67) and temperature (0.86). These measures as well as the optical comparison (Figure 2) give confidence that the meteorological conditions in 1816 / 1817 are successfully reproduced. Alike historical reports suggest, a triggering event in the beginning of July 1817 prior to the flooding was also reconstructed.

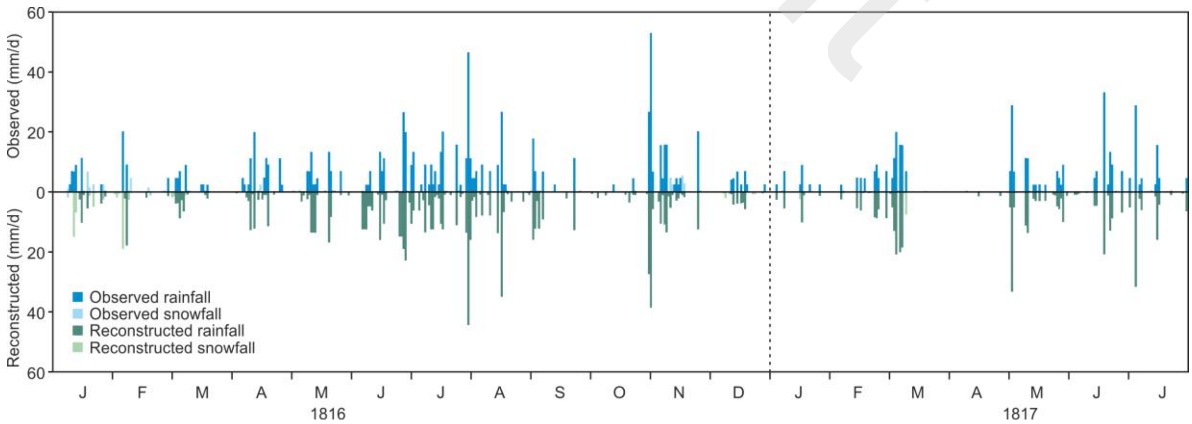


Figure 2: Comparison of reconstructed (lower part, greenish colours) with observed total precipitation (upper part, blue colour) for the gauge Geneva from Jan 1816 to Jul 1817. Dark and light colours indicate estimated rain and snowfall, respectively, based on daily mean temperature (threshold of 2 °C).

Reproducing the hydrological and snow conditions

The results of the simulated hydrology are analysed next. On an annual basis, we found that a discharge surplus for the Rhine at Basel (+ 25 % and +11 % compared to today's norm) exceeded the higher precipitation amount during 1816/1817 (+16 %, +5 % respectively), which indicates a considerable reduction in evapotranspiration as a consequence of the colder temperatures. Comparing the 1816/1817 annual values with the recent 1999 "extreme year", the results were comparative for the precipitation amounts, and a roughly equivalent number of wet days and discharge levels were found for 1816 and 1999. Hence, apart from the unusual temperature anomaly in 1816 and 1817, the annual hydro-meteorological conditions were close to the recent extreme year in 1999.

Table 2: Some basic hydro-meteorological values compared between 1816/1817 and the present-day normal period (1981-2009)

	Rhine basin 1816/1817	Rhine Basin Norm 1981-2009	Rhine Basin Year 1999	Bern 1816 1817	Bern Norm	Bern 1999
mean annual temperature [°C]	3.9 / 5.1	6.5	6.5	7.2	8.8	9
mean summer temperature [°C] (June - August)	9.8 / 12.7	13.2	13.6	14.5	17.3	17.1
annual precipitation sum	1642 / 1494	1410	1797	1156	1071	1322
number of wet days [>1 mm]	194 / 191	175	200	195	175	176
annual runoff at Basel [mm]	1256 / 1120	1003	1254			

A detailed glance at the daily resolution in the simulations reveals that the reconstructed weather conditions in 1816 and 1817 led to considerably different runoff of the Rhine River at Basel, compared to the normal and the year 1999 (Figure 3 a-c). This is particularly true during late spring and summer for both years. However, during January to June 1816, as well as from October 1816 to June 1817, and again after October 1817, the runoff reflects rather normal conditions, i.e., they remain within the IQR range (20-80 %) of the present-day normal period. The snowmelt-induced peak runoff that normally occurs in June was delayed by 2-3 months in 1816 and by 2-4 weeks in 1817, depending on where the peak was set. Those delays reflect the temperature conditions in both summers: on the one hand, the rather cold temperatures of 1816, and on the other hand, the closer-to-normal temperatures (Table 2) in 1817, which resulted in a weaker snowmelt delay. It is noteworthy that the snowmelt is not only postponed, but the total water volume during the snowmelt period is larger, as indicated by the curve integrals. A comparison against the 1999 discharge reveals approximately the same volume of deviations from the long-term mean. Comparing the simulated discharge peaks to the observed monthly discharge maxima taken from Amt für Wasserwirtschaft (1926), a heterogeneous pattern of peak representation becomes apparent. While monthly discharge maxima for Feb. 16, Apr. 16, Jun. 16, Jul. 16, Feb. 17, Apr. 17, Jun. 17, Aug. 17, and Sep. 17 are quite well represented, other events during the winter of 1816/1817 are not captured, especially the two highest events in Mar. 17 and in Jul. 17.

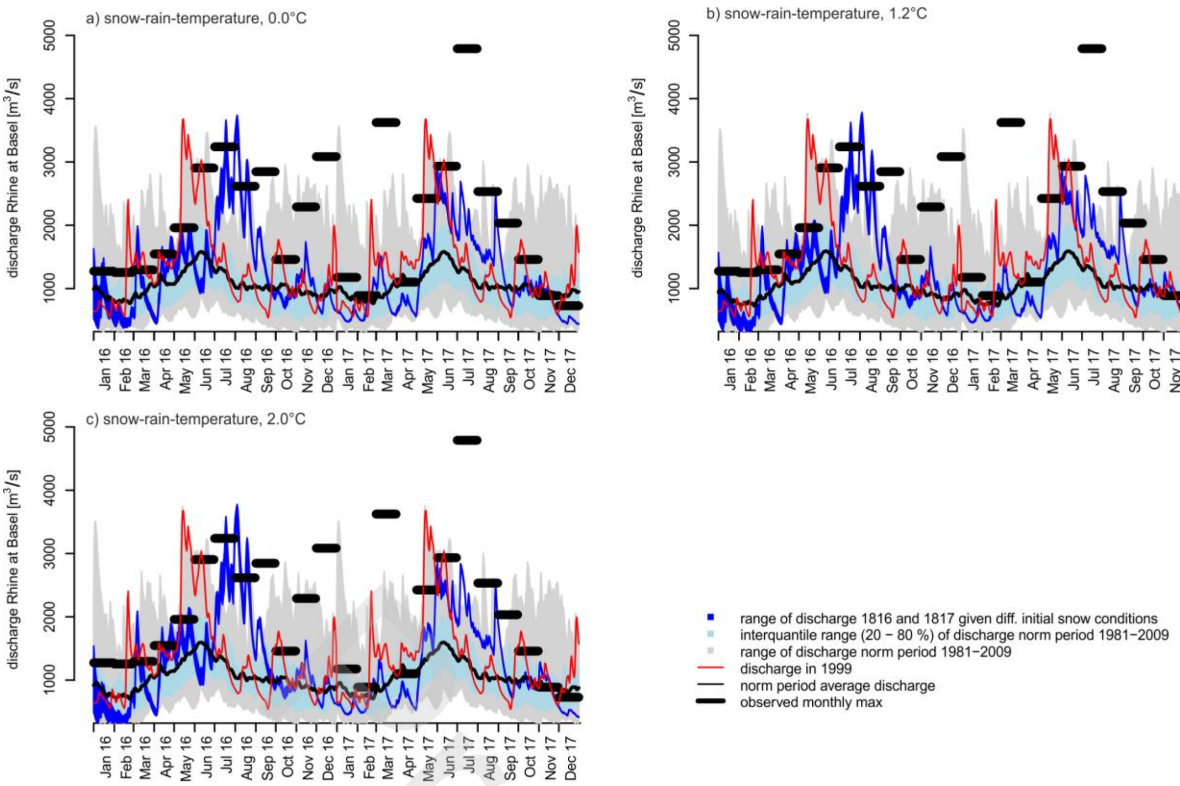


Figure 3: *Discharge at the Rhine in Basel in 1816 and 1817 (dark blue area) - considering different snowfall thresholds (a, b, c) and different initial conditions derived from 1982-2009 winters - displayed against present-day mean, interquartile range, range, and discharge data from 1999. Comparing the simulated flood peaks against observed monthly maximum values published by Amt für Wasserwirtschaft (1926) revealed only a partly successful representation: while flood peaks in summer 1816 and partly in 1817 are met, the highest and most relevant floods for this study, which occurred in July 1817 and during the winter 1816/1817, are clearly missed.*

The simulated water level at Lake Constance during both summers showed very high levels that meet the flood level that occurred in 1999. In line with the discharge, the lake level peak is delayed by 2-3 months (in 1816) and by 2-4 weeks in 1817 (Figure 4). The long lasting high lake level (~3 months) in 1817 is also remarkable. Interestingly, these findings are irrespective of the chosen snow-rain temperature threshold (Figure 4 a-c). A comparison of the simulated Lake Constance level with the observed water level peaks provides further indication of the quality of the reconstruction. Lake level recordings started in late 1816 and recordings were later corrected for reader errors (HZ 1913 in Jöhnk et al., 2004). The corrected observations (7th July 1817: 623 cm above zero level of 391.89 m above sea level (German standard) and 11th June 1999: 568 cm above zero level) are displayed in Figure 4, along with the simulated levels of the normal period, the year 1999 and the reconstructed level of 1816/1817. Clearly, the 1817 peak is missed in line with the underestimated flood peak for the Rhine in Basel. However, the simulations show a strong delay in the spring lake level peak in comparison to the present-day mean, irrespectively of the snow-rain-temperature threshold that was applied (a, b, c); a long lasting high lake level (1817 June to September) and a second flood in 1816 were also seen. The latter is often overlooked in historical reports.

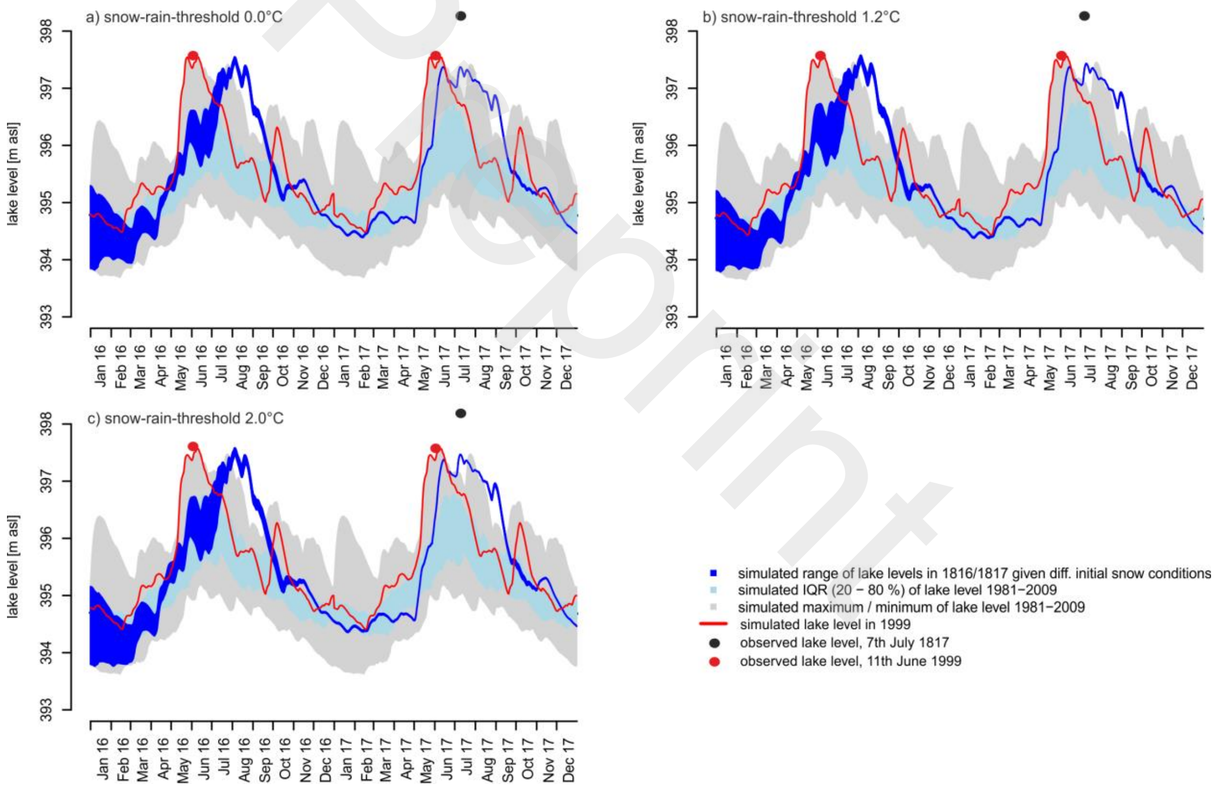


Figure 4: Water level of Lake Constance in 1816 and 1817 (dark blue area), considering different snow-rainfall thresholds (a, b, c) and initializing with different snow conditions derived from the 1982-2009 winters. These data are displayed against the interquartile range (light blue shading), range of present-day discharge (grey shading), and the extreme year of 1999. Observations of lake level from 11th June 1999 (red dot) and 7th July 1817 (according to HZ 1913 cited in Jöhnk et al.*, 2004).*

The crucial role of snow in the 1817 flood generation has been continually stressed in reports: The general interpretation is that the flood was a logical consequence of the melting of a massive amount of snow in the spring of 1817. This snow was regarded as the product of two consecutive winters, as the seasonal snowpack in 1816 remained partly present due to the cold summer temperatures. We quantified the snow contribution upstream of Lake Constance by calculating the total snowmelt and the snowmelt fraction to the total water input (rainfall plus snowmelt) for Jan. to Jul. (Table 3) for a threshold T0R of 1.2 °C. Clearly, the 1816 and 1817 absolute snowmelt contribution were among the highest values found, but interestingly, they were not the highest. In terms of the snowmelt fraction, both years, 1816 and 1817, are close to the present-day mean. However, the total input for both years, especially in 1817, was substantial and met the input level of 1999.

Table 3: Snowmelt and rainfall and resulting snowmelt fraction to the total input (rainfall plus snowmelt) for the upstream area of Lake Constance during Jan to Jul for T0R of 1.2 °C. Glacial meltwater, groundwater, and soil water are excluded.

	Snowmelt [mm]	Rainfall [mm]	Total Input [mm]	Snowmelt fraction [%]
1816	617	526	1143	54 %
1817	793	564	1357	58 %
1999	871	548	1420	61 %
Mean 1982 - 2010	593	435	999	56 %
Year of maximum snowmelt fraction 1982 - 2010	698	312	1010	69 % (1983)
Year of minimum snowmelt fraction 1982 - 2010	314	508	822	38 % (2007)

Year of maximum snowmelt amount 1982 - 2010	871	548	1420	61 % (1999)
Year of minimum snowmelt amount 1982 - 2010	291	452	743	39 % (1996)

We further analysed the spatial and temporal development of the snow water equivalent during 1816 and 1817. This analysis is especially sensitive to the applied snow-rain-threshold; hence, all three simulated alternatives need to be considered. A second variable that affects the estimation of snow-development is the snowfall prior to the start of the reconstruction in the winter of 1815. Although related uncertainties are considerable, the ensemble of the snow water equivalent simulation agrees on several aspects (Figure 5 a-c):

1) The snow accumulated in 1816 reached a normal to extraordinary level. Depending on the pre-conditions, the 1816 snowpack reached or even exceeded the amount of snow accumulated in 1999, which is the highest snow amount recorded in the last decades.
2) This snowpack melted slower than normal or in 1999, resulting in a considerable amount of snow still present in July to October of 1816, which was the highest summer SWE found in our analysis.
3) In October 1816, the SWE was still larger than normal; in absolute values, the additional snow amount lies within a range of +20 - +35 mm, depending on the snow-rain temperature threshold applied. Accordingly, the fresh snow during the winter of 1816/1817 followed extreme SWE conditions.
4) However, in February 1817, the SWE was back to normal, and the high SWE amount in 1817 was merely a result of intense snowfall in the late spring of 1817.

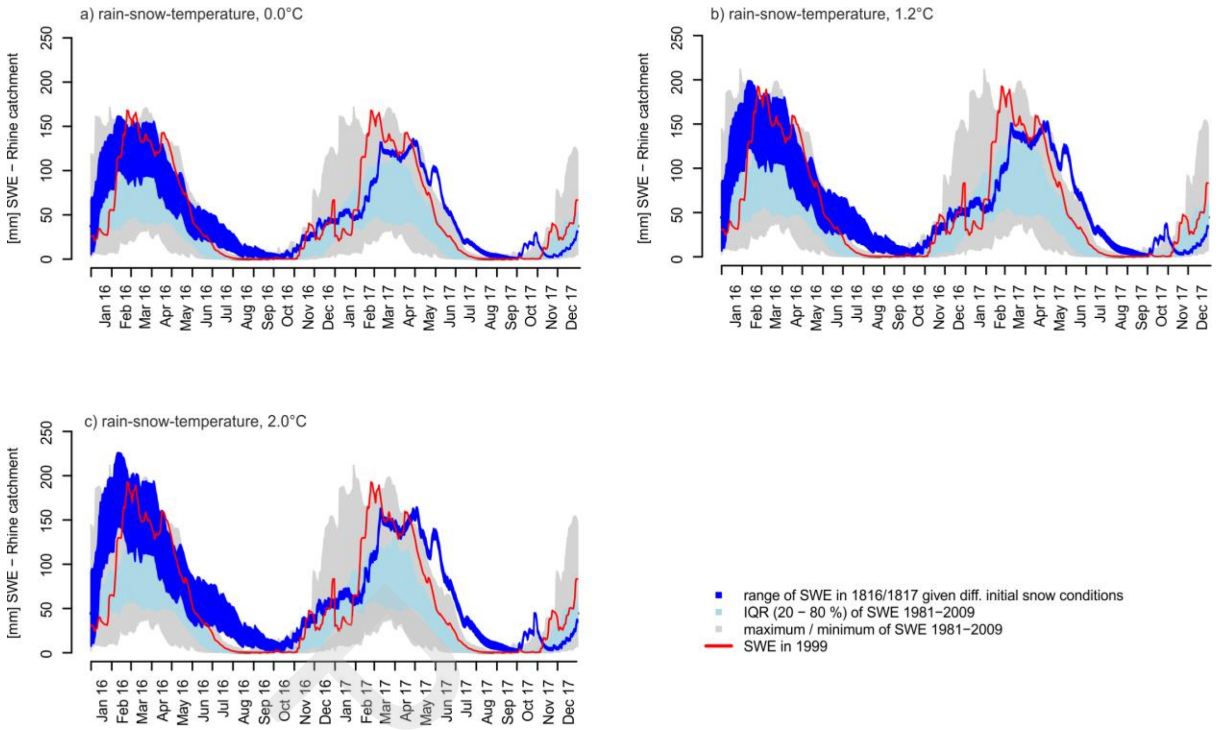


Figure 5: Development of the snow water equivalent (SWE) in 1816 and 1817 (blue area) considering the different initial SWE conditions taken from 1982-2009 and compared to the present-day, long-term mean (thick black line), maximum and minimum (dashed black lines), as well as to the extreme snow winter in 1999 (red line).

The following question remains: was the larger and longer lasting SWE during summer 1816 solely due to the remaining winter snow or was it a result of several snowfall events during the summer, as reported by Robbi in Pfister (1999, S. 154)? Figure 6a shows the fraction of the catchment covered by snow (at least 10 mm SWE) during 1816 and 1817, and panel b of this graph depicts the snow line succession in 1816 (both for T0R 1.2 °C). To avoid misinterpretations due to local snow storage, we displayed not only the minimum elevation of snow coverage area to represent the snow line, but also the 1 and 10 % lowest quantiles of snow coverage elevations. In addition, we animated the snow coverage over time for the summer of 1816 (June-September, Appendix A2 and online). All these analyses are based on the 1.2 °C snow-rainfall threshold with maximum snow storage initial conditions. The animation illustrates that the snow extent was mostly limited to the higher elevations, with three major snowfalls throughout the summer occurring down to the valley floors. The snow from these events melted shortly afterwards. This is also shown in Figure 6b, which also tracks several minor snowfall events during which the snowline only slightly decreased. Thus, the reconstruction of the snow conditions during 1816 and 1817 could strikingly confirm the historical reports of the low snow line with several snowfall events. However, the effects on the snow extent were very short lasting, and these effects surely contributed to the snow storage at higher altitudes.

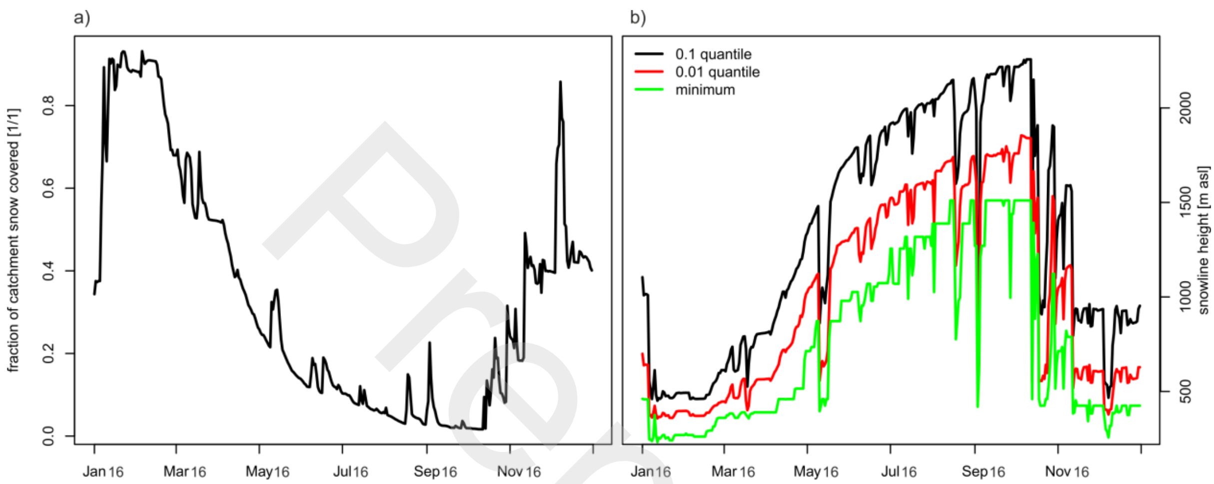


Figure 6: Fraction of the Rhine catchment that is snow covered during 1816 (a) depicts a constant decline from a maximum during January to March, intersected by several snowfall events, which is the strongest in May, August, and September. In parallel, the snow line (b) (minimum, 0.01 and 0.1 quantile of snow coverage area) increases and illustrates snowfall down to the lowlands in May and September 1816. The simulations are based on the 1.2 °C snow-rain-threshold T0R and maximum initial snow storage conditions.

Three scenarios with artificially introduced triggering events

Finally, we looked in more detail at why the simulations failed to capture the measured flood peak for the Rhine at Basel and the water level peak at Lake Constance. We found the triggering event - the flood causing precipitation - to be present in the reconstruction, but the reconstructed event was poorly simulated. In the applied reconstruction, the 10-day amount of rainfall prior to the 7th July 1817 (date of lake level peak) was 93 mm (73 mm in 5 days). While this is already a considerable amount of precipitation input, the precipitation amounts in the recent major floods of 2005 (155 mm in 10 days, 118 in 5 days), 2007 (128 mm / 107 mm) and 1999 (135 mm, 100 mm) were substantially higher. Note that only one precipitation series contributed to the analogue selection, and this series (Geneva) is not well placed for detecting the spatial pattern of heavy precipitation as it occurs, e.g., during so-called Vb situations (the 2005 event is an example). Furthermore, it is outside the studied catchment. However, the documentations from several locations (Aarau, Schaffhausen, Einsiedeln, St. Gallen, Marschlins) inside the catchment and inside the region typically affected during Vb situations report several days of heavy rain, which would be consistent with a rainfall amount similar to the abovementioned cases.

To simulate the magnitude necessary to capture the flood peaks at both Lake Constance and the Rhine at Basel, we set up a model experiment in which we applied the 10 days of precipitation from the three recent major floods prior to the 7th July 1817. Those scenarios show (Figure 7, magenta lines) increasing flood peaks for the respective days; however, only an event with a magnitude of 2005 (155 mm in 10 days) approximates the flood peaks. Furthermore, an artificial scenario with an additional day of high precipitation with a magnitude of 2005 (replication of 22nd August 2005) was tested and resulted in 120 mm of rainfall for 3 days (197 mm in 10 days). This simple artificial scenario led to a close approximation of the observations for both the water level peak of Lake Constance and discharge peak at the Rhine in Basel (Figure 7 a, b, green line). Hence, these scenarios show that a huge triggering event in combination with the vast snowmelt is able to cause both flood events.

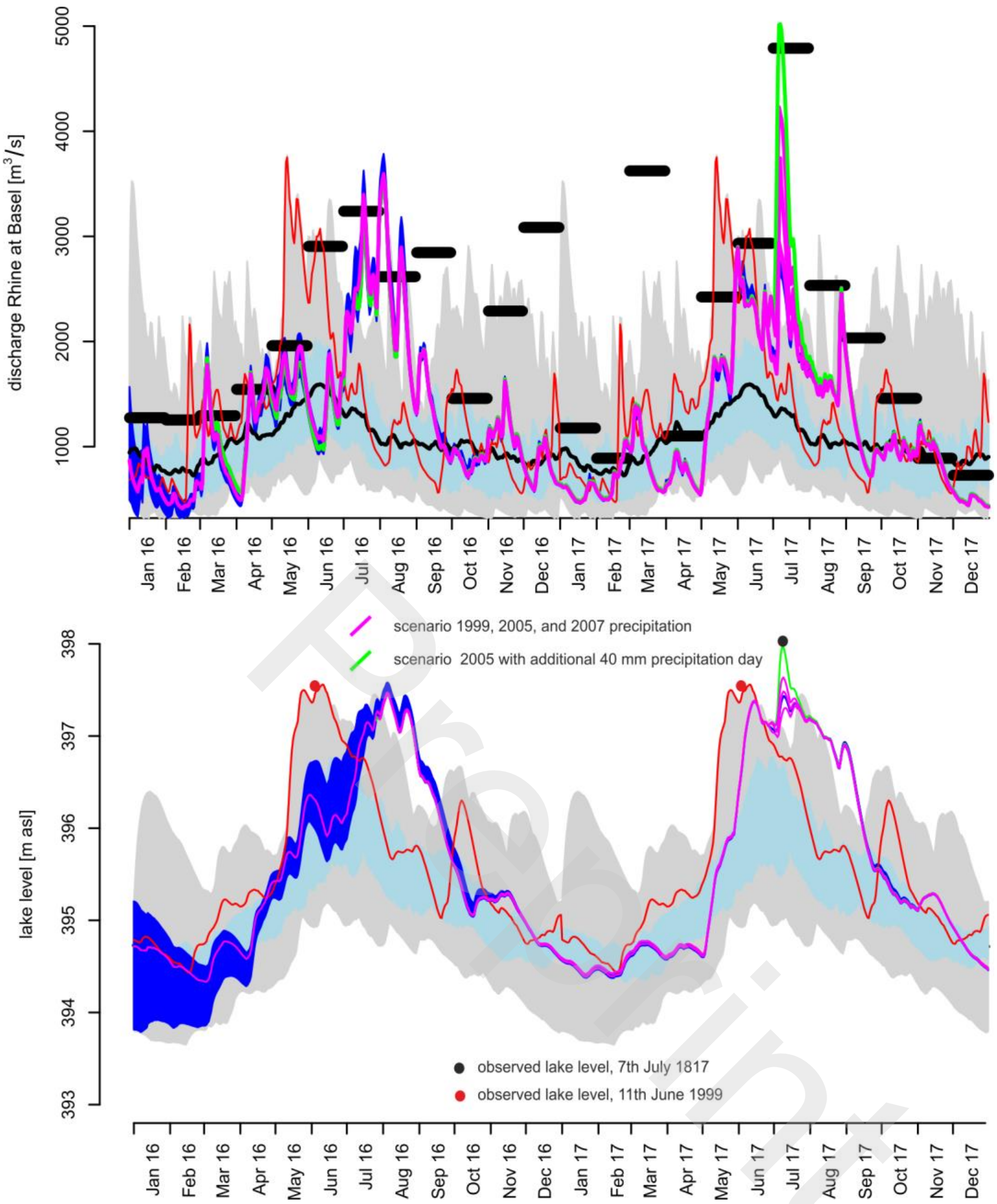


Figure 7: Discharge of the Rhine at Basel (a) and water level of Lake Constance (b) for 1816 and 1817 with modified precipitation amounts, considering the recent flood triggering precipitation field of 10 days prior to the flood type at Lake Constance, 7th July 1817, (magenta), and modified 2005 flood precipitation fields sums with one additional day of high precipitation (40 mm, green).

Discussion and Conclusions

In terms of the impact on Swiss hydro-meteorological conditions, our knowledge was mostly based on an analysis of historical resources (Pfister, 1999) and early measurements. However, the transfer of this historical information into a physics-based context and the quantification of processes and structures reported from 1816 and 1817 were lacking. Therefore, we aimed to fill this gap by applying the analogue method of Flückiger et al. (2017) in a hydro-meteorological modelling approach. We showed that the meteorological forcing data obtained are widely in line with historical observation and reports, although not entirely. While the temperature anomalies and the precipitation for Geneva events were well reproduced, the number of wet days was underestimated (cp. Table 2). Auchmann et al. (2012) found an 80 % increase of precipitation frequency in contrast to the 10 % of our study. Nevertheless, we were able to confirm several pieces of historical information and measurements, i.e., annual and summer temperatures means and precipitation sum, the majority of monthly discharge peaks of the Rhine at Basel, the 1816 summer snowline at approximately 2000 m (cp. Pfister, 1999:154), as well as the long lasting, high water level of Lake Constance in the summer of 1817 (Pfister, 1999), to name a few. These agreements give us confidence that our simulation realistically reproduced the general hydro-meteorological conditions.

However, we clearly missed the major flood events of the Rhine and Lake Constance. Several possible reasons for this failure exist: first, inaccuracies might occur due to our simplified assumption that the hydraulic and land use conditions remained unchanged. Despite the land cover in the early 19th century comprising a smaller forest fraction, which led to less rapid runoff responses, the less expanded river networks at that time resulted in a reduction of the flood peak. The effect of these simplifications is unknown, but the underestimation of the flood peak during July 1817 is too strong for the simplification to be the only explanation behind the failure. Furthermore, the flood peaks of many other monthly maximum values were met or even exceeded, which indicated the general ability of the approach to reproduce considerable flood peaks.

Second, the hydrological model is rather insensitive to highest flood peaks, which is indicated by the validation (Appendix 3). While flood peaks up to 4000 m^3/s were simulated correctly for the Rhine at

Basel, even higher discharges are underestimated. For the two highest uncaptured flood peaks, this limitation needs to be put into context as 4000 m^3/s discharge, which were not simulated in the historic simulations but were exceeded by the artificial scenarios (Figure 7). The model is able to generate those flood peaks at the expense of higher precipitation input required. In turn, the estimated triggering event magnitude in Figure 7 might be overestimated for the discharge of the Rhine at Basel.

Third, the limitations originate from the applied analogue method. The methods could detect heavy rainfall conditions during the time prior to the flood peaks in July 1817, but the selected analogue days from the donor dataset had less intensive precipitation than needed. In fact, comparing reconstructions and observations for Geneva for 1816 and 1817 (displayed in Fig. 2), we found that the daily precipitation sums below 15 mm are overestimated in the reconstruction, whereas the higher sums are underestimated.

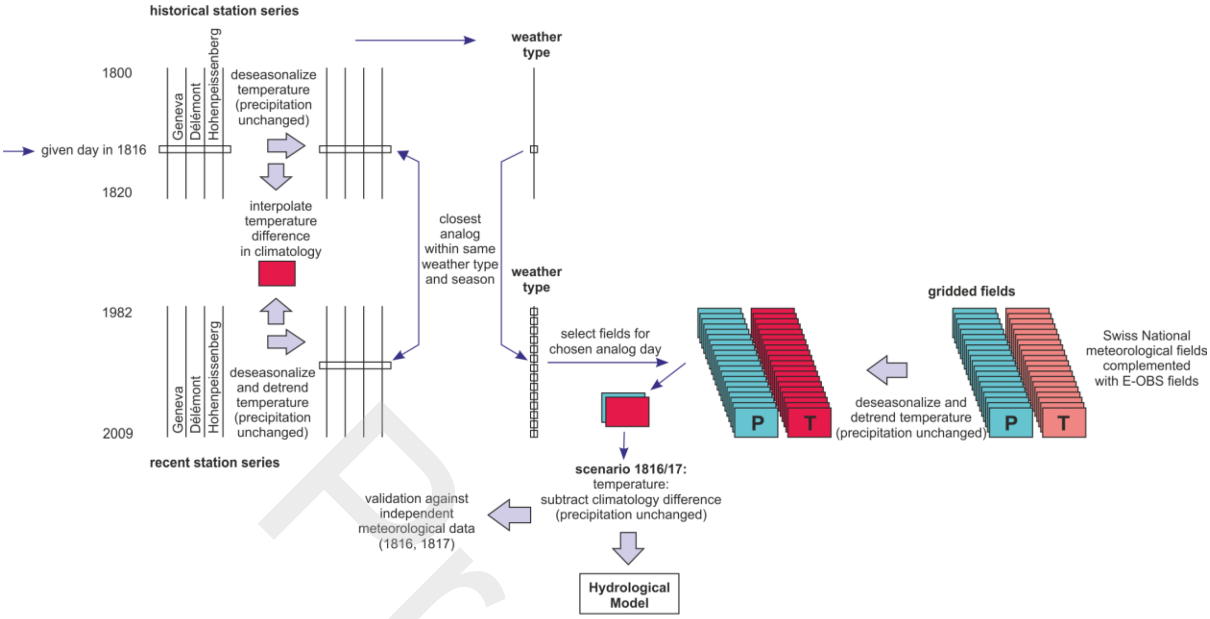
The importance of snowmelt for these flood events is indisputable; however, the interpretation of a snow build-up over two winters leading to a massive snowpack in 1817 needs to be specified. This accumulation of snow was restricted to higher mountain areas with a total surplus of 35 mm at most. Similar to February, the SWE amounts were back to present-day normal conditions, and it was merely a result of snowfall in the late spring of 1817, rather than the addition of a final winter snow. We argue that a flood would still have occurred in 1817, even in the presence of normal snow storage in the summer of 1816.

Despite the discussed limitations of this study, we were able to provide a detailed, physics-based impression of the hydro-meteorological conditions during the post-Tambora years. We could widely confirm the historical reports, but less evidence was found for the importance of a two-year snowpack as the prerequisite for the rainfall that triggered the flood events in 1817. We suggest that meltwater from the 1816/1817 winter was sufficient enough to act as the basic and variable characteristic to trigger the flood events. While we were not able to reproduce the recorded flood peaks because we missed the intensity of the triggering precipitation event, we were able to determine the necessary order of magnitude of this triggering event: rainfall amounts on the order of 130 mm over 5 days must have fallen in the Rhine catchment. Comparing the historic events with recent similar events, such as the flood of 1999, revealed that the flood characteristics from the precedent snowmelt for both events were very similar. However, 1817 was merely a combination of the extreme 1999 snow pack that lasted until early summer and a precipitation event that was close to 2005 magnitude. This adverse combination of two extreme weather phenomena led to both flood events in Basel and Lake Constance. Thus, the two post-Tambora years were not only characterized by an extreme climate (Auchmann et al. 2012) but also by extreme and adverse weather with respect to its hydrological impact.

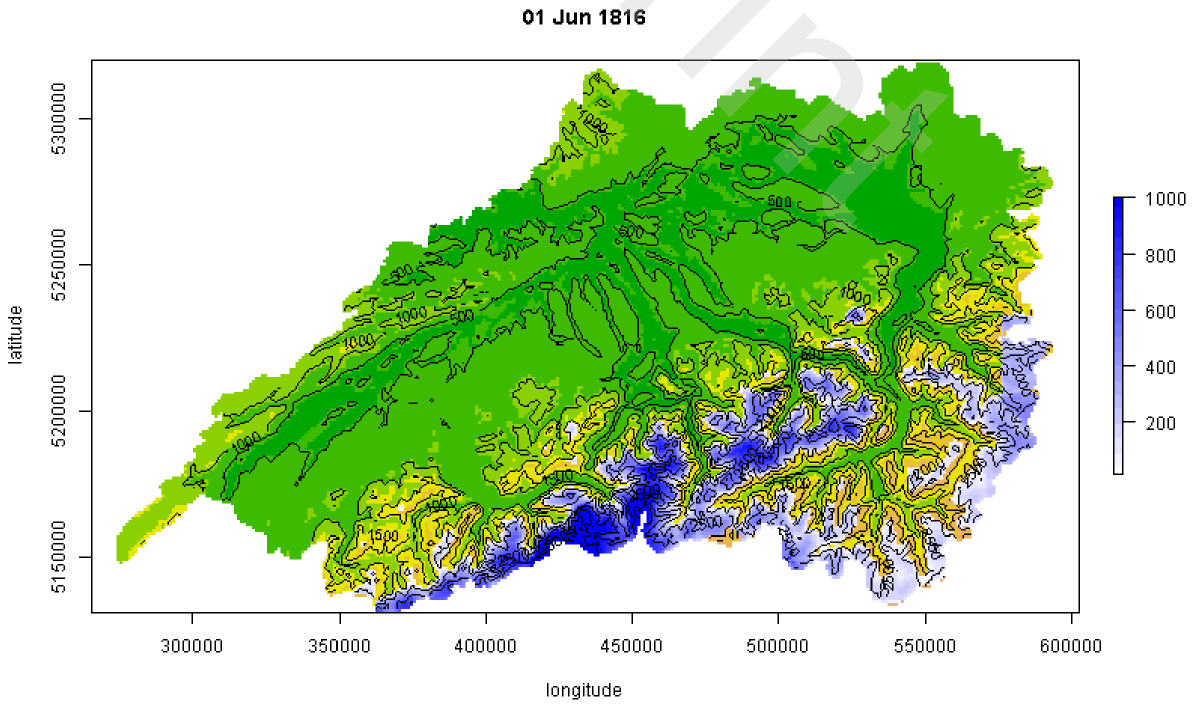
The present post-Tambora reconstruction provides information for present-day flood management. It reflects a worst-case scenario that actually occurred and proves its impact on floods at Lake Constance and Basel. A simulation of these extreme weather and climate conditions that challenges current flood management systems (e.g., Jura-waters-correction and accompanied management of further lakes) would be of great interest and require more detailed hydrologic-hydraulic simulations.

Acknowledgements: This study was supported by the Oeschger Centre for Climate Change Research at the University of Bern and the Swiss National Science Foundation projects EXTRA-LARGE and CHIMES.

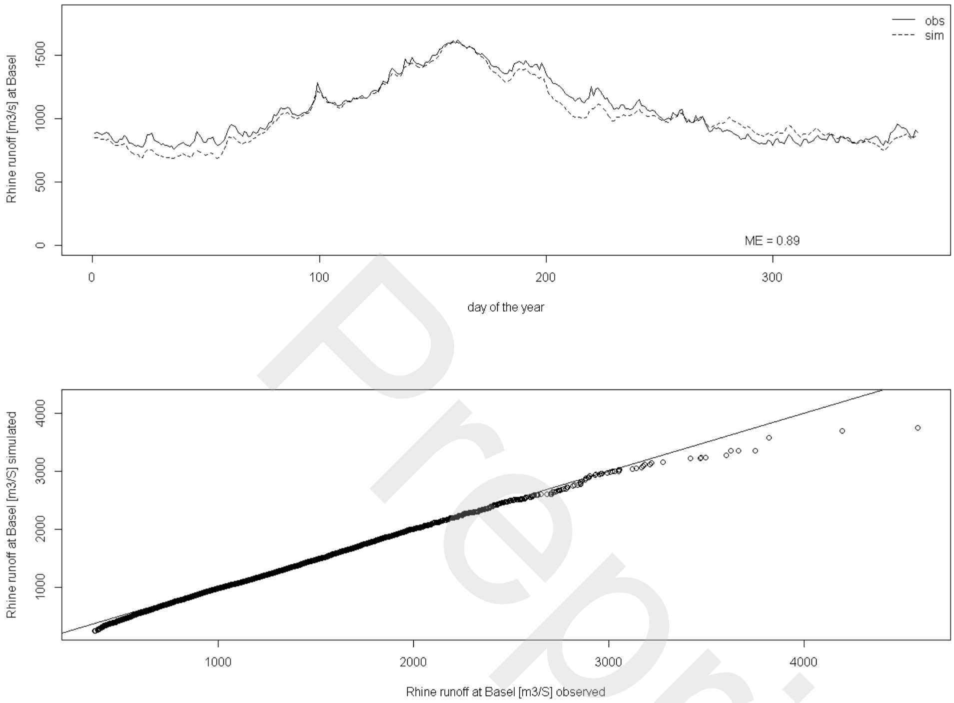
Appendix



Appendix 1: Depicting of the analog procedure applied to reconstruct daily meteorological fields for 1816 and 1817 that drives the hydrological model.



Appendix 2: Animation of the snow extent (bluish colours, SWE in mm) during the summer (01 June – 31 September) illustrating the snow distribution at higher elevations, with three snowfall events affecting the lower mountain valleys (June, August, and September) that melted soon afterwards. The animation is based on a T0R of 1.2 °C and maximum initial snow conditions.



Appendix 3: Validation of simulated Rhine discharge (dashed line) at Basel, Rheinhalle from 1981-2009 against observations (solid line). Upper panel depicts the long-term mean; lower panel depicts the quantile-quantile-plot for the same period.

References

Amt für Wasserwirtschaft, editor. Die Abflussverhältnisse des Rheins in Basel. Bern: Amt für Wasserwritschaft; 1926.

Auchmann R, Arfeuille F, Wegmann M, Franke J, Barriendos M, Prohom M et al. Impact of volcanic stratospheric aerosols on diurnal temperature range in Europe over the past 200 years: Observations versus model simulations. Journal of Geophysical Research:

Atmospheres 2013;118(16):9064–77. http://onlinelibrary.wiley.com/doi/10.1002/jgrd.50759/full.

Auchmann R, Brönnimann S, Breda L, Bühler M, Spadin R, Stickler A. Extreme climate, not extreme weather: The summer of 1816 in Geneva, Switzerland. Clim. Past 2012;8(1):325–35.

Bider M, Schüepp M, Rudloff H. Die Reduktion der 200 jährigen Basler Temperaturreihe. Arch. Met. Geoph. Biokl. B. 1959;10(1):164.

Brönnimann S, Krämer D. Tambora and the "Year without a summer" of 1816: A persepctive on earth and human systems science. Bern: Geographica Bernensia; 2016.

Flückiger S, Brönnimann S, Holzkämper A, Fuhrer J, Krämer D, Pfister C et al. Simulating crop yield losses in Switzerland for historical and present Tambora climate scenarios. Environ. Res. Lett. 2017;12(7):74026.

Frei C, Schöll R, Fukutome S, Schmidli J, Vidale PL. Future change of precipitation extremes in Europe: Intercomparison of scenarios from regional climate models. J. Geophys. Res. 2006;111(D6).

Froidevaux P, Schwanbeck J, Weingartner R, Chevalier C, Martius O. Flood triggering in Switzerland: The role of daily to monthly preceding precipitation. Hydrology and Earth System Sciences 2015;19(9):3903–24. https://www.hydrol-earth-syst-sci.net/19/3903/2015/hess-19-3903-2015.pdf.

Hall D, George Riggs, Vince Salomonson. MODIS/Terra Snow Cover 5-Min L2 Swath 500m, Version 5; 2006.

Haylock MR, Hofstra N, Klein Tank AMG, Klok EJ, Jones PD, New M. A European daily high-resolution gridded data set of surface temperature and precipitation for 1950–2006. J. Geophys. Res. 2008;113(D20):1691.

Jöhnk KD, Straile D, Ostendorp W. Water level variability and trends in Lake Constance in the light of the 1999 centennial flood. Limnologica - Ecology and Management of Inland Waters 2004;34(1-2):15–21.

Krämer D. "Menschen grasten nun mit dem Vieh": Die letzte grosse Hungerkrise der Schweiz 1816/17 ; mit einer theoretischen und methodischen Einführung in die historische Hungerforschung. Zugl.: Bern, Univ., Diss., 2013. Basel: Schwabe; 2015.

Laternser M, Schneebeli M. Long-term snow climate trends of the Swiss Alps (1931-99). Int. J. Climatol. 2003;23(7):733–50.

Luterbacher J, Pfister C. The year without a summer. Nature Geosci 2015;8(4):246–8.

MeteoSwiss. Documentation od MeteoSwiss Grid-Data Products. Daily precipitation (final analysis): RhiresD., 2013. http://www.meteoswiss.admin.ch/content/dam/meteoswiss/de/service-und-publikationen/produkt/raeumliche-daten-niederschlag/doc/ProdDoc_RhiresD.pdf (accessed October 11, 2017).

Pfister C. Wetternachhersage: 500 Jahre Klimavariationen und Naturkatastrophen (1496 - 1995). Bern: Haupt; 1999.

Raible CC, Brönnimann S, Auchmann R, Brohan P, Frölicher TL, Graf H-F et al. Tambora 1815 as a test case for high impact volcanic eruptions: Earth system effects. WIREs Clim Change 2016;7(4):569–89.

Schüepp. Lufttemperatur: Beiheft zu den Annalen der SMZ. Zürich, 1961.

Schulla J. Hydrologische Modellierung von Flussgebieten zur Abschätzung der Folgen von Klimaänderungen. Dissertation. Zürich; 1997.

Schulla J. Model Description WaSiM: www.wasim.ch, 2015. http://www.wasim.ch/ (accessed July 30, 2017).

Stahl K, Weiler M, Kohn I, Freudiger D, Seibert J, Vis M et al. The snow and glacier melt components of streamflow of the river Rhine and its tributaries considering the influence of climate change. Lelystad: CHR-KHR; 2016.

Wegmann M, Brönnimann S, Bhend J, Franke J, Folini D, Wild M, Luterbacher J Volcanic Influence on European Summer Precipitation through Monsoons: Possible Cause for “Years without Summer”, JClim 2014; 27(10): 3683–3691.

Winkler P. Revision and necessary correction of the long-term temperature series of Hohenpeissenberg, 1781–2006. Theoretical and Applied Climatology 2009;98(3):259–68.