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Past, current, and future changes in floods in Switzerland

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Zusammenfassung

Das Kapitel „Vergangene, aktuelle und zukünftige Veränderungen der Überschwemmungen in der Schweiz“ ist Teil der Hydro-CH2018-Studie zu den hydrologischen Auswirkungen des Klimawandels in der Schweiz. In diesem Kapitel fassen wir die wichtigsten Ergebnisse von Studien zu Hochwasseränderungen für Schweizer Flüsse zusammen und stellen sie in den Kontext von Hochwasseränderungen in Europa und weltweit. Wir beschreiben die neuesten Methoden der Forschung über Hochwasseränderungen und präsentieren diese systematisch und diskutieren die potenziellen Ursachen und Auslöser von Überschwemmungen und ihre Folgen für das Hochwasserrisiko. Das Kapitel wurde von der Schweizer Wissenschaftsgemeinschaft verfasst; in jedem Unterabschnitt sind die Autoren aufgeführt.

Überschwemmungen sind das Ergebnis der Umwandlung von Niederschlag in Abfluss im Einzugsgebiet. Ursächlich sind intensive Regenfälle, außergewöhnlich hohe Schneeschmelze, gesättigte Bodenfeuchtebedingungen oder eine Kombination davon. Da sich die Rahmenbedingungen für Überschwemmungen in der Vergangenheit geändert haben und sich auch in Zukunft ändern werden, können wir auch Änderungen der Häufigkeit und des Ausmasses von Überschwemmungen über die Zeit erwarten. Für die Beschreibung der Art des Hochwassertyp und -stärkenwechsels in einer Region ist es daher von vorrangiger Bedeutung, zunächst Änderungen des Hochwasserregimes in der fernen und jüngeren Vergangenheit zu quantifizieren. Damit können mögliche Ursachen identifiziert und dann Prognosen über mögliche Auswirkungen des Klimawandels in die Zukunft erstellt werden. Die Kapitel sind gemäss dieser Herangehensweise strukturiert.

In Abschnitt 2 untersuchen wir die ferne Vergangenheit und überprüfen Methoden zur Rekonstruktion der holozänen Hochwasserhäufigkeit und -intensitäten aus Paläoflutaufzeichnungen, die auf Sedimentablagerungen in Seen und Auen, aus Sedimentgeochemie und Korngrößen basieren. Dendrochronologische Methoden werden für kürzere Zeiträume vorgestellt. In Abschnitt 3 untersuchen wir, wie dokumentarische historische Hochwasserinformationen verwendet werden können, um die Hochwasserhäufigkeit und die Hochwasserintensitäten in der Zeit vor der Instrumentierung zu bewerten und zu rekonstruieren. In diese Zeit fallen auch starke menschliche Veränderungen von Landschaft und Flüssen. In Abschnitt 4 wenden wir uns statistischen Methoden zur formalen Erkennung von Änderungen (Trends) des Hochwasserzeitpunkts und der Intensitäten aus jüngsten Instrumentenaufzeichnungen zu. Wir zeigen, dass diese Studien in der Schweiz unterschiedliche Trends nördlich und südlich des Alpenkamms und klare saisonale Signale zeigen. In Abschnitt 5 betrachten wir dann die klimatischen und nicht-klimatischen Ursachen von Überschwemmungen und deren Veränderungen. Die betrachteten hydrometeorologischen Ursachen von Überschwemmungen sind intensive Regenfälle, starke Schneeschmelze oder Regen-auf-Schnee-Situationen, sowie Bedingungen mit hoher Bodenfeuchtigkeit. Die häufigsten nicht-klimatischen Ursachen für Überschwemmungen sind Veränderungen der Landbedeckung, Urbanisierung und des Flussbaus. Änderungen dieser Ursachen in der Schweiz werden aus Daten- und Modellstudien zusammengefasst.

Die zukünftigen Auswirkungen des Klimawandels auf Überschwemmungen werden in Abschnitt 6 vorgestellt, in dem wir die jüngsten Ergebnisse der neuen Schweizer Klimaszenarien CH2018 zusammenfassen. Drei hydrologische Niederschlagsabflussmodelle werden verwendet, um die Änderungen der jährlichen Hochwassermaxima und ihre Verteilung in bis zu 300 Einzugsgebieten zu quantifizieren.

Die Ergebnisse zeigen eine Tendenz zu einem zukünftigen Anstieg der Hochwasserintensitäten in der Schweiz von durchschnittlich 0-10%. Die Veränderungen liegen jedoch im Bereich der aktuellen natürlichen Variabilität . Dies macht Prognosen über zukünftige Änderungen der Hochwasserspitzen sehr unsicher, so dass diese größere Unsicherheiten als Änderungen des allgemeinen Abflussregimes aufweisen. In vergletscherten Einzugsgebieten im Hochgebirge sind die vorhergesagten Hochwasseränderungen vernachlässigbar oder sogar negativ, wenn die Beiträge der Eisschmelze zu den zukünftigen Abflüssen verschwinden. Das Erkennen von Unsicherheiten und Variabilitäten ist wichtig für Hochwasservorhersagen; dies wird zusammen mit methodischen Modellierungsaspekten diskutiert. Wir schließen das Kapitel mit einer Zusammenfassung der wichtigsten offenen Fragen zur Forschung von Hochwasseränderungen (Abschnitt 7) und geben Empfehlungen für die Zukunft ab (Abschnitt 8).

Resumé

Le chapitre «Évolution passée, actuelle et future des crues en Suisse» fait partie du projet Hydro-CH2018 sur les impacts hydrologiques du changement climatique en Suisse. Dans ce chapitre, nous synthétisons les principaux résultats des études sur l'évolution des crues des rivières suisses et les plaçons dans le contexte des changements des crues en Europe et dans le monde. Nous décrivons de manière systématique les méthodes les plus avancées utilisées dans la recherche sur l'évolution des crues et discutons les facteurs potentiels causant des inondations et leurs conséquences sur le risque d'inondation. Ce chapitre a été rédigé par la communauté scientifique suisse et chaque sous-section a une liste des auteurs contributeurs.

Les inondations résultent de la transformation des précipitations en ruissellement de surface à l'échelle d'un bassin versant. Ces ruissellements se produisent, lors de fortes pluies, de fonte des neiges exceptionnellement élevée, lorsque les sols sont humides, ou lors d'un effet combiné. Étant donné que les conditions induisant des inondations ont changé par le passé et continueront de changer à l'avenir, nous pouvons également nous attendre à des changements dans la fréquence et l'ampleur des crues. Pour décrire la nature de ces changements dans une région, il est donc primordial de quantifier d'abord les changements des régimes d'inondation dans un passé lointain et plus récent, d'identifier leurs possibles causes, puis de faire des projections des impacts possibles du changement climatique dans le futur. Ce chapitre est structuré suivant cette approche.

Dans la section 2, nous analysons le passé lointain et examinons les méthodes utilisées pour reconstruire, à l'échelle de l'Holocène, la fréquence et l'ampleur des paléo-crues à partir de dépôts de sédiments dans les lacs et les plaines inondables, en analysant la géochimie des sédiments et la taille des grains. Les méthodes dendrochronologiques sont présentées pour des échelles de temps plus courtes. Dans la section 3, nous examinons comment la documentation des inondations historiques peut être utilisée pour évaluer et reconstruire la fréquence et l'ampleur des crues pendant la période pré-instrumentale, durant laquelle les modifications humaines du paysage et des rivières étaient dominantes. Dans la section 4, nous nous tournons vers les méthodes statistiques utilisées pour la détection des changements (tendances) du moment d'occurrence et de l'ampleur des crues à partir d'enregistrements instrumentaux récents. Les études de détection des changements de crues en Suisse montrent des tendances différentes au nord et au sud de la ligne de partage alpin et des signaux saisonniers clairs. Dans la section 5, nous examinons ensuite de plus près les facteurs climatiques et non climatiques induisant des inondations et leurs changements. Les facteurs climatiques considérés sont les fortes pluies, la fonte des neiges ou la pluie sur neige, et les conditions d'humidité élevée du sol. Les facteurs non climatiques les plus courants sont les changements d'utilisation du sol, l'urbanisation et l'ingénierie fluviale. L'évolution de ces facteurs en Suisse est évaluée et résumée à partir d'études de données et de modélisation.

Les impacts futurs du changement climatique sur les inondations sont présentés dans la section 6 où nous résumons les résultats récents tirés des nouveaux scénarios de changement climatique CH2018 en Suisse. Trois modèles hydrologiques précipitation-écoulement sont utilisés pour quantifier les changements des crues annuelles maximales et leur distribution pour près de 300 bassins versants. Les résultats montrent une tendance à une augmentation de l'ampleur des crues en Suisse dans le futur (de l'ordre de 0 à 10%) en moyenne. Cependant, ces changements se situent dans la variabilité naturelle des inondations, même dans le climat actuel. Cela rend les

projections des changements des pics de crue dans le futur très incertaines et nous leur faisons beaucoup moins de confiance qu'aux projections de changement du régime général de ruissellement. Dans les bassins versants glaciaires de hautes altitudes, les changements de crue prédits sont négligeables, voire négatifs, lorsque les contributions de la fonte des glaces au ruissellement disparaissent à l'avenir. Il est important de reconnaitre l'incertitude et la variabilité dans les prévisions des inondations, point qui est discuté et mis en lien avec les aspects méthodologiques de la modélisation. Nous terminons le chapitre par un résumé des principales questions qui restent encore ouvertes dans la recherche sur les changements liés aux inondations (section 7) et formulons des recommandations pour l'avenir (section 8).

1. Introduction

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Floods are the outcome of the catchment transformation of precipitation into runoff under a combination of certain conditions, i.e. during heavy rainfall, exceptionally high snowmelt, wet soil conditions, or a combination thereof (e.g., BERGHUIJS et al., 2019; BLÖSCHL et al, 2019). Floods are already one of the most impacting natural hazards in Switzerland (HILKER et al., 2009), and flood-related damages are expected to continue increasing in Switzerland and many parts of the world in the future. This is mainly because of projected increases in the frequency of flood-generating conditions due to climate change, and increases in population density and assets in floodplains (e.g., BARREDO, 2009; IPCC, 2012; HALL et al., 2014; HIRSCH and ARCHFIELD, 2015; WINSEMIUS et al., 2016; VIGLIONE et al., 2016; BLÖSCHL et al., 2017, 2020). For describing the nature of flood change in a region it is therefore of primary importance to quantify changes in flood regimes in the distant and more recent past, identify their possible causes, and make projections of possible climate change impacts on floods into the future. In this Chapter we collect key research results on these aspects for Switzerland, taking into account complementary European and global findings.

In Section 2 we look into the distant past, and review methods to reconstruct flood frequency and magnitude from paleoflood records derived from sediment deposits in lakes and floodplains, from sediment geochemistry and grain sizes, at long (e.g. Holocene) timescales. Dendrochronological methods, which record damages in tree rings of riparian species, are presented for shorter timescales. Such paleoflood reconstructions are useful to fill gaps in instrumental records, extend time series of floods into the past, and provide envelope values for extreme floods which have not yet been observed. The authors of this section present case studies in Switzerland and make a connection between long-term climate variability and paleoflood variability.

In Section 3 we look at how documentary historical flood information can be used to assess and reconstruct flood frequency and flood magnitudes in the pre-instrumental period in which human modifications to the landscape and rivers were dominant. The authors of this section use Rhine and Limmat case studies to show how the anthropogenic influence on runoff conditions can be semi-quantitatively assessed. Data evidence is given for the clustering of floods into flood-rich and flood-poor periods due to a combination of climatic variables, and the differences in flood frequencies between regions and between catchments due to basin size effects and different rainfall-runoff transformation processes are discussed.

In Section 4 we turn to methods for the formal detection of changes (trends) in flood timing and magnitude from recent instrumental records. The authors of this section present several published and new case studies in Switzerland and globally, where statistical trend testing results for floods and potential climatic drivers are reported. Trend detection studies in Switzerland show the different tendencies north and south of the Alpine divide, and seasonal signals. Trends in floods are not consistent and may affect neighbouring catchments in different ways. Difficulties in interpreting cause and effect relations are presented, and the presence of non-stationarity in flood records is discussed.

In Section 5 we then look closer at the climatic and non-climatic drivers of floods and changes therein. The considered climatic drivers of flooding are heavy rainfall, snowmelt or rain-on-snow, and high soil moisture conditions. Floods can generally be attributed to one or more of these climatic drivers and changes therein. The most common non-climatic drivers of flooding are changes in land cover, urbanization, and river engineering infrastructures. Changes in both climatic and non-climatic drivers in Switzerland are summarised from data and modelling studies. The authors of this section stress that flood impacts and flood risk ultimately arise from the interplay of flood hazard, exposure and vulnerability, and their changes in time, and will continue to do so in the future.

In Section 6 we summarise recent studies on climate change impacts on floods, driven by the new CH2018 Swiss climate change scenarios. The authors of this section use three hydrological rainfall-runoff models forced by climate predicted by the CH2018 scenarios to quantify the changes in annual flood maxima and their distributions. Although the results show small increases in expected annual flood peaks on the average over Switzerland, there is large variability between catchments. In some catchments the climate change signal may hardly be visible, while in others it is strong and prominent. Recognizing uncertainty and variability is important for such predictions, and this is discussed in detail together with methodological modelling aspects.

We close the chapter with a summary of the main open questions (Section 7) and make some recommendations for future research (Section 8).

The overall goals of the Flood Chapter were (a) to synthesize the main results of flood change studies for Swiss rivers and place them in the context of flood changes in Europe and globally, (b) to describe the state-of-the-art methods used in flood change research and provide methodological guidance to readers, and (c) to systematically present and discuss the potential drivers of floods and the problem of attributing changes in floods to their possible causes (flood-generating mechanisms), and their consequences on flood risk. The Flood Chapter was written as a community effort and each section has the contributing authors listed.

2. Paleofloods: changes in prehistoric flood occurrence

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2.1. Introduction

Recurrence times of the most extreme events as well as periodicity of climate fluctuations usually exceed the time span of instrumental and historic records, so that knowledge of paleofloods is required to obtain a complete understanding of flood frequency and related controlling factors. Paleofloods are past or ancient floods that occurred without direct observation or recording by humans (BAKER 2006). Paleoflood records can be established by geologic (lake sediments, floodplains, geomorphology) or biologic (dendrogeomorphology, lichenometry) archives. These data can be merged with historic and instrumental data to obtain a complete past record of floods, also on younger timescales, and to calibrate the geologic/biologic archives. In this section, we focus on floods in Switzerland on a Holocene timescale and their analysis by means of paleoflood data, techniques and archive integration (SCHULTE et al. 2019a; 2019b; WILHELM et al. 2019).

The systematic records of streamflow from the Swiss urban areas in the lowlands go back to the early 19th century (e.g. the Basel–Rhine station, in operation since AD 1808). In the Alps, in contrast, instrumental hydrological measurements only go back 100 years and many of the time series are affected by flood gaps, e.g. from AD 1937 to 1967 (GEES 1997). For this reason, it is difficult to confidently assess floods with a return period of >200 years using short instrumental series (SCHULTE et al. 2015). The incorporation of paleoflood datasets into conventional flood-frequency analyses greatly extends the hydrological data series (COSTA and BAKER, 1981) reducing uncertainty (RUIZ-VILLANUEVA et al. 2013) and improving the data available for risk analysis (BAKER 2006; 2008). This approach is thus of great value for the planning of large-scale hydrological projects (e.g. OSTENAA and LEVISH 1996). Paleoflood data also provide a significant added value to the instrumental time series by defining the maximum limit of flooding in the analysis of envelope curves (ENZEL et al. 1993), or testing the analysis performed in the calculation of the probable maximum flood PMF (BENITO and THORNDYCRAFT 2005). The PMF has been used as a standard for hydrological analyses of dam safety, a critical topic in Switzerland, for decades. In Switzerland, dam safety guidelines prescribe the estimation of the so-called design flood with return period 1000 years, HQ1000, and the safety flood, estimated by 1.5·HQ1000 or the PMF for dam design (SFOE, 2008). Recent research has focused on using the PMF estimation based on hydrological modelling (ZEIMETZ et al. 2014; 2015), however, the use of paleoflood data series could also improve the estimation of HQ1000. A recent example in Switzerland is the EXAR project (Hazard information for extreme flood events on the rivers Aare and Rhine), which aims to acquire information on extreme floods with return periods between 10^3 and 10^7 years in the Aare and Rhine Rivers with paleoflood techniques. Also, the international FWG-INT project developed in the Bernese Alps is an innovative approach that integrates multi-archive datasets from floodplains, lakes, historical sources and botanical evidence for the development of a temporal-spatial (4-D) paleoflood model of alpine catchments (SCHULTE et al., 2019b).

Paleoflood studies do not necessarily provide analogues of future flood–climate episodes but they may provide evidence of flood response to climate shifts in terms of flood magnitude and frequency (KNOX 2000; REDMOND et al. 2002). Several paleoflood studies in Switzerland have documented the sensitivity of floods to climatic conditions and solar activity (SCHULTE et al. 2008; 2015; GLUR et al. 2013; WIRTH et al. 2013a, 2013b) and the preferential clustering of large floods in certain time periods, influenced by long-term trends in atmospheric circulation or oceanic sea-surface temperatures (SCHULTE et al. 2015; PEÑA et al. 2015).

2.2. Lakes as recorders of past flood events

Lakes act as efficient traps for clastic material eroded from the catchment slopes and floodplains and subsequently transported through the fluvial system (OLDFIELD 2000; SCHILLEREFF et al. 2014). Therefore, lacustrine sediments may record flood events in a continuous and high-resolution mode and thus provide an excellent archive for reconstructing past flood occurrence (e.g. NOREN et al. 2002; MORENO et al. 2008; DEBRET et al. 2010; GIGUET-COVEX et al. 2011; STØREN et al. 2012; WILHELM et al. 2012; CZYMZIK et al. 2013; GILLI et al. 2013; GLUR et al. 2013; WIRTH et al. 2013a). An important advantage is that lake sediments are barely prone to erosion (GILLI et al. 2013) when compared to much more erosive systems in fluvial sedimentary sequences (e.g. SHEFFER et al. 2003; MACKLIN et al. 2005; THORNDYCRAFT et al. 2005; SCHULTE et al., 2019). The intercalation of continuously deposited background sediment with discrete flood layers, usually differing strongly in lithology (**Box 2.1**), offers the potential for the reconstruction of a temporally complete flood record (GILLI et al. 2013). The temporal resolution of such lake-sediment sequences depends on the background sedimentation rate but in the case of annually-layered lithology (varves), even the seasons of paleofloods can sometimes be determined (WIRTH et al. 2013a). These lake-sediment sequences usually contain abundant terrestrial organic matter so that reliable radiocarbon dating can be established.

Extreme precipitation mobilizes and entrains large amounts of sediment particles in a catchment and feeds them into the river network. In the next downstream lake, these floods produce characteristic turbidite layers (MULDER and CHAPRON 2011; GILLI et al. 2013: SCHILLEREFF et al. 2014). Best-suited lakes for flood reconstructions have sufficient relief in the catchment, have inflows forming deltas, and are characterized by a flat and horizontal basin floor, where the flood turbidites accumulate and consequently level out inherited topography (GILLI et al. 2013). Single-lake records may be strongly influenced by local signals or particularities of the specific catchment, such as anthropogenic impact, glacier-cover change, or hydrologic changes. Regionally more significant paleoclimate reconstructions can be obtained using multiple-lake records through investigating and averaging as many sites as possible (see two case studies in sections 2.2.1 and 2.2.2).

Box 2.1: Lacustrine flood layers

Flood layers show a characteristic particle-size grading reflecting the waxing (i.e. coarsening up) and waning (i.e. fining) of the paleoflood hydrograph (**Figure**) (MULDER et al. 2003; LAMB and MOHRIG 2009; MULDER and CHAPRON 2011; GILLI et al. 2013). The top part of the flood layer shows the finest particles and has often a distinctive light colour. Sometimes, several stacked graded intervals within the same flood layer indicate multiple discharge peaks (GILLI et al. 2013). Similar turbiditic deposits may originate from subaquatic mass movements triggered by earthquake-induced shaking, delta overloading, or lake-level fluctuations (e.g. GIRARDCLOS et al. 2007; STRASSER et al. 2007; WIRTH et al. 2011). Hence, it is important to distinguish between flood- and mass-movement-induced turbidite layers (BECK 2009; WIRTH et al. 2011; SIMONNEAU et al. 2013). Mass-movement turbidites are composed by remobilized lake sediments showing a different grain-size pattern and mineralogical and organic composition than flood turbidites. They are often, but not necessarily, thicker than flood layers with a weaker grain-size sorting and a higher content of endogenic minerals and a dominance of aquatic organic material (ARNAUD et al. 2002; SIMONNEAU et al. 2013).

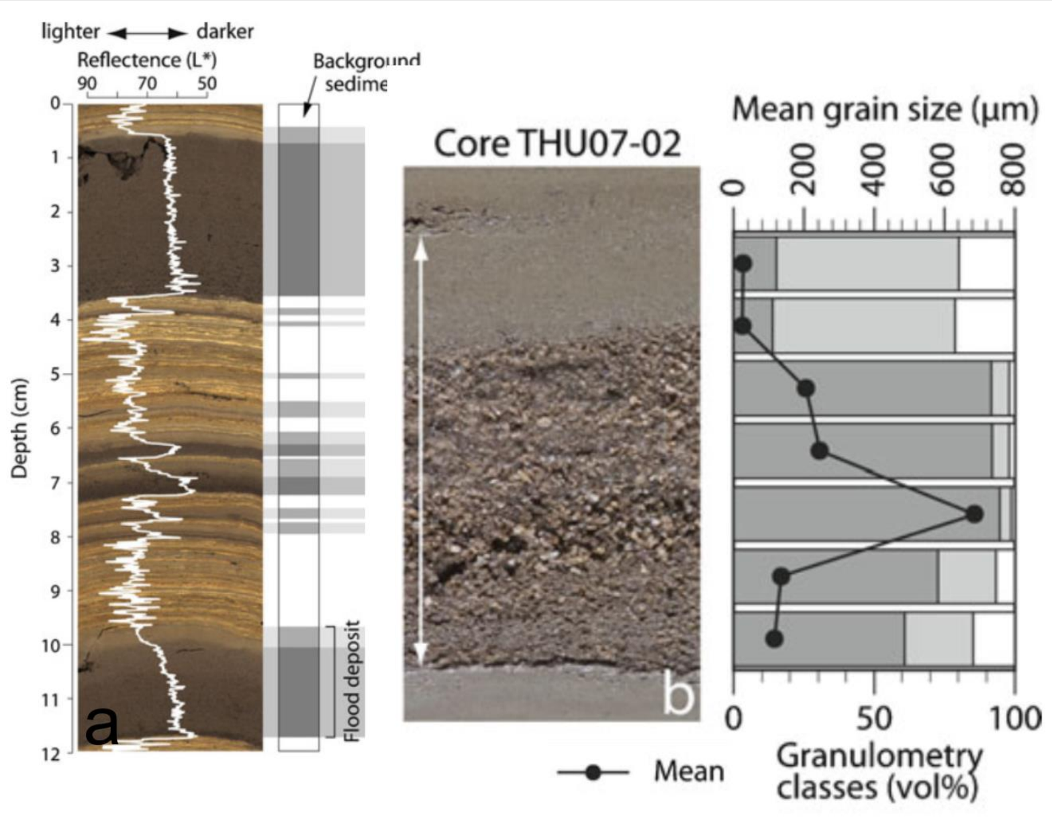

Figure: (a) Contrasting lithologies between background deposits and flood layers. Flood layers (grey bars) are characterized by the fine-grained top part of the layer ('clay cap') marked in light grey bars; (b) Grain-size measurements across one flood layer indicated by the white arrow in Lake Thun (core width = 6 cm) (modified from GILLI et al. 2013).

In addition to the occurrence and age of paleofloods, several studies indicated that paleoflood intensities can be reconstructed using lacustrine flood layers (BROWN et al. 2000; MULDER et al. 2003; BUSSMANN AND ANSELMETTI 2010). The thickness of a detrital layer reflects the volume of mobilized particles, whereas the grain-size distribution of the flood turbidites may reflect the flood dynamics and magnitude. However, these characteristics of the flood layers are also influenced by sediment availability in the catchment, which in turn is influenced by climate, human impact and vegetation cover.

2.3. Geoarchives and historical data from floodplains

2.3.1. Multi-archive analysis of floodplains

Most Pleistocene, glacier-scarped main valleys of the Alps are hotspots of flood risk in Switzerland. The principal reason is the dense population and very limited space for settlement, corresponding mostly to distal areas of alluvial cones and river floodplains, and the fast flood response of small- and mid-size Alpine catchments to heavy rainfall (WEINGARTNER et al. 2003; VISCHER 2003). The on-site analysis of flood archives on floodplains where major damage occurs is promising, but also challenging, due to the complexity of physical processes involved in a dynamic mountain environment (SCHULTE et al. 2019b). Nevertheless, the floodplains of Alpine main valleys and deltas in Switzerland provide excellent sites to reconstruct a continuous flood history (SCHULTE et al. 2009a; SCHULTE et al. 2015; LAIGRE et al. 2013). For example, fluvial erosion, aggradation, channel shifting and avulsion, crevasse splay, effects of embankment and channel correction, generated a characteristic spatial imprint of valley floor geomorphology over centuries in the Aare River valley **(Figure 2.1)**.

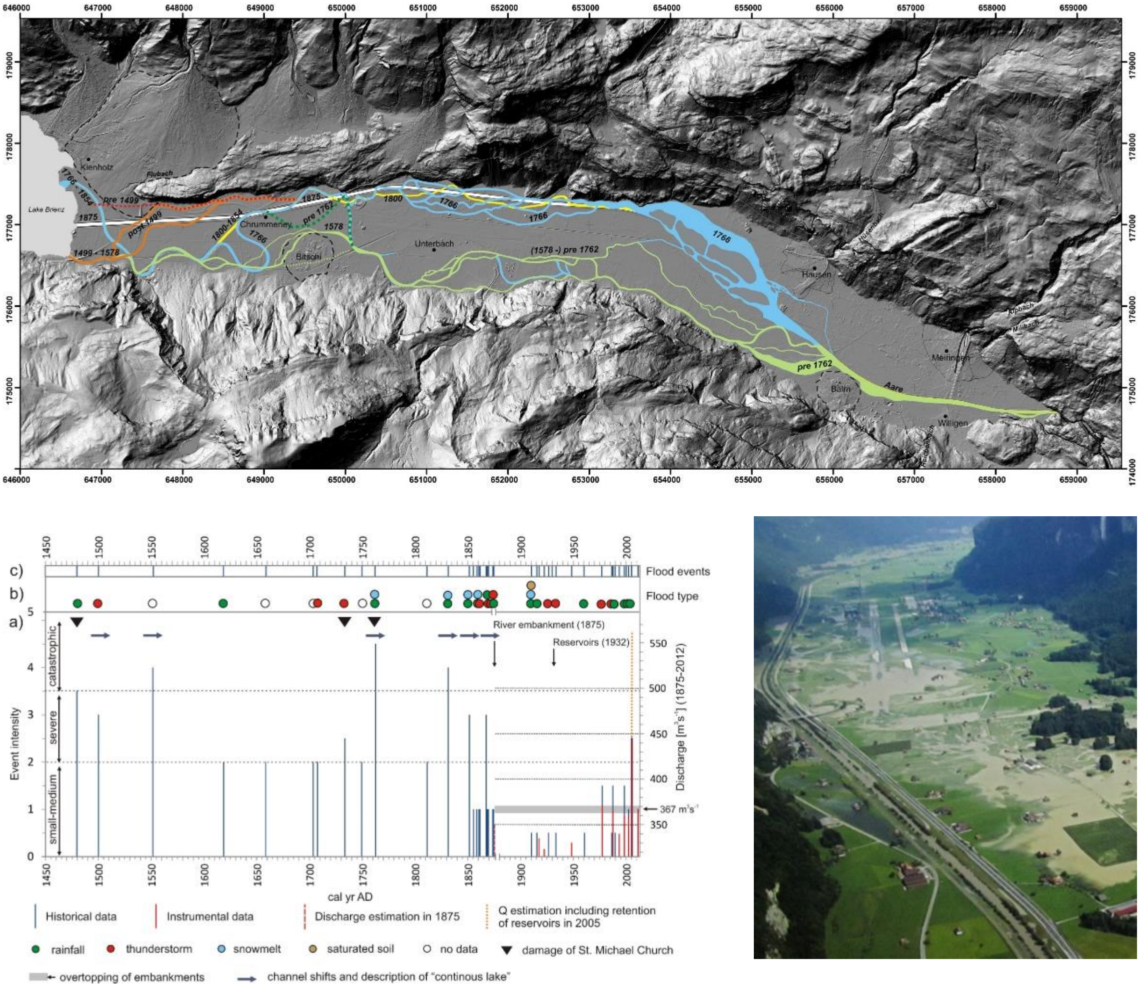

*Figure 2.1: Top -- Evolution of Aare River paleo-channels reconstructed from historical maps, field survey and documentary sources. Bottom left -- Historical flood chronology of the Aare river in the Hasli Valley from AD 1480 to 2012 (*SCHULTE et al. 2015*). Bottom right -- Oblique aerial photograph (Credits Schweizer Luftwaffe) of the 2005 flooding of the Hasli-Aare floodplain.*

The problem of complexity of the time-space evolution of floodplain dynamics can be overcome by an accurate multi-archive reconstruction as demonstrated by SCHULTE et al. (2009a), (2009b), (2015) for the Lütschine and Lombach Deltas and the lower Hasli-Aare Valley (**Figure 2.1**). From the integration of historical data, channel capacity and instrumental measurements, the authors concluded that before AD 1875 a discharge of 351 m^3s^{-1} (a conservative estimate) produced small-medium intensity damage, whereas a discharge of 500 m^3s^{-1} or higher, probably caused catastrophic damage.

2.3.2. Flood reconstruction from floodplain deposits

Sedimentary and geochemical proxy data can be obtained from floodplain deposits (SCHULTE et al., 2008; 2015; CARVALHO and SCHULTE, 2013; **Box 2.2**). These data can be used to reconstruct flood activity by tracing geochemical signatures in floodplain deposits (SMITH and BOARDMAN 1989; PAINE et al. 2002; SCHULTE et al. 2008; JONES et al. 2012; BERNER et al. 2012).

Box 2.2: Sedimentary floodplain archives

Different sediment structures, facies and mineralogy of flood layers result from colluvial, fluvial, alluvial and soil-formation processes. Channel and crevasse splay deposits are generally composed by coarse sand and gravel, levees by sand layers, and over-bank deposits by fine sand and silt, and interdistributary basins contain clay-rich and organic-rich layers as well as peat horizons (**Figure**). River channel shifts and avulsions may cause erosion and re-deposition, whereas sediments in intradistributary basins are deposited conformably. In addition, grain size also reflects flood magnitude. During larger floods, coarse-grained flood layers are deposited, while during moderate and minor floods, fine, sand and silt deposits, and organic-rich horizons are generally formed (SCHULTE et al. 2009a; BERNER et al. 2012).

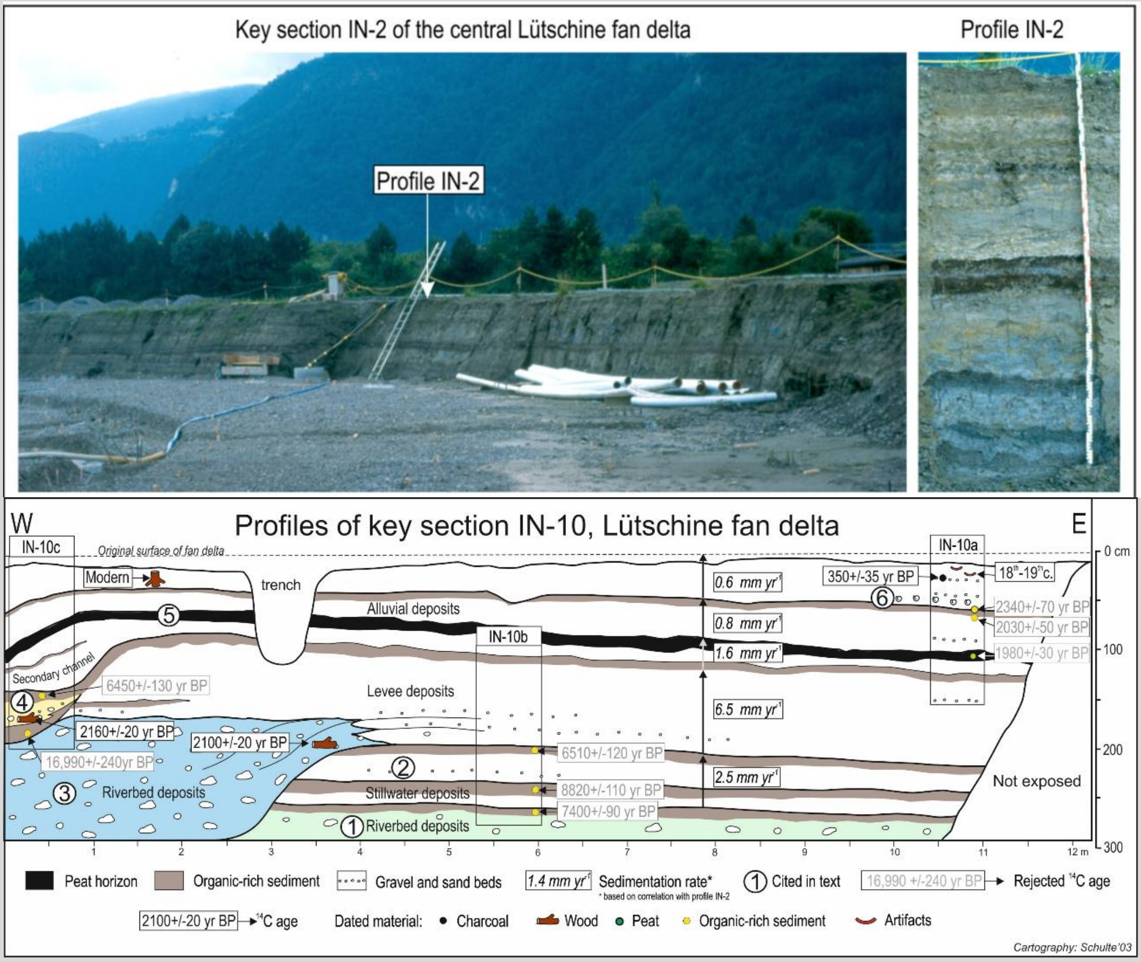

Figure: Top -- IN-2 key section of the Lütschine fan delta. Below -- Lithology, facies and chronology of the IN-10 key section, located 250 m southwest of the IN-2 section. Radiocarbon dates presented in grey were not used for the chronological model (modified from SCHULTE et al. 2009a*).*

BERNER et al. (2012) reconstructed the modern river flood history of the Rhine River based on the correlation between discharge and carbonate content of the suspended load of the Rhine River and floodplain chemostratigraphic characterization. SCHULTE et al. (2008), (2009), (2015) studied the provenance, deposition and diagenetic processes of sedimentary materials and pedological features in several floodplains of the Bernese Alps.

Figure 2.2 shows several major deposition pulses and geochemical variability of upward thinning sequences in a key-section of the Hasli-Aare floodplain. The aggradation of sandy overbank deposits during major flooding is accurately recorded by Zr/Ti, Sr/Ti and Ca/Ti peaks associated with coarse-grained flood layers. Between AD 1480 and AD 1875 (termination of the Aare River Correction) twelve of the fourteen historically recorded extreme events were also recorded by coarse-grained flood layers (**Figures 2.1 and 2.4**). Furthermore, the ratios of stable elements provide information on the provenance of sediments. Zircon is a tracer for sediment supply from the highest area of the basin because this heavy mineral is present in the crystalline rocks such as syenite, granite and amphibolites of late Palaeozoic intrusions.

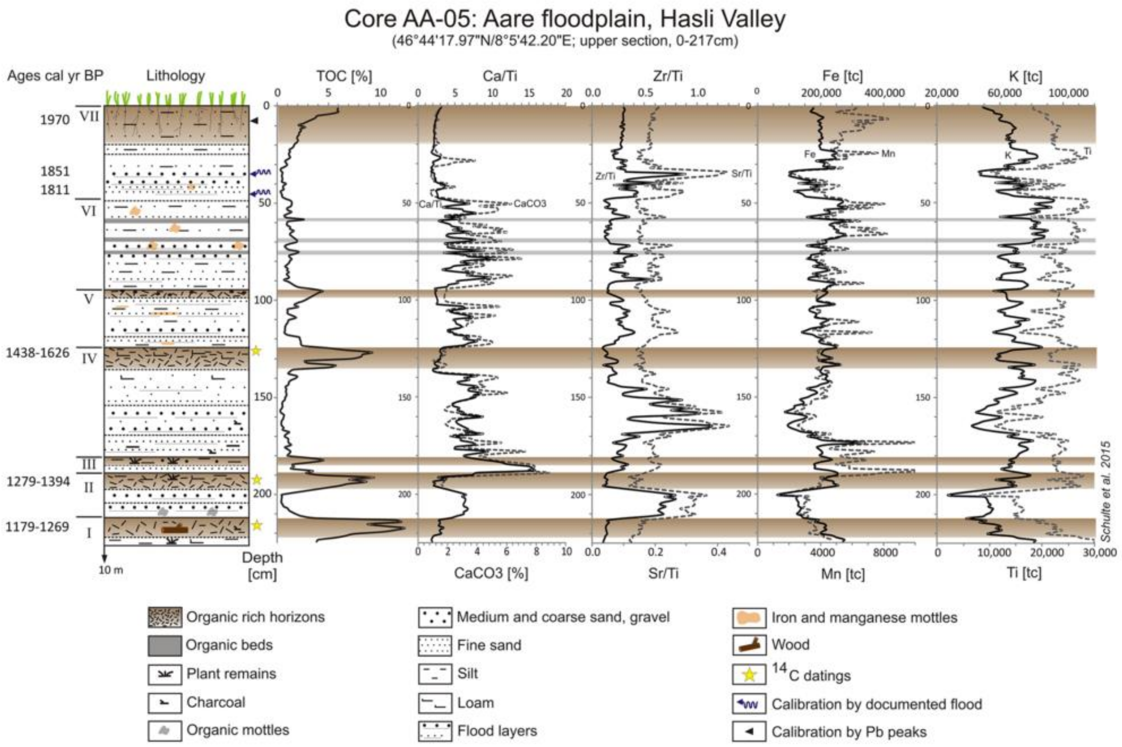

Figure 2.2: Lithology, chronology and geochemical stratigraphy of a core from the Aare floodplain. (from SCHULTE et al. 2015).

2.4. Paleoflood reconstructions based on tree rings

Trees preserve evidence of floods in their annual growth rings whenever they are impacted by floods. The use of trees as paleoflood indicators is based on the 'process–event–response' concept (SHRODER 1978), in which a flood represents the 'process', the 'event' is the resulting tree disturbance (e.g., abrasion scars, abnormal stem morphologies, eroded roots, tilted trunks, or standing dead trees) and the 'response' refers to the physiological response of trees to the disturbance, which results in a specific anatomical imprint created within the tree's annual growth rings (STOFFEL and CORONA 2014; BALLESTEROS-CÁNOVAS et al. 2015a). Scars on tree trunks are the most common evidence of past flood activity. Scars are caused by the impact and abrasion of debris and wood transported during floods (STOFFEL and BOLLSCHWEILER 2008). Scarring can also cause secondary growth and anatomical signatures, such as tangential rows of traumatic resin ducts, changes in vessel size, or callus tissues (BALLESTEROS et al. 2010; ARBELLAY et al. 2012). These features are used to identify the year of past floods, and sometimes even determine the season of flooding (STOFFEL and CORONA 2014). The height of scars can be used to derive peak discharge estimates (BALLESTEROS-CÁNOVAS et al. 2011).

Other paleoflood evidence recorded by trees include (**Figure 2.3**): (i) abrupt decreases in tree-ring widths due to partial tree burial, which limits their nutrient supply and ability to take in water (FRIEDMAN et al. 2005; KOGELNIG-MAYER et al. 2013); (ii) changes in root anatomy after exposure by bank erosion (MALIK 2006), or (iii) anatomical anomalies produced when trees are inundated for weeks during the early growing season (ST. GEORGE et al. 2002; WERTZ et al. 2013).

The use of tree-ring records as a surrogate of flood timing and magnitude has expanded substantially in recent time (ZIELONKA et al. 2008, THERRELL and BIALECKI 2015, BALLESTEROS-CÁNOVAS et al. 2017). A detailed review of paleoflood studies based on tree rings is given by BALLESTEROS-CÁNOVAS et al. (2015a).

The reliability of tree-based paleoflood estimates has been tested against historical and instrumental flood records. The accuracy of the approach depends in part on tree age (TICHAVSKÝ et al. 2017) and species (BALLESTEROS-CÁNOVAS et al. 2015b) . Because riparian trees can be damaged by other causes (e.g. human activities), trees must be selected carefully to minimize the influence of non-flood signals. Moreover, because flood damage can vary between neighbouring trees, samples must be taken from a sufficiently high number of trees to replicate the flood signals and develop reliable estimates of past flood events (BALLESTEROS-CÁNOVAs et al. 2015a; CORONA et al. 2012).

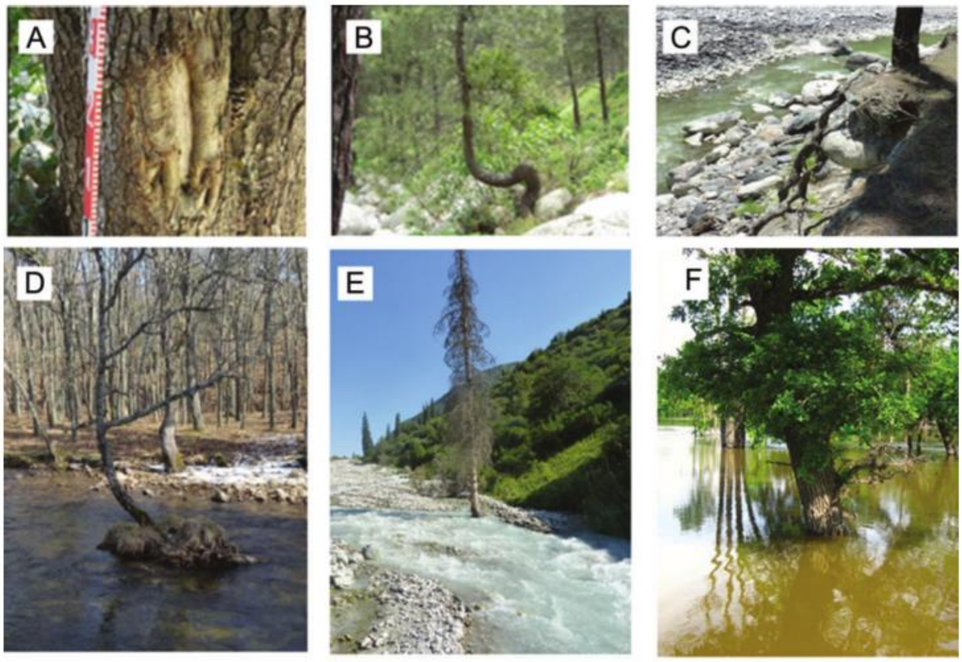

Figure 2.3: Types of botanical evidence to identify paleofloods using tree rings: (A) tree injuries; (B) broken stems and unusual stem morphologies; (C) exposed roots; (D) tilting trees; (E) dead trees; (F) abnormal anatomical structures due to inundation (from BALLESTEROS-CÁNOVAS et al. 2015a).

Tree rings have also been used to reconstruct mass-wasting processes in Switzerland, such as debris flows (STOFFEL and BOLLSCHWEILER 2008; SCHNEUWLY et al. 2012), landslides (SAVI et al. 2013; LOPEZ-SAEZ et al. 2017), rockfalls (STOFFEL et al. 2005; TRAPPMANN et al. 2013; MOREL et al. 2015) or snow avalanches (STOFFEL et al. 2006; FAVILLIER et al. 2017, 2018). To-date, tree-ring studies have not been applied widely to reconstruct floods in Switzerland.

2.5. Paleofloods and climate variability

2.5.1. Floods in the Northern Alps during the last 2500 years

A 2500-year long flood reconstruction for the Northern Alps, on the basis of dated sedimentary flood deposits from ten lakes in Switzerland, showed strong decadal to centennial-scale variations in the occurrence of floods (GLUR et al. 2013). The condensed signal on the basis of over 800 identified and dated flood layers is interpreted to be a regional paleoclimatic signal less influenced by local effects. These data were compared to an independent temperature reconstruction using tree rings sampled in an adjacent region (BÜNTGEN et al. 2011). The comparison indicates that high flood frequency coincides significantly with cool summer temperatures reflecting varying climate states through the last 2500 years affecting both temporal patterns of temperature and of precipitation extremes.

This pattern implies that enhanced (decreased) occurrence of westerly and Vb storm tracks during cooler (warmer) summers increase (decrease) the frequency of flood events in the Alps. As the main determining factor for the frequency of intense precipitation events in the Alps, a variable extent of the Hadley Cell and consequently changing atmospheric circulation patterns were proposed. This wet-cold synchronism suggests enhanced flood occurrence to be triggered by latitudinal shifts of Atlantic and Mediterranean storm tracks. This paleoclimatic perspective reveals natural analogues for varying climate conditions, and thus can contribute to a better understanding and improved projections of weather extremes and floods under climate change.

2.5.2. Holocene flood frequency across the Central Alps

Over 4700 flood layers from 15 lacustrine sediment records from the Northern and Southern Central Alps were identified, dated and merged in a comprehensive Alpine flood catalogue covering the past 10,000 years (WIRTH et al. 2013a). This Holocene flood record provides the possibility to investigate flood occurrence during warm (e.g. Holocene Thermal Maximum) and cool (e.g. Neoglaciation) periods at a large spatial extent, potentially providing information on characteristic atmospheric circulation patterns during different climatic conditions (**Figure 2.4**). At this large temporal and spatial scale, flood frequency was found to be higher during cool periods, coinciding with lows in solar activity. Periodicities of flood occurrence match those from reconstructions of solar activity from ^{14}C and ^{10}Be records. As mentioned above, the likely driving mechanism, an expansion/shrinking of the Hadley cell with increasing/decreasing air temperature, causing dry/wet conditions in Central Europe during phases of high/low solar activity is suggested. Furthermore, differences between the flood patterns from the Northern Alps and the Southern Alps indicate changes in North Atlantic circulation. Enhanced flood occurrence in the South compared to the North suggests a pronounced southward position of the Westerlies and/or blocking over the northern North Atlantic, hence resembling a negative NAO state (most distinct from 4.2 to 2.4 kyr BP and during the Little Ice Age). South-Alpine flood activity therefore provides a qualitative record of variations in a paleo-NAO pattern during the Holocene.

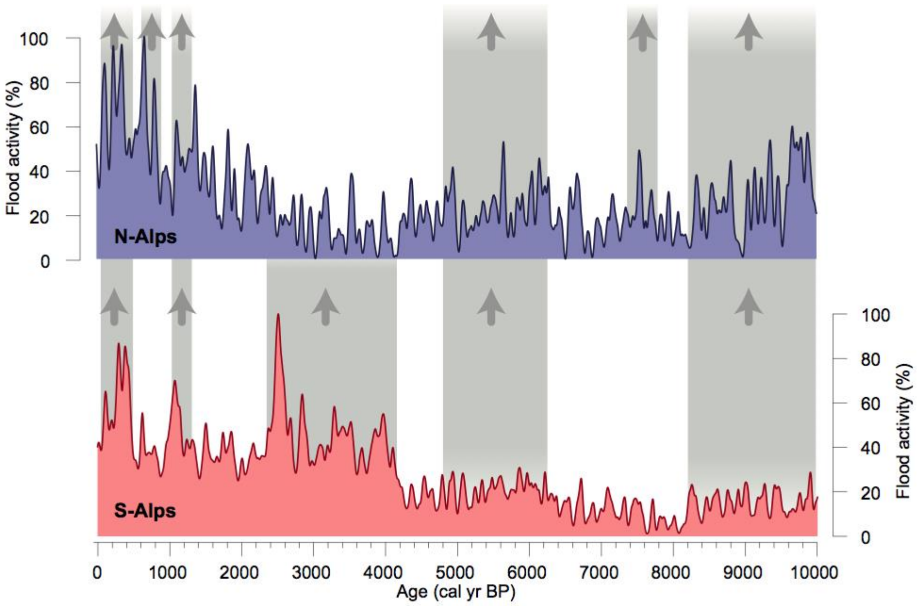

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Figure 2.4: Stacked flood records for the N- and S-Alps (100-year low-pass filtered) spanning the past 10 kyr. Grey areas and grey arrows mark periods with increased flood activity (from WIRTH et al. 2013a).

2.5.3 2600-yr sedimentary flood record from the Hasli-Area floodplain

In the Bernese Alps SCHULTE et al. (2008), (2009), (2015) showed the possibility to correlate geochemical floodplain proxies with paleoclimate variability over three millennia. **Figure 2.5** shows that seven paleoflood clusters defined by flood layers deposited predominantly during periods of reduced solar irradiance, cooler summer temperatures and phases of drier spring climate. Cooler climate pulses typically generate glacier advance, more extensive snow cover, and snow patches through the summer. Water storage and larger areas susceptible for melting processes associated with rainfall episodes and abrupt rises in temperature can increase surface runoff on slopes and consequently the discharges of Alpine rivers. However, three flood clusters occurred during warmer climate pulses (1380-1420; around 1760; 1977-present). Glacier and snow melt, higher snow limits, reduced snow cover and consequently a larger area of surface runoff combined with intense summer precipitation promoted flooding in the valley floor in these periods.

Spectral analysis of the geochemical and pollen time series and climate proxies such as Total Solar Irradiance and $\delta^{18}O$ isotopes from Greenland ice cores, temperature and precipitation reconstruction from tree-rings, and climate teleconnection indices (NAO, SNAO), indicate similar periodicities around 80, 100, 120 and 200 years (Gleissberg and Suess cycles). Thus, the mechanisms of the flood processes, at this large scale, are influenced not just by local factors but are strongly influenced by the North Atlantic dynamics and solar forcing.

The influence of atmospheric circulation dynamics on flood frequencies in the Hasli-Aare Valley is observed when flood intensities and geochemical proxies from the Hasli Valley and indices of atmospheric modes AD 1670 to 2000 are compared (**Figure 2.5**; SCHULTE et al. 2015; PEÑA et al. 2015). Severe floods occurred mostly during positive trends of Summer North Atlantic Oscillation (SNAO) phases or short positive SNAO pulses (cyclones of Mediterranean origin) following years or even decades dominated by negative SNAO (North Atlantic front systems; PEÑA et al. 2015; PEÑA and SCHULTE, 2020). This combination underlines the importance of the effect of snowmelt during short warm episodes within cool climate periods characterized by larger snow cover and glaciers.

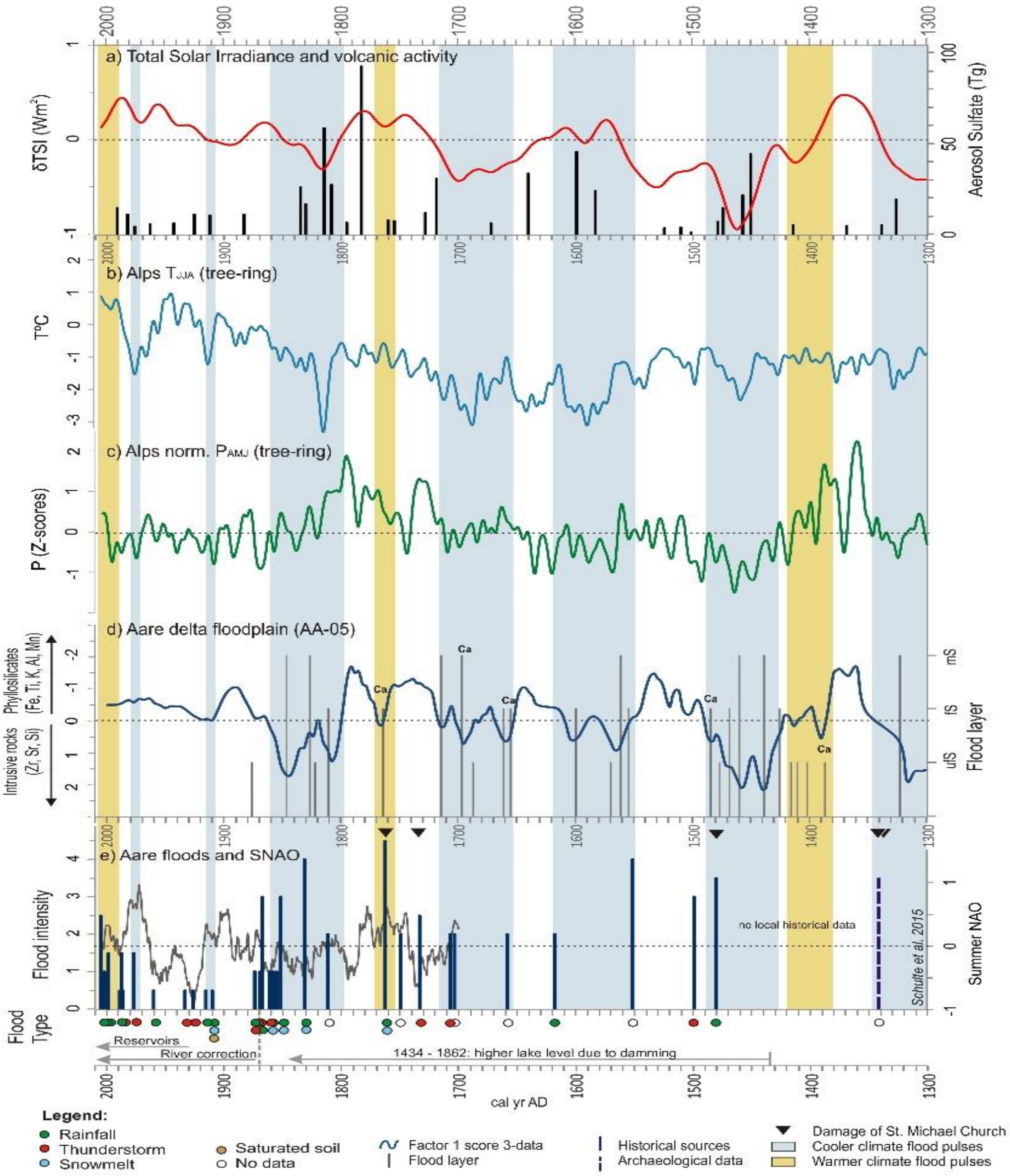

Figure 2.5: Comparison between historical flood reconstruction of the Hasli-Aare and solar and volcanic activity, tree-rings and climate proxies (1300-2010 cal yr AD) (from SCHULTE et al. 2015).

2.5.4 Temporal-spatial integration of multi-archive datasets in the Bernese Alps

The spatial and temporal integration of multi-archive flood series from the Hasli-Aare, Lütschine, Kander, Simme, Lombach, and Eistlenbach catchments constitutes an innovative approach to the reconstruction of accurate flood pulses over the last six centuries and the development of a temporal-spatial model of past flood behaviour (SCHULTE et al. 2019a, 2019b). Paleoflood records obtained from floodplains (four flood series) and lake sediments (four series), together with documentary data (six series), were analyzed and compared with instrumental measurements (four series) and the profiles of lichenometric-dated flood heights (four series).

The most accurate, continuous series, corresponding to the period from 1400 to 2005 CE, were integrated employing a complex integration process that involved data selection, normalization, filtering and factor analysis with different settings into a synthetic flood master curve that defines ten dominant flood pulses. This robust master curve improved the previously published individual floodplain and lake paleoflood data series. It is worth to note that the pulses of sedimentary floodplain proxies are similar to the flood evidences provided in documentary data series, showing the large flooding in the settled floodplains and deltas, whereas lake records from small catchments reflect more erosion processes related to hydro-meteorological events. Six of the integrated flood pulses correspond to cooler climate pulses (around 1480, 1570, 1760, 1830, 1850 and 1870 CE), three to intermediate temperatures (around 1410, 1650 and 1710 CE), while the most recent corresponds to the current pulse of Global Warming (2005 CE). Furthermore, five coincide with the positive mode of the Summer North Atlantic Oscillation, characterized by a strong blocking anticyclone between the Scandinavia Peninsula and Great Britain.

For two of the most catastrophic flood events in the Bernese Alps (those of 1762 and 1831 CE), the location and magnitude of all the flood records compiled were plotted to provide an accurate mapping of the spatial pattern of flooding. This was then compared to the pattern of atmospheric variability by applying CESM-LME simulations (SCHULTE et al. 2019b; PEÑA and SCHULTE, 2020). The event-related spatial information including low and high altitudes of flood evidence and the simulation of composite sea level pressure maps give a deeper insight in flood dynamics and forcing.

Take-Home Messages
• Reconstructions of paleoflood occurrence (and magnitude) are possible from <u>sediment deposits in lakes and floodplains</u> where sediments record floods, which together with sediment geochemistry and grain-size distributions, provide indications of flood magnitude and timing. • Paleoflood reconstructions for shorter time periods can also be achieved by <u>dendrochronology and lichenometry</u>, which record a range of flood damages in the tree rings of riparian species and heights of flood levels by lichen colonization. Such paleoflood reconstructions are useful to fill gaps in instrumental records, extend time series of floods, and provide envelopes on extremes. • Data show a connection between <u>long-term climate variability and floods</u> at a regional scale, where evidence of large-scale shifts in weather pattern and long-term climatic oscillations lead to the clustering of floods into flood-rich and flood-poor periods. The analysis of the paleoflood records provides insights into how future climatic variations might influence flood magnitude and frequency. • <u>Centennial to millennial-scale fluctuations</u> in flood activity are governed by periodicities in climatic mechanisms and forcing factors. Variations in solar activity are an important factor in climate variability as well. For example, high flood activity correlates to low solar activity, Holocene cold events, and to global/Alpine glacier advances. • <u>Human activities</u> such as deforestation and agriculture, especially in the northern part of the Alps, could have resulted in the increasing trend in flood activity during the past 2-2.5 kyr on top of climate forcing. River regulation and reservoirs mask the climate signal of floods since the 19th century. • A <u>new integrative approach</u> developed and tested in the Bernese Alps provides a comprehensive 4-D picture of paleofloods which facilitates an in-depth understanding of floods and flood forcing in mountain catchments.

3. Historical floods: changes in floods since the 13th Century

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3.1. Introduction

Historical hydrology is based on data derived from historical written, pictorial and epigraphic documentary evidence (e.g. BRÁZDIL et al. 2006a, PFISTER et al. 2006). It is situated at the interface between hydrology and environmental history, using methodologies from both disciplines (BRÁZDIL et al. 2006b, 2012; BENITO et al. 2015) to significantly extend the measurement period (WETTER 2017) with flood experience from the pre-measurement past, especially within the period of human activity in the landscape affecting rivers. Quantitative hydrological, meteorological and climatological information is paramount for the analysis of possible changes in the magnitude and frequency of floods. Such information can support not only flood hazard assessment, but also enables the identification of interconnections between flood frequency and severity with climate, land use and river morphology (MACDONALD and BLACK 2010; BENITO et al. 2015). For example, the EXAR project attempted to acquire data on analogues to the 10^3 to 10^7 years flood in the catchment area of the Aare River. Such extreme events cannot be adequately assessed by using standard statistical methods as the extrapolation from short reference series causes high level of uncertainties. In this section, we present how the inclusion of documentary flood information significantly expands the assessment of flood changes in Switzerland from instrumental records in the recent past (**Box 3.1**).

Box 3.1: Documentary evidence on floods in Switzerland
Documentary evidence on floods, droughts and other extreme events are found in chronicles, annals, memorial books, memoirs, diaries, travel reports, newspapers, journals, early scientific expert reports, municipal accounts, accountings, paintings, photographs, maps, flood marks, hunger stones or river profiles (WETTER 2017). According to PFISTER (1999), historical documentary evidence can be "direct" (DD) and "indirect" (ID). DD describe the course of events per se, while ID refer to (bio)physically based phenomena associated with such events. DD in continuous chronologies often contain sufficient information for identifying and characterizing floods (BARRIENDOS AND RODRIGO 2006), as they usually provide flood date, magnitude and socio-economic impacts (BRÁZDIL et al. 2006b; 2012; GLASER et al. 2010; BENITO et al. 2015). With respect to the generation of historical documentary evidence, PFISTER (2018) differentiates between individual (IS) and institutional sources (IN). IS are shaped by the social background, motivations and preferences of their authors (BENITO et al. 2015), and their temporal scope is limited. IN on the other hand are produced by institutions (i.e., bodies in charge of performing official functions including taxation, law, etc.). IN generally involve a good level of standardization, which is a good prerequisite for creating long-term homogeneous series of climate and flood parameters. Swiss IN,

for example like the books of weekly expenditures of the city of Basel, do have a very good potential for hydrological and climatological analysis, as shown by SPYCHER (2017), who found 70 high water and flood episodes for the river Rhine and 218 events for the brook Birsig which is a local tributary of the Rhine for the period between 1600 to 1650, while chroniclers only reported 3 Rhine and 5 Birsig floods. The significantly "sharper observation skills" towards minor events by IN is explained by the fact that infrastructure may already be endangered by relatively small events, whereas IS (e.g. chroniclers) only focus on spectacular extreme events. IN like the weekly expenditures are at hand for almost every other Swiss town.

3.2. High Rhine River flood occurrences since the 13th Century

The River Rhine at Basel drains two thirds of the Swiss territory (approximately 36'000 km^2), and as such reflects the major flood occurrences in Switzerland (e.g., BELZ et al. 2007). The drainage area of the main tributary, the Aare River (17 779 km^2) is entirely situated in Switzerland. Its runoff was affected by an artificial diversion of one of its tributaries, the Kander River, to Lake Thun in 1714, and since 1868 and 1891 it is controlled by the First Jura-Waters Corrections (FJWC), which diverted the Aare into Lake Biel in 1878. These regulations considerably reduced the peak discharges of the River Aare and, thus, those of the Rhine at Basel (see **Figure 3.1**).

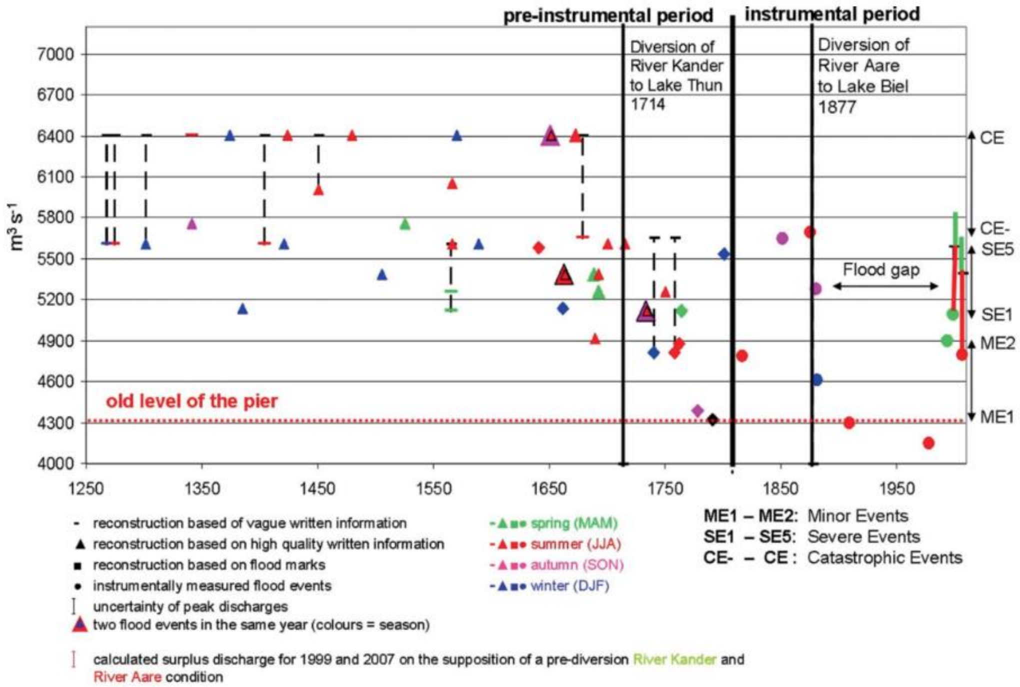

*Figure 3.1: Rhine River discharges between 1250 and 2010 based on documentary and instrumental evidence assessed by reconstructed peak water levels based on IS and unsteady 1D flood routing modelling (*WETTER et al. 2011*).*

All severe events except two floods (1999 and 2007) occurred before 1877, with no single severe event documented between 1877 and 1998 (**Figure 3.1**). This intermediate 121-year-long "flood disaster gap" is unique in the period from 1268. Chroniclers repeatedly mentioned that the Lakes of Neuchâtel, Biel and Murten including their adjacent shore and swamp areas merged into a huge lake for several days, suggesting that the peak floods on the lower course of the Aare were considerably dampened. However, the above-mentioned river engineering measures (Kander and FJWC) may not be the only reason for the observed peak discharge reductions but additional climatological explanations should be considered as well (WETTER et al.

2011). Some of the pre-instrumental flood events were described in such detail, that the triggering meteorological conditions could be reconstructed in sufficient detail. For example, the flood event of 1480 was described in great detail by the Bernese chronicler Diebold Schilling the Older (1446-c 1486) as the “Deluge of the Rhine”. He writes: “On Maria Magdalena Day it began to pour down in the form of driving rain persisting three days and nights without cessation.” The preceding days were very hot, melting the snow at higher altitudes. Indeed, due to a cold spring and early summer the snowmelt was delayed. Assuming an average rainfall intensity of 10 mm/h for the 72 hours between 29th and 31th July we get an estimated precipitation amount of 720 mm for this storm.

3.3. Low and high flood frequency periods since the 16th century in Swiss river basins

Documentary sources are also key to reconstruct flood frequencies over longer periods of time and to identify cycles of high and low flood activity. One recent period without significant floods was identified by the flood reconstruction for the High Rhine River in Basel. However, it would be interesting to know if the same low flood frequency period affected other river basins in Switzerland and Europe or if other periods of high or low flood frequencies can be identified and explained.

To answer these questions SCHMOCKER-FACKEL et al. (2010a) collected historical flood data for 14 Swiss catchments dating back to 1500 AC (**Figure 3.2**). These catchments were all situated in northern Switzerland, either in the Alps or in the Swiss Plateau. The largest catchment is the Rhine River catchment up to Basel and the smallest is the Renggbach in central Switzerland (12 km^2). In this study, a flood event was counted if the name of a river and flood damage caused by the river were mentioned explicitly in documentary records. The use of different catchments, sources and definitions of flood events lead to differences in the final reconstruction, and this should be taken into account when comparing different historical flood series.

The obtained data series resulted in 400 historical flood events in the 14 catchments. More than 100 events affected more than one catchment and 48 events were classified as large-scale flood events (i.e., a flood occurred in more than three catchments at the same time and caused extensive damage). Flood-rich periods alternate with lower flood frequency periods in all catchments, independently of catchment size. The recent increase in flood frequencies, starting in the 1970s is still in the range of observed natural variability. In a further step, SCHMOCKER-FACKEL et al. (2010a) tried to explain the changes in flood frequencies using generalized parameters like climate periods, solar activity, the north Atlantic oscillation (NAO) index, mean air temperatures, or length variations of glaciers.

The results in **Figure 3.2** show that the periods characterized with reduced flooding correspond to the end of the Spörer Minima (1420–1550), the Maunder Minima (1645–1715) and the Dalton Minima (1790–1820) of solar activity. However, solar activity alone does not explain flood frequency, as in the 20th century period characterized with low flood frequency, solar activity was high (see following and previous chapters). The authors did not find a clear relation between the flood data and the reconstructed summer and winter NAO indices, meaning that the forcing of the NAO in the Alpine region might be weak and NAO phases do not correlate well with Alpine precipitation. No clear relationships could be identified between mean air temperatures (winter or summer) and flood frequency. However, high flood frequency periods correspond to periods of rapid climatic change in the Alpine region. According to these observations, it was not possible to explain the detected flood frequency changes with single generalized climatic parameters, as the reasons for these changes are likely due to a combination of several factors.

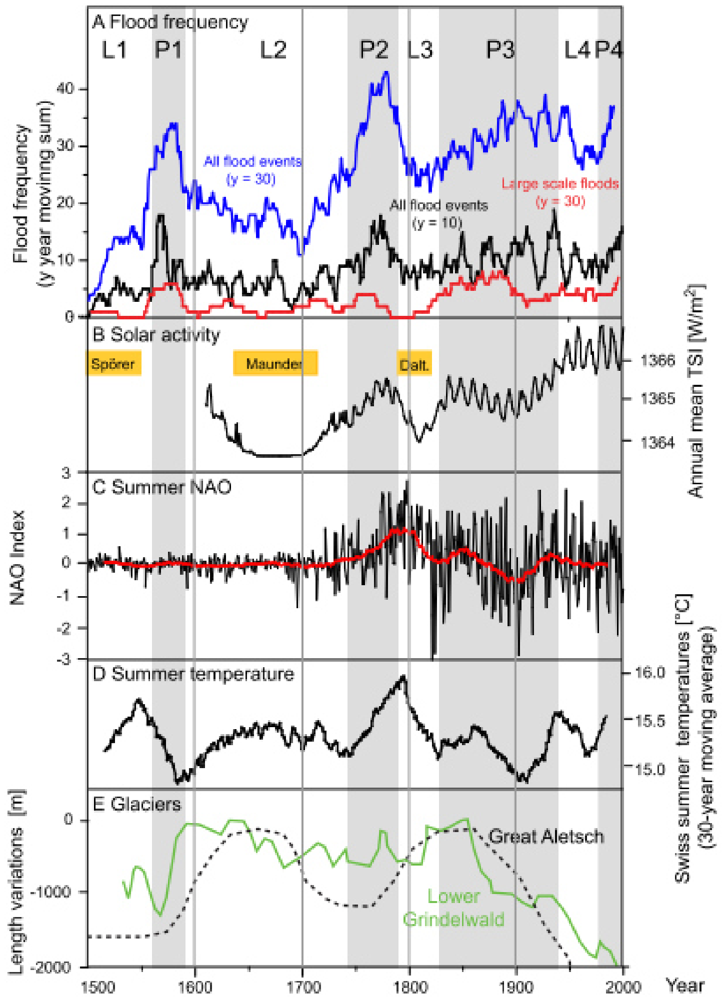

Figure 3.2: (A) Frequency of flood events in 14 Swiss catchments and catastrophic events throughout Switzerland. P1-P4 are periods with many floods and L1-L4 with few floods in northern Switzerland. (B) Spörer, Maunder and Dalton periods of low solar activity and the total solar irradiance TSI. (C) Annual summer NAO values (black) and the 30-year moving average (red). (D) Reconstructed Swiss summer temperatures. (E) Advances and retreats of the Lower Grindelwald and the Great Aletsch glacier (from SCHMOCKER-FACKEL et al., 2010a).

Other authors also found that flood frequencies in Europe have changed at intervals of 30-100 years during the last 500 years (e.g. BÖHM and WETZEL 2006; BRÁZDIL et al. 2006b; GLASER 1998; HALL et al. 2014) or even within the past millennium (GLASER and STANGL 2004). 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 (SCHMOCKER-FACKEL et al. 2010a). This seems to be the case also on a global scale (e.g. BERGHUIJS et al. 2017). 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. Although it seems likely that changes in atmospheric circulation patterns on decadal time scales may be responsible for these spatially heterogeneous changes in flood frequency (JACOBEIT et al. 2003, MUDELSEE et al. 2004; WANNER et al. 2004), there are also other factors at play.

Similar patterns can be observed at the Limmat river in Zurich (**Figure 3.3**) for the interval from 1300 to 2015. A local increase in flooding occurred at around 1567 (0.12 events per year). The subsequent 17th and early 18th centuries saw significantly reduced flood risk, in agreement with findings for other regions in central Europe

(LUTERBACHER et al. 2001; MUDELSEE et al. 2003; 2006). A second peak in flood occurrence was reached at around 1867 (0.14 events per year), from this time on the flood occurrence rate steadily decreased. Such a downward trend during the recent decades has also been observed for the rivers Elbe and Oder during winter (MUDELSEE et al. 2003).

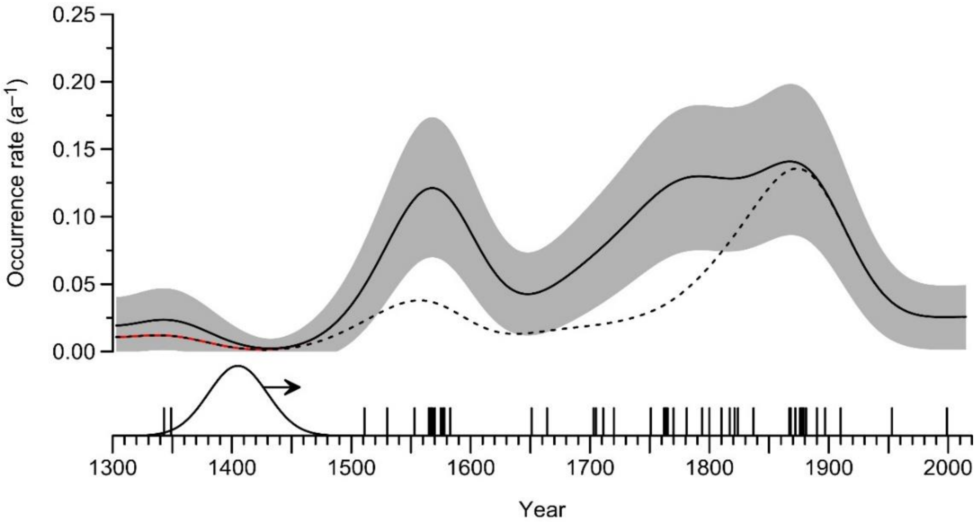

Figure 3.3: Estimated flood occurrence rate (number of floods per year, solid line; 90% confidence band, grey) analysed using a Gaussian kernel function (shown with an arrow in the bottom part) for the river Limmat in Zurich for the interval 1300-2015. The estimation is performed on all m = 47 historical events (shown as bar chart in the bottom part). Omission of the uncertain event in AD 1349 (m = 46) leads to an indistinguishable estimation (red line). Utilization of only the historically critically examined events (m = 26) leads to a lower occurrence rate (dashed line). See MUDELSEE et al. (2003), (2004) and (2014) for further methodological details.

An important limitation of historical flood data series analysis is that man-made or natural morphological changes in the river channel geomorphology, river flow capacity, or the anthropogenic construction of dams and channelization works over centuries (**Box 3.2**), may lead to homogeneity problems (CAMUFFO and ENZI, 1996; SCHULTE et al. 2009; SCHMOCKER-FACKEL et al. 2010, HALL et al. 2014a). Methods have been developed to quantify the changes due to anthropogenic river engineering measures on the overall in- and outflow runoff conditions of a location of interest (e.g. WETTER and SPECKER 2014; WETTER et al. 2016; NÄF-HUBER et al., 2016; WETTER 2017). Once the relevant anthropogenic changes to the overall runoff conditions are known and quantified, two things become possible. First is the identification of hot spots, i.e. locations where failure in river engineering measures could dramatically change floods, and second is that correction can be applied to flood events that took place in the pre-anthropogenic conditions, to homogenise them to the contemporary runoff conditions.

For example, at the Limmat River, five periods were identified as having homogenous runoff conditions and then homogenised to the current runoff conditions. According to the homogenised flood series we are now able to see that in the last 718 years there were at least three flood events (1876, 1817 and 1720) that most probably would have been more extreme than the 1999 flood event if they had taken place under current runoff conditions in Zürich. Flood risk analysis may thus now be based on long term homogenised flood evidence which simulates the risk under current runoff conditions (see **Fig. 3.3.**).

Box 3.2: Floods and anthropogenic changes

Rivers are dynamic systems, which adjust their geometry, morphology, grain size to the dominant discharges and sediment supply, thereby affecting flooding. All of these processes may have experienced important variations due to environmental and anthropogenic changes during the last centuries. The human action produced not only land cover and land use changes, but includes also direct alterations due to river regulation, deviation and the construction of embankments. The identification of such long-term spatial changes requires a complex approach (e.g. SCHULTE et al. 2009; 2015) that integrates multiple archives and methods (e.g., geomorphological mapping, systematic coring of floodplain sediments, location of historical buildings and archaeological sites, the study of historical maps, sources and aerial photographs. This spatial integration contributes to the understanding of current as well as historic flooding, channel shifts and aggradation of sediments which effected settlements and local communities. For example, the repeated flooding of the Lütschine fan delta and the changes of drainage to Lake Brienz and/or the Bödeli-Aare River are shown by the reconstruction of the paleo drainage systems in 2003 (see **Figure**; SCHULTE et al. 2009) which were reactivated during the 2005 flood.

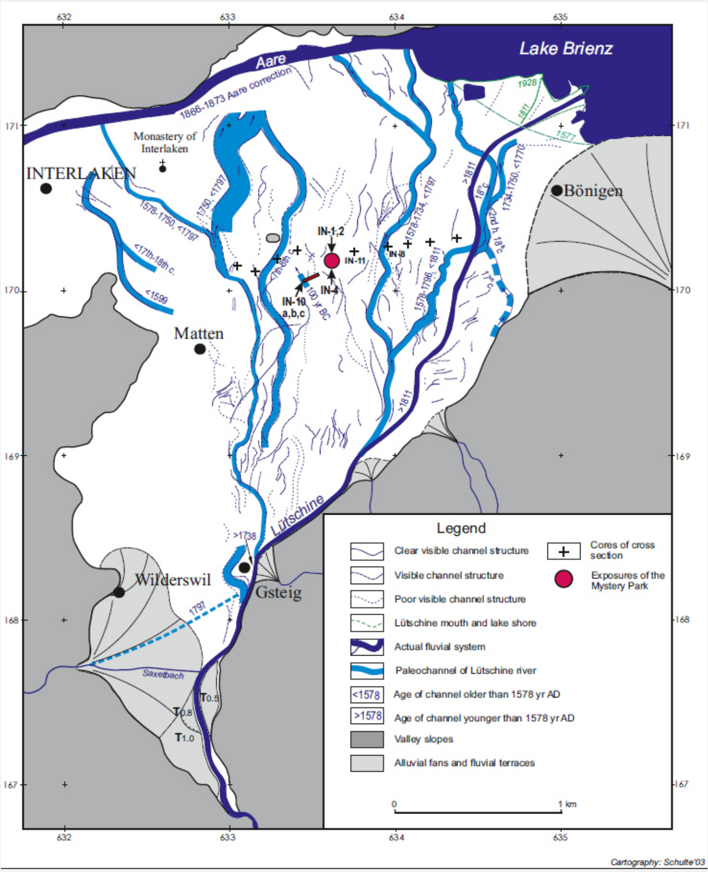

Figure: Morphological map of the historical evolution of the fluvial channels on the Lütschine fan delta (from SCHULTE et al. 2009*).*

Take-Home Messages

- Documentary flood information can be used to reconstruct flood frequency and flood magnitudes beyond the measurement period for several centuries into the pre-instrumental (measurement) past affected by human modifications to the landscape and rivers. Long-term anthropogenic influence on runoff conditions can be semi-quantitatively assessed.
- Reconstructed and homogenized long-term flood magnitudes in combination with incorporated (anthropogenic) changes to runoff conditions improve the assessment of extreme value statistics and the definition of design flood events (e.g. HQ100).
- All reconstructed historic flood series in Switzerland and Europe show changes in flood frequency over time intervals between 30 and 100 years. Flood-rich periods do not occur at the same time for all investigated rivers, but differ between regions and between catchments of different sizes. The latter can be explained with scale effects of mechanisms causing floods: e.g. long duration, large-scale rainfall and snowmelt events in the Rhine to local small-scale convective heavy precipitation events in small Alpine catchments.
- It is very likely that long-term changes in atmospheric circulation play an important role in causing these changes in flood frequency. However, due to the lack of good quality data about the atmosphere in the past it may be difficult to establish a clear cause-and-effect chain.

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.

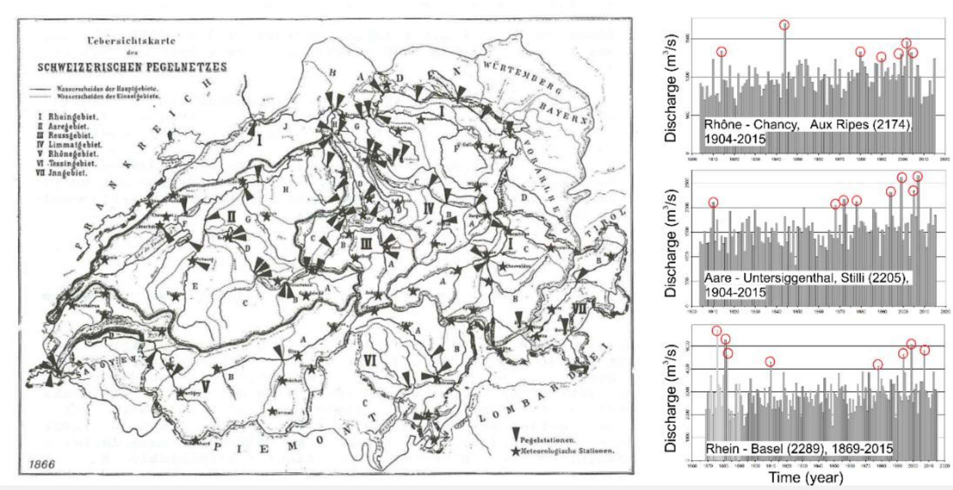

Figure: Map of hydrometric stations in Switzerland in 1866. Modified from (EMMENEGGER 1988). *Three of the longest systematic annual maximum discharge time series available in Switzerland: Rhône, Aare and Rhein Rivers. Red circles show the largest floods recorded.*

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.

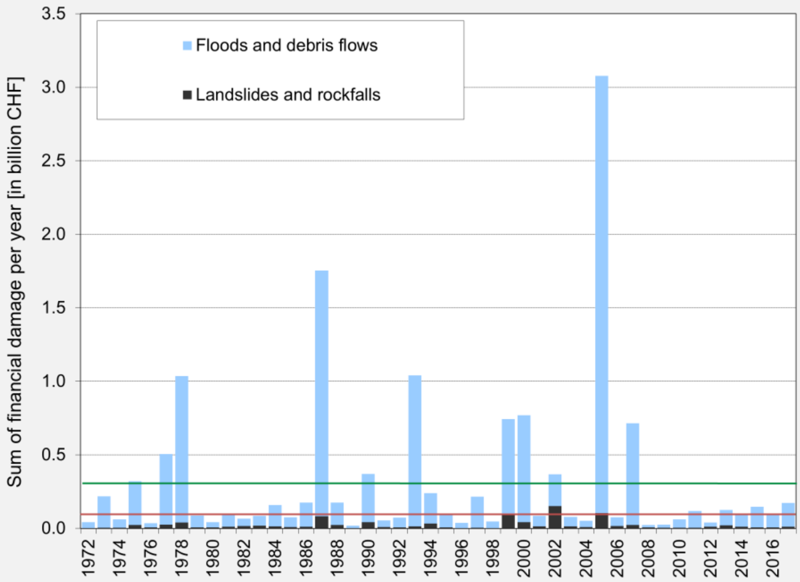

Figure: Annual financial damage due to natural hazards floods/debris flows and landslides/rockfalls in Switzerland 1972-2017 (inflation corrected). The long-term mean (green, 307 Mio. CHF) and median (red, 93 Mio. CHF) are displayed with horizontal lines.

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).

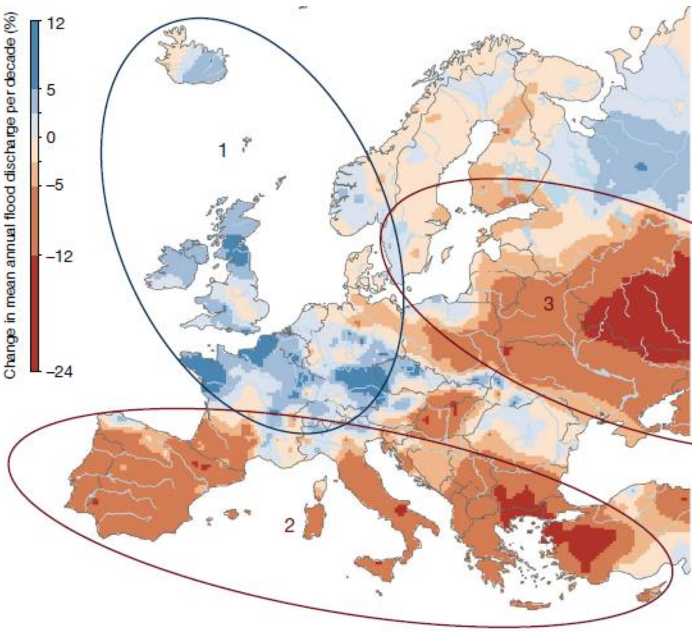

Figure 4.1: Changes in flood magnitudes across Europe in % per decade in the period 1960-2010, with different regions showing increases (1) and decreases (2,3) due to different dominant flood-generating mechanisms (from BLÖSCHL et al. 2019).

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**).

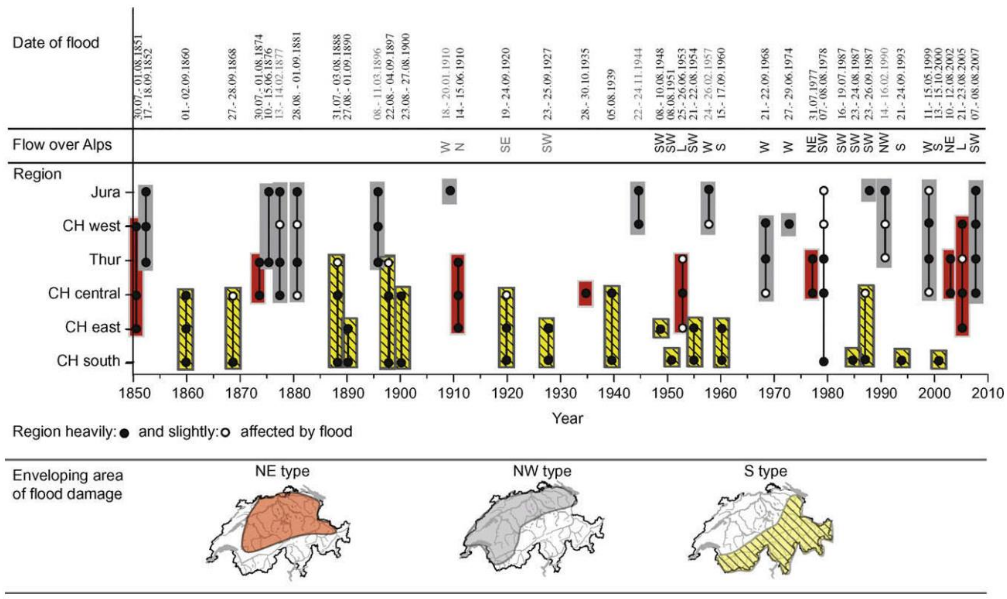

Figure 4.2: Spatial extent of large-scale flood events in Switzerland since 1850. According to the regions affected, the flood events were classified into three types NE-NW-S (maps in bottom row). From SCHMOCKER-FACKEL et al. (2010).

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**).

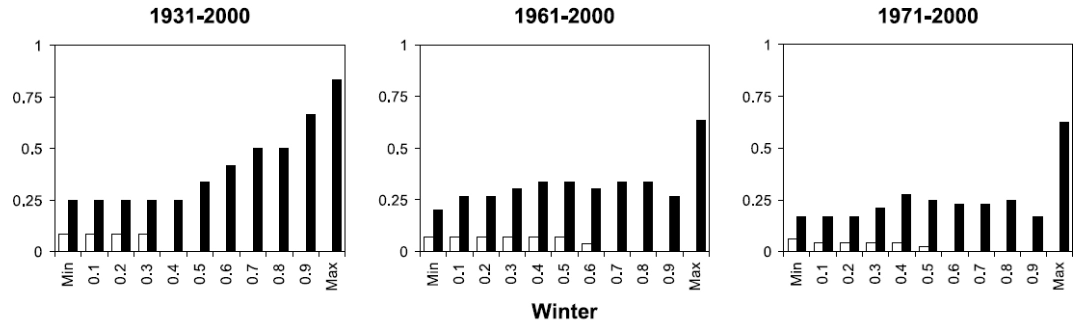

Figure 4.3: Proportion of statistically significant trends -- both increases in black bars and decreases in white bars -- in annual and seasonal daily winter discharge quantiles for three periods found by BIRSAN et al. (2005). The winter (annual) maxima are labelled "Max".

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).

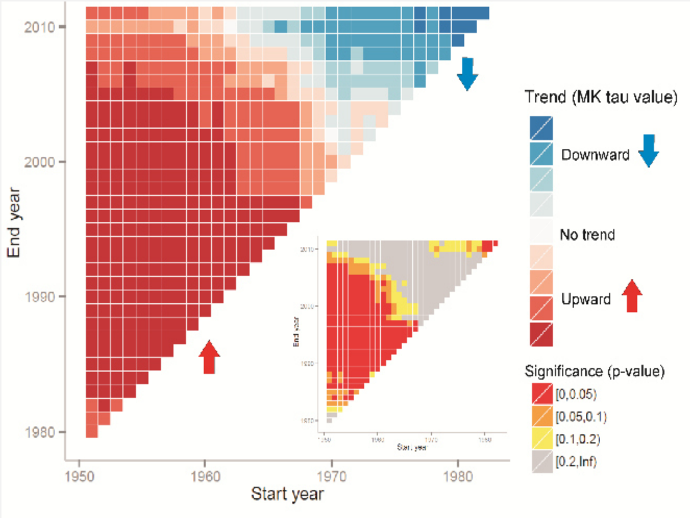

Figure: Example to illustrate the multi-temporal flood trend analysis for the period 1951-2011. Blue and red colours correspond to negative and positive MK tau values respectively, and the inset graph shows the significance (p-value) of the trends. The Figure shows significant upward trends for the period 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.

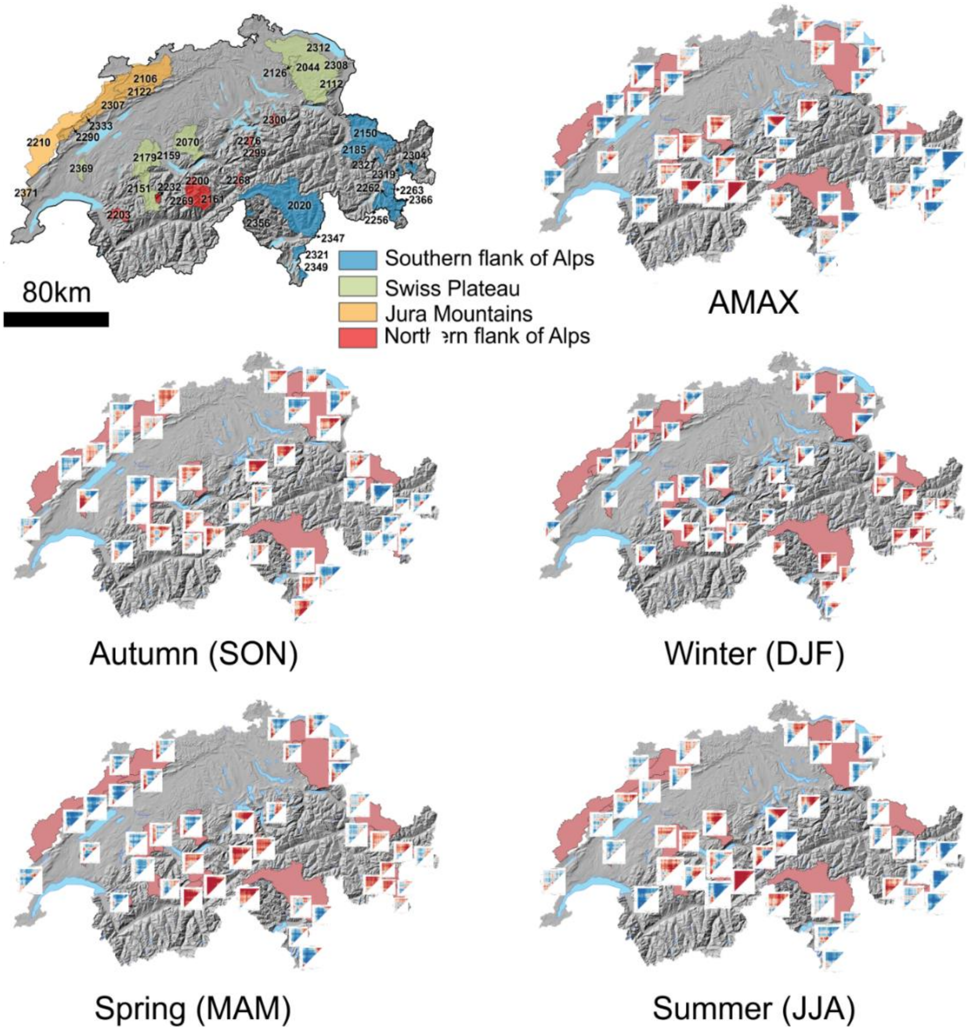

Figure 4.4: Maps showing the catchments and the multi-temporal matrices of the trend analysis for the annual (AMAX) and seasonal (Autumn, Winter, Spring and Summer) maxima discharge. Red colours in the matrices show upward trends and blue downward trends, the darker the colour the more significant the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

5. Understanding flood triggering mechanisms and flood risk changes

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5.1. Introduction

Floods are caused by the interaction of several physical processes and factors including meteorological conditions, the soil moisture state of the catchment, the type of the dominant runoff generation processes, and river routing (e.g., NIED et al. 2014). Detailed knowledge of the synoptic-scale and meso-scale meteorological conditions leading to the triggering of flood-producing rainfall, information on the antecedent wetness conditions of soils in the catchment, and detailed information of the relevant hydrological processes that lead to runoff formation, all contribute to a better understanding and prediction of floods.

The first part of this section (5.2) provides a summary of the current knowledge of both climatic and non-climatic divers of floods in Switzerland and globally. The second part of this section (5.3) discusses anthropogenic influences on flood frequency and magnitude. The third part (5.4) discusses exposure and vulnerability aspects of flood risk. The final fourth part (5.5) summarizes our current knowledge of changes in flood triggering mechanisms and flood risk factors in the recent past.

5.2. Climatic drivers of floods

5.2.1 Flood generating hydro-meteorological processes

MERZ et al. (2003) proposed a classification of the flood generating hydro-meteorological processes in Alpine environments based on rainfall duration and snowmelt processes. They distinguished long-rain floods, short-rain floods, flash floods, rain-on-snow floods, and snowmelt floods. HELBLING et al. (2006) and DIEZIG and WEINGARTNER (2007) adapted this characterization to Swiss floods and added the category of glacier melt floods (**Figure 5.1**). The same hydro-meteorological categories were used by SIKORSKA et al. (2015) for a flood type categorization in 9 Swiss catchments. Their approach takes into account that flood events are usually caused by a mix of different processes, and that thresholds for a deterministic classification are to some extent subjective. KELLER et al. (2018) defined more complex flood storylines for the Thur catchment that combine information on the catchment snow cover and the duration and intensity of the flood triggering precipitation. It is clear from such classification studies that not all floods in the Alpine area are generated by heavy precipitation alone, and that the flood generating processes depend on the size and characteristics (e.g., elevation range, soil properties, geology, land cover) of the affected catchments.

The temporal scales of flood response are closely related to the spatial scales, i.e. catchment size. Small catchments tend to be more susceptible to high-intensity short duration (sub-daily) precipitation than larger catchments (DIEZIG and WEINGARTNER 2007). Short-duration (sub-daily) high-intensity precipitation events are typically related to thunderstorms which may lead to flash floods with high damages (PANZIERA et al. 2016). Modelling studies have shown that the temporal distribution of rainfall intensity within storms becomes more important for small basins, while in large mesoscale basins short duration variations in rainfall intensity become less important (e.g. SIKORSKA et al. 2018). This is consistent with the finding that at the mesoscale, most observed annual and seasonal flood events develop due to medium intensity precipitation that lasts for at least 12 hurs or are rain-on-snow events. In both cases, the exact sub-daily precipitation distribution is not as important.

FROIDEVAUX et al. (2015) considered the pre-conditioning of the catchments in their analysis of annual discharge peaks in 101 Swiss catchments. They proposed to separate the preceding (antecedent) precipitation (~4 days to 1 month prior to the flood events) from the flood triggering precipitation and showed that the precipitation accumulation during the 3 days before the flood events is most relevant for floods. The antecedent wetness condition of the soil was found to be more relevant for flood peaks than the temporal and spatial structure of the rainfall in a modelling study of PASCHALIS et al. (2014), where the authors also showed that the clustering of the saturated areas in space increased flood peaks.

5.2.2 Synoptic-scale flow and moisture sources of heavy precipitation events associated with floods in Switzerland

In general, three typical hydrometeorological conditions explain regional patterns in flooding across Switzerland (SCHMOCKER-FACKEL et al. 2010; SCHNEEBERGER et al., 2018):

- north-westerly flow, affecting western and northern Switzerland may produce flooding in NW;
- north-easterly flow or changing flow directions including the Vb flood events, affecting north-eastern and Central Switzerland may produce NE floods;
- southerly flow, affecting southern Switzerland (Valais, Ticino and Grisons) and sometimes, through overlapping of precipitation to the north side of the Alps, also Central and north-eastern Switzerland may lead to S floods.

Exceptionally large floods generally result from particular weather patterns. STUCKI et al. (2012) presented five flood-related weather types based on the analysis of 24 major Swiss flood events between 1868 and 2010 (**Figure 5.1**):

- Pivoting cut-off low pressure systems (PCO) located to the east of Switzerland. PCOs result in the advection of moist air towards northern Switzerland from the north-east (see also e.g., BEZZOLA and HEGG 2007);
- Meridionally elongated and narrow troughs over western Europe (ECO) that are associated with moisture advection towards the Alps from the south, destabilization of the atmosphere, and orographically-forced ascent (see also MASSACAND et al. 1998, 2001; MARTIUS et al. 2006; SCHLEMMER et al. 2010). This flow situation results primarily in heavy precipitation on the Alpine south side (Valais, Ticino, parts of Grisons) and in some cases also in the central Alps and in the north-east of Switzerland (GIANNAKAKI et al. 2015);
- Broad troughs over the Atlantic (CAT) that bring moist air towards Switzerland from the southwest, resulting in heavy precipitation in Ticino but also in south-western Switzerland and in the Jura mountains;
- Stationary fronts (STF) over Switzerland;

- Zonal flow conditions (ZOF) that affect primarily northern Switzerland (see also GIANNAKAKI et al. 2015).

In addition to these five classes, strong moisture advection from the north in a northerly flow has been linked to a recent flood event in the Kander- and Lötschental (RÖSSLER et al. 2014, PIAGET et al. 2015) and to several flood events in the Jura (FROIDEVAUX et al. 2015). STUCKI et al. (2012) and PEÑA et al. (2015) further emphasize that stationary high-pressure systems (atmospheric blocks) were present over Europe during many Swiss summer flood events. Such blocking systems can slow down the propagation of precipitating weather systems and hence support heavy precipitation in the same location over several days (LENGGENHAGER et al. 2019).

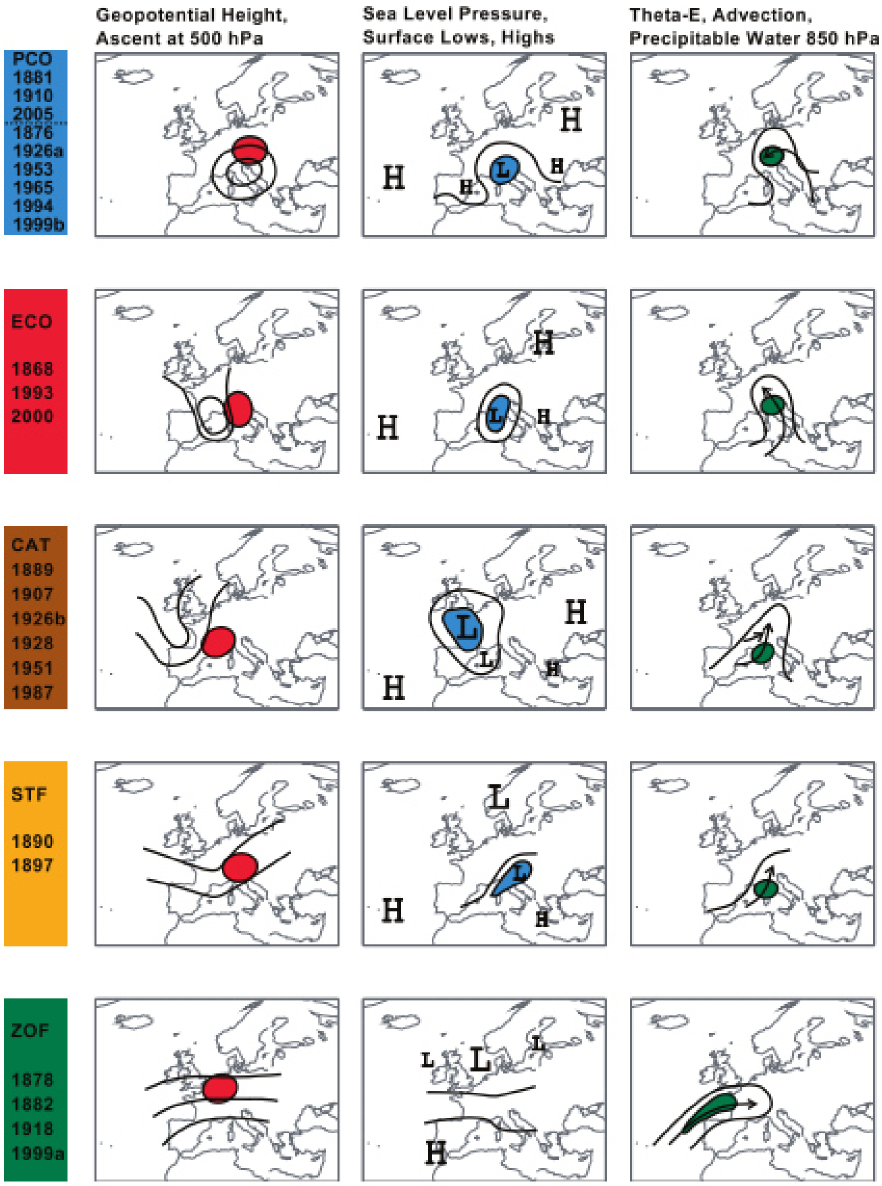

Figure 5.1: Schematic showing flood-causing atmospheric patterns categorized into five types (coloured box with dates of representative flood events): PCO (Pivoting Cut-Off; subtypes separated by dashed line), ECO (Elongated Cut-Off), Canarian Trough (CAT), Stationary Front (STF), and Zonal Flow (ZOF). Left column -- Geopotential height (black lines) at 500 hPa and the core area of large-scale mid- tropospheric ascent (red structures). Middle column -- Sea level pressure (black lines) and location of primary and secondary surface highs (H) and lows (L). Blue fields indicate stationarity. Right column -- Areas of precipitable water (green structures) with wind direction at 850 hPa (as black arrows) and the surrounding field of enhanced He (frontal structures; as black lines). From STUCKI et al. (2012).

Heavy precipitation related to flood events in Switzerland is often tied to exceptionally high moisture transport into the region and against the mountains (Alps and/or Jura) (MARTIUS et al. 2006; PIAGET et al. 2015; FROIDEVAUX and MARTIUS 2016). Such high moisture transport episodes sometimes correspond to atmospheric rivers (AR, see also PIAGET et al. 2015,FROIDEXAUX and MARTIUS 2016), however, not all flood-related high moisture transport episodes are atmospheric rivers, because the high moisture transport regions are too short (<1000km) to classify them as such.

Considering the central role of coherent large-scale high atmospheric moisture transport, it is important to know where this moisture has been taken up by the airstreams leading to heavy precipitation over Switzerland. WINSCHALL et al. (2012) show that besides the Mediterranean, the eastern North Atlantic is an important atmospheric moisture source for heavy precipitation events on the Alpine south side. A climatological analysis of the moisture sources of heavy precipitation events in Switzerland in the 20th century shows that the North Atlantic is a major moisture source for atmospheric river-like structures that bring large amounts of water vapour towards the Alpine ridge resulting in heavy precipitation in the inner Alps, the plateau and Jura (**Figure 5.2**.).

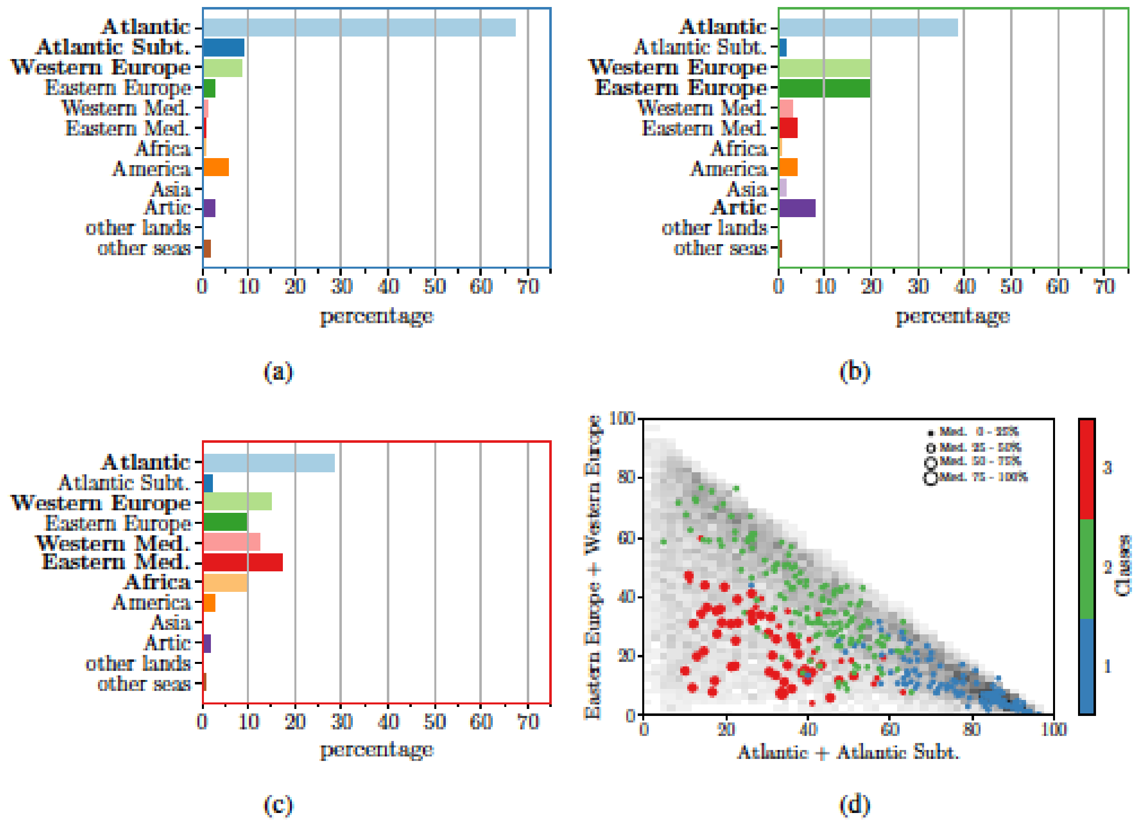

Figure 5.2: Three categories of precipitation events in Switzerland in the period 1979 to 2011 according to their moisture sources (a – mainly North Atlantic, 114 events; b – mainly continental, 141 events; c – mainly Mediterranean, 67 events) based on the ERA-Interim Reanalysis dataset from the European Centre for Medium Range Weather Forecasts. In a,b,c the category average evaporative moisture source contribution of different regions to the heavy precipitation events is shown. In panel d a scatter plot of the three major evaporative precipitation sources, namely the North Atlantic, continental Europe and the Mediterranean is shown for each heavy precipitation event from the three categories (coloured dot). The grey shading indicates the density of points when using all precipitation events from the same period.

In addition to oceanic sources, the land surface is an important moisture source for precipitation over Switzerland especially during summer (SODEMANN and ZUBLER 2010). High values of continental moisture recycling with a large fraction of plant transpiration in the evapotranspiration flux can be detected in summer and autumn from direct measurements of the stable water isotope composition of atmospheric water in Switzerland (AEMISEGGER et al. 2014) . A recent example for the importance of land surface processes is the major European flood event in June 2013 for which central and eastern Europe was the dominant atmospheric moisture source (GRAMS et al. 2014). Strong mid-level cyclonic flow around the Alps is generally responsible for the advection and convergence of moisture from eastern and northwestern Europe for this type of event leading to heavy precipitation in the eastern and central Swiss Alps (**Figure 5.2**).

The interaction between multiple (simultaneous or compound) climate drivers can also play a major role in generating floods. In this regard the notion of compound extreme events is an emerging research topic in extremes research (LEONARD et al. 2014; HAO et al. 2018; ZSCHEISCHLER et al. 2018). Examples of flood events arising from compound drivers are concurrent heavy precipitation and high soil moisture content (e.g., BERGHUIJS et al., 2019), the temporal clustering of precipitation extremes (e.g., BARTON et al. 2016) or the combination of heavy precipitation and concomitant snowmelt (e.g., RÖSSLER et al. 2014).

5.2.3 The interplay of rain and snow (melt)

In high latitudes or Alpine areas not only intensive rainfall but also snowmelt can have a substantial effect on flood generation. So-called rain-on-snow flood events are defined as events where rain falls onto the snow-cover over a major part of the catchment. Rain-on-snow events have a specific process regime: depending on the snow conditions snow can temporally store the rainwater, concentrate the rainfall runoff in preferential flow paths, or immediately release the rainwater. Sensible and especially latent heat fluxes need to be considered as major drivers of snowmelt. If the rain-snow interaction occurs only in a small part of the catchment, the flood is predominantly triggered by the normal rainfall–soil interaction (infiltration capacity, etc.) that is additionally accompanied by snowmelt.

The rain-on-snow flood type has been defined by several authors (MCCABE et al. 2007; MERZ AND BLÖSCHL 2003) and is part of the general classification of Alpine flood types (see Section 5.2.1). The generating processes of rain-on-snow floods do not only include precipitation intensity, but also the elevation of the freezing line and the water equivalent and areal extent of the snow pack at the onset of the event (MCCABE et al. 2007; PARAJKA et al., 2019). Furthermore, snow conditions such as the initial liquid water content, as well as snow depth are of central importance for runoff generation (WÜRZER et al. 2017). Hence, even moderate rainfall amounts can lead to large floods because significant melt due to turbulent sensible and latent heat fluxes (DYER and MOTE 2002; DADIC et al. 2013) with a supporting role of high wind speed (HARR 1981; BERRIS and HARR 1987) enhance snowmelt. In addition, snowmelt may saturate significant parts of the catchment storages thereby facilitating overland flow when rain occurs (e.g., MERZ et al. 2003).

Rain-on-snow flood events can reach exceptionally high discharge peaks at regional scale when adverse meteorological causes coincide. For the October 2011 flood in the Lötschental Valley, for example, RÖSSLER et al. (2014) found that snowfall was followed by warm and moist air transport towards the Alps, enhancing local rainfall by topographic effects, leading finally to substantial snowmelt and flooding in a group of tributaries to the main valley. Within their framework, the authors also demonstrated that a good quantification of both the latent and sensible heat fluxes is necessary to reconstruct the dynamics of the snow cover during such an event. Few observations have been available for rain-on-snow events, making model-based forecasts of the complex rainfall-snow interactions difficult. Hence, different research groups have conducted artificial rain-on-snow irrigation experiments (JURAS et al. 2017) to provide this data. WÜRZER et al. (2017) have been able to implement the observed preferential flow into a snowpack model and thereby improved flood forecast quality.

Flood events generated from substantial contributions of snowmelt and heavy rainfall that do not fit in the definition of rain-on-snow events (i.e., high water levels of headwater streams due to snowmelt, while rain is falling only in the lower parts of the catchment). can affect larger-scale catchments and cause severe flood events across major parts of Switzerland (e.g., STUCKI et al. 2012). Two notable examples are the flood events in the period 1816/1817 and in May 1999. Using an analogue method based on historical measurements, RÖSSLER and BRÖNNIMANN (2018) generated temperature and precipitation fields for 1816/1817 for the Rhine River basin down to Basel and demonstrated that snow storage in spring 1816 and 1817 was in the same order of magnitude as at the end of the snow-rich winter of 1999. For the upstream area of Lake Constance, they found the input from snowmelt to be 17% (1816), 41% (1817) and 59% (1999) higher than that of rainfall. In addition, the analysis revealed that the triggering rainfall event of the 1817 flood event was likely higher than that causing the largest recent flood in August 2005. They concluded that both rainfall and snowmelt contribution were necessary to generate the flood.

5.2.4 The interplay of rain and soil moisture

Continental-scale studies in the USA (BERGHUIJS et al. 2016) and Europe (BLÖSCHL et al., 2017; 2019; BERGHUIJS et al. 2019) have shown that regional patterns of seasonality and interannual variabilities of maximum annual floods are often poorly explained by rainfall alone. Soil moisture dependent precipitation excess is found to be a much better predictor, on top of snowmelt and rain-on-snow events. The study of BERGHUIJS et al. (2016) demonstrated this for 420 catchments in the USA, where the timing of annual flood peaks was related to evaporation-controlled soil moisture maxima in a majority of the catchments where snow was not dominating the flow regime. Relating the timing of annual floods with potential flood driving mechanisms in 4262 catchments in Europe BLÖSCHL et al. (2017) showed that earlier annual soil moisture maxima in western Europe and the UK may be responsible for earlier annual flood peaks in these regions.

5.3. Non-climatic drivers of floods

While climatic drivers and climate-driven soil moisture variability have a decisive role in causing floods, there are several other important non-climatic flood-driving factors. These include natural physiographic catchment properties (size, topography, etc.), river properties (channel conveyance capacity, morphology, etc.), and the geological, soil, vegetation and land use characteristics of the catchments (e.g., WEINGARTNER et al. 2003; FERCHER et al. 2018). Following the proposal made by MERZ et al. (2012) and HALL et al. (2014a) two groups of non-climatic drivers are distinguished acting at different scales: (a) catchment-scale drivers such as soil type, forest and vegetation cover, land use, etc.; and (b) river-scale drivers, such as river morphology, conveyance, roughness, floodplain and hillslope connectivity, floodplain storage, and the presence of riparian vegetation.

It is important to stress that there are complex and nonlinear dynamic interactions between climatic and non-climatic drivers in flood generation, which make it difficult to separate the effects of the drivers and/or determine one main single flood driver.

5.3.1. Non-climatic flood drivers at the catchment scale

Several non-climatic factors influence the surface and near-surface hydrologic processes and thereby the volume and timing of runoff and flood discharge. Without describing the full hydrological cycle here, we summarize some of the most important ones. Catchment size and topography, geology and soil cover are the primary characteristics influencing runoff generation and flow pathways at the catchment scale. Particular geological settings have distinctive drainage systems and responses.

Steep topography is an important control on runoff generation (WEINGARTNER et al. 2003; KAMPF and MIRUS 2013) leading to a rapid response of runoff to rainfall. Steep topography is typically found in headwater catchments where flash floods occur (BORGA et al. 2014). Slopes have also an indirect effect on runoff generation by influencing soil development (WEINGARTNER et al. 2003) due to processes such as weathering, bioturbation, sediment transport, compaction, etc. Soil properties then determine infiltration and runoff formation. Catchments in the Alps characterized by steep slopes and shallow soils with underlying impermeable bedrock, such as gneiss and granite, are therefore vulnerable to soil saturation, fast runoff formation and high flood peaks (e.g., BACCHI and RANZI 2003; RANZI et al. 2007).

Vegetation and forest cover (i.e., vegetation type, areal extent, and canopy density) play an important role for interception, evapotranspiration, and infiltration. Vegetation influences the micro-climate and local energy balance, and plant physiology and plants roots are important factors in transpiration (KRAMER and BOYER 1995; LAI and KATUL 2000). Interception of rainfall by the canopy strongly depends on vegetation type, and interception losses are much higher in forests compared to grasslands and crop fields and vary seasonally.

An important aspect of surface runoff generation is above-ground and sub-surface connectivity. Connectivity can be defined as the landscape, hydrological and geomorphological coupling of the movement of water from hillslopes to channels and along a channel network (e.g., BRACKEN and CROKE 2007; CROKE et al., 2013; WOHL 2017). Reservoirs, sinks or storage are important components in connectivity affecting the routing of flows. Connectivity in surface flow together with the spatio-temporal pattern of the rainfall can play an important role for flood runoff generation. Depending on the topology of the river network, the timing of streamflow accumulation along the river network driven by spatially distributed rainfall influences peak discharge in the individual river reaches (e.g., NICÓTINA et al. 2008; ZISCHG et al. 2018b; NIKOLOPOULOS et al. 2014; PASCHALIS et al. 2014; PATTISON et al. 2014; EMMANUEL et al. 2016; ZOCCATELLI et al. 2011). Thus, flood assessment at the catchment scale requires knowledge of the space-time variability of rainfall within a catchment, hydrological (soil and vegetation) processes leading to local runoff formation, and the propagation thereof through the river network.

5.3.2. Non-climatic flood drivers at the river corridor scale

Along a river corridor (active channel and floodplain) several processes affect the propagation and magnitude of floods. Morphological variables (e.g., channel width, depth, slope, roughness) and channel processes, such as sediment transport and bank erosion, are probably the most relevant flood modulating factors. Increased channel roughness attenuates the peak discharge and delays the arrival of the flood peak. Roughness is also affected by riparian vegetation and in-channel wood. The hydraulic resistance offered by particular plants, or plant communities, vary with size and constituting elements, particularly the density of foliage and the branch structure (JÄRVELÄ 2002). Moreover, riparian vegetation may strongly affect the rates of erosion and deposition, and the overall stability of fluvial surfaces (HUPP and OSTERKAMP 1996). In general, floodplain storage and floodplain-channel connectivity play a fundamental role in flood propagation and also influence the ecological resilience of rivers to disturbance (WOHL 2017). Any anthropogenic alteration of the natural river corridor e.g., through the construction of dams, channel embankments, levees, dikes, removal of riparian vegetation and in-channel wood, etc. will have significant effects on floods as well as floodplain ecosystems.

5.4. Flood change attribution

5.4.1. Recent changes in climatic drivers of floods

As stated above, flooding is a complex phenomenon and the attribution of detected trends or changes is challenging (BLÖSCHL and MONTANARI 2010). At the same time, most of the studies described in Section 4 were able to explain some of the observed changes in flood frequency and magnitude by changes in climatic drivers. In the 20th century, substantial decadal-scale variability in the frequency and magnitude of discharge peaks in Switzerland has been observed (SCHMOCKER-FACKEL et al. 2010a, 2010b; PEÑA et al., 2015). The drivers of this decadal-scale variability are still not fully understood. A comprehensive discussion of recent trends and decadal-scale variability of weather variables in Switzerland can be found in the CH2018 report. Here, we provide a short summary of recent changes in flood-relevant climatic variables.

Circulation patterns

A few typical circulation patterns are linked to most major flood events in Switzerland (5.2.2). Very little is known about past trends and decadal changes in the frequency of these circulation patterns. SCHWANDER et al. (2017) found a weak dependence of central European Weather types on the solar cycle and ROHRER et al. (2019) found no significant effect of decadal variability patterns (Atlantic Multidecadal Oscillation) on the weather type frequency in central Europe. In addition to frequency changes, positive trends in temperature and in the moisture content of the atmosphere might change the effectiveness of flood-prone weather situations to trigger floods.

Recent studies by PEÑA et al. (2015) and PEÑA and SCHULTE (2020) compared large-scale atmospheric circulation and summer floods in Switzerland using the 20CR reanalysis data set going back to 1871 (**Figure 5.3**), and the reconstructed monthly sea level pressure fields over the North Atlantic and Europe (LUTERBACHER et al. 2002) for the period 1659–2000. PEÑA et al. (2015, 2020) found that the positive phase of the Summer North Atlantic Oscillation (SNAO) was linked to summer flooding in the alpine region in the period 1940-2010. Whilst, the SNAO in the negative phase affected summer floods in the northern and western part of the Swiss Alps in the period 1800-1940. The SNAO time series showed a positive and significant trend over the period from 1800 to 2008, suggesting a change in the hydro-climatic pattern from last stages of the Little Ice Age to the present. FREI et al., (2000), SCHMOCKER-FACKEL et al. (2010) and BRÖNNIMANN et al. (2019) suggest that changes in atmospheric circulation, and thus in precipitation, are responsible for the changes in flood frequency in the 19th and 20th century in Switzerland and Europe.

For the flood periods investigated in the alpine Aare catchment, PEÑA and SCHULTE (2020) suggest that the phase changes of the simulated SNAO in the Industrial era (1850–2005 CE) using the Community Earth System Model-Last Millennium Ensemble (CESM-LME) were consistent with changes in the reconstructed (CR20) and observed SNAO. Furthermore, the comparison of flood reconstruction using geochemical proxies from floodplain sediments and paleoclimate simulations provided evidence that the SNAO in negative/positive phase modulated by solar variability (negative/positive anomalies) can play a substantial role in driving flood frequencies in the Hasli-Aare catchment and even in influencing their spatial distribution.

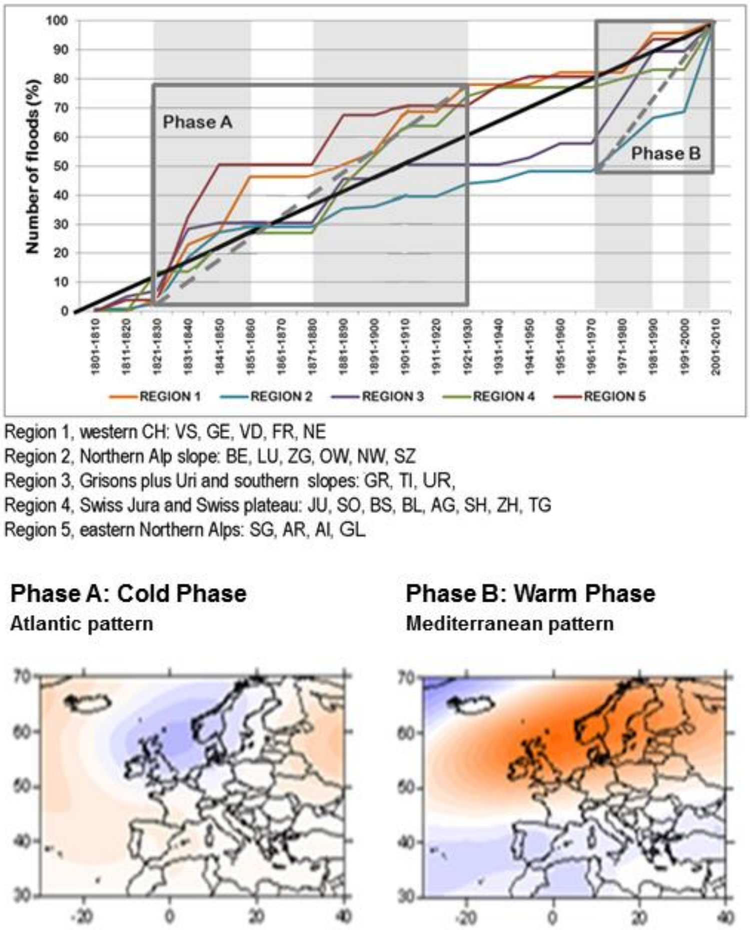

Figure 5.3: Changes in patterns of large-scale atmospheric circulation and extreme precipitation. Top panel -- Decadal cumulative number of regional floods (in %) versus time. Grey areas: high flood frequency period. Bottom panel -- Left side, Atmospheric patterns of Cold period (Phase A) defined as Atlantic pattern, and right side, Warm Period (Phase B) named Mediterranean pattern. Maps are the composites of flooding years. The red (blue) colours in atmospheric patterns indicate positive (negative) standardized anomalies of Sea Level Pressure (values range: 2 to -2, without units). Figure modified from PEÑA et al. (2015).

Mean temperature and precipitation

As in other regions in Europe (BLÖSCHL et al., 2020), the second part of the 20th century, especially in northern Switzerland and Alpine catchments, has been characterized by a flood rich period, most likely related to increases in precipitation and temperature. There was a pronounced increase in mean temperatures in Switzerland (~1.3 °C/100 years). This led to a decrease in the number of days with minimum temperatures below the freezing level. These temperature trends affect the timing, duration and spatial extent of the snow cover, the distribution of permafrost and frozen soil, glacier melt, and the partitioning of liquid versus solid precipitation.

An increase of precipitation events was observed in northern Switzerland since 1970 (e.g., COURVOISIER 1998; BADER and BANTLE 2004; SCHMOCKER-FACKEL and NAEF 2010b). These studies also referred to an increase in temperature since the late 1970s as a potential driver of changes in precipitation and hence in floods (BADER and BANTLE 2004; SCHMIDLI and FREI 2005).

Upward trends in winter maximum discharge observed by BIRSAN et al. (2005) and others was explained by an increase in winter temperature, which resulted in a decrease in snowfall and an increase in liquid precipitation in combination with increased snow melt. This increase was attributed to the increase in the number of days with minimum temperatures above 0°C. HÄNGGI and WEINGARTNER (2011) pointed out the important role of winter temperature for discharge volume. Instead in summer lower precipitation and increased evapotranspiration could explain the decrease in moderate seasonal discharge extremes.

Extreme precipitation

Extremes of daily precipitation and temperature have been increasing during the 20th century at most locations in Switzerland (SCHERRER et al. 2016). At more than 90% of all observing stations an increase in extreme precipitation intensity has been found (average ~+12%) for this period as well as an increase in the frequency (~+26%) of daily extreme precipitation events. Less is known about trends in sub-daily precipitation extremes. A seasonal shift in the occurrence of (moderate) daily precipitation extremes from a maximum frequency in summer towards more events in spring and fall is reported by BRÖNNIMANN et al. (2018). This shift in seasonality is not found for the most extreme daily precipitation events.

Detailed description about changes in extreme precipitation can be found in the Hydro-CH2018 Synthesis report; CH2018, 2018; NCCS, 2018).

Snow cover and 0°line

Negative trends in the number of snowfall days and days with a snow pack are found throughout Switzerland since the 1980s. These trends are strongest at lower elevations. There is a reduction of the snow cover duration since 1970 and this reduction is mainly attributed to an earlier snowmelt in spring. The 0°C isotherm in winter (December, January, February) has been rising by 150–200 m per 1°C warming since 1961 which is equivalent to an increase of approximately 350 m. A higher 0 °C isotherm may result in more precipitation to fall in liquid form increasing the area contributing effectively to runoff (STOFFEL et al. 2016).

5.4.2. Recent changes in non-climatic drivers of floods

Besides changes in climatic drivers of floods, many Swiss rivers and/or their drainage areas have been modified in the past century. Examples of such anthropogenic interventions that are shaping today's rivers are the construction of flood defences such as levees and dams, and various in-channel modifications. These anthropogenic modifications aim at reducing flood risk, utilizing flow for hydropower generation and navigation, and more recently also for river restoration. The construction of levees as flood protection measures in one reach can have adverse effects downstream (e.g., PINTER et al. 2006; WARD et al. 2008; TOBIN 1995; MUNOZ et al. 2018), and thus results in trade-offs between upstream and downstream reaches (e.g., RYFFEL et al. 2014; SALZMANN et al. 2016). Moreover, floodplains can be affected by land subsidence due to drainage or groundwater extraction (CARISI et al. 2017). These changes may also affect flood hazard (i.e., flood frequency and magnitude) and other factors contributing to flood risk (i.e., changes in exposure and vulnerability).

Land use and forest cover changes

Land use has changed significantly in the last centuries. Main land use changes relevant for flooding include deforestation, afforestation, grazing, crops, urbanization, mining, artificial drainage, terracing, etc. Land use change has, potentially, a very strong effect on floods. However, studies that examine the impact of land use changes on streamflow and floods often obtain contradictory results (ROGGER et al. 2017). In general, field drainage, wetland loss and urbanization result in increased runoff and ‘flashiness’ of floods, which means more rapid downstream transmission of flood waves and less floodplain storage (e.g., PFISTER et al. 2004). These effects are most important for micro (<100 km2) and mesoscale (100–1000 km2) river basins. As described by PFISTER et al. (2004) for the Rhine and Meuse basins, the increased urbanization and artificially drained agricultural land since 1945 have had little effect on the flood frequency, in comparison to the impact of climatic change. As the catchment scale increases, it becomes more difficult to identify any land use change effects on floods due to multiple controlling factors and process interactions (VIGLIONE et al. 2016; ROGGER et al. 2017).

In the late 18th and early 19th centuries the Swiss Forestry underwent a fundamental transformation (MATHER et al. 2000; STUBER, 2020). Until then the communities managed the forests mostly autonomously. These “supply forests” ensured local timber and firewood supply, served as wood pastures and for pollarding needles for litter. This resulted in light forests without sharp boundaries to the surrounding pastures (BUERGI, GIMMI and STUBER 2013). The political changes after the downfall of the Ancient Régime (1798) resulted in considerable deregulation, clear cutting and export of timber. Especially so in the mountain areas that were viewed at that time as the timber reserved for the lower lying regions. Major floods occurred during this period (1834, 1839, 1847, 1856, 1868) that were linked to this deforestation (PFISTER and BRAENDLI 1999). This resulted in the Swiss Forestry Police Law (1876) that provided a legal framework for the professional and sustainable use of the forests first only for the Alps and the pre-Alps and 1902 for all of Switzerland. Between 1880 and 2000 the forested area increased by 20 percent. However, this was not only a consequence of forestry legislation. Rather, one of the main reasons was the natural reforestation of former agricultural pasture land, the use of which was abandoned as a result of the changed energy basis (LORAN et al., 2017).

Changes in connectivity, channel capacity and channel processes

Most human activities within river channels resulted in a decrease in hydrological, sediment, biological and landscape connectivity (WOHL 2017; WOHL et al. 2018). Channelization reduces irregularities of the bed and banks, artificial levees reduce channel-floodplain connectivity, and flow regulation typically decreases the magnitude of variation in discharge. Changes in channel capacity might be as important for floods as changes in climatic flood drivers as they alter flood risk (SLATER et al. 2015). Active-channel contraction, incision of the channel bed and reduction of the floodplain storage capacity have occurred in response to river management (ARNAUD-FASSETTA et al. 2009). These modifications affect flood wave propagation and therefore can change the peak, timing and shape of the flood hydrographs (HALL et al. 2014a). Current river restoration efforts aim to remove or push back levees to offer more space for natural river dynamics and thus reduce flood peaks (ROHDE et al., 2006).

In Switzerland, the rising numbers of reservoirs or dams for hydropower production are also important for flood propagation. Particularly the trapping of sediment affects flood dynamics (VÖRÖSMARTY et al. 2003; NILSSON et al. 2005; SYVITSKI et al. 2005). The feedbacks between floods and sediment transport are complex: sediment-starved rivers tend to incise or degrade and narrow, whereas excessive sediment load leads to river bed aggradation with adverse effects for flood conveyance capacity. River incision is one of the sometimes-unwanted effects of river engineering and channelization measures. This leads to the scouring of the lateral river bank slopes and of bridge foundations. River incision often leads to an increase of the transport capacity and thus to a decrease in the frequency of flooding outside of the river channel. In the Emme River between Burgdorf and Gerlafingen, riverbed incision following the construction of river engineering measures and lateral levees resulted in a remarkable decrease in flood risk for houses in the adjacent floodplain (ZISCHG et al. 2018a).

Box 5.1: River corrections and long-term changes in flood risk in the Aare valley

The effects of river engineering measures on flood risk can be studied with a model experiment in which an inundation model that is representing the current state of the river morphology with all anthropogenic modifications can be exchanged with a model that is representing the natural state of the river. This historical digital terrain model can be reconstructed by means of the historic maps and terrestrial surveys that have been conducted during the planning phase of the early river corrections in the 19th century. These highly accurate and reliable topographic maps can be merged with geomorphic signs of historic states of the riverbed by means of recent high-resolution digital terrain models. A flood event can be modelled with both digital terrain and inundation models; and subsequently the comparison allows to quantify the effects of the anthropogenic interventions. This approach was applied to the floodplains of the Aare River basin upstream of Bern (ZISCHG 2016) Selected observed and well-documented flood events of the last decades were modelled using historic states of the river reaches. The documented flood events were compared with the simulations in terms of inundated area and exposed buildings. The river corrections reduced the flooded areas by 88-96% in comparison to a natural state of the river. The examples show that the effects of the main river corrections are remarkable for today's economic activities in the floodplains. Therefore, the maintenance of the former river correction works is an important part of today's risk management practice.

5.5. Changes in flood exposure and risk

Flood events are only hazardous and costly if they affect settlements or other values that are sensitive to flooding. The optimal allocation of resources for flood management must be based on information about the physical flood event and the potentially exposed values. ZISCHG et al. (2018a) presented a method for isolating the individual drivers of flood risk change and applied it to the floodplain of the Emme River between Burgdorf and Gerlafingen. To assess the change in settlements, they used historical topographic maps of five different dates between 1820-2015. For the analysed floodplain, they identified river engineering and changes in river morphology as the main drivers which decrease flood risk over the last century. However, they also found a rebound effect in flood risk due to increase in settlements since the 1960s.

Studies of the change in settlements from multiple regions cannot be based on topographic maps, because the formats of historical maps (prints or uninterpreted scans of prints) do not allow to identify settlements automatically. Recent studies at the national scale in Austria, the Netherlands and Switzerland used georeferenced datasets of the building stock instead of historical maps (JONGMAN et al. 2014; FUCHS et al. 2017; RÖTHLISBERGER et al. 2016). These studies derived the settlement evolution from the buildings years of construction, which are registered at address level in national databases. For all three countries, these studies showed a considerable increase in the absolute number and/or value of exposed buildings over the last decades. However, regarding the share of exposed residential buildings, the analyses by FUCHS et al. (2017) and RÖTHLISBERGER et al. (2016) found an overall decrease in flood exposure ratios of both the newly constructed buildings (see **Figure 5.4**) and the existing buildings in Switzerland for the time period 1919 to 1980.

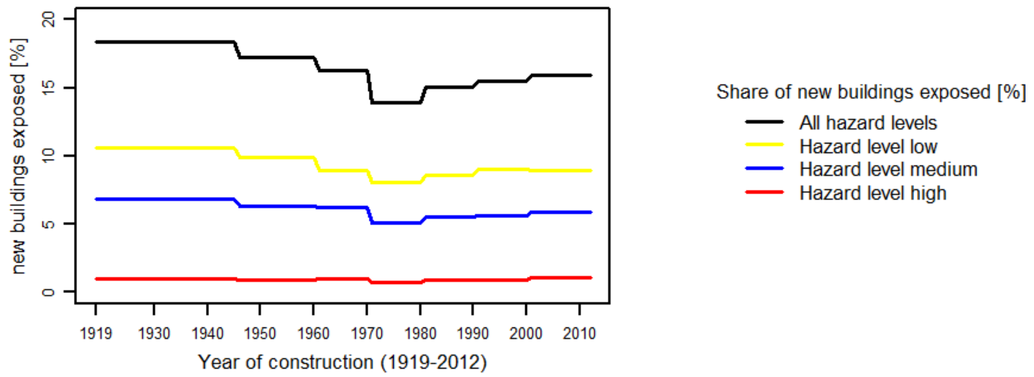

Figure 5.4: Percentage of flood-exposed newly constructed residential buildings for seven construction periods between 1919 and 2012 in Switzerland. The "share of new buildings exposed" is the ratio of the number of "newly constructed buildings that are potentially exposed to floods (according to the Cantonal flood hazard maps as of June 2015)" to the number of "total newly constructed buildings for which a flood hazard map exists" (adapted from RÖTHLISBERGER et al. 2016).

For the more recent periods, there is a slight increase in the exposure ratio for newly constructed buildings in Switzerland. The temporal evolution seemingly questions the effectiveness of current flood risk management strategies, which have been introduced in Switzerland over the past thirty years and prioritise spatial planning over engineering construction. According to RÖTHLISBERGER et al. (2016) and confirmed by BRUCHEZ (2017) in a detailed study over the period 2009 to 2015 for all of Switzerland, there are two possible explanations for this mismatch: a time lag in flood hazard mapping, and obstacles to the enforcement of flood hazard maps in spatial planning.

Take-Home Messages

- Climatic drivers of flooding are heavy rainfall, snowmelt or rain-on-snow, and high soil moisture conditions. Floods can generally be attributed to one or more of these climatic drivers. Rainfall as a driver of major floods in Switzerland in the last 150 years can be meaningfully categorized into five typical flood-prone weather situations.
- Changes in flood frequency and intensity over time arise from a complex interplay of changes in climatic drivers (e.g. change in the elevation of the snowline, changes in extreme precipitation), changes in the river morphology, and changes in non-climatic factors such as land use, forest cover and flood protection infrastructure.
- Compound flood events such as rain-on-snow events can result in significant impacts and are difficult to reproduce and forecast. Because of anticipated increases in air temperature in the future, rain-on-snow events will likely increase in importance.
- Flood risk arises from the interplay of flood hazard, exposure and vulnerability and flood risk changes over time depend on changes in the hazard, in the exposure and to a lesser degree in vulnerability. The combined effect of and the interaction between flood hazard and flood exposure changes will determine the future effectiveness of flood risk mitigation and adaptation measures in Switzerland.

6. Future changes in floods

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6.1. Introduction

Future changes in floods are commonly quantified by forcing watershed models with variables simulated by climate models. These numerical experiments commonly follow a modelling chain where for a selection of greenhouse gas emission scenarios (RCPs) several (global-regional) climate models are run for current and future periods, the climate variables are downscaled and sometimes ensembles are generated, and finally used as input into watershed models with different degrees of hydrological process conceptualization. From these simulations, hydrological regime change can be estimated by comparing future and current climate reference periods, and sources of uncertainty can be quantified. The hydrological regime changes usually focus on mean streamflow and seasonality, less frequently on low flow regimes and floods (e.g. examples in Switzerland ADDOR et al. 2014, KOEPLIN et al. 2014, FATICHI et al. 2015).

Analyses of flood changes with similar setups in the past in Switzerland (with fewer climate models and simpler hydrological model setups) focused mostly on changes in flood seasonality. For example, KOEPLIN et al. (2014) examined floods in a 22-year period in 189 catchments in Switzerland for two periods in the 21st century based on an ensemble of climate scenarios. They showed clear shifts in flood seasonality. In catchments where snowmelt driven floods dominated, changes in flood seasonality were most pronounced, shifting floods earlier into the spring season. In catchments where rainfall was projected to increase in the future, floods also increased but only marginally (KOEPLIN et al. 2014). ADDOR et al. (2014) applied climate change scenarios to six catchments with three different watershed models with a focus on changes in the seasonality of the average streamflow regime and sources of uncertainty. The results showed that (a) even though the dominant uncertainty came from climate models and internal climate variability, a climate change signal emerged by the end of the century even under the lowest emission scenario; and (b) the watershed model predictions varied and were elevation-dependent, highlighting the need to better understand the distributed effect of possible flood changes across the country.

In this section we focus on the effect of climate change on floods defined as annual maxima, i.e. the largest discharges every year at hourly or daily resolutions. We do not follow the entire model chain described above, rather we use the climate change scenario datasets produced by the CH2018 (Climate Change Scenarios for Switzerland) project which are already downscaled to a reasonably high spatial resolution (2x2 km grid). These climate data are used to train a stochastic weather generator to explore the effects of internal climate variability, and they are used as input into three hydrological models and many more catchments than in previous studies. For methodological details see Section 6.2. We extract seasonal and annual streamflow maxima from the simulations and statistically analyse them to summarise what are possible future changes in floods in Switzerland, with a special focus on variability and uncertainty.

6.2. Methodological details

The analysis chain is shown in detail in **Figure 6.1**. The details of the CH2018 Climate Scenario development chain can be found in CH2018 (2018) and are not repeated here. The quantile-mapped daily climate simulations produced on a 2x2 km grid were either used as direct daily input into watershed models PREVAH and HBV Light without stochastic downscaling, or further downscaled to hourly timescales by the 2-d stochastic weather generator AWE-GEN-2D (PELEG et al., 2017; 2019) and used as input into the watershed model TOPKAPI-ETH. PREVAH and HBV Light are conceptual (semi-)distributed watershed models which have been used in climate change impact studies in Switzerland in the past, and are applied here to 195 basins (HBV Light), 93 (PREVAH UNIBE), and 307 basins (PREVAH WSL) at the daily resolution, while TOPKAPI-ETH is a physically-based fully-distributed model which was applied to three basins at the hourly resolution. More details about the individual model applications are in Section 6.3.

Annual maxima (*Q*) were extracted for every year of the simulations and a standard Generalized Extreme Value (GEV) flood frequency analysis was conducted to estimate the flood peaks (Q_R) for return periods R = 2, 5, 10, 20, 30 and 50 years. For the models without stochastic downscaling (PREVAH and HBV Light) this meant a single realisation of annual floods at the daily resolution and estimates of Q_R for every climate model chain from which we computed the multi-model-median (MMM) of Q_R values for the future (FUT) and control (REF) periods and their ratio (see **Figure 6.1**). For the model with stochastic downscaling (TOPKAPI-ETH) this meant multiple realisations of annual floods at the hourly resolution and estimates of Q_R for a reduced set of climate model chains from which we computed the multi-model and ensemble median of Q_R values for the future (FUT) and control (REF) periods and their ratio. The future (FUT) periods were in both cases sliding 30-year periods from the current time to end of the century (1981-2099).

In the analysis we focussed on the signal in mean flood change at the daily scale and the spatial variability between the basins in Section 6.3, and on the stochastic and climate model uncertainty in flood change at the hourly scale for RCP 8.5 in the Thur catchment in Section 6.4.

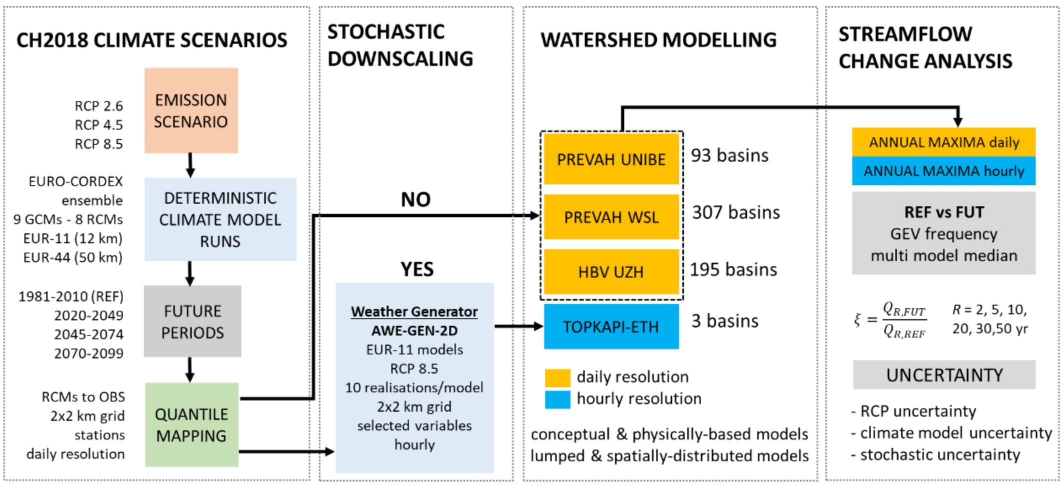

Figure 6.1: Scheme of the climate change impact analysis on hydrological processes and floods conducted as part of the Hydro-CH2018 Project (P Molnar).

6.3. Projected flood changes

PREVAH (Modellers: Zappa, Brunner, Martius, Mülchi)

Two applications of the PREVAH model were developed by the University of Bern (PREVAH UNIBE) for 93 selected basins with gauging (here we show results for a larger selection of 106 basins), and WSL (PREVAH WSL) for 307 basins covering the whole country. The main differences between these two applications of the same hydrological model are in the way they prepare model inputs and calibrate parameters. The UNIBE setup used the climate gridded input and calibrated each basin separately against observations on even years for the period 1985-2014 with the PEST algorithm. The WSL setup used the climate station input which was gridded internally and regionalised the parameters of the model to a 500x500 m grid in a calibration process that involved 140 catchments for the period 1993-1997 (more details in BRUNNER et al. 2019). The WSL setup provides predictions for area-filling catchments in Switzerland, while the UNIBE setup provides predictions for catchments corresponding to the hydrometric stations. As a result, despite using the same hydrological model, the simulations are not identical.

The relative change in flood peaks (FUT divided by REF in percent) for the 30-yr return period is shown in **Figure 6.2** for the UNIBE setup and **Figure 6.3** for the WSL setup. The box plots represent the variability between basins for 30-yr moving windows until 2099. The main messages of both model applications are as follows. First, although the median flood magnitude of all basins is slightly increasing into the future, temporal variability is large. The median increase found in both RCP 2.6 and RCP 8.5 emission scenario is only in the range of 0-10% and in fact temporal fluctuations in median change make predictions highly uncertain. In RCP 2.6 in both model applications the median change drops to almost no change by the end of the Century. Second, spatial variability between basins is large. In many catchments flood change is hardly detectable (or even negative), in others it may reach up to +50%. For example, 25-35% of the basins showed negative change in RCP 2.6, while in RCP 8.5 it was about 27% in mid Century and 2-16% at the end of the Century. The results for floods with lower return periods are similar.

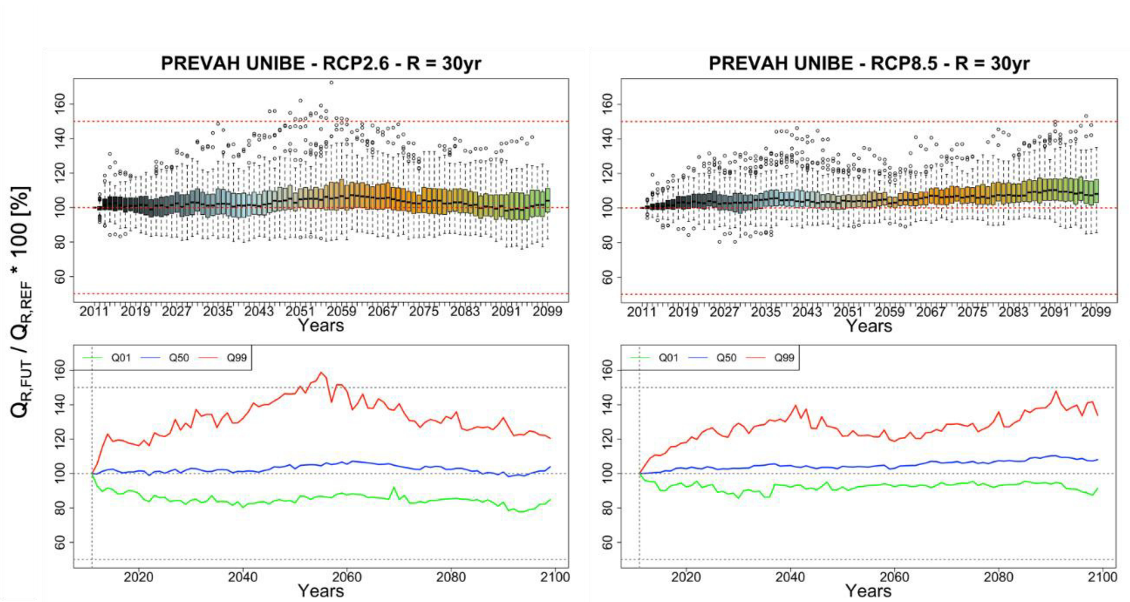

Figure 6.2: Example of simulated changes in Q_{30} with (left) RCP 2.6 and (right) RCP 8.5 for the PREVAH UNIBE model setup. Changes are in % of Q_{30} for FUT/REF in 30-yr moving windows until 2099. The boxplots (top) represent the spatial variability between catchments, the quantile plots (below) show the 1%, 50% and 99% percentiles. Colours indicate progression in time.

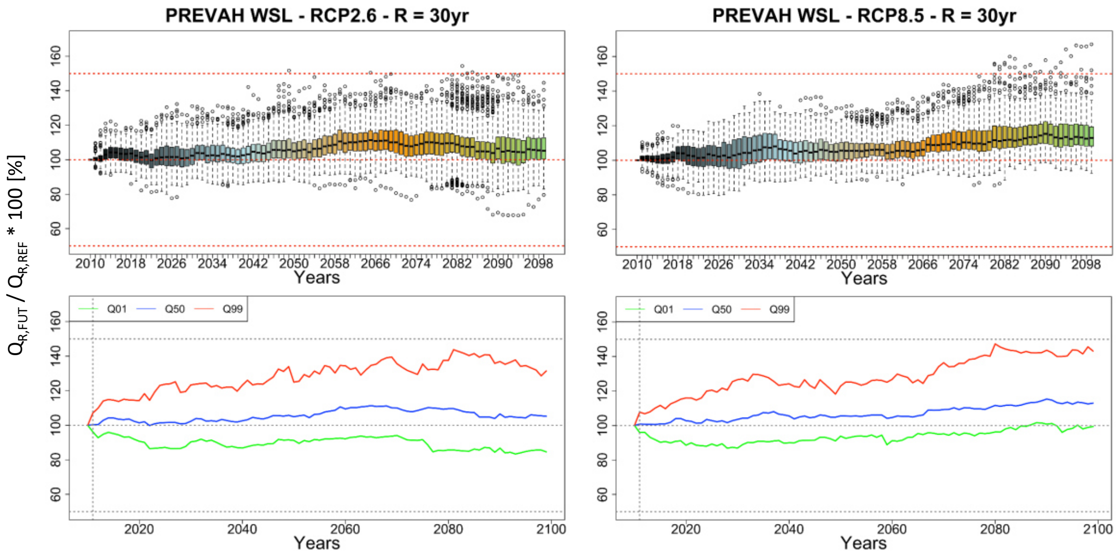

Figure 6.3: Example of simulated changes in Q_{30} with (left) RCP 2.6 and (right) RCP 8.5 for the PREVAH WSL model setup. Changes are in % of Q_{30} for FUT/REF in 30-yr moving windows until 2099. The boxplots (top) represent the spatial variability between catchments, the quantile plots (below) show the 1%, 50% and 99% percentiles. Colours indicate progression in time.

HBV UZH (Modellers: Seibert, Freudiger)

The same results are plotted for the HBV Light model calibrated and validated on 195 basins in Switzerland in **Figure 6.4**. The HBV application was oriented on the streamflow response in catchments with important cryosphere processes. In the calibration and regionalisation of parameters headwater catchments at high elevations were used – 190 of them with glacier cover and 5 without. Despite this difference in elevations, HBV and PREVAH models generally agree that there is large temporal variability in the median change and large spatial variability between basins. HBV results also show that in several catchments flood changes were strongly negative. Although the RCP 8.5 scenario has a slightly stronger signal than RCP 2.6, like in PREVAH, the natural temporal variability in flood change contains the no-change scenario.

The spatial distribution of changes in flood magnitudes between the catchments is shown in **Figure 6.5** for all models for mid-century (2050) and end-of-century (2099). There seems to be an indication towards stronger increases in flood peaks in the mountain catchments in PREVAH, while in HBV there are large differences between individual catchments. The strongly negative changes (orange and red) in RCP 8.5 in HBV simulations belong to the 20 most glacierized catchments (out of 195) modelled. For example, the dark red catchment at the end of Century in southern Switzerland is at the mouth of the Gorner glacier, where simulations show a dramatic reduction in streamflow and floods due to glacier retreat. In this case, increased rainfall in a future climate is not high enough to compensate for the loss of the glacier melt contribution to discharge. Overall, spatial variability in flood change predictions is large and it is difficult to highlight spatially consistent trends at the level of individual catchments from the results reported in **Figure 6.5**.

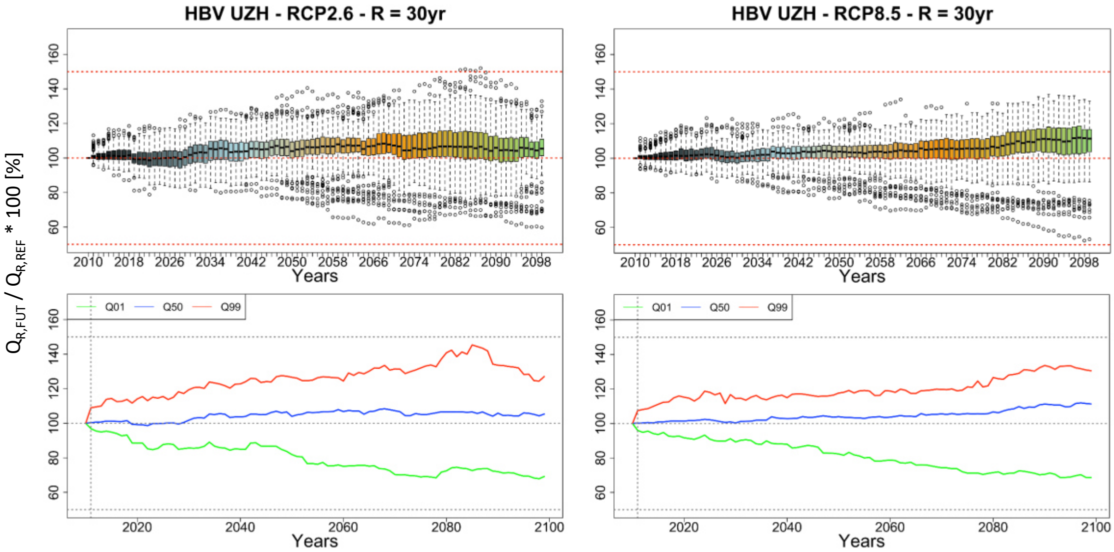

Figure 6.4: Example of simulated changes in Q_{30} with (left) RCP 2.6 and (right) RCP 8.5 for the HBV model. Changes are in % of Q_{30} for FUT/REF in 30-yr moving windows until 2099. The boxplots (top) represent the spatial variability between catchments, the quantile plots (below) show the 1%, 50% and 99% percentiles. Colours indicate progression in time.

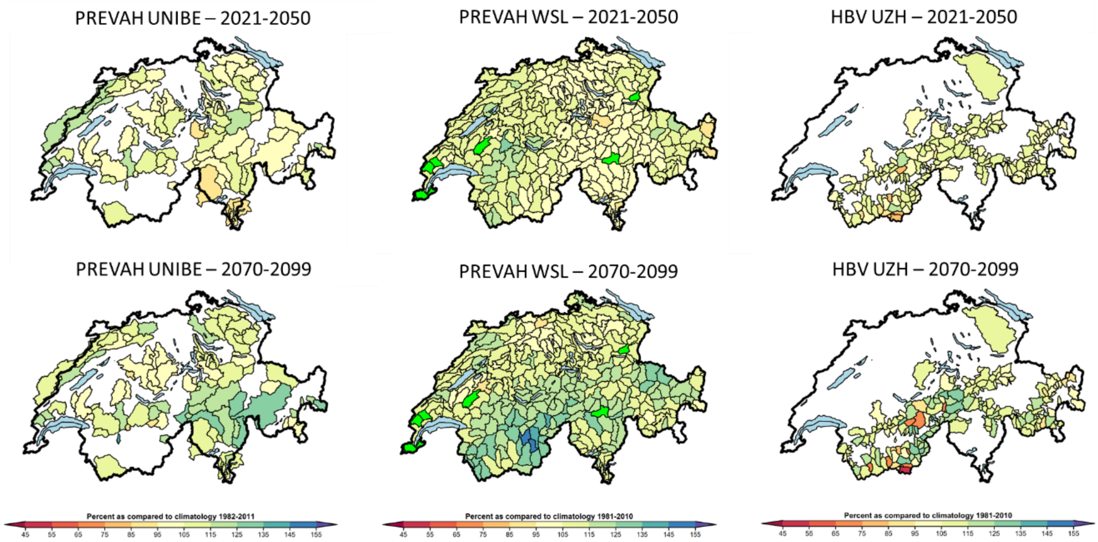

Figure 6.5: Example of simulated changes in Q_{30} for all analysed basins with PREVAH UNIBE (left column), PREVAH WSL (centre) and HBV UZH (right column) for the RCP 8.5 scenario in mid-century (top row) and end-of-century (bottom row). Changes are expressed as % of the estimated Q_{30} for FUT/REF. Green tones indicate increases, red tones indicated decreases in flood peaks. Bright green means that the GEV fit failed in those catchments and no results are reported.

A summary table of the results for all models and two return periods is provided in **Table 6.1** for all catchments as well as a subset of catchments with mean elevations above 1600 m. It can be concluded that flood peaks on the average are increasing in all modelled scenarios in the range 0-10%. However, the uncertainty is large already in the case of small return periods, the mean change is of similar magnitude to the spatial standard deviation between catchments. This becomes even more obvious for higher return periods. This means that although there is a clear tendency towards increases in floods, it has to be acknowledged that the rates of increases are small and the regional signal in flood change is highly uncertain.

ALL CATCHMENTS

	RCP 2.6 - R = 5yr		RCP 8.5 - R = 5yr	
Model	Yr 2050	Yr 2099	Yr 2050	Yr 2099
PREVAH WSL	103% ± 5%	104% ± 7%	105% ± 4%	110% ± 8%
PREVAH UNIBE	104% ± 5%	101% ± 7%	104% ± 5%	106% ± 8%
HBV UZH	106% ± 7%	107% ± 10%	105% ± 7%	104% ± 13%

	RCP 2.6 - R = 30yr		RCP 8.5 - R = 30yr	
Model	Yr 2050	Yr 2099	Yr 2050	Yr 2099
PREVAH WSL	105% ± 8%	105% ± 10%	106% ± 7%	113% ± 9%
PREVAH UNIBE	105% ± 12%	104% ± 9%	104% ± 7%	108% ± 10%
HBV UZH	104% ± 8%	105% ± 11%	104% ± 6%	111% ± 13%

CATCHMENTS > 1600 m

	RCP 2.6 - R = 5yr		RCP 8.5 - R = 5yr	
Model	Yr 2050	Yr 2099	Yr 2050	Yr 2099
PREVAH WSL	105% ± 5%	111% ± 6%	105% ± 4%	114% ± 9%
PREVAH UNIBE	104% ± 5%	103% ± 8%	103% ± 4%	105% ± 9%
HBV UZH	106% ± 7%	107% ± 10%	105% ± 7%	104% ± 13%

	RCP 2.6 - R = 30yr		RCP 8.5 - R = 30yr	
Model	Yr 2050	Yr 2099	Yr 2050	Yr 2099
PREVAH WSL	104% ± 7%	105% ± 12%	104% ± 7%	119% ± 10%
PREVAH UNIBE	103% ± 7%	100% ± 10%	103% ± 6%	115% ± 11%
HBV UZH	104% ± 8%	105% ± 11%	104% ± 6%	111% ± 13%

Table 6.1: Mean change in median Q_R for R = 5 and 30 years with range ±1 standard deviation for three models and RCP 2.6 and RCP 8.5. Results are shown for mid-century and end-of-century for all catchments (left) and catchments with mean elevation > 1600 m (right).

The analyses reported above have additional important limitations. First, the hydrological models have their own parameter and model uncertainty which affect performance at individual basins. This is obvious when the annual flood frequency curves for REF and FUT are shown for the individual models in the same catchment, e.g. Thur in **Figure 6.6**. TOPKAPI ETH and PREVAH WSL predict decreases in flood peaks in this catchment in the future, while PREVAH UNIBE and HBV UZH predict no consistent change. The models also don't predict the annual flood observed data equally well, especially if these were not included in the calibration procedure (e.g. TOPKAPI-ETH was calibrated on hourly data). Second, the uncertainty in the GEV fitting procedure can be equally important, i.e. the confidence bounds predicted by GEV for high return periods will easily overlap for REF and FUT simulations. This is a warning that catchment specific parameterizations and hydrological model choice may be equally important for predictions and deserve detailed attention in future studies.

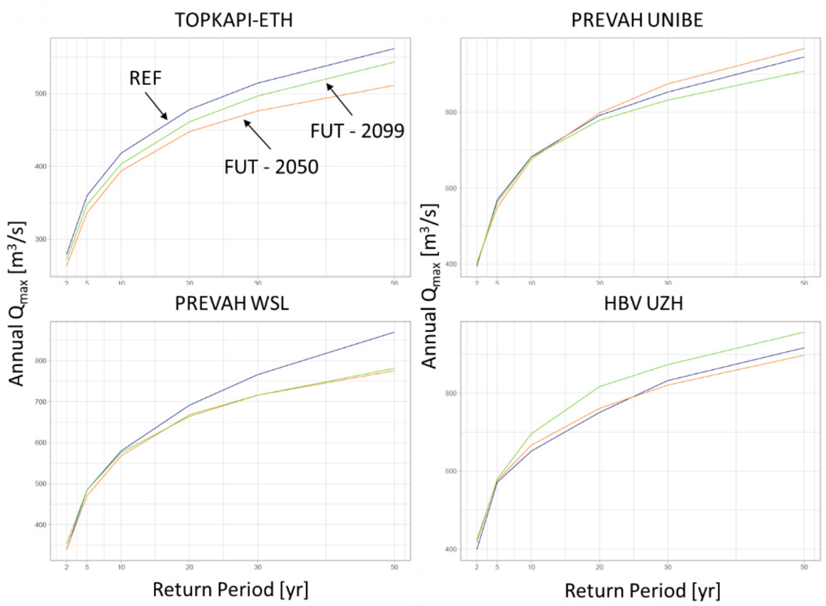

Figure 6.6: Example of simulated changes in flood frequency curves (daily maxima) by all four models for the RCP 8.5 emission scenario for current climate, mid-century 2049 and end-of-century 2099 at the Thur Catchment.

6.4. High resolution (hourly) changes

TOPKAPI-ETH (Modellers: Moraga, Peleg, Molnar)

In three pre-Alpine catchments (Kleine Emme, Thur, Maggia), the physically-based watershed model Topkapi-ETH was used together with a stochastic weather generator model to make flood predictions at the hourly resolution. The weather generator simulated 10 realisations of hourly climate variables (precipitation and air temperature) for the current climate (REF) and future climate (FUT) periods for 9 climate model runs EUR-11 (see **Figure 6.1**). The individual climate model runs were used to quantify internal climate variability (stochastic uncertainty) in floods for each model run and the multi-model-median (MMM). The results in **Figure 6.7** for the Thur Catchment are shown for all studied return periods. The TOPKAPI-ETH model predicts no change in flood peaks in the Thur for the MMM. Some climate model simulations (bars) show a decrease in future flood peaks while other show an increase. Changes in annual maximum streamflow were statistically not significant and within the range of present-day natural variability (first grey bar in figure). Internal climate variability clearly produces a large variability in flood peak estimates. Similar results were found for the Kleine Emme and Maggia catchments.

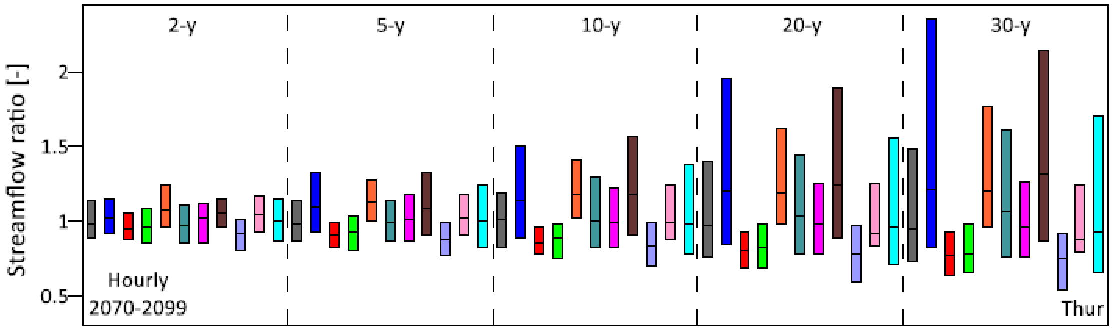

Figure 6.7: The ratio between annual maximum streamflow for a given return period of present climate (REF) and end-of-century climate (FUT 2070–2099) at the hourly scale. Bars from left to right refer to observed natural variability (grey bar), the 9 different climate models, and the multi-model mean (MMM, light blue). Box plots represent the stochastic uncertainty for each climate trajectory (model uncertainty), and for MMM they represent the combination of stochastic and climate model uncertainty. Central lines in the box plots represent the median change computed from the simulated ensemble using GEV distributions, while the boxes represent the 5–95th percentile range of the data. The simulated ensemble for each climate trajectory is composed of 30 realizations of 30 years each, bootstrapped from an archive of 100 years (N. Peleg).

Take-Home Messages
• The results of Hydro-CH2018 analysis for 3 watershed models and up to 300 basins suggest a tendency towards increases in flood magnitude in Switzerland in future (in the range 0-10%) on the average. However, the changes in flood magnitudes are much less significant than the changes in the general hydrological regime due to the differences in how floods are represented in the hydrological models and the role of internal climate variability in their generation.
• There is large temporal variability in flood change predicted by the climate models, temporal fluctuations in median change make predictions highly uncertain, especially for RCP 2.6.

- There is large spatial variability in predicted flood changes, some catchments are very sensitive to changes in precipitation and air temperature and produce much larger floods, and in others such as the glaciated catchments the predicted flood changes are negligible or even strongly negative when ice melt contributions to runoff disappear in the future.
- Including internal stochastic variability in climate forcing leads to the conclusion that changes in flood peaks, especially for very large floods, are extremely uncertain, and lie within the natural variability of floods even in the current climate. This means that predictions of flood changes in individual catchments based on the watershed model results are still challenging.

7. Research gaps and open questions

This section lists open questions and research gaps collected by each author group in their respective sections. The lists are not necessarily in order of importance.

7.1. Paleofloods: changes in prehistoric flood occurrence

An important open research gap is the quantification of uncertainty in paleoflood estimates. Paleoflood reconstructions contain many uncertainties connected to the interpretation of flood processes from indirect evidence in flood deposits, sparsely sampled in lake deltas or floodplains in discontinuous or poorly dated stratigraphies, etc. The actual pathways of sediment carried during floods to depositional areas are often unknown, and geochemistry does not always allow a unique identification of sediment sources. It would be useful to add uncertainty estimates on both timing and magnitude of paleofloods in this qualitative framework. An open research question is also the connection between catchment properties and flood generation processes in long-term (e.g. Holocene) reconstructions, where we do not know the catchment surface cover and climate and their changes in time with any certainty.

Despite these uncertainties, paleoflood techniques have progressed considerably over the last decades, and they are especially effective for the documentation of low-frequency, large magnitude flood events. The use of paleoflood data can provide a comprehensive understanding of the variability of past flood events, extend the hydrological time series and improve the data available for flood risk assessment. Nevertheless, paleoflood data is today rarely considered in design applications. This reluctance may derive from the related uncertainty associated with the determination of flood ages or with the calculation of flood magnitudes. Therefore, one important challenge would be to bridge the gap between paleoflood science and practice. Initiatives like those lead by PAGES (http://pastglobalchanges.org/ini/wg/floods/wp3) are going in that direction.

A new promising approach has been developed in the Bernese Alps to close some of these gaps. This methodology integrates multi-archive datasets from floodplains, lakes, historical sources, tree rings, lichens, archaeological sites, historical buildings and documentary sources for the development of a temporal-spatial (4-D) paleoflood model of alpine catchments (SCHULTE et al., 2019b). Despite the uncertainties of long-term paleoflood reconstructions such combinations improve considerably the spatial information and can provide envelopes on extreme floods which are not recorded by instrumental and historical data. In the Swiss context it remains very important to continue the search for evidence of these large events, and compare Alpine lakes where human effects are low, with evidence from floodplains where settlements are affected by floods, to understand their clustering in space and time, and to disentangle changes of flood dynamics produced by climate and/or human action.

7.2. Historical floods: changes in floods since the 13th Century

Quantitative, documentary-based evidence of floods and historical hydrological analysis (including reconstructed flood magnitudes, either in water levels, discharge or various indexes) have so far been developed only for (major) cities, like Zürich, Lucerne or Basel in Switzerland, whereas possible rural investigation sites have been more or less ignored, probably because documentary data availability is generally less easy. Furthermore, it has to be stated that documentary evidence on rural sites usually cover significantly shorter periods. Still, in the Lower Hasli-Aare valley, for example, an alpine historical flood series could be reconstructed back to 1480 (SCHULTE et al. 2015) from the integration of historical sources, historical maps, geomorphological stratigraphy of river channels, coring and dating of floodplain sediments. Another example from a recent study about the brooks of the municipalities Riehen and Bettingen revealed that although there are no current measurements, the experience base could be significantly expanded to the last two hundred years by including historical documentary evidence on floods (WETTER 2017).

Institutional documentary flood evidence has so far not been analyzed at all, except the 50-year period (1600-1650) from the books of weekly expenditures of the city of Basel (SPYCHER 2017). A more complete analysis of institutional documentary flood sources would expand the experience base about small and normal flood events, which so far is strictly limited to the measurement period, for several centuries into the pre-instrumental past. Reconstructions like this, once analysis has been expanded to other sites, would significantly deepen our understanding of the genesis of particular flood events, and allow us to draw principal conclusions about meteorological triggers and low frequency climatic variability (e.g., WETTER 2017; PEÑA et al. 2015).

According to the benefit historical hydrological analysis may provide to already existing standard extreme value statistical approaches, guidelines in Switzerland should mandatorily regulate quantitative considerations of historical pre-instrumental flood information, as it is already implemented in the EU since 2007 (Guideline 2007/60/EG of the European Parliament and Council from 23 October on assessment and management of flood risks, Official Journal of the European Union, L 288, 27-34, Brussels, 2007). More efforts should be also devoted to the reconstruction of precipitation prior to the network measurements. Historical Climatology has the knowledge and the concepts to provide a major contribution to achieving this objective.

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

A research gap in the identification of changes in flood records is the analysis of their regional coherence, for which standard statistical tests which determine field significance are sometimes not suitable, and/or new approaches need to be developed (e.g. BERGHUIJS et al. 2019). It is necessary to develop better data-driven approaches to find similarity in trend matrixes (such as the mutli-temporal windows) and relate these to potential climatic drivers (e.g., RUIZ-VILLANUEVA et al. 2019).

The attribution of cause and effect by finding the (strength of the) relations between changes in potential climatic drivers (like rainfall and air temperature) and floods is imperfect, especially when increases in flood frequency are interpreted in this way. It is necessary to find more data-based evidence for these relations which include other hydrological factors, possibly employing physically-based hydrological models in the process. Along the same lines, the effects of snow and ice melt on increasing runoff is often mentioned and analysed in Switzerland, but for future impacts in Alpine streams it is also necessary to know if and when glaciers may disappear as a source of runoff.

7.4. Understanding flood triggering mechanisms and flood risk changes

Efforts are still needed to better understand decadal-scale variability in flood frequency in Switzerland. While efforts to understand single drivers of extreme floods will continue, the importance of compound events in triggering floods may require more attention in the future. This includes a more detailed understanding of rain-on-snow flood events, a better understanding of the role of precursor precipitation, i.e., precipitation that does not include the flood triggering precipitation event, for flood triggering. While high snow accumulations in the flood preceding seasons can contribute substantially to major floods (ASCHWANDEN 2000; FORSTER and HEGG 2000; STUCKI et al. 2012b; RÖSSLER and BRÖNNIMANN 2018), the role of precursor precipitation is less clear.

Further studies on changes of non-physical drivers of hazardous flood events are also needed. The investigations must be expanded towards other factors of flood risk, i.e. exposure and vulnerability. With ongoing changes of both the climatic and non-climatic drivers of flood risk in Switzerland, the question about the relative importance of changes in drivers, e.g., exposure versus changes in climatic drivers, needs to be answered, as it is of central importance for informed and sustainable flood adaptation planning but also for attribution studies.

Locally detailed modelling and exposure reconstruction studies such as the one by ZISCHG et al. (2018b) allow for a quantification of the role of different flood risk drivers. However, on a national scale, such analyses are not yet possible due to a lack of high-quality digitized data of historical exposure, river bed morphology and flood protection structures. Even more challenging are projections into the future as the future evolution of exposure depends both on land-use policies and economic development. For these reasons, projections of flood risk in the future remain highly uncertain. Moreover, the vulnerability of the values at risk is still a relevant factor for the uncertainty in flood risk assessments.

7.5. Future changes in floods derived by modelling

Modelling-based climate change impacts on hydrological processes remain an important avenue for future research. There remain many open questions about the effects of watershed model types (conceptual versus physically-based) and their parameterizations, spatial and temporal resolution, and making different model predictions better comparable. In this context it is important to try to include water management actions in climate change studies, for example including hydropower storage facilities and their operation in watershed models (e.g. FATICHI et al., 2015).

Another line of research expands the hydrological processes investigated in climate change impact modelling studies. It is well known that climate warming will impact snow accumulation and melt processes, glacier retreat, evapotranspiration, and all of these may jointly impact flood changes. Elevation dependence is important and is already being investigated in many modelling studies (e.g. KÖPLIN et al. 2014, MORAGA et al., 2020), flood peak and volume dependencies deserve closer attention (e.g. BRUNNER et al. 2019), as well as a general robust classification of flood drivers and changes therein (e.g. BERGHUIJS et al. 2019).

Finally, a strong push should be directed at uncertainty analysis in climate change impact modelling studies on floods. The propagation of uncertainty from greenhouse gas emission scenarios, through climate models, watershed models, to discharge and floods, including the stochasticity of weather (i.e. internal climate variability) has made dramatic methodological and applicative progress in the recent past. In particular stochastic weather generators are an available and attractive alternative to drive watershed models to account for this uncertainty propagation as it is done now with climate variables (e.g. PELEG et al. 2017; 2019). This is important because as examples from this chapter show, climate change signals in flood peaks often lie within natural variability, which masks the details of change we can be confident in (e.g. FATICHI et al. 2016).

8. Concluding remarks and recommendations

This chapter provided an overview of the nature of flood changes in Switzerland in the distant and recent past and looked into possible flood change we may expect in the future. The following main concluding remarks and recommendations can be drawn.

- Historical hydrological investigations and reconstructions of paleoflood estimates with modern geochemical, geomorphological, biological methods need to continue because they provide a comprehensive, nationwide coverage of flood data which includes rural sites and smaller catchments with high flash flood risk, which will be disproportionally affected in a future warmer climate in Switzerland.
- Detection and attribution of flood change remain important areas of research, which should combine innovative statistical data-driven methods with deeper hydrological and climatological process understanding and physically-based modelling support. To this end, the investment in monitoring and quality control of flood records at BAFU and Cantonal networks is critical.
- Significant process has been made in recent years in characterizing the potential hydro-meteorological drivers of floods in Switzerland (rainfall, snowfall, high soil moisture). Such studies need to continue so that changes in these drivers in the past century can be linked to global warming and changes in rainfall patterns. This applies also to decadal scale variability in flood occurrence in Switzerland (flood rich versus flood poor periods), which are still not fully understood.
- Clearly more effort should be devoted to modelling based studies of climate change impacts, improving climate models, downscaling techniques, coupling with watershed models, inundation models, flood risk and uncertainty analysis. There is a need to push into higher time and space resolutions that match hydrological process variability in Alpine environments. Advances in such frameworks will provide credibility to climate change impact assessment and acceptance of the results of such studies by decision-makers and society.

9. References

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10. Appendix

Table A1: Summary of works analysing changes and trends in recorded streamflow and floods in Switzerland, Europe and globally.

Country	Period analysed	record length (years)	number of sites	Flood variables anlysed	Main findings	Reference
Australia	1955-2004	39 to 97	491	Annual maxima (AM)	Significant **downward trend** in the AM in the south-east and south-west regions of Australia	ISHAK et al., 2013
Australia	1950-2014	≥30	222	Annual total, seasonal flows, AM and several quantiles	**Significant reduction** in AM during the middle to late 1990s	ZHANG et al., 2016
Austria	1952-1991	≥10	441	AM, number of floods per year (POT)	POT in the decade 1972-1981, and in the decade 1982-1991, the AM showed **positive linear trend**	NOBILIS and LORENZ, 1997
Austria	1951–2006	55	27	AM and peaks-over-threshold (POT)	No significant trends	VILLARINI et al., 2012
Canada					decreasing trends in both magnitude and timing of annual and spring maximum flow	BURN et al., 2010
Finland	1912–2004	<92	25	Monthly, seasonal and annual discharge (AM)	No significant trends	KORHONEN and KUUSISTO, 2010
France	NA	≥40	179	AM and date of the AM (DAM)	flood trends consistent with the observed rainfall	RENARD et al., 2008
France	1968–2008	≥40	209	AM, annual cumulative volume of POT, DAM, date of POT (DPOT)	AM shows a clear difference between the north, with generalized **positive trends** (especially northeast), and the south, with generalized **negative trends** (especially in mixed regime mountainous regions of the low Pyrenees and Massif Central).	GIUNTOLI et al., 2012

Germany	1951–2002	52	122	AM and seasonal maxima (SM)	Field-significant **increasing trends** for winter in the West and East. For summer, **increasing** and **decreasing** trends are detected in the South and East, respectively	PETROW and MERZ, 2009
Germany	1814–2006	≥50	78	AM and annual flood stages	No significant trends	BORMANN et al., 2011
Ireland	1976–2009	<63	37	AM, SM, annual maximum 10-day flow,annual maximum 30-day flow	High-flow indicators show strong and persistent **positive trends**	MURPHY et al., 2013
Poland	1921-1990	70	39	AM and SM	**Decreasing trend** both in the mean and the SD	STRUPCZEWSKI et al., 2001
Poland	1951–2011	40	14	AM, SM, peak over threshold frequency (POTF) and magnitude (POTM)	More extreme, although perhaps less frequent floods, with a shift in the seasonality, **decreasing** trends in winter and **increasing** trends in autumn and spring.	RUIZ-VILLANUEVA et al., 2016
Poland	1956–2016	>36	147	AM	**decrease** in AM between 1981–2016 in the northern, in southern **mixed increased and decrease** trends	PINIEWSKI et al., 2018
Portugal	1921-2006	NA	10	AM depth and POT	Events constitutes an inhomogeneous Poisson process, hence the occurrence rates are nonstationary	SILVA et al., 2012
Rumania	1961-2009		44	different streamflow quantiles	Increase in winter and autumn streamflow since 1961 and a decrease in summer flow since 1975	BIRSAN et al., 2014
Slovakia	1976-2005	29	NA	Annual and monthly discharge	No significant trends	PEKAROVA et al., 2008
Slovakia	NA	40-109	59	AM	A significant **rising trend** in the upper part of the catchment, and a **decreasing trend** in the lower part	JENEIOVÁ et al., 2014

Slovenia	1941-2005	≥50	22	mean annual flow depth and POT	A **falling trend** at stations with predominantly high-mountain and karstic catchment areas	ULAGA et al., 2008
Slovenia			77		Both significant negative and positive trends found for maximum flows (slightly more stations with negative trends). Negative trends were found for predominantly high mountain and karstic catchments	JURKO, 2009
Spain	1961–2000	39	20	Long-term quantiles, exceedance series (number of days), AM and SM	A general trend of **decrease** in the frequency and magnitude	MORÁN-TEJEDA et al., 2012
Spain	1942–2009	40	30	AM, SM, peak over threshold frequency (POTF) and magnitude (POTM)	A general **decreasing** trend in magnitude and frequency of floods, an **increasing** trend in the timing	MEDIERO et al., 2014
Sweden	1901–2002	59	61	Annual runoff, AM, SM	No significant trends, a slight increase in annual (and spring) floods	LINDSTRÖM and BERGSTRÖM, 2004
Sweden	1961–2010	49	69	Anomalies in annual maximum daily flow, AM, SM	Dry and wet periods identified, but no significant trends	ARHEIMER and LINDSTRÖM, 2015
Switzerland	1931–2000	≥30	48	AM, SM	**Increase** in winter, spring and autumn, summer with both **upward** and **downward** trends	BIRSAN et al., 2005
Switzerland		up to 105 years (minimum record length 10 years)	83	>10 year flood (HQ10)	Flood-rich periods linked with changes in large scale atmospheric circulation	SCHMOCKER-FACKEL and NAEF, 2010
Switzerland		>91	17	AM	Significant changes in the frequency regime of annual maxima and **increasing** trends in the magnitude of annual flood peaks	CASTELLARIN and PISTOCCHI, 2011

Switzerland	1800-2008		26	Annual Flood damage index	Identification of flood periods. Flood pulses related to atmospheric pattern, particularly to SNAO.	PEÑA et al., 2015
Bernese Alps, Switzerland			6	Annual Flood damage index	Identification of flood periods. Flood pulses related to atmospheric pattern, particularly to SNAO. Increase during the 19th c. and end of 20th also due to anthropogenic factors.	SCHULTE et al., 2019
Turkey	NA	25-66	96		Statistically **significant decrease** in maximum flows	CIGIZOGLU et al., 2005
United Kingdom	1870–1995	-	890	AM and POT	No significant trends	ROBSON et al., 1998
United Kingdom	1959–2003	NA	87	Annual maximum 10-day flow, annual maximum 30-day flow, prevalence of flows above Q10, AM, POTF	Significant **positive trends**	HANNAFORD and MARSH, 2008
United Kingdom	1961-2010	20	446	AM, SM	Different patterns for changes	PROSDOCIMI et al., 2014
United Kingdom	1884–2013	NA	NA	Flood impact reports	**Upward trend** in flooding over time and flood events	STEVENS et al., 2016
United States	NA	NA	14893	Flood magnification factor	Significant **positive** magnification factors	VOGEL et al., 2011
United States	1962–2011	≥50	774	AM, SM and POTF	No significant trends	MALLAKPOUR and VILLARINI, 2015
United States	1940-2013	≥20	369	Streamflow thresholds	Complex, fragmented pattern of flood change, no meaningful generalizations about flood change across the United States	ARCHFIELD et al., 2016
United States	1950-2013	NA	401	Flow stage, frequency, discharge	Flood frequency nonstationary, with **increasing** flood hazard	SLATER et al., 2016
United States	NA	≥30	7506	AM	No significant trends	VILLARINI, 2016

Multiple countries (Denmark, Finland, Iceland, Norway and Sweden)					General **increasing** trend in streamflow magnitude and a trend in the timing of floods in the Nordic countries (except Iceland), given that they tend to arrive earlier in spring.	WILSON et al., 2010
Germany, Switzerland, Czech Republic, and Slovakia	1817–2008	≥75	55	AM, SM	No significant trends	VILLARINI et al., 2011
Alps (6 countries)		≥40	177	Daily discharge and snowmelt flow indices	**Higher** spring flows (snowmelt-related) and **increase** in volume and peak for glacier regimes	BARD et al., 2012
multiple Baltic countries	1922-2008		70	Spring floods	**Downward** trends over longer times, only significant **upward** trends in recent period	REIHAN et al., 2012
multiple European countries		Review of some of above and others			No significant trends	MADSEN et al., 2014
multiple countries (25 European countries)	1900–1999	≥42	102	AM, POT	a **decreasing trend** in the magnitude, a **decreasing trend** in the timing, a **mixed pattern** of changes in the POT	MEDIERO et al., 2015
multiple countries (38 European countries)	1960–2010	≥35	4262	DAM	A clear **shift in the timing** of floods **Positive and negative changes** in flood peaks	BLÖSCH et al., 2017 BLÖSCH et al., 2019
multiple continents	review from above					HALL et al., 2014
	1965-2005	41	629	AM, POTF and POTM		MANGINI et al., 2018
multiple continents (Australia, Brazil, Europe and the United States)	1980–2009	≥30	1744	DAM and frequency of extreme floods	Overall **increases** in both the frequency and magnitude of extreme floods	BERGHUIJS et al., 2017
multiple continents	1985–2015	31	NA	Flood frequency and duration	No significant trends in the frequency of short-duration floods, but a significant **increasing trend** in the annual median of flood durations	NAJIBI and DEVINENI, 2018

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