Report

Understanding flood triggering mechanisms and flood risk changes

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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).

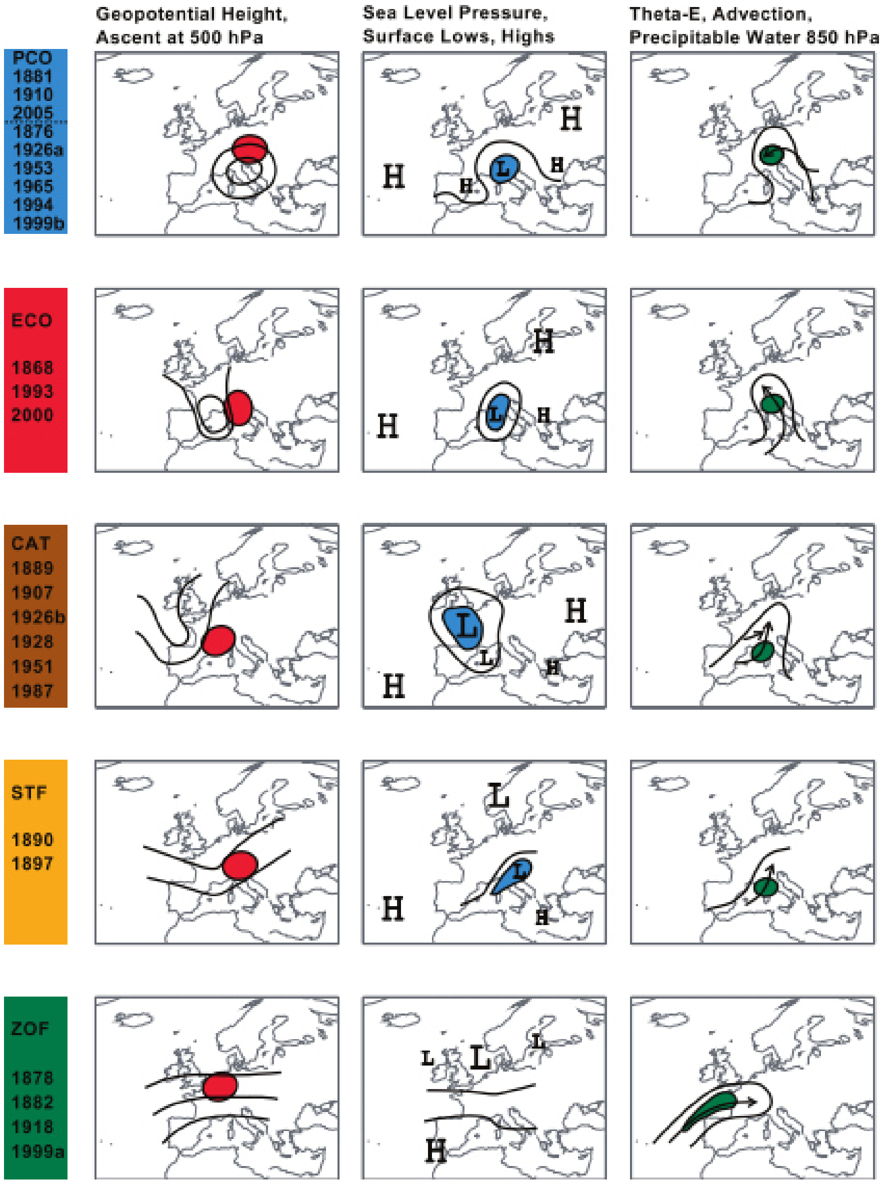

Figure 5.1: Schematic showing flood-causing atmospheric patterns categorized into five types (coloured box with dates of representative flood events): PCO (Pivoting Cut-Off; subtypes separated by dashed line), ECO (Elongated Cut-Off), Canarian Trough (CAT), Stationary Front (STF), and Zonal Flow (ZOF). 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**.).

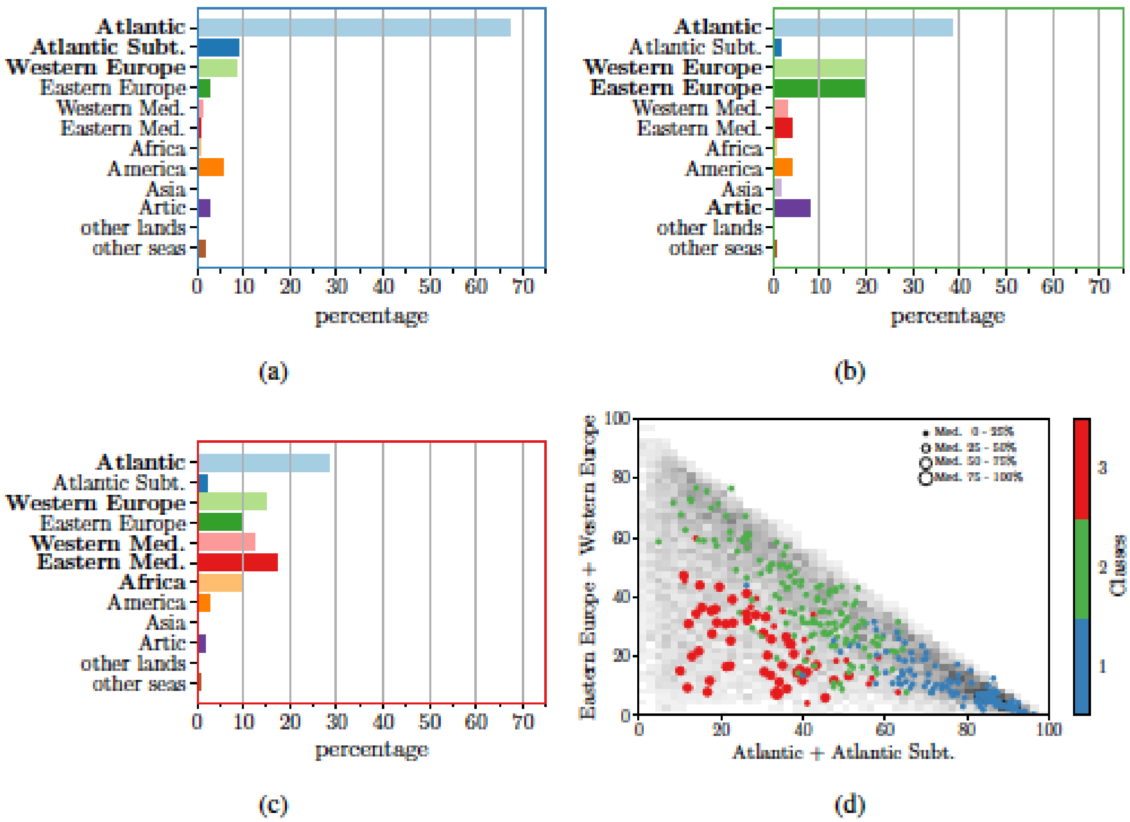

Figure 5.2: Three categories of precipitation events in Switzerland in the period 1979 to 2011 according to their moisture sources (a – mainly North Atlantic, 114 events; b – mainly continental, 141 events; c – mainly Mediterranean, 67 events) based on the ERA-Interim Reanalysis dataset from the European 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.

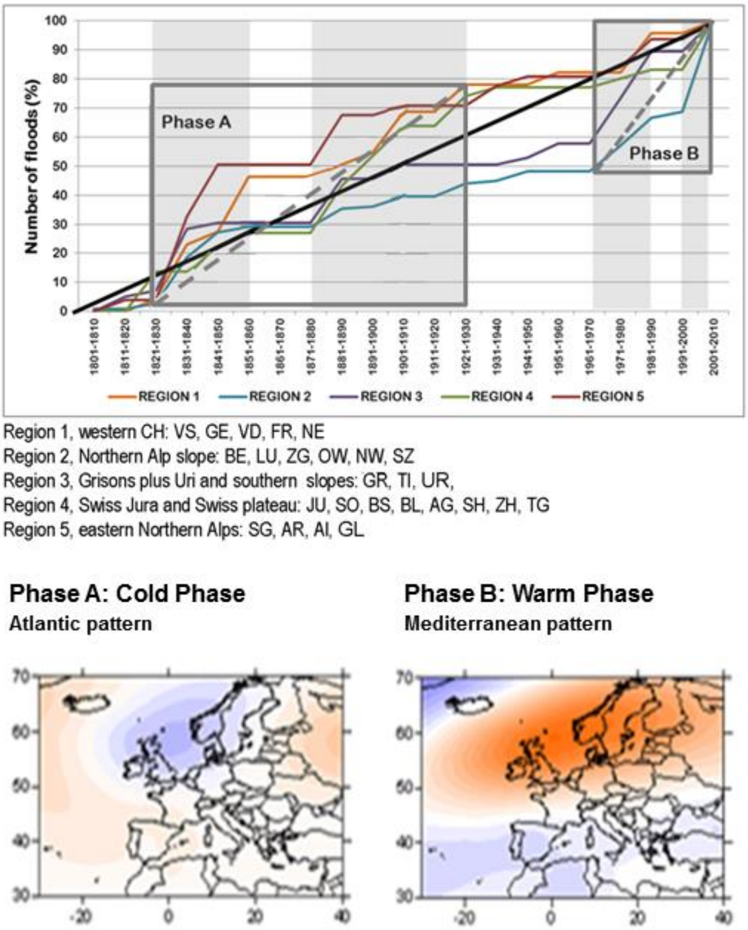

Figure 5.3: Changes in patterns of large-scale atmospheric circulation and extreme precipitation. Top panel -- Decadal cumulative number of regional floods (in %) versus time. Grey areas: high flood frequency period. Bottom panel -- Left side, Atmospheric patterns of Cold period (Phase A) defined as 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.

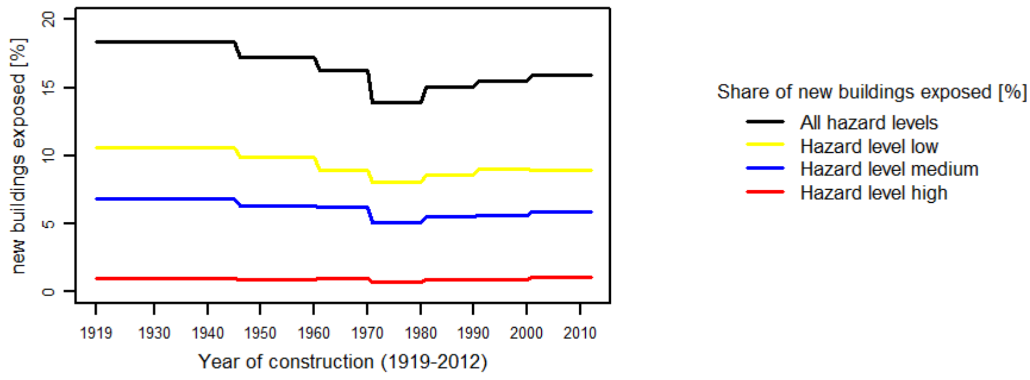

Figure 5.4: Percentage of flood-exposed newly constructed residential buildings for seven construction periods between 1919 and 2012 in Switzerland. The "share of new buildings exposed" is the ratio of the number of "newly constructed buildings that are potentially exposed to floods (according to the 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.