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Changes in flood frequencies in Switzerland since 1500

P. Schmocker-Fackel[1,*] and F. Naef[2]

[1]Mountain Hydrology and Torrents, Swiss Federal Research Institute WSL, Switzerland
[2]Institute for Environmental Engineering, Swiss Federal Institute of Technology Zürich, ETHZ, Switzerland
[*]now at: Hydrology Division, Federal Office for the Environment FOEN, Bern, Switzerland

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Correspondence to: P. Schmocker-Fackel (petra.schmocker-fackel@alumni.ethz.ch)

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Abstract

In Northern Switzerland, an accumulation of large flood events has occurred since the 1970s, preceded by a prolonged period with few floods (Schmocker-Fackel and Naef, 2010). How have Swiss flood frequencies changed over the past 500 years? And how does the recent increase in flood frequencies compare with other periods in this half millennium? We collected historical flood data for 14 Swiss catchments dating back to 1500 AC. All catchments experienced marked fluctuations in flood frequencies, and we were able to identify four periods of frequent flooding in Northern Switzerland, lasting between 30 and 100 years. The current period of increased flood frequencies has not yet exceeded those observed in the past. We tested whether the flood frequency fluctuation could be explained with generalised climatic indices like solar activity or atmospheric circulation patterns. The first three periods of low flood frequency in Switzerland correspond to periods of low solar activity. However, after 1810 no relationship between solar activity and flood frequency were found. Nor could a relationship be established between reconstructed NAO indices or reconstructed Swiss summer temperatures. We found re-occurring spatial patterns of flood frequencies on a European scale, with the Swiss periods of frequent flooding often in phase with those in the Czech Republic, Italy and Spain and less often with those in Germany. The pattern of flooding in Northern Switzerland and the Czech Republic seem to be rather similar, although the individual flood events do not match. This comparison of flooding patterns in different European countries suggests that changes in large scale atmospheric circulation are responsible for the flood frequency fluctuations.

1 Introduction

Large floods occurred in Northern Switzerland in 1977, 1978, 1999, 2005 and 2007. This flood-rich period was preceded by a period with relatively few floods (Schmocker-Fackel and Naef, 2010). Another accumulation of large flood events in this region was observed in the second half of the 19th century (Rötlisberger, 1991). Can we identify other periods of high or low flood frequencies during the last 500 years? How does the recent flood-rich period fit in with this context? And is it possible to explain flood frequency fluctuations with generalized climatic indices?

To answer these questions, long flood time series are needed. Therefore, we include historical information about floods back to 1500 in our analysis. In Switzerland, detailed descriptions of floods which occurred prior to runoff measurements exist. Hächler (1991) and Rötlisberger (1991) collected data on such historical floods and Pfister (1984 and 1998) used historical floods as one parameter in more extensive climatic studies. In numerous case studies, historical floods have been used to extend the measured annual flood series to improve design flood estimations (e.g., Gees, 1997; Schaub et al., 1990). We collected the historical flood time series of 14 catchments in Central and Northern Switzerland. We always referred to more than one, or even all, time series in our interpretations to minimise the problem of possibly incomplete, erroneous and inhomogeneous historical flood time series. This is a new approach to interpreting historical flood data in Switzerland hydrologically. We also address the problem of comparing historical data with current discharge measurements.

Records of historical floods have been used to study changes in the flood frequencies of European rivers during recent centuries or even the whole millennium and have been related them to climatic parameters (e.g., Benito et al., 2003; Camuffo and Enzi, 1995; Glaser and Stangl, 2004; Sturm et al., 2001). A good overview over European historical hydrology is given by Brázdil et al. (2006a). We compare Swiss flooding frequencies with those of other European rivers, and finally, discuss some theories about possible causes for the flood frequency fluctuations.

2 Methods

2.1 Study sites

Switzerland is a small country (41 285 km^2) in Western Europe with large climatic differences due to the Alpine mountain range which runs from west to east across Switzerland. North of the Alps, a temperate Middle European climate dominates, while the climate south of the Alps is Mediterranean. For this study, we used data from 14 Swiss catchments situated in the Alps and in the Swiss Plateau (Fig. 1). The largest one is the Rhine catchment up to Basel (35 924 km^2), which drains most of Northern Switzerland as well as parts of Austria and Germany, and the smallest is the Renggbach in Central Switzerland (12 km^2).

In small catchments with limited storage capacities of soil and geology like the Renggbach, the Urnäsch and the Sitter, floods are mainly caused by convective rainfall events of limited spatial extent but high rainfall intensities. In the remaining 11 catchments, large-scale rainfall events with lower rainfall intensities but longer duration produce large floods. In addition, high water levels in the pre-alpine lakes after extensive snow melt influence flood formation in the Rhine River.

2.2 Historical flood information

Historical records, such as chronicles, diaries, letters or parish chronicles often mention floods and the damage caused by them. These records allow the reconstruction of the flood distribution over many centuries and contain valuable information about magnitude, formation and development of floods. In our study, historical floods from 1500 onwards were compiled from the WSL historical and recent flood damage databases (Rötlisberger, 1991; Hegg et al., 2000), the Weikinn compilation (Weikinn, 1958 to 2002) and data from Gees (1997), Hächler (1991), Pfister (1984; 1998) and Schaub et al. (1990). An event was counted as a flood if a river name and flood damage were mentioned explicitly. If a flood occurred in more than three catchments in Switzerland at the same time and caused extensive damage, it was classified as a large-scale flood. We found records of over 400 historical flood events in the 14 catchments. More than 100 affected more than one catchment and we classified 48 of them were as large scale flood events.

Historical records have some limitations, since historical flood series, especially before 1750, may not be complete and may be partly incorrect (e.g. contain dating errors). And the written sources are often subjective (Glaser and Stangle, 2004) and vary in their accuracy and information content. This can result in large uncertainties when interpreting single time series, but this can be overcome to some extent by looking at several time series together.

2.3 Connecting historical flood information with recent discharge measurements

Details of floods tended to be recorded, if substantial damage occurred. However, each river has its own discharge threshold, which often changes over time, above which damage occurs at a given site. These thresholds depend on the river channel capacity and the damage potential along the river. Therefore, the frequencies of flood damage varies from river to river, so that the absolute number of floods recorded in the different sources cannot be compared for different catchments. However periods when there was frequent or little flooding can be compared.

Direct runoff measurements provide another source of information. Measurements were started for the Rhine in Basel in 1808 (Ghezzi, 1926), but for the other rivers (Table 1) no records are available before the 20th century (FOEN, 2007), and for the Renggbach none have been recorded.

Historical information about floods and discharge measurements may be combined in two ways. Sometimes, historical sources contain such a wealth of information about river bed geometry and historical water levels that it is possible to estimate the flood discharge through hydraulic calculations (e.g., Naulet et al., 2005; Macdonald et al., 2006; Schaub et al., 2001). In most of our catchments, the data was too sparse to use this approach. Another possibility is to convert a continuous discharge measurement series into a flood event series. Sturm et al. (2001), for example, counted a discharge event as a flood if the peak discharge was larger than the mean yearly flood discharge plus one or more standard deviations, and then compared the resulting event series visually with the historic flood series.

In this study, we also converted our discharge series into flood event series using three different approaches:

(1) We assumed the same frequency of floods in the measurement period as in the historical period between 1750 and 1900.

(2) We defined a flood as a yearly flood discharge larger than a flood with 10 year return period (HQ 10, calculated according DVWK, 1999).

(3) For the Rhine in Basel and the Thur in Andelfingen, we estimated a discharge threshold by comparing the historical flood series with early discharge or water level measurements.

Only one historic flood was considered per year to ensure the single flood events were independent. The discharge thresholds above which a discharge is defined as a flood comparable to the historic floods together with some other hydrologic parameters is shown in Table 1.

Figure 2 illustrates how with the example of the annual flood series of the Rhine in Basel from 1808 to 2007 historical data may relate to runoff measurements. Years with records of flood damage are marked with a star. The flood discharge thresholds determined with the three methods described above are also given. From 1750 to 1900, 18 flood events caused damage. Using the Method 1 “same frequency” this corresponds to 13 flood events since 1900 and a discharge threshold of 3600 m^3/s.

In the first Jura water correction J1 between 1868 and 1891, the Aare, a Rhine tributary, was redirected into the large lakes (Biel, Neuchâtel and Murten), which now serve as large equalizing reservoirs (Vischer, 2003). We considered the effect of flood protection measures and the construction of large reservoirs in all our other time series as well, based on the work of Margot et al. (1991).

Other possible sources of inhomogeneity in long flood time series are changes in the quality of historical data sources, increases in damage potential with time and man-made or natural changes in the river flow capacity, e.g. sediment accumulation or erosion (Camuffo and Enzi, 1996). Possibly some of our time series are also affected by these inhomogeneities, which is why we did not interpret the flood series of single catchments but always used at least three catchments. By using the historical flood information carefully, the flood history of a river or a region can, we belive, be reliably reconstructed over several centuries.

3 Results

3.1 Hydrological evaluation of historic flood data

Figure 3 shows the historic flood frequencies of the 14 catchments, combined with the flood frequencies determined from the annual flood series. Flood-rich periods alternate with periods of lower flood frequency in all catchments, independent of catchment size. The number of floods differs between the catchments, with several showing a recent increase in flood frequency in the range of earlier periods.

The estimated threshold discharge above which damage occurred along the Rhine and the Thur corresponds approximately to a discharge with a 10-year return period (HQ 10). Historical floods also correspond approximately to floods with a return period of 10 years in a further seven catchments.

For the Muota and the Plessur, the historical floods have return periods of 40 and 70 years, respectively. It seems that, in both catchments, only large floods caused damage and were therefore recorded.

In the Schächen, Method 1 “same frequency” estimates slightly more floods and significantly more floods in the Alpenrhein than Method 2 “HQ10”. In the Alpenrhein, the floods identified with Method 1 correspond to floods with only a two year return period. Before the large river correction starting in 1892, the Alpenrhein was a braided river system transporting and accumulating large amounts of sediment and had only minimal river bank protection. Therefore, even small floods could cause damage. However, the earlier the records, the fewer the small floods recorded, resulting in an apparent increase of floods with time.

Figure 4 shows the number of historical floods in each catchment and their seasonal distribution. Summer and fall floods (June to October) dominate in all catchments. The percentage of winter floods (November to February) is below 10%. Only in the Rhine at Basel and in the Thur do they comprise around 20% of all events. Spring floods (March to May) are also of minor importance. The seasonal distribution of flood frequencies has changed little during the last 500 years.

3.2 Periodicities of flood frequency in Switzerland

In Fig. 5a, the 10- and 30-year moving sums of all flood events per year at the 14 catchments are shown, with events that occurred in more than one catchment counted only once. Large-scale flood events in the whole of Switzerland are also shown. The apparent increase in flood events over time is probably mainly the result of more information about flood damage with time, the fluctuations within the time series cannot be explained by incomplete data.

Figure 6a shows the flood-rich decades for each catchment separately. During flood-rich decades more floods occurred than the mean number of floods per decade for the period 1700 to 2000 plus one standard deviation. Likewise, flood-rich periods overlapping two decades were identified from the 10-year running mean of observed flood frequency. From 1500 to 1700, flood-rich decades could only be identified visually. Figure 6b shows how many catchments in each decade experienced an above average number of floods.

Based on the data displayed in Figs. 5a and 6, periods of low and high flood frequency in Northern Switzerland were identified. Four periods with peaks in flood frequency (P1 to P4) and four periods with lows in flood frequency (L1 to L4) are discussed in more detail below.

1500–1560 (low 1)

This was a period of low flood frequency in Northern Switzerland. According to Brázdil et al. (1999), 1506 to 1559 was an exceptional long period of low flood frequency for the Rhine in Basel. The apparent absence of floods in some catchments can partly be ascribed to missing data.

1560–1590 (peak 1)

During this period, flood frequency peaked especially in the large north alpine catchments Rhine, Thur, Emme and Sihl, as well as in the Alpenrhein in Grisons. In 1566 and 1570 there were catastrophic floods caused by extreme summer precipitation over large areas of long duration, accompanied by high lake-water levels due to extensive snow melt. Although the four neighbouring alpine catchments Muota, Schächen, Linth and Reuss in Central Switzerland also experienced some floods during this period, flood frequencies do not appear to have been higher. This, however, may well be due to missing data.

1640–1720 (low 1)

Between 1640 and 1720, especially after 1690, there were exceptionally few floods throughout Switzerland. The total number of flood events in Northern Switzerland was very low during this period, as were the number of large-scale flood events and flood-rich decades (Figs. 5a and 6b). In the 1690s there seem to have been only two small flood events and none of our catchments had a flood rich decade. Pfister (1999) found no historic evidence of any catastrophic floods between 1641 and 1706 in the Alpine region and maintains that this finding cannot be explained by missing data alone.

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1740–1790 (peak 2)

This is the period with the highest flood frequency in our records. In the 1760s eleven of the 14 catchments had a flood-rich decade and two catastrophic floods occurred in 1762 and 1764. For the flood in July 1762, damage was recorded in eight of the 14 catchments. Only the three smallest catchments Renggbach, Urnäsch and Sitter did not seem to have had a peak in flood frequency in the 1760s, but they did in the 1740s.

1790–1810 (low 2)

Between 1790 and 1810, another short period of low flood frequency occurred in Northern Switzerland.

1820–1940 (peak 3)

During this period, a very long and heterogeneous peak in flood frequency was observed throughout Switzerland. Most catchments had several peaks during this period. The annual flood series of the Rhine (Fig. 2), for example, contains peaks with markedly increased flood frequency around 1820, 1850 and 1870. Again two sub-periods can be distinguished, one before and one after 1890. Catastrophic flood events were more frequent between 1830 and 1890, while there was a peak in all flood events after 1890. The apparent increase in the number of small flood events towards the end of this period might be partly due to more data being availabel later in this period (e.g. first continuous runoff measurements).

1940–1970 (low 3)

In this period there were few floods in Northern Switzerland, especially in Central and NE Switzerland (Schmocker-Fackel and Naef, 2010). The only places where several floods occurred in the 1940s and 50s, are the three small catchments, and the Alpenrhein and the Plessur in the Grisons.

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Since 1970

Since the 1970s, the flood frequency in most catchments has increased, especially in NE Switzerland and, since the 1990s, also in Central Switzerland (Schmocker-Fackel and Naef, 2010). However, the flood frequencies observed during the past 40 years in our 14 catchments are still within the range of or lower than those observed during the last five centuries.

3.3 Can we explain the fluctuations in observed flood frequency?

According to our study and the reviewed literature, the flood frequencies in Europe have changed at intervals of 30–100 years during the last 500 years. Glaser and Stangl (2004) even see such fluctuations within the past millennium. Studies that include paleoflood records show that the magnitudes and recurrence frequencies of floods can change very abruptly (Knox, 2000; James, 1993). However, the exact climatic mechanisms responsible for these changes in flood frequencies are not yet clear (Redmond et al., 2002; Benito et al., 2004 and studies referenced in there).

It is possible that changes in flood frequencies may be connected to some generalized climatic parameters such as climate periods, solar activity, the North Atlantic Oscillation (NAO), atmospheric circulation patterns, mean summer temperatures or length variations of glaciers. Glaser (1998) for examle, claims there is a connection between fluctuations of flood frequencies in Central Europe and the onset and end of the little Ice Age (1430–1850). Periods of high flood frequency in the Mediterranean basins of Spain (Benito et al., 2003), the Yangtze River in China (Jiang et al., 2005) and the Upper Mississippi River, USA (James, 1993) also correspond to the initial and final decades of the medieval warm period and the Little Ice Age. In Switzerland, high flood frequencies could also be observed in the second half of the 15th (Rötlisberger, 1991) and in the19th century at the onset and end of the little ice age. However, there were also large fluctuations during and after the little ice age.

Vaquero (2004) found a relationship between low flood activity on the Iberian Peninsula and the Maunder Minimum period of solar activity, which suggests that solar activity may have caused the flood frequency oscillations. In Switzerland, the periods L1, L2 and L3 of reduced flooding correspond to the end of the Spörer Minima period of solar activity (1420–1550), to the Maunder Minima (1645–1715) and to the Dalton Minima (1790–1820) (Fig. 5b). There appear to have been exceptionally few floods during the late Maunder Minimum (1675–1715). However, flood frequency was low in the 20th century (L4) when solar activity was high (Solanki et al., 2004; Lean, 2000). During the first half of the Spörer Minimum, the flood frequency was probably also high, since several catastrophic floods occurred in Switzerland in the 1470s and 1480s (Rötlisberger, 1991). Camuffo and Enzi (1995) found little if any cause-effect relationship between solar activity and the flood frequencies of the Po, Tiber and Adige rivers in Italy during the past 2000 years including the Wolf and Spörer Minima. Pauling and Paeth (2007) found no clear connection between winter precipitation extremes in Central Europe and solar, volcanic or anthropogenic forcing.

Floods in English and Welsh upland catchments seem to mainly occur during the negative North Atlantic Oscillation NAO (Macklin and Rumsby, 2007). However, we found no relationship between our Swiss flood data and the reconstructed summer NAO indices of Luterbacher et al. (1999 and 2002a), or the reconstructed winter NAO values of Trouet et al. (2009) (Fig. 5c). Clearly, the forcing of the NAO is weak in the Alpine region (Casty et al., 2005), and NAO phases do not correlate with Alpine precipitation (Frei et al., 2000). Bouwer et al. (2006) also found no strong relationship between winter river discharges and the NAO index in Northern Europe.

No relationship between Swiss summer temperatures (Fig. 5d) or variations in length of Swiss glaciers (Fig. 5e) and flood frequency could be found. However, both indices indicate that the periods P1 to P4 of high flood frequency in Switzerland correspond to periods of rapid climatic change in the Alpine region.

One link between climate change and the occurrence of hydrologic extremes in Switzerland might be through changes in large-scale atmospheric circulation patterns (Frei et al., 2000). Knox (2000) showed that common jet-stream configurations over

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North America may be associated with positive and negative anomalies of flooding in the Upper Mississippi Valley. Changes over the last 500 years in large-scale atmospheric circulation patterns, determined from reconstructed sea level pressure grids (Luterbacher et al., 2002b) correlated with flood frequency in Central Germany during winter (Sturm et al., 2001; Jacobeit et al., 2003, Mudelsee et al., 2006). The winter discharges of several rivers in Northern Europe also seem to be significantly correlated with the frequency of westerly flow during the period 1926–2003 (Bowler et al., 2006). Summer floods in Central Europe could be linked to special atmospheric circulation patterns such as Vb tracks (Jacobeit et al., 2006; Kundzewicz et al., 2005). For Switzerland, large-scale atmospheric flow classifications and flooding has not been compared. It might, however, be more difficult to find a clear relationship in Switzerland since the atmospheric circulations patterns assisiated with floods in different regions in Switzerland (e.g. westerly flow, southerly flow, Vb tracks) differ greatly. Moreover, the Alps have considerable local influence on extreme precipitation (Grebner, 1993). Another problem is that most floods occur during summer when reconstruction skill of pressure fields is lower than in winter (Luterbacher et al., 2002b).

3.4 Swiss flood cycles in the European context

To find out whether the observed fluctuations in flood frequency in Northern Switzerland correspond to fluctuations found in other parts of Europe, we compared our results with those obtained for the other European rivers and regions listed in Table 2 according to the following rules:

Whenever possible, periods were classified as rich or poor in floods according to similar methods to those used in this study, or according to the respective authors' classifications. However, if the data did not allow such a classification, periods rich and poor in floods had to be estimated visually, and therefore rather subjectively.

We used the time intervals described above for Northern Switzerland. For the catchments and regions where the time intervals were different, we allocated the dominant mode, taking into account that a flood-rich period may have started a little earlier or later than in Switzerland. Where sufficient data are available, such deviations are mentioned in the text.

In Fig. 7, the flood frequencies for different catchments in Europe for selected periods between 1560 and 1810 are shown. During period 1560–1590 floods were frequent in Switzerland. High flood frequencies occurred in the Po River in Northern Italy (Camuffo and Enzi, 1995), in the Czech Republic (Brázdil et al., 2006b) and in the Middle Elbe and the Saale in northeastern Germany (Sturm et al., 2001). Böhm and Wetzel (2006), however, found lower than average flood frequencies in the Lech and Isar rivers in Southern Germany during this period. As did Sturm et al. (1991) in the Weser in Northern Germany and Camuffo and Enzi (1995) in the Adige and Tiber rivers in Italy.

Between 1590 and 1630 the Eastern and Southern European catchments had high flood frequencies. Benito et al. (2003) identified this period 1580–1620 as an “intense, prolonged phase with hydrologic extreme events doubling mean values in basins of the Mediterranean Spanish coast”, whereas Switzerland and Germany experienced a quieter period.

Between 1640–1690, few floods occurred in Switzerland, the Czech Republic, Spain and the Adige and Tiber catchments in Italy. On the other hand, most German catchments as well as the River Po had high flood frequencies.

From 1690–1720, the flood frequency was low in all the European catchments used in this comparison. Barriendos and Rodrigo (2006) found no large floods in the two decades 1661–1670 and 1711–1720 in the Iberian Peninsula.

During the second Swiss peak in flood frequency between 1740 and 1790, the spatial European distribution of flood frequencies resembles those of period 1590–1630 (P1). From 1790–1810, few floods were recorded in Europe with the exception of Spain. In several Atlantic basins in Spain a peak in flood frequency occurred between 1790 and 1800 (Benito et al., 2003). The flood frequency distribution in Northern Switzerland seems to correspond better to that in Spain, Italy and the Czech Republic than to that in Germany.

It is interesting to note that, during three of the six investigated time periods, flood frequencies Europe appear to follow a NW and a SE pattern: During the periods 1590–1630 and 1740–1790, few floods occurred in the NW part of Europe but took place in SE. During the period 1640–1690 the pattern was reversed, and during two periods 1690–1720 and 1790–1810, very little flooding occurred in most catchments.

For the periods after 1810, the pattern of flood frequency is much more heterogeneous, in Switzerland as well as in Europe, which is why the comparison should be at decadal time intervals. With the data available, such a comparison could be only made with the four catchments Vltava, Elbe, Ohre and Morava in the Czech Republic (Brázdil et al., 2006b). For the Czech catchments, we determined the flood-rich decades with the method we used in this study (see also Table 2). In Fig. 8, the percentages of catchments with flood-rich decades for Northern Switzerland and the Czech Republic are displayed for the period 1500 to 1920.

The flood frequency cycles in Switzerland and the Czech Republic seem to be quite similar. Only during peak 2 were slight differences, with a peak in flood frequency in the Czech Republic in the 1740s and one in Switzerland in the 1760s. There has been a recent increase in flood activity after a relatively quiet period, with disastrous floods in the Czech Republic in 1997, 1998 and 2002 (Brázdil et al., 2006b). This corresponds to a similar increase in Northern Switzerland, with large floods in 1999, 2000, 2005 and 2007 after the quiet period between 1940–1970 (Schmocker-Fackel and Naef, 2010).

However, while the periods with high flood frequencies correspond in Switzerland and the Czech Republik, the individual flood events do not. This holds true for recent decades as well as for the 16th and the 19th century. Brázdil et al. (1999) compared flood events in the 16th century in the Rhine (Basel) with the Vltava and Upper Elbe in the Czech Republic and found no floods that occurred at the same time in both countries. Using the Czech data, we also found no individual flood events that matched with any flood in our 14 catchments. During the maximum flood activity in the Czech Republic in the 19th century, there was a prevalence of winter floods (Brázdil et al., 2006b), while in Switzerland summer floods always dominated. This phenomenon was also observed in Spain, where there is a clear coincidence between periods with high flood frequencies in the Mediterranean and Atlantic watersheds, although autumn and spring floods dominate in the Mediterranean watersheds and winter floods in the Atlantic watersheds (Benito et al., 2003).

Flood frequency cycles in the Europe rivers investigated are only partially in phase. Some reoccurring patterns of flood frequency, such as the NW–SE pattern in Europe, were found. But even in regions which were in phase, the floods did not occur on the same dates. It seems that changes in atmospheric circulation patterns on a decadal time scale might be responsible for the changes in flood frequency.

4 Summary and conclusions

Since 1500, periods of higher flood frequencies have alternated in Switzerland with quieter periods. Active periods occurred between 1560 and 1590, around 1760 and in the 19th century. The recent increase in flood frequencies, starting in the 1970s is still in the range of formerly observed ones. Quiet periods were between 1630 and 1720, 1790 and 1810, and 1940 and 1970.

It is not possible to explain these variations with generalized climatic indices. For example, between 1500 and the 19th century, flood frequency was low in Northern Switzerland during extended periods of low solar activity (Spörer, Maunder and Dalton Minima). Between 1700 and 1720 (Late Maunder Minimum), between 1790 and 1810 (Dalton Minimum), low flood frequencies also occurred in many other European countries. However, since 1810 flood between flood frequency and solar activity no longer appear to correlate. In Northern Switzerland, there also seem to be no correlations between flood frequency and either reconstructed NAO indices or reconstructed summer temperatures.

A comparison with the flood patterns of other European rivers suggests that flood frequencies are not in phase over Europe but reoccurring spatial patterns of flood frequency do seem to occur. The flood frequencies in Northern Switzerland are often in phase with those of rivers in Spain, Italy and the Czech Republic, but less with those in Germany. Flood frequency patterns appear to be similar in Switzerland and in the Czech Republic, although neither individual flood events nor the seasonal flood distribution match. It seems likely that changes in atmospheric circulation patterns on decadal time scales are responsible for the spatially heterogeneous changes in flood frequency.

Atmospheric circulation patterns and winter flood frequencies in Central Europe have been found to correlate (Jacobeit et al., 2003), as have jet stream configurations and flooding frequency in North America (Knox, 2000). In Switzerland, different kinds of weather situations can produce large floods (Schmocker-Fackel and Naef, 2010), which makes it more difficult to identify similar relations in Switzerland. Analysis of food frequency data from additional European countries like France, Great Britain and Austria could help to reconstruct changing atmospheric circulation patterns on a scale large enough to show flooding patterns in different parts of Europe.

Procedures for defining design floods assume that the reoccurrence probabilities of floods remain constant over longer periods. Our study, however, indicates that flood reoccurrence probabilities are not constant over time. Since 1500 three periods with high flood frequencies lasting between 30 and 120 years have occurred. This suggests that the current period with more floods in Northern Switzerland, which started in the mid 1970s, might continue for some decades under natural climatic variation. Such natural variation is supplemented by the effects of recent global warming. To estimate future event reoccurrence probability, Frei et al. (2000) suggest including in forecasts (1) changes in large-scale atmospheric circulation, and (2) the greater humidity of the atmosphere induced by global-warming. To reduce the uncertainty in predicting the future frequencies of floods, the causes of the long-term changes in atmospheric circulation have to be better understood.

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Table 1. Hydrologic parameters of the 14 catchments used in this study and the discharge thresholds above which a discharge is defined as a flood comparable to the historic floods.

Catchment, Station	Area [km^2]	Discharge measured since	Annual flood discharge Maximum [m^3/s]	[$m^3/s\,km^2$]	Mean [m^3/s]	Flood discharge threshold [m^3/s] HQ10[a]	Same frequency[b]	Estimated
Alpenrhein, Diepoldsau	6123	1919	2665	0.44	1357	1958	1560	–
Emme, Emmenmatt	443	1909	513	1.16	218	325	280	–
Glatt, Rümlang	302	1948	93	0.31	39	70	67	–
Linth, Mollis	600	1914	402	0.67	195.5	262	275	–
Muota, Ingenbohl	316	1917	425	1.34	169	244	285	–
Plessur, Chur	263	1930	90	0.34	50	71	90	–
Renggbach	12	–	80–120[c]	6.5–9.6[c]	–	–	–	–
Reuss, Seedorf	832	1904	735	0.88	308	454	478	–
Rhein, Basel	35 924	1808	5090	0.14	2839	3700[d] 3800[e]	3600	3600
Schächen, Bürglen	109	1930	165	1.51	35	62	45	–
Sihl, Zürich	336	1919	340	1.01	146	244	260	–
Sitter, Appenzell	74	1908	195	2.63	80	117	128	–
Thur, Andelfingen	1696	1903	1130	0.67	586	818	720	770
Urnäsch, Hundswil	64	1961	120	1.86	65	104	118	–

[a] Flood discharge with 10-year return period.
[b] Same frequency of floods in measurement period as in historical period 1750–1900.
[c] Hydraulically reconstructed discharge of largest flood event in 20th century (VAW, 1995).
[d] After Jura lake correction.
[e] Before Jura lake correction.

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Table 2. The catchments, data and methods used for a comparison of flood frequency on a European scale for the period 1560–1810. In all cases unless otherwise mentioned, we determined the periods rich and poor in floods.

Region	Nr	Catchments	Data available	Method to determine periods rich and poor in floods	Data from
Northern Switzerland	1	14 catchments of this study			
Southern Germany	2	Lech Isar	31-year running flood frequency	Frequency>5	Böhm and Wetzel, 2006
Czech Republic	3	Vltava Elbe Ohre Morava	Decadal flood frequencies	More than one SD from mean	Brázdil et al., 2006b
Northern and Central Germany	4	Pegnitz	Cumulated and filtered flood data	Visually	Glaser, 1998
	5 6 7 8 9	Saale Middle Elbe Weser Main Middle Rhine	Standardized 31-year running seasonal flood frequency	More than one SD from mean determined by authors	Sturm et al., 2001; Glaser and Stangl, 2004
Northern Italy Central Italy	10 11 12	Adige Po Tiber	Frequency distribution of floods	Visually	Camuffo and Enzi, 1995
Spanish Mediterranean coastal area	13	10 Mediterranean basins	Absolute decadal frequency of catastrophic floods and averaged decadal flood frequencies	Visually	Barriendos and Martin-Vide, 1998; Barriendos and Rodrigo, 2006
Spain Atlantic Basins	14	Tagus and several other Atlantic basins	Averaged decadal flood frequencies	Visually	Benito et al., 2003; Barriendos and Rodrigo, 2006
France	15	Drac and Isère	Cumulated flood number (data starting 1600 only)	Visually	Barriendos et al., 2003

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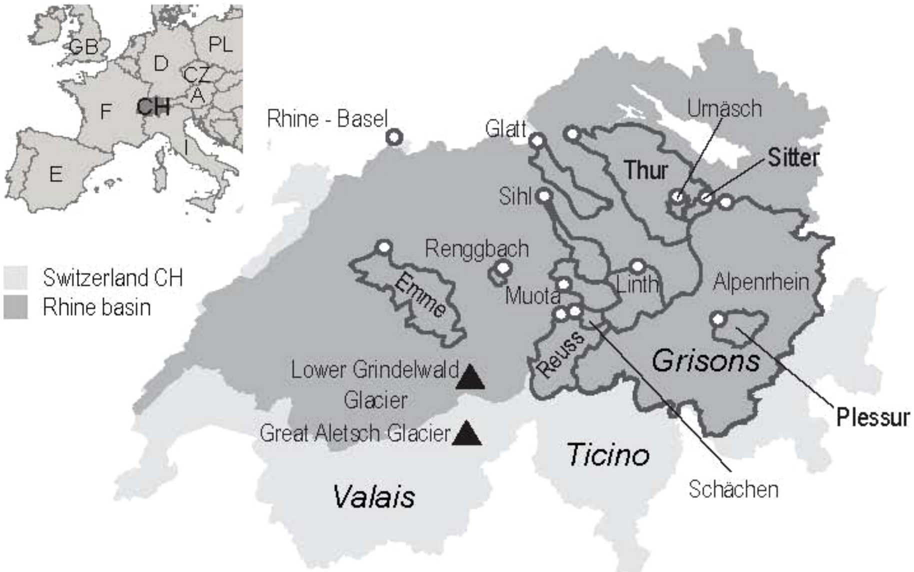

Fig. 1. Location of 14 catchments investigated and the geographical names used in this study.

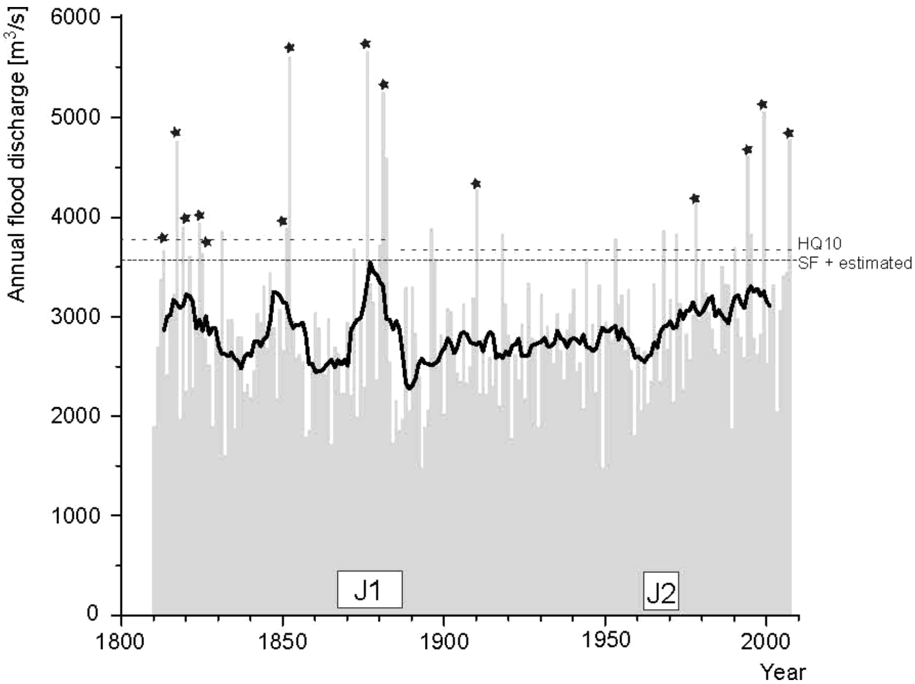

Fig. 2. Annual flood series of the Rhine river in Basel between 1808 and 2007 (grey bars) and its 11-year running mean (black line). Years in which flood damage was recorded are marked with stars. Horizontal lines correspond to the different discharge thresholds used in this study to define a flood (SF=same frequency method). The HQ10 discharge was estimated separately for the time before and after the first Jura water correction (J1). Data from FOEN (2007) and Ghezzi (1926).

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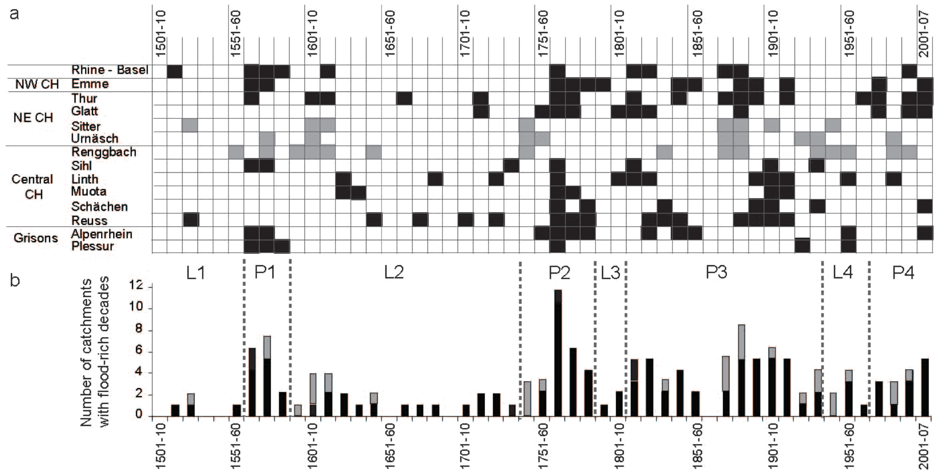


Fig. 3. Decadal flood frequencies and three decadal mean running flood frequencies for 14 catchments in Northern Switzerland. For the period with runoff measurements, different methods were used to define a flood (see Sect. 2.3). Also shown are changes in the river or catchments that influence flood damage and/or flood discharge.

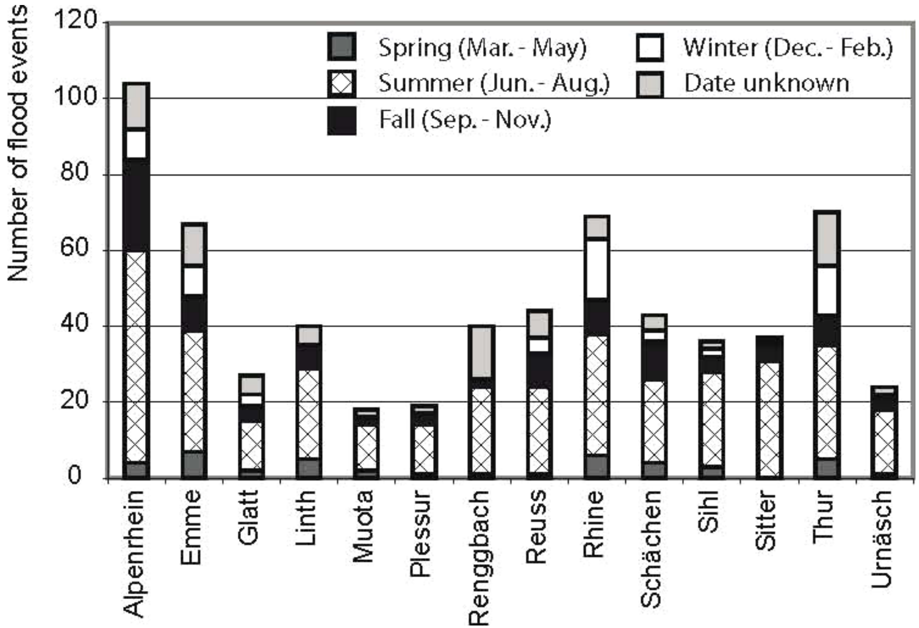


Fig. 4. Seasonal distribution of historic flood events for the period 1500–2007 in the 14 catchments studied. Summer floods dominate in all catchments.

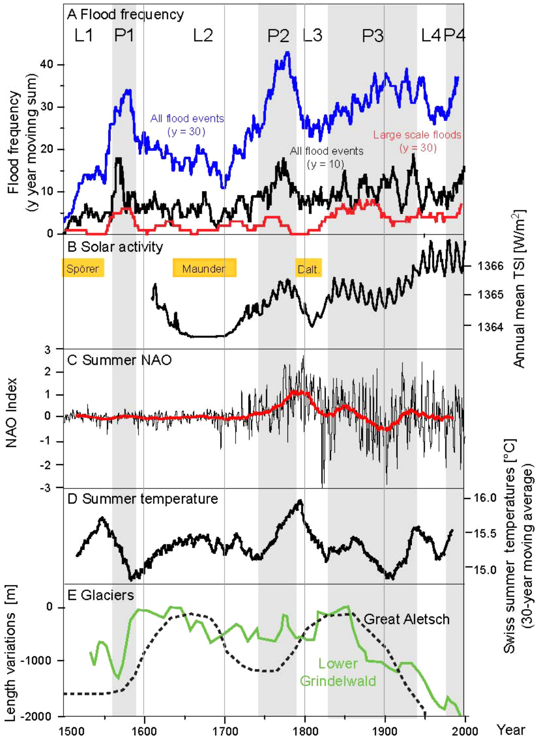


Fig. 5. Frequency of flood events in the 14 Swiss catchments and catastrophic events throughout Switzerland. P1–P4 are periods with many floods and L1–L4 with few floods in Northern Switzerland **(A)**. Also shown are the Spörer, Maunder and Dalton periods of low solar activity and the total solar irradiance TSI from Lean (2004) **(B)**. The reconstructed yearly summer NAO values (black) and the 30-year moving average (red) are from Luterbacher et al. (1999, 2002a) **(C)**, the reconstructed Swiss summer temperatures **(D)** are from Casty et al. (2005) and the advances and retreats of the Lower Grindelwald and the Great Aletsch glacier are from Holzhauser and Zumbühl (1999) **(E)**.

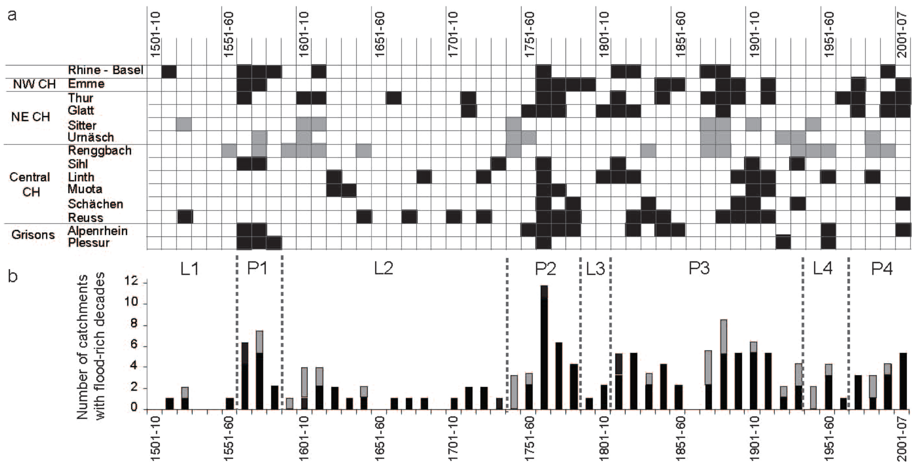
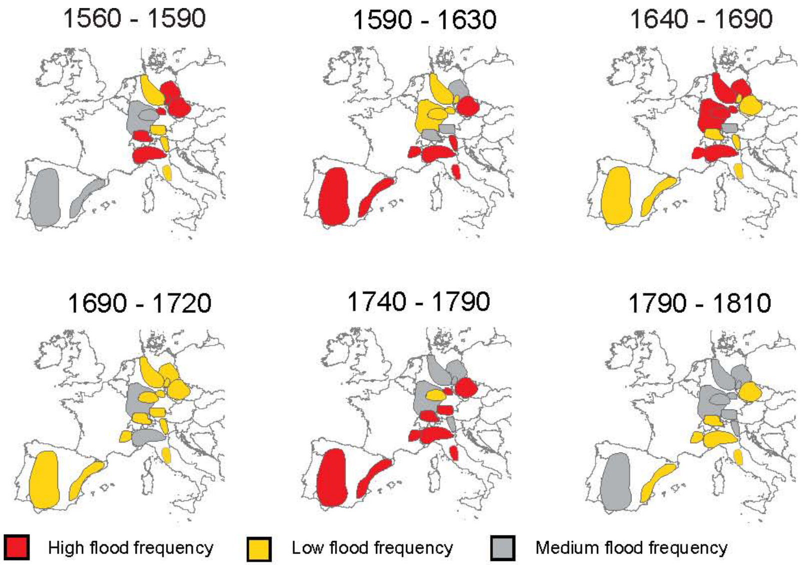


Fig. 6. Flood-rich decades in our 14 catchments (black: flood-rich decade in large catchments caused by long duration rainfall events, grey: small catchments where convective rainfall events are important). Also shown are the periods rich (P1–P4) and poor (L1–L4) in floods in Northern Switzerland, as defined in this study (vertical dotted lines).



No	Catchments:	Data from
1	The 14 Swiss catchments in this study	
2	Lech and Isar, Germany	Böhm and Wetzel, 2006
3	Vltava, Elbe, Ohre, Morava, Czech Rep.	Brázdil et al., 2006b
4	Pegnitz, Germany	Glaser, 1998
5	Saale, Germany	
6	Middle Elbe, Germany	
7	Weser, Germany	Sturm et. al, 2001 Glaser and Stangl, 2004
8	Main, Germany	
9	Middle Rhine, Germany	
10	Adige, Italy	
11	Po, Italy	Camuffo and Enzi, 1995
12	Tiber, Italy	
13	Mediterranean coastal area, Spain	Barriendos & Martin-Vide, 1998; Barriendos & Rodrigo, 2006
14	Atlantic Basins, Spain	Benito et al., 2003; Barriendos & Rodrigo, 2006
15	Drac, Isère, France	Barriendos et al., 2003

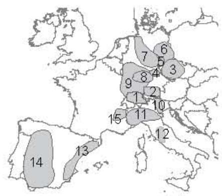


Fig. 7. Schematic presentation of spatial and temporal distribution of periods with very frequent and less frequent flooding in Europe for selected periods between 1560 and 1810.

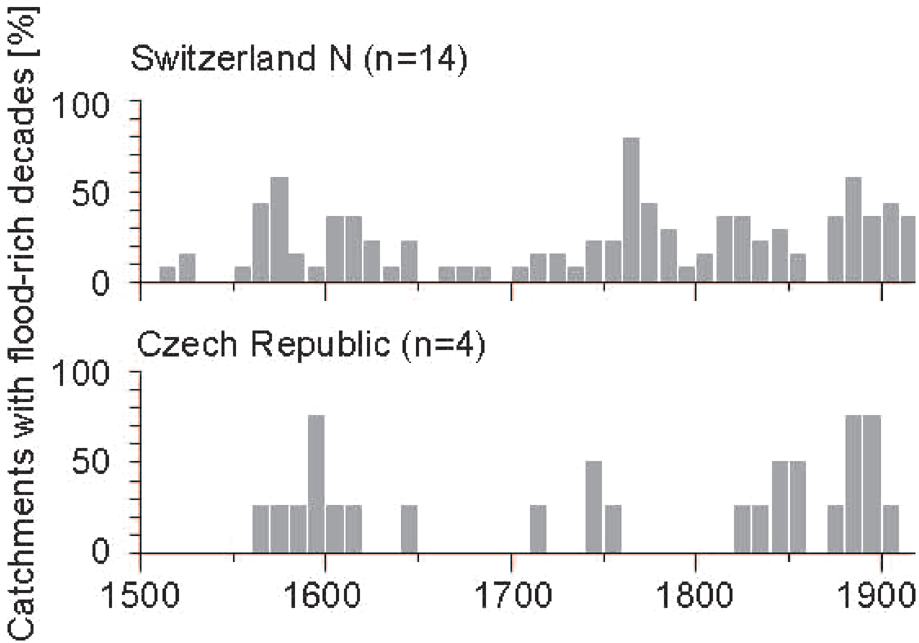


Fig. 8. Comparison of flood frequencies between Switzerland and the Czech Republic (data from Brázdil et al., 2006b), for the period 1500–1920.