Recent floods: changes in floods since the 19th Century

Report

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4. Recent floods: changes in floods since the 19th Century

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4.1. Introduction

The previous sections show how paleohydrologic information and historical hydrology provide important data to extend the systematic streamflow time series to better understand the flood regime. Such long records are necessary to decipher past changes or trends in flood frequency and magnitude. Still, locations with pre-instrumental streamflow records are very limited, and very often flood trend analyses focus only on recorded discharges in the very recent period with systematic gauging, e.g. of annual maximum discharge. In the recent period it is also possible to analyse changes in flooding by analysing other data sources, such as impacts or damage (STEVENS et al. 2016), which are usually recorded by authorities, research institutions or insurance companies (**Box 4.1**).

Floods may be generated by several driving factors, such as atmospheric or climatic factors, antecedent soil wetness conditions, or catchment and river factors (e.g. BLÖSCHL et al. 2017; 2019; BERGHUIJS et al., 2019). These are discussed in Section 5. Here we focus on studies that have investigated changes and trends in recorded streamflow and floods in Switzerland since the 20th Century. We summarize the statistical methods used and the main results of these studies, and put them in context with other findings in Europe and globally (see Table A1 in the **Appendix**).

Box 4.1: Systematic hydrological records in Switzerland and the Swiss flood and landslide damage database

Switzerland has some of the longest hydrological data series available in Europe (PFISTER et al. 2006), as shown by the daily measurements taken in the River Rhine at Basel from 1808. BRÁZDIL et al. (2012) mentioned an even older gauge on the River Rhône in Geneva since ca. 1803 with variations in the Rhône water level recorded daily. Systematic gauging started at the end of the 19th century with the establishment of national hydrometric services, such as the Hydrometrische Centralbureau in 1863 (“Hydrometric Commission” of the Swiss Association of the Natural Sciences; **Figure**).

According to the Hydrological Atlas of Switzerland (https://hydrologischeratlas.ch/), in the year 2000 there were 447 federal, 389 cantonal and 41 private stream gauges (e.g., installed by hydro-electric power companies or universities), including measuring stations for water levels and river discharges. The Federal Office of the Environment (FOEN-BAFU) is responsible for the continuous monitoring of river stages at the federal stations, providing quality-controlled data https://www.hydrodaten.admin.ch/ aggregated to hourly and coarser time resolutions. Flood peaks are reported and flood frequency analysis is conducted at most stations. BAFU also provides stage-discharge rating curves at the controlled measurement cross-sections, which are occasionally checked and updated.

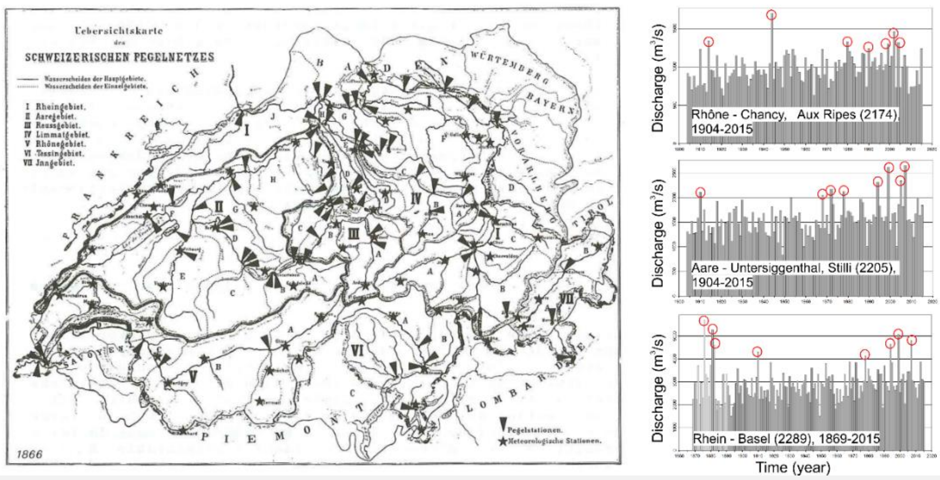

Figure: Map of hydrometric stations in Switzerland in 1866. Modified from (EMMENEGGER 1988). *Three of the longest systematic annual maximum discharge time series available in Switzerland: Rhône, Aare and Rhein Rivers. Red circles show the largest floods recorded.*

Since 1972 the Swiss Federal Research Institute WSL has been systematically collecting and analysing damage due to floods, debris flows, landslides and since 2002 also rockfall. The data collection is based on reports of approximately 3'400 printed Swiss newspapers and magazines, scanned by a media-monitoring company. Additional information is gathered from insurance companies and the internet (e.g. websites of public authorities). Over 21'000 entries are stored in the database for the period from 1972 to 2019. The database is described in more detail in HILKER et al. (2009), BADOUX et al. (2014) and ANDRES and BADOUX (2018). All events since 1972 have caused total damage amounting to almost 14.5 billion CHF (taking inflation into account). These costs are dominated by a few major events (**Figure**). For example, the event of 21-22 August 2005, with total damage amounting to nearly 3 billion CHF, was the costliest event in Switzerland since 1972.

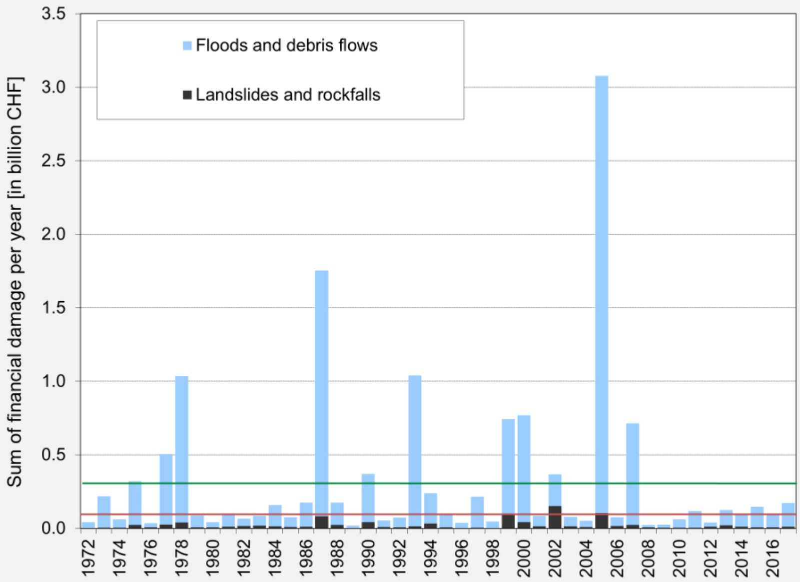

Figure: Annual financial damage due to natural hazards floods/debris flows and landslides/rockfalls in Switzerland 1972-2017 (inflation corrected). The long-term mean (green, 307 Mio. CHF) and median (red, 93 Mio. CHF) are displayed with horizontal lines.

4.2. Flood change detection and attribution

The terms detection and attribution are used to refer to the two steps in any flood change study. These terms were initially defined by the IPCC and reviewed by MERZ et al. (2012) for application to floods. “Detection” is the identification of a change that is significantly different (in a statistical sense) from what can be explained by natural internal variability. Hence, detection is a statistical argument, without explaining the causes for change. Establishing the most likely causes for the detected change is the aim of “attribution” (see Section 5).

Flooding is a complex phenomenon, caused by a number of factors, integrating the influence of climatic and land surface variables over a watershed (KUNDZEWICZ and SCHELLNHUBER 2004); SVENSSON et al. 2006; MERZ et al. 2012; RUIZ-VILLANUEVA et al. 2016). As a result, local conditions can make flood change detection and attribution challenging and site-dependent (BLÖSCHL AND MONTANARI 2010). Flood trend detection is significantly influenced by data quality and time series homogeneity, but also record length and the methods (e.g. statistical test) used (KUNDZEWICZ and ROBSON 2004). For example, in order to detect changes in flood time series influenced by changes in climatic drivers (rather than by land use changes), the use of data from close to natural river basins is recommended, but these conditions are rare. In Switzerland many rivers are affected by hydropower regulation and therefore may not be suitable for detecting natural changes in floods.

In addition, the study period has an impact on trend detection. In general, flood discharge records show high natural variability and may contain large scale periodic behaviour or cycles, and therefore, change or trend analyses should be conducted on periods that are longer than these cycles, ideally about 50 years at least (KUNDZEWICZ and ROBSON 2004; BIRSAN et al. 2005).

Numerous studies have been conducted to understand potential changes in flood regimes (i.e., changes in flood magnitude, frequency and timing) in Europe and across the Globe. We provide a Table in the Appendix with the most relevant ones. Although it is difficult to extract general conclusions from these studies, they do show that spatial heterogeneity in flood change is high due to the strong influence of local processes that affect flooding. A particularly good example is the series of studies of annual floods in almost 4000 catchments in Europe where it was shown that floods increased in some areas (e.g. north-western Europe) and decreased in others (BLÖSCHL et al., 2019), at rates of about +10 to -20% per decade (**Figure 4.1**). These changes were tied to the dominant flood generating mechanisms, which also changed in time and affected the timing of the annual maximum floods (BLÖSCHL et al., 2017, BERGHUIJS et al., 2019).

Climate (and thus climate change) is not the only possible driver of a change in floods, land use and land cover changes together with other human impacts (i.e., river training and engineering) are impacting flood time series as well (SVENSSON et al. 2006; HALL et al. 2014a). More importantly, several drivers may act in parallel and interact with each other, and the detected changes in floods are the integral response of the catchment to these different drivers and their interactions (MERZ et al. 2012).

Therefore, flood change detection and attribution are challenging, and should be enhanced by improving process understanding and separation of anthropogenic from natural variations, and avoiding overemphasis on statistical trend testing only (BLÖSCHL and MONTANARI 2010; CASTELLARIN and PISTOCCHI 2012; MERZ et al. 2012). A better knowledge of past flood changes and their drivers will greatly enhance the capability of anticipating future flood changes (HALL et al. 2014a; VIGLIONE et al. 2016).

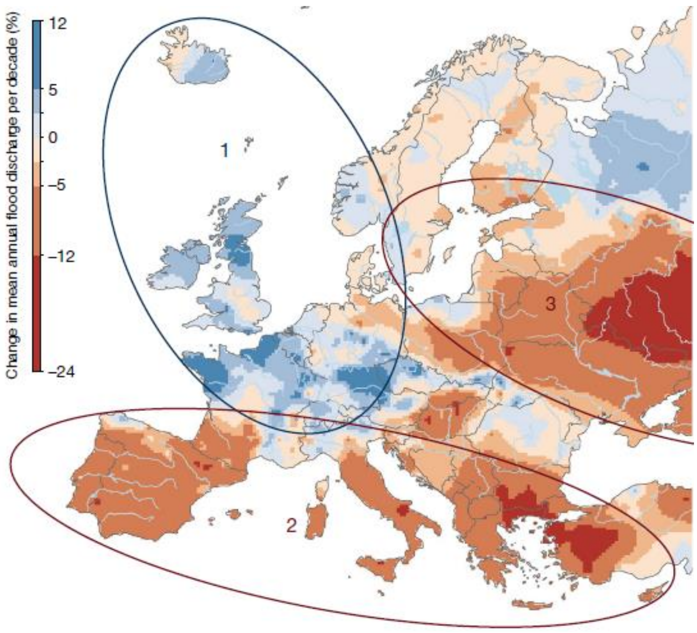

Figure 4.1: Changes in flood magnitudes across Europe in % per decade in the period 1960-2010, with different regions showing increases (1) and decreases (2,3) due to different dominant flood-generating mechanisms (from BLÖSCHL et al. 2019).

4.3. The relevance of non-stationarity

The analysis of changes in floods have a significant societal relevance as extreme events are often most damaging, they influence the design of major civil engineering structures, and shape the fluvial and riparian environment (BERGHUIJS et al. 2017). Moreover, future changes in flood discharges, their exceedance probabilities and time of flood occurrence within the year, are the key variables needed in order to be able to prepare future flood management strategies (HALL et al. 2014a).

Previous studies showed that flooding is a non-stationary process and this has important consequences in the way we address flood risk. Stationarity is assumed in most of the standard statistical flood frequency analyses, meaning that the flood generating process is assumed to be invariant in time (see also MATALAS 1997 and KOUTSOYIANNIS 2006). However, this assumption has been challenged (MILLY et al. 2008) and global flood studies show that the occurrence of large floods is indeed a non-stationary process with large temporal variability (e.g. BERGHUIJS et al. 2017).

Other studies revealed that, under certain circumstances, a stationarity assumption and long-term flood records (e.g., including historical information) still may provide reliable flood discharge quantiles (MACHADO et al. 2015). The rejection of the stationarity hypothesis in the UK resulted in a new recommendation when designing hydraulic structures (see Defra, Flood and Coastal Defence Program). The structure should be designed to convey the 100-year flood, which is estimated based on the traditional flood frequency analysis; however, it is recommended to use a precautionary safety factor (i.e., a safety margin of 20% to represent changes expected by 2085; PROSDOCIMI et al. 2014; REYNARD et al. 2004). Similar guidelines exist in other countries (e.g., Belgium, Denmark, Germany, Norway, Sweden, Australia), some include a correction factor from model-based assessments of future climate projections. These factors range between 10 to 75% depending on the location and the return period considered (MADSEN et al. 2014). In Switzerland, no such correction factors currently exist for design.

The attribution of non-stationarity to climate change is still under debate. Several studies have shown that violations of the stationarity assumption are associated with the presence of abrupt, rather than slowly varying changes, and they are often related to anthropogenic changes such as changes in land use, river regulation through dams and reservoirs (VILLARINI et al. 2011).

4.4. Trends in floods in Switzerland since the 19th century

Several flood change and trend detection studies on instrumental records have been carried out in Switzerland. Although it is difficult to issue a general statement about flood changes due to the different sites, observation periods, and the variety of methods used, here we summarize the main results and findings obtained so far.

SCHMOCKER-FACKEL et al. (2010) analysed trends in flood events in annual maximum discharge records between 1931 and 2007 and from 1850 using historical archives. They focused just on floods, defining a flood event as a discharge greater than the 10-year return period discharge, or as an event mentioned in the historical records. They observed for northern Switzerland (especially along the northern flank of the Alps), numerous floods between 1874 and 1881 and since 1968, while few floods occurred in-between. On the contrary, in southern and eastern Switzerland, the second half of the 19th century and between 1920 and 1960 were flood-rich periods. They concluded that flood rich periods in northern Switzerland corresponded to quiet periods in southern Switzerland and vice versa for the period between 1850 and 2007, with a recent increase in flood frequency and flood discharge along the central and western northern flank of the Alps. According to several studies, a strong increase of precipitation events was observed in northern Switzerland since 1970 which may partly explain the increase in floods (COURVOISIER 1998; BADER and BANTLE 2004; SCHMOCKER-FACKEL et al. 2010). These studies also referred to the observed increase in air temperature since the late 1970s as a potential driver of changes in precipitation and hence in floods (BADER and BANTLE 2004 and SCHMIDLI and FREI 2005). Besides precipitation and air temperature, changes in atmospheric circulation were also suggested as possible causes of the observed changes in large-scale flood frequency (**Figure 4.2**).

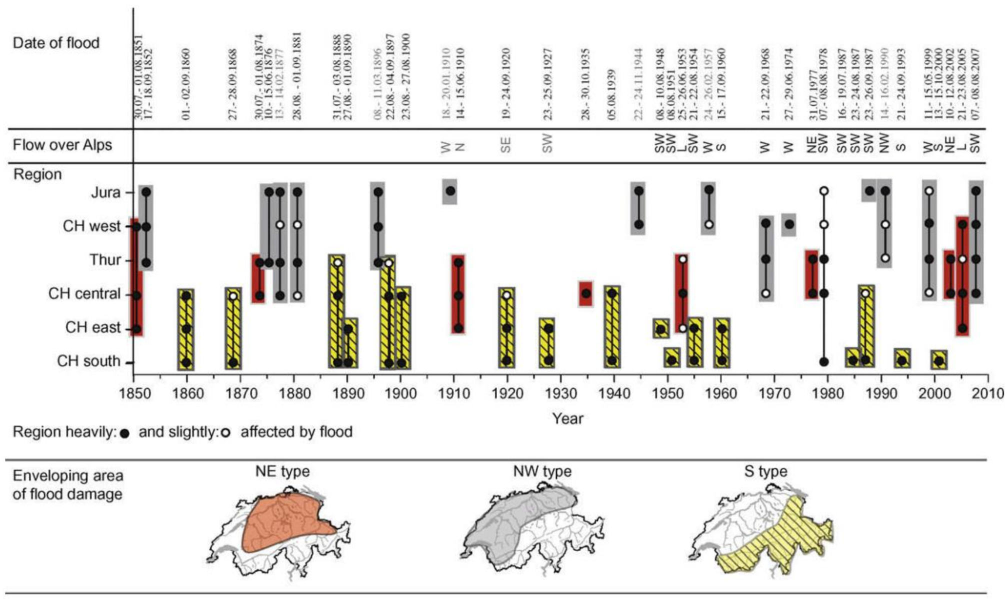

Figure 4.2: Spatial extent of large-scale flood events in Switzerland since 1850. According to the regions affected, the flood events were classified into three types NE-NW-S (maps in bottom row). From SCHMOCKER-FACKEL et al. (2010).

One of the first available studies on trends in annual flood discharges is the work by SPREAFICO and STADLER (1986) who investigated the period between the beginning of the 20th century and 1984. In this study the authors found no significant trends in the majority of the analysed catchments.

BIRSAN et al. (2005) analysed trends in annual and seasonal daily streamflow (including annual maximum discharge) in 48 catchments across Switzerland and for three different periods (1931-2000, 1961-2000 and 1971-2000) using the nonparametric Mann-Kendall test. They observed mainly significant upward trends in streamflow for the three periods, and especially a statistically significant increase in winter floods at more than 50% of the stations in all periods (**Figure 4.3**).

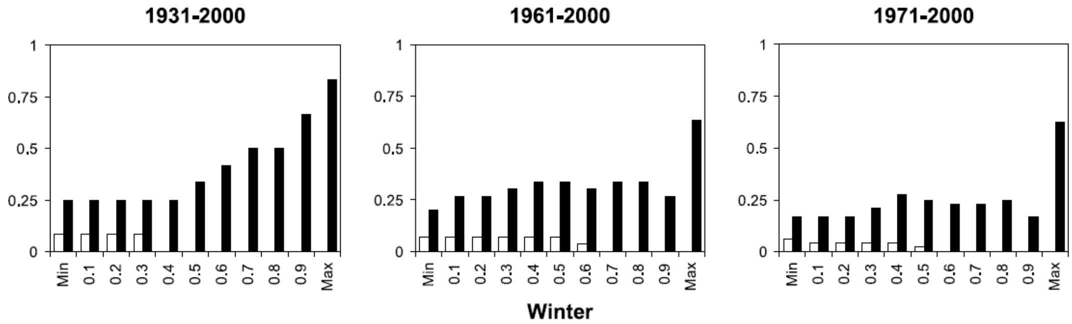

Figure 4.3: Proportion of statistically significant trends -- both increases in black bars and decreases in white bars -- in annual and seasonal daily winter discharge quantiles for three periods found by BIRSAN et al. (2005). The winter (annual) maxima are labelled "Max".

In a pan-European analysis, VILLARINI et al. (2011) tested the presence of change-points and monotonic trends in daily maximum discharges, including 13 catchments in Switzerland with at least 75 years data series. These authors did not find statistically significant increasing or decreasing trends for the vast majority of the cases. This may be explained by the approach they used, in which if a statistically significant change-point in the mean was detected, the authors split the record into two sub-series (before and after the year of the change-point) and performed the trend analysis on each sub-series separately. They found change-points in several of the data series from Switzerland, many of them were presumably associated with river regulation and the construction of dams for hydro-power production mainly between 1950s and 1970s.

Contrary to these results, another analysis was focused on 17 medium to large Swiss alpine catchments by CASTELLARIN et al. (2012), in which all annual maximum series were tested for trends and abrupt changes in the mean and variance. Their results showed evidences of an increase in the frequency of severe floods in the last century and variations in the frequency regime of floods for the last five decades in the studied mountain catchments.

SCHUMANN (unpublished) revisited these studies to characterize spatial patterns of flood variability on decadal time-scales. This work applied a multi-temporal trend analysis (**Box 4.2**) to examine the extent to which observed trends varied as a function of the period of study as well. Regional patterns were identified by correlating the observed patterns in flood variability over the analysed catchments with the Mantel test of dissimilarity between two matrices and non-parametric correlation.

Box 4.2: Multi-temporal flood trend approach
An important consideration in flood trend analysis is that a trend in any fixed period (even over a very long timescale) may be not representative of historical variability. To avoid this, a statistical test can be applied in a multi-temporal framework, where the start and end of the tested time period may be continuously varied (following the approach

proposed by HANNAFORD et al. (2013) and RUIZ-VILLANUEVA et al. (2016). The Figure below illustrates one example where all the combinations of a 30-year window starting in 1951 and ending in 2011 can be observed. This means that every pixel in the graph is one period of 30 years within these start and end dates, and the annual flood peaks are tested for that period. In this example, the statistical Mann-Kendal test (MK) results (MK tau and p-value) are reported for each pixel (period). Blue colours represent downward trends and red pixels upward ones. In the small graph red colours mean p-values less than 0.05 (95% confidence in change), while grey pixels denote p-values greater than 0.2 (confidence lower than 80%), which means the trends are not statistically significant. The figure shows a significant upward trend since the beginning of the data series (1950) until 2008 (red colours), and a downward trend first appearing during the most recent period (blue colours).

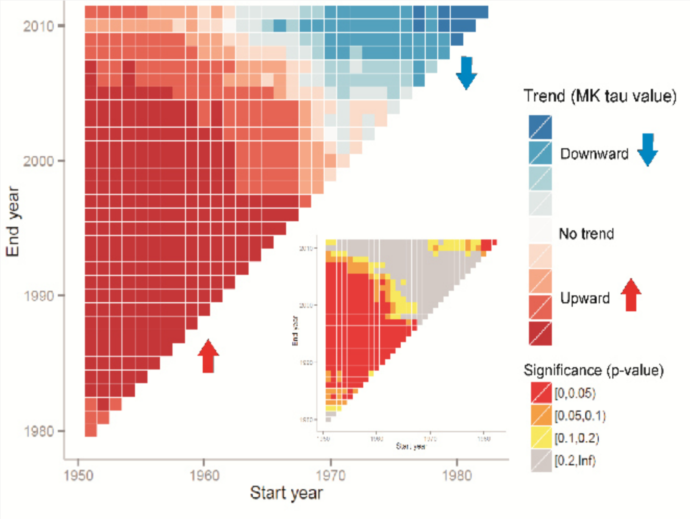

Figure: Example to illustrate the multi-temporal flood trend analysis for the period 1951-2011. Blue and red colours correspond to negative and positive MK tau values respectively, and the inset graph shows the significance (p-value) of the trends. The Figure shows significant upward trends for the period between 1951 to 2011, while the more recent period 1980-2011 shows downward tendencies. Modified after RUIZ-VILLANUEVA et al. (2016).

The multi-temporal analysis was applied to daily streamflow data series from 41 stations distributed across Switzerland, with records between 1921 and 2015. Three station groups were analysed, one formed by stations with records between 1921 and 2015 (9 stations), another with records between 1931 and 2015 (14 stations) and finally the 41 stations with records between 1971 and 2015. The patterns of multi-temporal trends at several stations in annual and seasonal flood maxima are shown in **Figure 4.4**.

As observed in previous studies, differences between northern and southern Alps appeared. For the most recent period (1971-2015) the generalized pattern showed that the annual maximum discharge (AMAX) significantly declined in the Southern flank of the Alps and in the Jura Mountains, while it increased in the Swiss Plateau and the Northern flank of the Alps. In the latter, upward trends were significant for this period, with an outstanding example in the Massa River, where the significant upward trend started in the 70s and continues until now. Similar upward trends for this period were observed for the Gürbe, Minster, Allenbach and Grosstalbach, starting in the last two decades. Contrasting to these cases were the Ova dal Fuorn, Poschiavino, Ova da Cluozza and Riale di Roggiasca Rivers, where significant downward trends were observed since the late 70s until now. This regional pattern was confirmed by the correlation between the stations and analysis of the similarities between the trend matrices (Mantel test).

For the longest period only 9 stations (i.e., Emme, Ticino, Thur, Birs, Sitter, Birse, Landquart, Simme and Doubs Rivers) were analysed and trends showed larger variability with alterations of upward- and downward- dominated times. The Emme River showed a general increasing annual discharge since the beginning of the 20th Century, however, trends were not significant. The Ticino River showed significant decreasing discharges for the period 1921-2015 and the most recent period 1971-2015. The same pattern was observed for the Sitter and Landquart rivers. Maximum and total precipitation trends explained this variability in the discharge, as confirmed by the significant correlation between them.

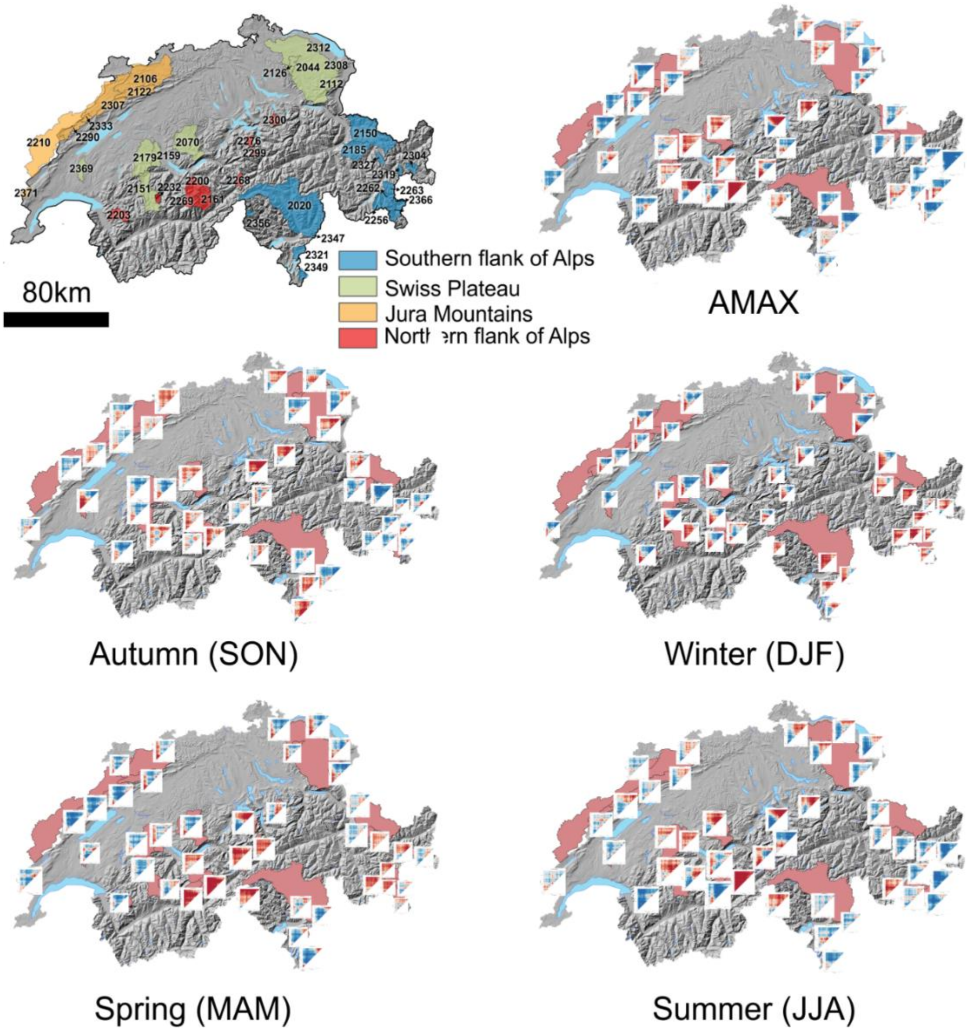

Figure 4.4: Maps showing the catchments and the multi-temporal matrices of the trend analysis for the annual (AMAX) and seasonal (Autumn, Winter, Spring and Summer) maxima discharge. Red colours in the matrices show upward trends and blue downward trends, the darker the colour the more significant the trend.

Seasonal patterns were similar to the AMAX trends, with strong differences between northern and southern Alpine flanks. The significant upward trends identified for AMAX in the recent time (1971-2015) and in the norther flank of the Alps and the Swiss plateau were mostly the result of the significant upward trends observed in Spring and partially in Summer. The Winter season on the other hand showed a different pattern, with significant upward trends in the southern flank of the Alps since the 70s, while the rest of the regions revealed a changing tendency from upward trend from the 70s until now, to a decreasing trend in the last decade. Rivers like the Ticino, Berninabach Rosegbach and Dischmabach showed significant decreases in winter discharges since the 70s, but in general, this tendency seemed to be reversed for other sites in the late 90s or early 2000s. Autumn discharge showed very few significant trends, some of the most relevant were the general downward trend in the Dischmabach, or the recent general upward trends in the Grosstalbach and Minster rivers.

Despite the few upward trends found in the previous analysis, a recent study using flood damage information contained in the Swiss flood and landslide damage database indicated no statistically significant increase in flood damage over time between 1972–2016 (ANDRES and BADOUX 2018). The data was normalized and socio-economic developments including those related to population and wealth were accounted for. Because of the normalization, much higher values were obtained in the earlier years. The spatial analysis of the damage costs showed that damage occurred more frequently in summer by surface water floods (BERNET et al. 2017) and in the central part of Switzerland. These studies suggest that the assumption of an increase in damage due to flooding in the last decades is not fully supported by data everywhere.

Take-Home Messages

- Flood trend analysis results depend on the observational time window and homogeneity of the flood series, catchment characteristics, and statistical trend testing methods used. Methods like the nonparametric Mann-Kendall test are suitable tools to detect changes in flood time series, but they have to be applied and interpreted with caution, as they are affected by data quality, short record length, periodicity, etc.
- It is important to recognize non-stationarity in flood records. Long-time series of measurements are extremely important for trend detection. Multi-temporal trend analyses should be used where possible, to identify the coherence of changes in floods in time between catchments.
- Trend detection studies in Switzerland have shown recent increases in the northern flanks of the Alps, and decreases in southern Switzerland, changes are most pronounced in spring and summer, and related to changes in precipitation and air temperature increase which enhance snow melt. However, changes in floods are still often in the range of observed floods since 1500.