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1868 – the flood that changed Switzerland:

Causes, consequences and lessons for the future

GEOGRAPHICA BERNENSIA

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Causes, consequences and lessons for the future

Preface

This booklet is the outcome of an idea that originated at the Oeschger Centre for Climate Research at the University of Bern, and builds on a long Bernese tradition: the study of historical floods and their relevance to the present. With the participation of several research groups from the Oeschger Centre and the Mobiliar Lab for natural risks, and in cooperation with MeteoSwiss, Meteotest and the Swiss Federal Research Station for Forest, Snow and Landscape, the idea has grown into a research project over the past two years.

The starting point was the question: How well we can reproduce past heavy precipitation events, floods and their consequences in order to draw lessons for the future? Soon the interactions between the environment and society became a major topic. From the point of view of atmospheric science, the aim was to reproduce weather situations and heavy precipitation events in as much detail as possible in a numerical weather-prediction model. The heavy precipitation events reconstructed in this way should then be incorporated into a hydrological-hydraulic model with which the relevant factors leading to flooding, as well as areas affected by flooding, can be estimated. The aim of the scientific-historical analysis was to collect and evaluate information on the damage and social effects of these floods in their historical context. Finally, the contribution of risk research was to outline today's flood protection measures and management practices and how they developed from a sequence of historical events and societal processes. These different approaches led to an extremely fruitful exchange of ideas between scientists from various disciplines, which ultimately led to this booklet.

Looking back far into the 19th century allows the analysis of many individual events – and thus enables much more reliable statements than if only the past 30 years had been investigated. The view also leads us back to a time which shaped flood protection in Switzerland to this day. The measures taken in the 19th and early 20th centuries are still effective today. At the same time, the 19th century view is also connected with a scientific mystery: Floods were apparently more frequent at that time than during most of the 20th century. Why was this the case, and why does the frequency of flooding fluctuate at all? Understanding this was one of the goals of this project.

From the very beginning, however, the focus of our work was on one specific event: the catastrophic floods of 1868 (Fig. 1) — an event that truly changed Switzerland. Only late in the project we realised that in September 2018 the event would be exactly 150 years ago, and chose this date to publish this report. Anniversaries of past events have traditionally played an important role in coping with extreme events. In this sense, this booklet follows the tradition of a "culture of remembrance", which we, however, approach in a different way – with an interdisciplinary, scientific, and quantitative approach. (For a photographically tangible collective memory of floods, see the website of the Mobiliar Lab for Natural Risks at the University of Bern: *www.ueberschwemmungsgedaechtnis.ch*).

The work is based on several projects funded by the Swiss National Science Foundation and the Federal Office for the Environment (FOEN).[2] Printing was supported by the Oeschger Centre for Climate Research, the FOEN and the Atmospheric Physics and Chemistry Commission of the Swiss Academy of Sciences.

***Fig. 1:** The flood of 1868 in Lustenau, Vorarlberg (cf. map[1] in the Appendix). The photo is typical for photos of floods before 1900: Due to the long exposure times, people had to stand still as if in a photo studio. It was not yet technically possible to depict water in motion. In addition, the boats in the streets emphasise the drama of the event. However, the water was probably not deep enough for boats to float – it hardly reaches the knees of the children in the photo. The photographer was probably already on dry ground with his camera (see also Fig. 5).*

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Introduction

When a dear family member dies, the surviving dependants often dedicate a memento to him. (...)
The catastrophe of 1868, to which many lives, possessions and property of extraordinary amount fell victim,
can certainly be considered a grave. Thousands of people who have suffered
have gathered around this grave in order to plant a forget-me-not,
for the memory of the living and for the edification of their descendants.
(Kaiser and Killias, 1870)[3]

This preface to a contemporary report on the floods of 1868 bears witness to the suffering of those affected, but it also looks into the future. Today, 150 years later, we can look back, reconstruct, and re-assess the event. We can ask ourselves how nature, landscape, and society have changed since then and what we can learn about today's floods. The authors of this foreword, written in 1870, could not yet know that this flood would change Switzerland well into the 21st century.[4] While the physical traces of the flood have long since disappeared, the measures taken at that time, and the changes in political processes initiated through this event, are still imprinted on Swiss mountain forests, rivers, and settlement areas today. The floods of 1868 thus became a force that shaped the landscape and, likewise, shaped society. It was not the only flood with such effects. The events of 1978, 1987, 1999, and 2005 again led to a rethinking of flood protection – again with effects on the landscape.

Current and future events and society's response to them will also shape the future landscape. The flood of 1868 is therefore not only an interesting example of a flood that helps us to better understand the processes in the atmosphere and to better model the runoff, but it also mirrors the interactions between society and the environment.

This booklet focuses on the present. It presents the processes that lead to flooding, shows the consequences for society, and discusses possible strategies for coping with them. Many factors are involved in the generation of a flood (Fig. 2): First, a heavy-precipitation event is required, which in turn is linked to certain weather situations. The heavy precipitation leads to high runoff, but only if further preconditions are met. For example, the soil must be water-saturated, the lake levels must already be high, or there must be a melting snow cover. Whether high discharge leads to flooding depends on the river bed and the processes taking place in it. Dams, embankments, existing structures, and also wedging trees play a role here. Heavy precipitation events can trigger debris flows, which in turn change the riverbeds and alter sediment supply. Flooding causes death and injury, and damage to buildings, infrastructure, and cultivated land. The extent of these damages in turn depends on how people use the endangered areas – and thus also on decisions taken in the past. An extreme event can lead to decisions that will have an effect in the future. For example, the floods of 2005 changed the warning system in Switzerland, improved administrative procedures, and led to the implementation of flood protection measures.

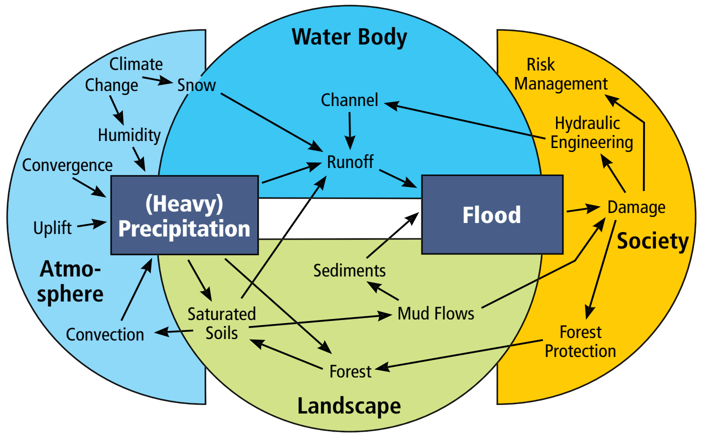


***Fig. 2:** Heavy precipitation and floods depend in many ways on meteorological, hydrological, geomorphological, and social processes.*

All these aspects are covered in this booklet, with a double page dedicated to each topic. The focus of these contributions lies on the current state of knowledge on a given topic. In a second text element on each double page, reference is made to the 1868 event. It shows how the processes took place in this concrete case. If we succeed in reconstructing and modelling the processes of 1868, the role of influencing factors and of the preconditions can be estimated – knowledge that can still serve as a basis for our decisions today.

In the first part of this booklet, the scientific processes are presented, starting with atmospheric processes. Floods are usually caused by heavy precipitation, which in turn requires three main ingredients: Humidity, convergence and uplift (large scale in weather systems or small scale in the form of convection). Three chapters on the processes in the atmosphere examine the weather conditions, the origin of water vapour, and the role of convection. Two chapters shed light on the development of floods from a hydrological perspective, first discussing the basic disposition which depends on spatial factors, then the triggering factors for individual floods.

But how do we come to this knowledge? The second part of the booklet describes the methods with which we can study heavy precipitation and floods – today and in the past. The basis for the study of the past is, on one hand, historical documents from which valuable information can be obtained with the help of source work. On the other hand, long meteorological and hydrological measurement series provide important information. A chapter of the booklet outlines the current measuring, forecasting, and warning systems. To quantitatively reconstruct an event such as 1868 today, a whole chain of methods is necessary. In order to reconstruct the weather from past measurements, science uses so-called "reanalyses" – weather data sets obtained from the combination of measurements and numerical weather-prediction models, which are presented in one chapter. In separate chapters, the spatial refinement of these reanalyses, by means of downscaling as well as hydrological modelling, and finally hydraulic modelling are presented. The latter calculates the probability of flooding on a very small scale. These are the tools with which the processes taking place in nature are recorded, evaluated, analysed, and reproduced.

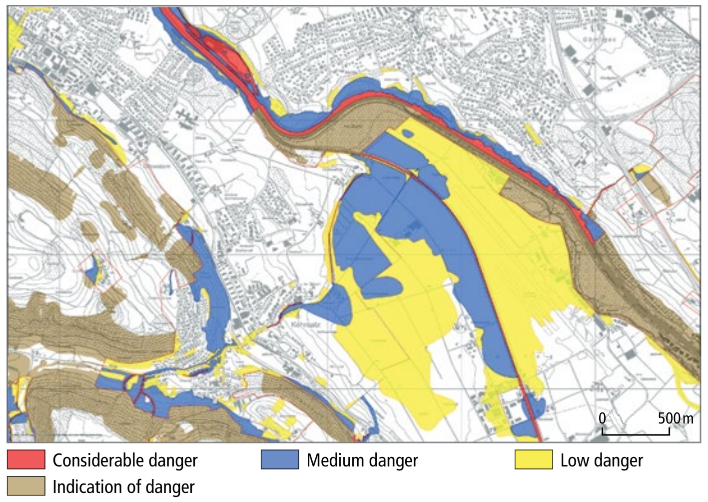


***Fig. 3:** Excerpt from the natural hazard map of the Canton of Bern, Kehrsatz-Belpmoos area.*

The third part of the issue deals with the effects of floods. The following questions are discussed: How are heavy rainfall and floods interacting with the terrain? What damage occurs to buildings and infrastructures? But also: What happens afterwards? How does society cope with floods? Which prevention measures are possible and meaningful (cf. Fig. 3)? And how will floods change our society in the long term?

The fourth and final part of the booklet deals with changes in flood frequency. First, a long-term perspective is taken and the question is asked whether warm epochs are actually richer or poorer in floods than cold ones. The focus of the second chapter of this part is on changes over the past 200 years. This period is particularly relevant for today's society, but also for the future: If during that period, the frequency of flooding has fluctuated over multiple decades, as the analysis shows, it will likely continue to do so in the future. Finally, the last chapter looks at expected changes over the next 50 years: What do we have to prepare for? Will heavy precipitation events become even more intense in the future? What effects will these changes have on the frequency and severity of floods in the future?

***Fig. 4:** Cleaning up after a flood.*

The severe floods of 1868

After an already rainy September 1868 (and correspondingly high sea levels), two heavy precipitation events occurred within one week. The first rainfall episode on 27 and 28 September mainly affected the cantons of Ticino, Grisons and St. Gallen; the second phase from 1 to 5 October affected Ticino, Valais and Uri. The precipitation sum of 1118 mm on the San Bernardino Pass, accumulated over eight days, is a record-breaking figure for Switzerland.

The intense rainfall led to flooding on both sides of the Alpine ridge. Numerous rivers left their banks. The Rhine Valley and Magadino Plain were submerged. Lake Maggiore reached its highest-ever measured level of 199.98 m above sea level on 4 October 1868 (Fig. 5).

The damage of the event was enormous. A total of 51 people died. Numerous bridges were washed away or damaged, and parts of the village of Vals were covered with a metre of sediments. According to an estimate by historian Christian Pfister, the event was the most expensive catastrophe between 1800 and the floods of 1978.[5]

The damage exceeded the financial capacities of the affected communities and cantons. Extensive donations from less-affected areas, and even from abroad, enabled the communities to rebuild.[3,4] But the effects of the floods reached further. They range from the implementation of (previously discussed) river engineering measures[5] and a corresponding paradigm shift in the political process of flood management, to the debate on the role of deforestation for floods, which ultimately led to the Swiss Forestry Law.[4,7]

In the text elements with blue background in this booklet, the processes discussed in the main text are explained using 1868 as an example. These short texts discuss the large-scale weather conditions, discharge, and lake levels. They show quantitative reconstructions of atmospheric processes, runoff, and flood areas of 1868, and analyse the damage and how society copes with it, as well as longer-term effects. Finally, the text boxes embed the floods of 1868 into the long-term climatic fluctuations.

***Fig. 5:** Flood of Lake Maggiore in Verbania[1] in 1868 (left). At the time of the highest level, the water reached over the arcades of the old town houses (flood mark in the photo on the right).*

Flood-prone weather types in the Alps

The weather in the Alps depends on the spatial arrangement of high- and low-pressure systems over the Eastern Atlantic and Europe. These pressure patterns determine the large-scale circulation and, thus, the temperature distribution, wind direction, or humidity in the Alpine region. Three weather types in particular are responsible for floods in the Alps. They are called Vb type, PV streamer and blocking.

Weather types

In meteorology, typical pressure patterns that appear repeatedly in a similar configuration are often summarised into so-called weather types.[8,9] Three common examples for Switzerland are Bise, westerly wind, and Föhn. The Alps form a weather barrier, such that large-scale weather conditions can have very different regional and local effects: clouds and rain on one side of the Alps, sunny and dry on the other.[10,11]

While detailed and reliable forecasts of precipitation require numerical weather-prediction models (see p. 22), the use of weather types as a simplified view of weather systems also has advantages. Firstly, large-scale weather systems often determine regional precipitation intensities and areas over several days. Accordingly, the connection between large-scale atmospheric circulation and regional precipitation in the Alpine region can be captured with weather types. Secondly, typical atmospheric or hydrological developments (e.g. towards extreme events) can be analysed and understood more easily for weather types than for any individual weather situation. Thirdly, severe and extreme flood events in the Alpine region over the last 150 years were often connected to similar weather types.[12,13] Hydrometeorological investigations of such analogous cases can therefore help to understand and recognise typical constellations for extreme floods at an early stage.

In the past, weather types were often defined and attributed based on the subjective analysis of surface and upper-level weather maps and weather fronts. Today, various objective, statistical methods are used for this purpose. These methods can also be applied to station data.[14,15] To date, both subjective and objective terms have been used to describe flood weather conditions in the Alpine region. In the following section, we take a closer look at three common types.

Vb type, PV streamer and blocking

The name Vb type goes back to a subjective classification from 1891,[16] which classified weather conditions on the basis of the tracks of low-pressure systems (Fig. 6). From the original list, only the term Vb is still sometimes used today; for example, for the weather conditions that were decisive during the Alpine floods in August 2002 or August 2005.[17–19] Vb cyclones are typically formed over the Mediterranean, south of France, and intensify in the Genoa region. Controlled by a southerly upper-level flow, they move around the eastern Alps and then further northwards. On the upstream side of the upper-level flow, very warm and increasingly humid air is transported northwards across the Mediterranean Sea. Depending on the exact position, speed, and direction of the Vb cyclones, the moist air masses finally flow towards the north side of the Alps from a north-easterly direction, as for example during the flood in August 2005.[12,17–19] A combination of factors such as upgliding over blocked cold air in the ground layer, the forced uplift of the moist air at the pre-Alpine ridges, and convection can then lead to very strong and very persistent precipitation north of the Alps.

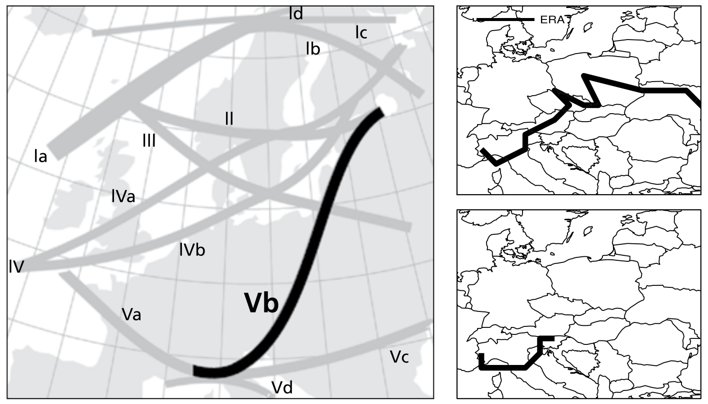


Fig. 6: *Left: Tracks and names of barometric minima (low-pressure systems) between 1876 and 1880 according to W. J. van Bebber.[16] Right: Tracks of the low-pressure systems during the floods of 10–13 August 2002 (top) and 20–24 August 2005 (bottom).[17,18]*

So-called "PV streamers" (PV stands for potential vorticity) are regarded as meteorological precursors of extreme precipitation on the southern side of the Alps. A streamer is a narrow (100–500 km wide), elongated (about 2000–3000 km long) tongue of stratospheric air, which extends from the polar region south over Western Europe far into the Mediterranean region[20–22] (Fig. 7, see also Fig. 44). Typically, streamers propagate slowly towards the east. On their upstream side (often above the western Alps), the upper-level winds are directed towards the north or northeast. Below, in the lower and middle troposphere, the stability of air layers decreases and large-scale uplift begins. In addition, warm and humid air is directed in a constant flow from the southern Mediterranean towards the Alps. As a result of this quasi-stationary weather situation, the humid air masses converge along the southern Alpine arc, rise, and can discharge as heavy precipitation. Often this process repeats over the same region over several days.

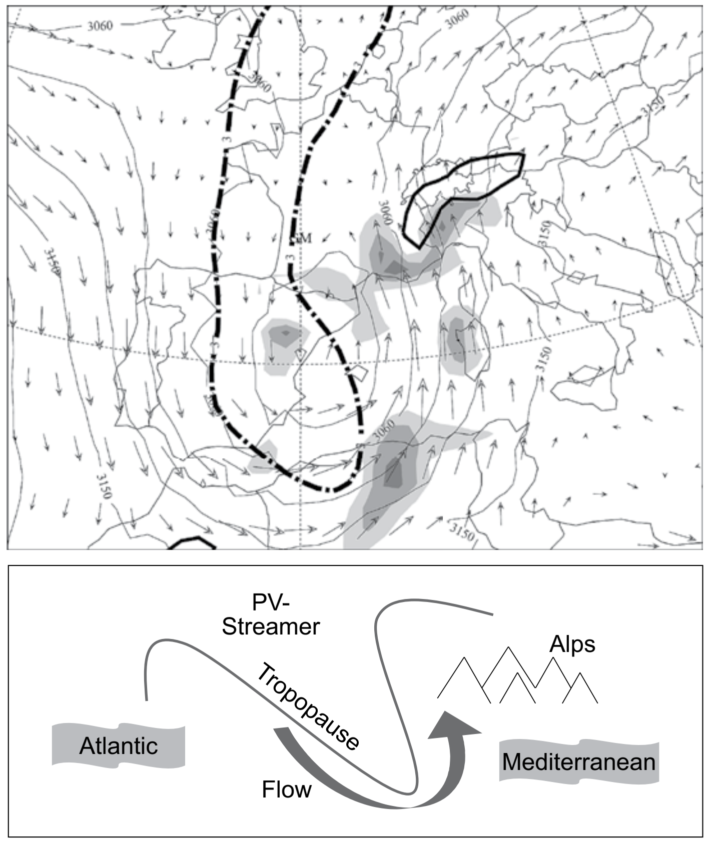


Fig. 7: *Weather situation during the September 1993 flood event. Top: Tropopause (bold dotted), geopotential altitude (at 200 hPa; solid lines), elevation of air masses (grey shading; Pa/s) and wind (arrows) in the upper troposphere. Bottom: Corresponding flow concept.[20]*

So-called "atmospheric blocking" can also lead to large-scale, long-lasting and extreme precipitation events. "Blocks" are long-lived (at least three to five days), quasi-stationary, high-pressure systems that block the progression of low-pressure systems from west to east. A low-pressure system can come to a halt, or several successive disturbances are diverted onto similar detour paths. Blocking weather types can occur on the upstream side (i.e. east) or on the downstream side (i.e. west) of a low-pressure area, and both types can also occur simultaneously (see Fig. 8). An omega block can emerge between two low-pressure systems (the isobars then draw the letter Ω). Last but not least, blocking situations can also contribute to the formation of PV streamers. Blocking played a role on the southern side of the Alps during various phases of the 1993 and 2000 floods[23] or on the northern side of the Alps in 2005 and 2011.[12,24]

Figure 8 shows the flood event in August 2005 as an example of different perspectives on weather types. Here, the quasi-blocked Genoa low is in the first phase of a Vb track (Fig. 6). The definitions are subjective and often not entirely clear: for example, this cyclone left the actual Vb track after crossing the Alps,[10,12] i.e. it did not continue northwards. Also, some experts would not consider the weather situation in August 2005 to be a blocking situation according to the definition (see column, right).

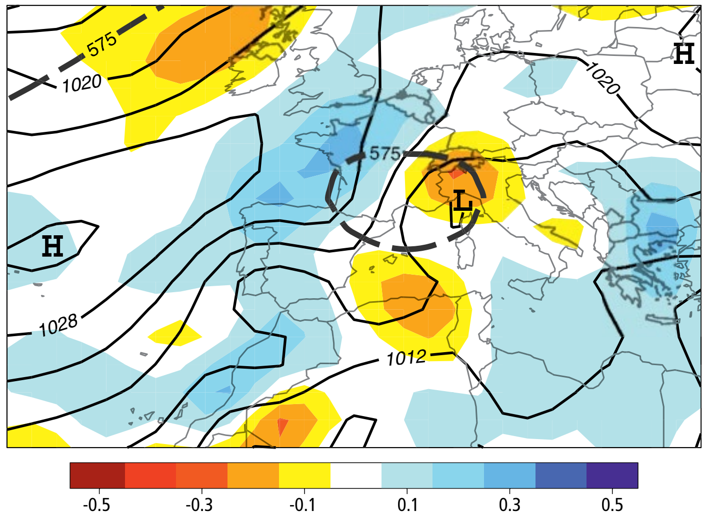


Fig. 8: *Weather situation during the flood event on 21 August 2005.[25] Below a cold air mass at 500 hPa (approx. 5 km, dotted in bold[12]) a low develops near Genoa (L; continuous lines mark the surface air pressure in hPa), which is blocked between two high-pressure systems (H). The vertical movement (Pa/s; red means uplift) is shaded in colour at a height of approx. 5 km (500 hPa).*

Weather types in autumn 1868

For the flood event in September/October 1868, no original weather maps are yet available (see p. 23) from which subjective weather types could be derived. However, weather types can be objectively identified from station data[14] or from reanalysis data sets (see p. 24). Although there were not many pressure measurements in 1868, both methods provide very plausible weather types for the flood event.

The event was characterised by the sequence of four more-or-less blocked highs, two of which developed into slowly advancing PV streamers reaching far to the south. They were accompanied by upper-level winds from southerly or even south-easterly directions in the area of the Alps – such a reversal of upper-level winds is often considered a criterion for blocking (cf. text on the left). For the episode around 3 October 1868 (Fig. 9), the data clearly show the large-scale uplift of the air masses over the Mediterranean and along the western Alps. The associated low-level flow (see p. 10) apparently took up moisture from the warm Mediterranean before it reached the Alps. Accordingly, the first PV streamer led to prolonged, heavy precipitation on the southern side of the Alps, which caused the water level of Lake Maggiore to rise by about 2 m; the second, decisive episode caused another increase by almost 3 m (see p. 21).

The weather conditions before and during the flood event were typical for floods at the southern side of the Alps. From a meteorological point of view, the extraordinary severity of the event resulted from a combination of four consecutive, long-lasting, and rain-intensive weather conditions, which were characterised by PV-streamers. Due to the clear atmospheric patterns, this extreme flood could today be predicted very early. In the following boxes, individual aspects are examined in more detail.

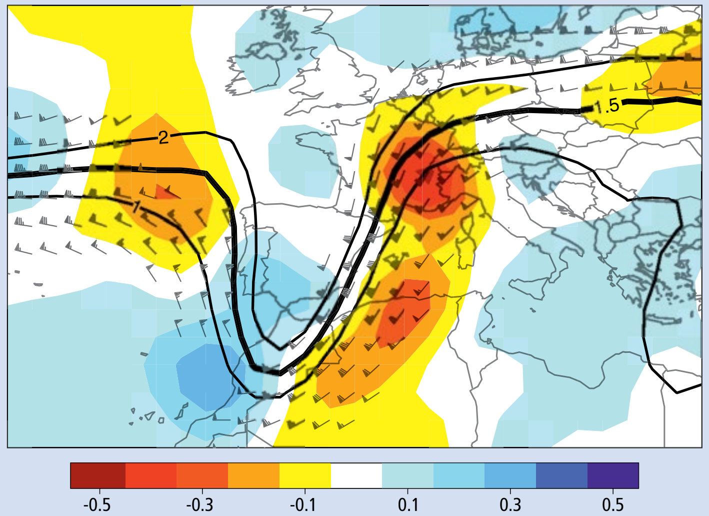


Fig. 9: *Weather situation with PV streamer at 12:00 UTC on 3 October 1868.[25] Continuous lines show PV units (1.5 PVU bold as tropopause). The wind barbs show the strong-wind band in the upper troposphere (at 250 hPa; only speeds of at least 50 knots are shown). Shades of colour show the vertical movement (Pa/s; red means ascent) of the air masses in the mid troposphere (500 hPa).*

Heavy precipitation, atmospheric rivers and flood events in Switzerland

Strong precipitation (i.e., that falls over a place during several days) requires heavy and continuous supply of moisture in the form of water vapour, which, in turn, will be transformed into precipitation. The mechanisms of transport and the origins of this water vapour are described here.

Precipitation requires a sufficient and sustained supply of atmospheric moisture. This moisture either originates from evaporation on site or it is transported by winds from remote sources to the precipitation area. Local evaporation comes from the plants, soil, or directly from open water surfaces. Remote sources for moisture in Switzerland are manifold, and comprise, in decreasing order of relevance, the North Atlantic, the Mediterranean, the European continent, the North Sea and the Baltic Sea.[26] On the north side of the Alps, moisture comes primarily from the Atlantic Ocean, whereas on the southern side it comes mostly from the Mediterranean.[26] In winter, moisture is predominantly of oceanic origin, whereas in summer, the moisture that evaporates over land is also important.

The heavy precipitation events that can trigger flood events need a more intense and, depending on their duration, longer-lasting moisture supply compared to normal precipitation events. In fact, episodes with a very strong and sustained moisture supply are important indicators for heavy precipitation and flood events in Switzerland.[27,28] Thereby, the moist air is pushed towards the Alps, forced to rise, to condense, and finally rains out.

The transport of moisture in the atmosphere is not constant nor is it chaotic; it is rather often organised in elongated structures along the cold fronts of low-pressure systems. These structures are called "atmospheric rivers". An example of such an atmospheric river over the Atlantic is presented in Figure 10. Shown is the vertically integrated moisture transport in the atmosphere on 10 October 2011 at 06:00 UTC (07:00 in Switzerland). Moisture transport results from the combination (multiplication) of wind and water-vapour content of the atmosphere. The units state how many kilogrammes of water vapour are transported per second across a horizontal length of 1 m and throughout the whole atmosphere over this metre. The name atmospheric river is justified since the amount of water that is transported in narrow bands over the North Atlantic corresponds to the discharge of the largest rivers on Earth (e.g. the Amazon or the Ganges).

Unlike in rivers, moisture in atmospheric rivers is continuously renewed during transport through repeated rain and evaporation.[29] This renewal primarily occurs over oceans since the evaporation is significantly weaker over land. Hence the largest part of moisture of atmospheric rivers stems from oceans. The transport also typically weakens as soon as an atmospheric river reaches a continent because, from then, more moisture will rain out than will evaporate (Fig. 10). Nevertheless, atmospheric rivers can still transport high amounts of water vapour towards the continent's interiors and lead to strong precipitation there.

The example from 10 October 2011 clearly illustrates this, and led to highly damaging floods in the Kander and Lötschen valleys.[24] The water that finally rained out over the Bernese Highlands and the Valais partly evaporated over the Northeast Atlantic and partly over the subtropical Atlantic.[24] The moisture transport towards the Alps on 10 October 2011 (Fig. 10) was extraordinarily strong. During the last 30 years on the north side of the Alps, only a handful of similarly strong episodes of moisture transport occurred. They all led to large flood events.[28] For north-western Switzerland, a strong moisture transport from northwest to north is particularly dangerous. For north-eastern Switzerland, a strong moisture transport from northeast is particularly dangerous. On the south side of the Alps, moist air reaches Switzerland from the south. The absolute values of moisture transport are in general slightly higher on the south side of the Alps because the Mediterranean is warmer than the North Atlantic, therefore more water can evaporate. This fact is also reflected by the somewhat higher precipitation amounts on the south side of the Alps.

Besides the intensity of moisture transport, the duration of strong moisture transport can also play an important role for the total precipitation amount. While episodes of extremely intensive moisture transport rarely last longer than 12 hours, large amounts of moisture can also be transported towards the Alps during several days.[28] This was, for example, the case in autumn 1868 (see box, right).

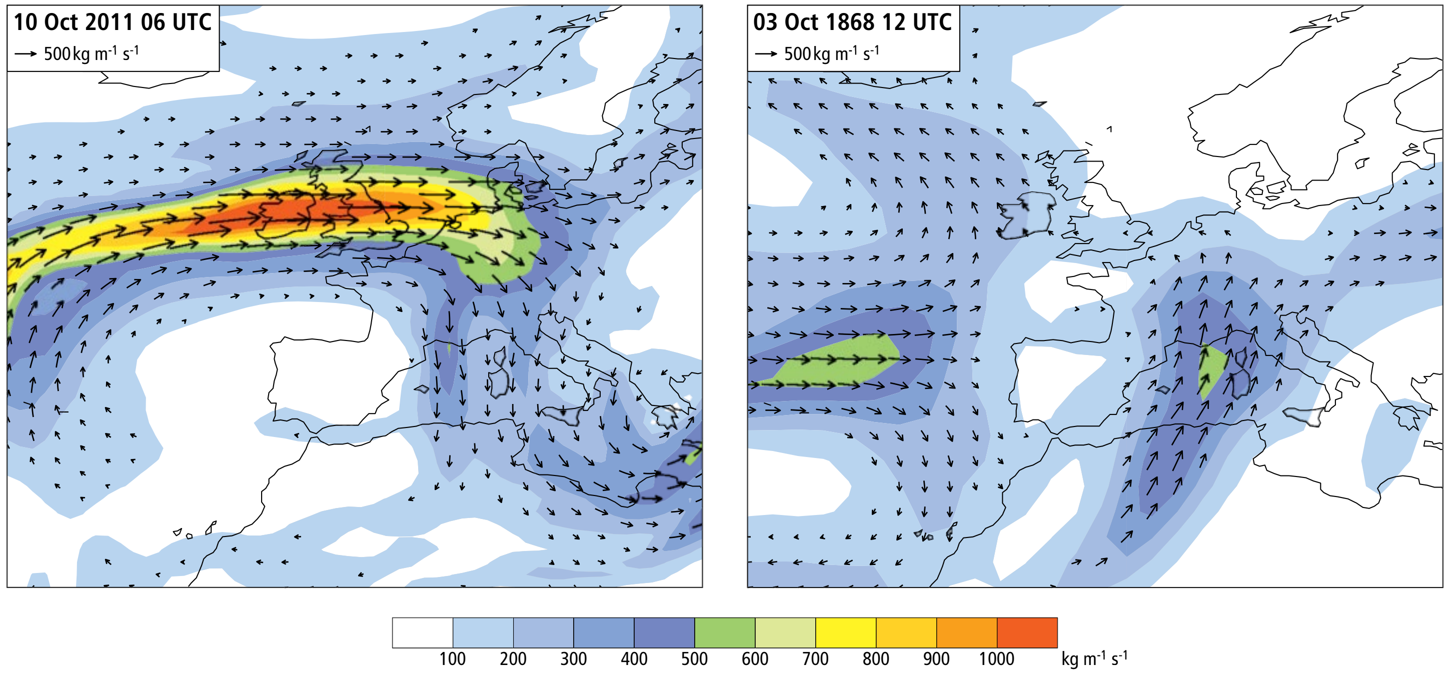


Fig. 10: *Vertically integrated atmospheric moisture transport (kg m^{-1} s^{-1}, colour shades) on 10 October 2011 at 06:00 UTC (left) and on 3 October 1868 at 12:00 UTC (right). The arrows show the direction of transport. The atmospheric river is recognisable on the left panel as a long and narrow structure. In October 2011, the moist air reached the Alps from the north, on 3 October 1868 from the south.[25]*

Nowadays, weather models can forecast moisture fluxes earlier and better than precipitation.[30] The forecasted moisture fluxes can, in turn, be used to forecast flood events. Information about the direction and intensity of atmospheric rivers, as well as the transport of water vapour in the atmosphere, is especially used for medium-range forecasting (five to 10 days in advance) of heavy precipitation and potential flood events. Very strong moisture fluxes towards the Alps therefore represent early warning signals for potential flood events.

Preliminary analyses show that atmospheric moisture transport will intensify in a warmer climate. Figure 11 shows the percentage change of extreme moisture transport (99th percentile) by the mid and end of the 21st century for three different global climate models. The climate models assume a continuously increasing greenhouse gas concentration in the atmosphere without reduction measures. The changes differ depending on the model. However, all three models show a clear increase in moisture transport from the wind direction that is relevant for flood events. Moreover, this increase will intensify by the end of the 21st century.

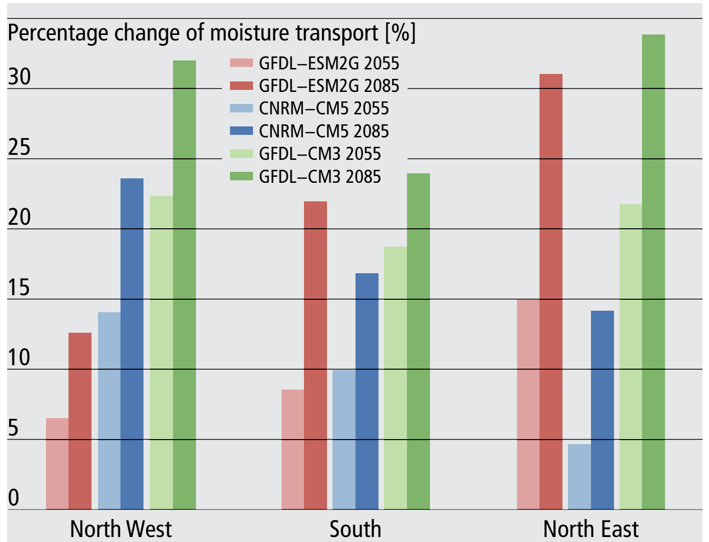


Fig. 11: *Percentage change of extreme moisture transport episodes in north-eastern Switzerland, north-western Switzerland, and on the southern side of the Alps as calculated by three different global climate models. The light colours show the change by the mid-21st century, the dark colours by the end of the 21st century. All three climate models show a clear increase of extreme moisture transports.*

Where did the water of the flood of 1868 come from?

There are several approaches for answering this question from a meteorological point of view. One can, for example, consider the vertically integrated atmospheric moisture transport over a given domain and a given time. The right panel of Figure 10 shows, for the event of 1868, a high moisture transport over the western Mediterranean (blueish and greenish colours) that is directed towards the south side of the Alps (see the arrows). This is an indication that the water vapour partly stems from the Mediterranean.

A second approach relies on so-called "trajectories". This assumes that an air parcel is transported by the wind like some sort of balloon. Accordingly, Figure 12 shows the "flight tracks" of air parcels that, within three days, reached the south side of the Alps together with very strong precipitation (on 27 September and 3 October 1868). Close to the ground, the air parcels moved slowly north over the Tyrrhenian Sea. At higher altitudes, the path led over the western Mediterranean or even over the subtropical Atlantic. This means that a lot of water vapour could be taken up during several days over the still warm Mediterranean. All air parcels then experienced lifting at the end of the trajectory, when reaching the south side of the Alps. Much of this water vapour condensed during the lifting.

The third approach is not feasible for the case of the flood of 1868. It relies on the analysis of rainwater that shows different isotopes depending on its origin. Of course, there is no rainwater from the event of 1868 left available for analysis. We know, however, from studies of recent and similar events, that some part of the water vapour stems from the saturated land surface. This implies that this water is regionally recycled by repeated atmospheric convection.[31]

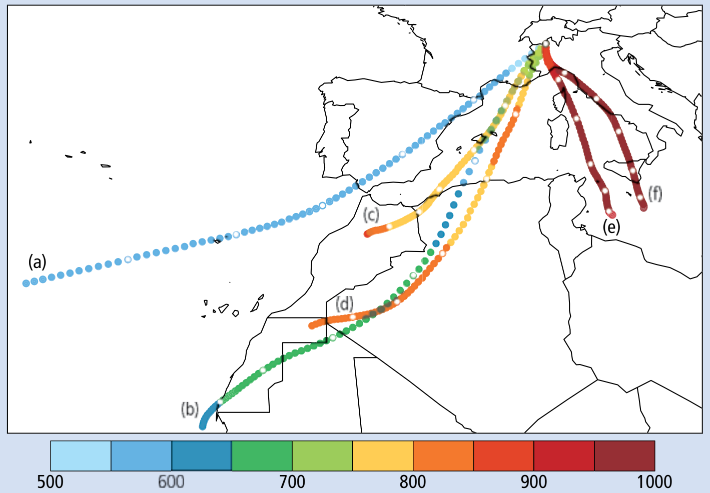


Fig. 12: *Backward trajectories over three days in the Twentieth Century Reanalysis (20CR, p. 24). The air parcels end up at the grid point 46° E 8° N on 27 September 1868 at 12:00 UTC for lines (a), (c) and (e) and on 3 October 1868 at 12:00 UTC for lines (b), (d) and (f). Shown are trajectories ending up at different altitudes, namely at approx. 5.5 km above sea level (corresponding to 500 hPa) for the lines (a) and (b), 3 km (700 hPa) for the lines (c) and (d) and 1.5 km (850 hPa) for the lines (e) and (f). Colours show the pressure in hPa along the trajectories. Every 12 hours, a white dot is drawn.[32] A higher pressure means that the air parcel is close to the ground, a lower pressure means that the air parcel is located at a higher altitude.*

Orographic precipitation and convection

We have seen in preceding chapters that large-scale flow situations can lead to sustained, strong moisture fluxes towards the southern Central Alps. When moist air reaches an orographic barrier like the Central Alps, it can be blocked by the barrier, pass around, or pass over. If the flow passes over, the air rises, expands, and cools down. Cold air can contain less water vapour than warm air, so that the air may reach 100 per cent relative humidity as it rises. From then, water vapour condenses, cloud droplets form, and precipitation might finally be produced.

Flow around or flow over?

The flow path of an air mass reaching a mountain chain can be characterised by the Froude number. If the wind against the mountain is weak, the mountain is high, and the atmospheric stability is high, the Froude number is lower than unity and the flow is either blocked by the mountain or diverted around the mountain. Conversely, if the wind is strong, the mountain small, and the stability low, the flow passes over the mountain chain. The latter is a Föhn situation (Fig. 13). Saturated air also ascends more easily than non-saturated air. The ability of an airflow to pass over a mountain thus depends on its vertical characteristics of wind, humidity, and temperature (stability).

The stability has an important role. If the atmosphere is "stable", the air that tries to pass over the mountain will sink back downwards. The horizontal wind towards the mountain must thus be especially strong so that the flow can counteract the stability and still pass over. If the atmosphere is "neutral", the air will rise over the mountain without resistance. If the atmosphere is "conditionally unstable", the air that rises over a mountain will eventually become saturated. This air might then continue to rise by itself as an ensemble of warm bubbles (the convective cells). This atmospheric convection is also responsible for thunderstorms. The convective air can rapidly reach altitudes higher than the mountain summits. Hence, convection can significantly enhance the local intensity and quantity of precipitation.

Fig. 13: *A "Föhnwall" over the Jungfrau.[1] The air coming from south condensates as it rises over the Alps and a cloud forms. As the air descends on the other side, the cloud evaporates. The result is a stationary cloud resembling a wall.*

The vertical characteristics of airflow related to heavy precipitation in the Lake Maggiore region were investigated for recent events. Information came from balloon soundings from Milan Linate airport, from the radar images of Monte Lema (Ticino), and from a measurement campaign of the Mesoscale Alpine Program.[33] During the campaign, aeroplanes and different instruments on ground were used simultaneously to observe, in detail, the atmosphere over the Alps. During heavy precipitation events around Lake Maggiore, the following typical characteristics were found[34] (see also Fig. 14): (1) south-easterly winds in the Po Valley below approximately 1000 m above sea level and south-westerly winds above; (2) a relative humidity close to 100 per cent from approx. 500 m to 3–4 km above ground (i.e. the southerly winds transport humidity towards the southern Central Alps) and; (3) a stability that is neutral or even conditionally unstable.

Convection and hail

It is, in fact, the presence of conditional instability, and thus of convection, that often makes the difference between "extreme" and only "intense" precipitation.[34] In case of heavy precipitation in Switzerland, the incoming flow is often cloudy and the local clouds formed by convection or by forced lifting of the air above a mountain flank are often hidden by the general cloud cover. The local clouds can however influence precipitation in various ways. Typically, the convective cells live for a few hours and only extend over a few square kilometres. If several cells follow each other over the same location, they can nevertheless result in a large accumulation of precipitation (Fig. 14).

Convection is also necessary for hail. Hail forms by negative temperatures in so-called "mixed-phase" clouds. Snowflakes collect droplets and then re-freeze. Ice pellets form, which collect droplets again, and merge with other ice pellets, then re-freeze, and so on. The limiting factor for the size of hailstones is the strength of ascending currents, which need to maintain bigger and bigger ice pellets or hailstones in the air. Ascending currents strong enough to obtain large hailstones are only found in convective clouds.

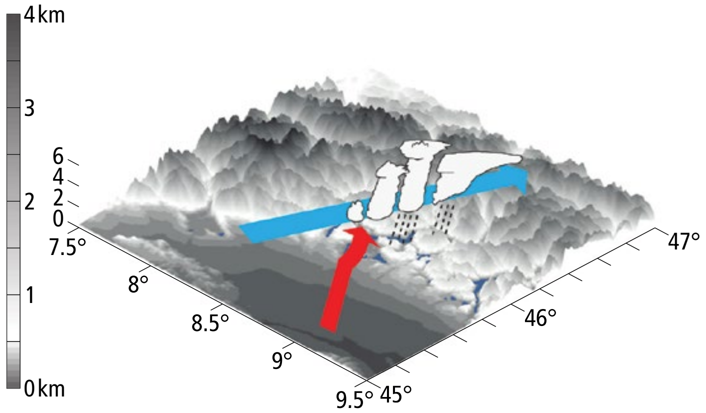


Fig. 14: *Conceptual scheme of convection over the Lake Maggiore region.[34] The conditionally unstable and humid low-level air (red) is forced to rise. Convective cells are initiated and then transported by the mid-level flow (blue). The convective cells follow almost identical trajectories and produce precipitation over the same location. This succession leads to strong local accumulations of precipitation.*

Devastating flood in Emmen Valley, 1837

On 13 August 1837, a thunderstorm in a side valley triggered the largest-known flood of the Emme. The event became known through a document by Jeremias Gotthelf: "Die Wassernot im Emmental am 13. August 1837". Gotthelf, who wrote the document based on his impressions and on discussions collected as he visited the valley directly after the catastrophe, describes how the devastating flood was triggered by a series of thunderstorms. In 2002, model-based studies showed that besides the intensity and amount of precipitation, the antecedent history of the catchment was also crucial: without the thunderstorms on the previous days, there would not have been any large flood.

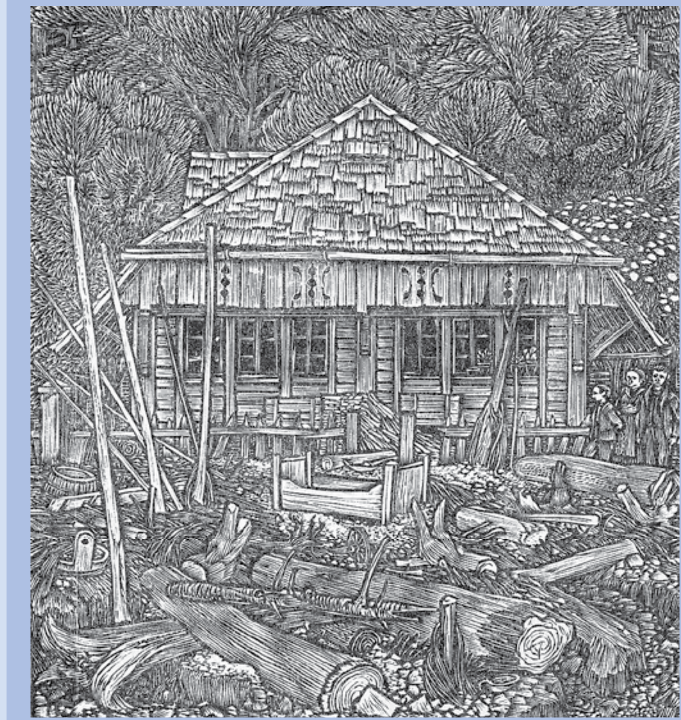


Fig. 15: *Woodcut from Emil Zbinden; illustration from a publication by the Büchergilde Gutenberg (1951).*

How important was convection for the event of 1868?

The processes described in this chapter happened in a similar way during the flood event of 1868. This is documented in different sources and confirmed by the simulations.[32] During the two main precipitation phases between 26 September and 4 October 1868, historical sources report on sustained rain, strong thunderstorms, and isolated hail events.[3,35] The daily precipitation sums during this period (e.g. on 3 October 1868, Fig. 33) infer thunderstorm activity: the precipitation amounts are rather independent from altitude, and strong and weak precipitation amounts are often found close to each other.[32]

Figure 16 illustrates the importance of convection for the 1868 event as it is reconstructed by the WRF model (see p. 26). The airflow below 4 km altitude (600 hPa) moves north (from left to right along the figure), and the airflow above moves east (comes towards the reader). The light green colour above 900 hPa over Genoa indicates that the air flow is not saturated there. When this flow crosses the Po Valley and encounters the southern Central Alps, it is lifted and becomes saturated. A deep cloud cover forms over the Alps and produces rain. The green-grey colour corresponds more or less to the cloud cover. Rainfall is not shown. The numerous red contours between Locarno and Genoa show the ascending current of a convective thunderstorm approaching Locarno. The storm is moistening the upper levels and generates a very deep cloud. The air is saturated from ground to 300 hPa (around 9000 m above sea level) at the location of the storm. In the model, the storm then moves further north and produces heavy precipitation over Lake Maggiore four hours later (see p. 27).

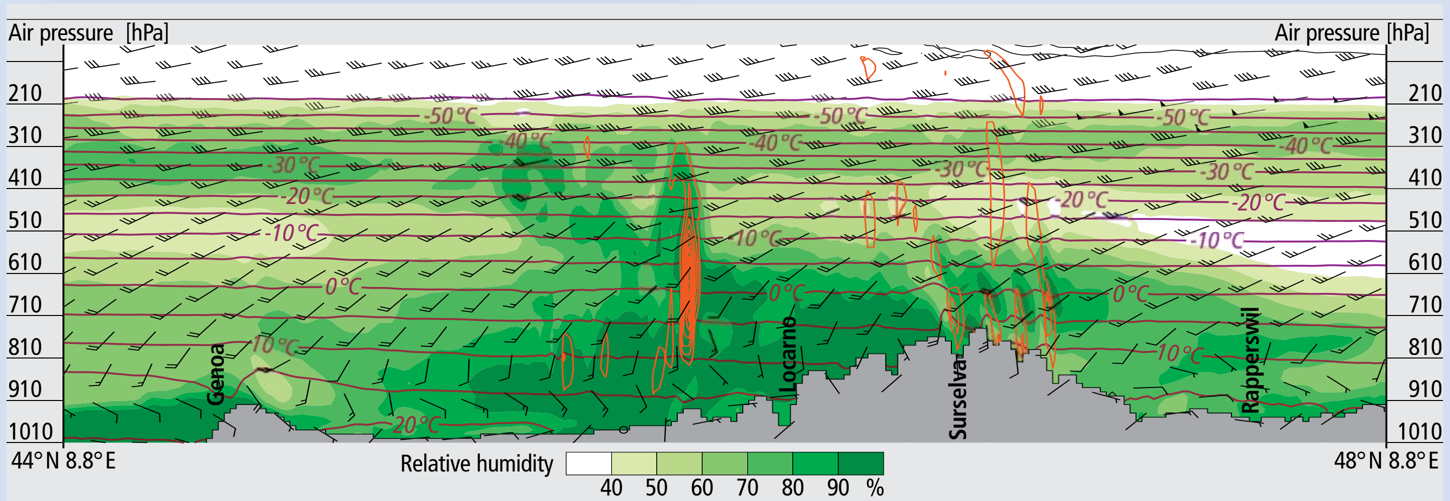


Fig. 16: *Cross-section across the Alps on 26 September 1868 at 21:00 UTC from south (left) to north (right). The data come from a simulation with the weather model WRF (see p. 26) on a 2-km grid and with 40 layers. The topography (white area) corresponds to the model topography. Colours indicate the relative humidity. Wind barbs show the horizontal wind: pointing upwards for southerly wind (wind coming from south), pointing right for westerly wind, etc. The more side bars the wind barbs have, the stronger the wind (10 knots, so about 20 km h^{-1} per side bar). The red contours represent areas of ascending air. Temperature is shown by black lines with labels. The zero-degree line lays around 630 hPa (about 4000 m above sea level).*

Generation of floods – basic disposition

Floods occur through a complex interaction between basic disposition, variable disposition, and the triggering precipitation. Soils, geology, land use, and topography determine the basic disposition of a catchment area. They define how a catchment area reacts to heavy precipitation, what proportion of precipitation ends up being drained, and how the floodwaters run off. The amount, duration, and intensity of precipitation, as well as further variable factors, must be considered to understand the overall flooding characteristics of a catchment.

Runoff formation – development of floods

The proportion of precipitation that ultimately runs off is a deciding factor for determining the characteristics of a flood. It makes a big difference whether 10 or 70 per cent of the precipitation runs off directly. In this context, we refer to runoff generation processes. These vary within a catchment area depending on soil type and geological conditions. Generally, four main types can be distinguished: (1) If the soil is relatively impermeable, precipitation cannot drain and will flow over the surface. (2) If the soil is saturated (e.g. marshes), then precipitation also cannot infiltrate. In both of these cases, the precipitation largely runs off directly and with little delay. (3) If the precipitation infiltrates the soil, either through the soil substrate or macro pores, it becomes important to know whether there are any impermeable layers within the soil. In this case, the water flows off horizontally in the soil and contributes to the flood to a lesser extent and with a delay. (4) From a flood protection point of view, it is particularly favourable when precipitation drains through the soil into a permeable geological formation. In this case, the precipitation does not run off until days or even weeks later, and thereby does not contribute directly to a flood.

The underlying flooding characteristics of a catchment area can be assessed based on the spatial distribution of these four soil types. In the case of the Allenbach in Adelboden (Fig. 17), types (1) and (2) not only cover a large surface area, but they are also located in steep areas near streams. Large floods occur in summertime after intense thunderstorms.

Besides the dominating influence of soils and geology, other factors such as land use and slope gradient impact runoff generation. The role of forests is the subject of much controversial discussion. Through the detention of precipitation by the treetops and the generally favourable permeability characteristics of forest soils, forests certainly have a flood dampening effect that comes into play, particularly during smaller events. With large precipitation events, however, these factors are of lesser importance.

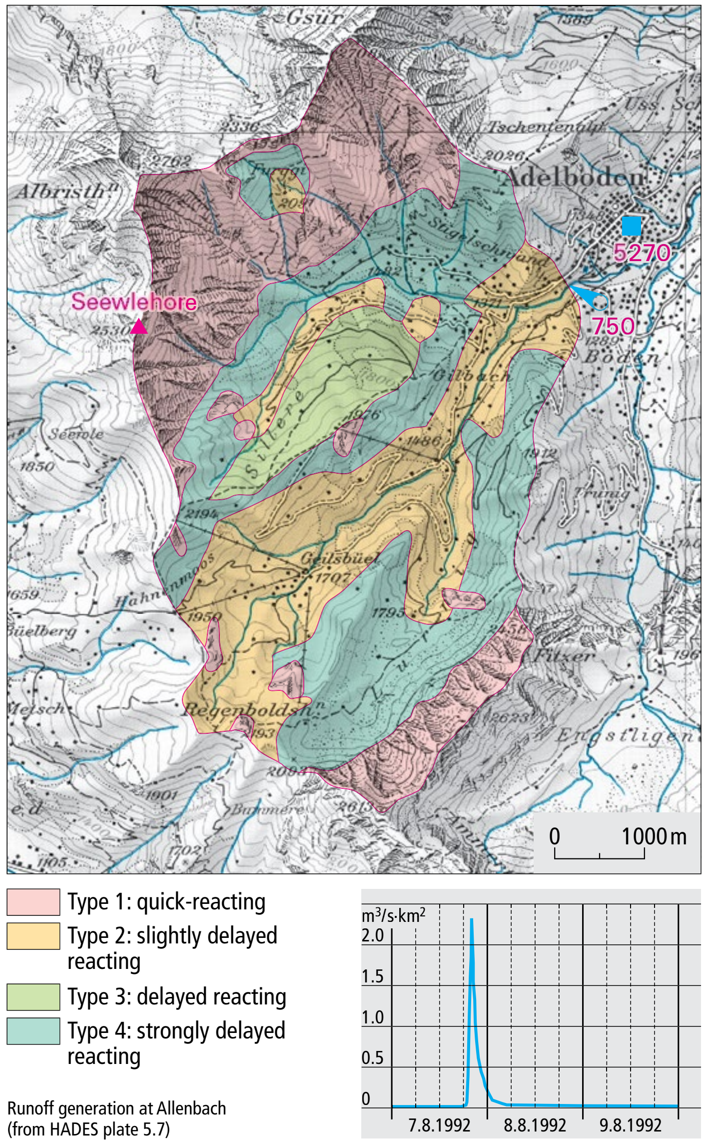


Fig. 17: *Runoff generation at Allenbach in Adelboden[1]: determination of the basic dispostion.[36]*

Runoff concentration – floodwaters run off

The runoff concentration describes how runoff generated at a site flows through a watercourse network. Factors such as slope gradient, density of the watercourse network, and the characteristics of the river/streambed are decisive. In a circular catchment area, water simultaneously flows together into the watercourse network due to similar lengths of the flow pathways. Greater peak floodwaters result, as compared to more elongated catchment areas.

In Switzerland, the pre-Alpine catchment areas on the northern side of the Alps and the higher elevation southern Alpine catchments have a basic disposition that promote intense flood responses: the catchments are steep and have a dense watercourse network. In combination with intense or long-lasting precipitation, both of these regions have the highest amounts of floodwaters per km² (runoff rate; see Fig. 18).

Over the past 200 years, most streams and rivers have been dammed and straightened. These hydraulic-engineering interventions improved protections against floods up to a certain size. Simultaneously, they led to the intensification of peak floodwaters for two reasons: (1) Floodwaters in straightened channels run off much faster than in natural, branching channels, leading to greater peak floodwaters. (2) Areas alongside rivers, which were previously flooded on a regular basis, are nowadays protected by dams and serve as spaces for residential areas, industry, and transportation. As a result, valuable flood-retention areas, where floodwaters could be stored to buffer peak floodwaters, were lost.

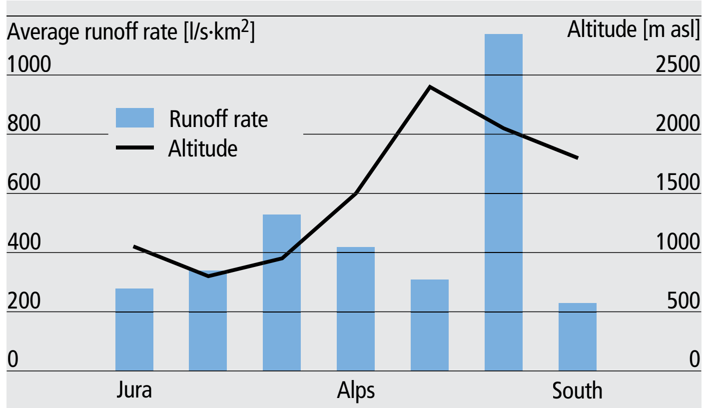


Fig. 18: *The runoff rate of a medium-sized flood along a north-south transect through Switzerland.[37]*

A lake can also buffer floodwater peaks depending on its storage capacity (see Fig. 19). This varies from lake to lake. The deciding factor for determining the extent of the buffering capacity is the relationship between storage capacity and inflow. Lakes with a small storage-to-daily-inflow ratio have a low buffering capacity. This is, in particular, the case for Lake Thun and Lake Sarnen. However, the flood spillway tunnels installed at Lake Thun in 2009 have created additional storage capacity.

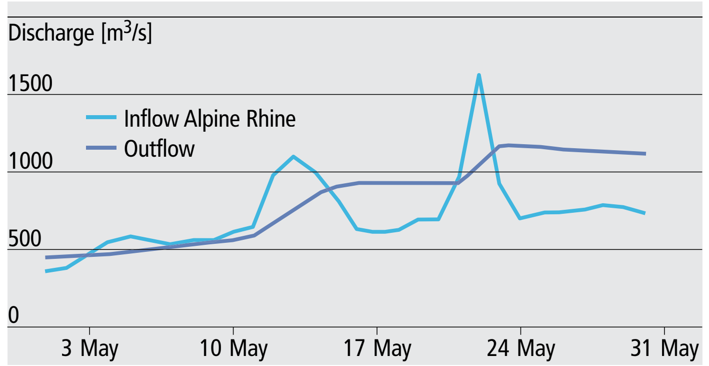


Fig. 19: *The buffering effect of Lake Constance during both flood events in May 1999 (Data: FOEN).*

These examples illustrate how humans can influence the basic disposition to a certain degree, by altering water bodies or creating flood-retention areas (areas in which water can be held back). This is not the case for other decisive factors, such as slope gradient or substrate conditions.

Lake name	Inflow [km²]	Lake area [km²]	Buffer storage capacity [mm]1)	Inflow during a 100-year event [mm/d]	Ratio storage capacity to inflow [d]
Lake Constance	11 887	541,2	69	24	2,88
Lake Zurich	1840	90,1	32	30	1,07
Lake Lucerne	2251	113,6	44	43	1,02
Lake Sarnen	267	7,5	30	60	0,50
Lake Zug	259	38,3	151	49	3,08
Lake Brienz	1129	29,8	40	35	1,14
Lake Thun	2490	48,4	12	24	0,50
Jura lakes	8217	280,7	41	19	2,16

1) Volume between the regular level (or average lake level) and the floodwater limit, based on the size of the catchment area

Tab. 1: *Flood-relevant parameters of Swiss lakes.[38]*

Basic disposition 1868

The basic disposition of the Lake Maggiore catchment area are greatly enhanced compared to other regions of Switzerland. Figure 20 compares three basic factors of the basic disposition in the main river basins of Switzerland. The river basin of Ticino – the catchment area of Lake Maggiore – has a steep topography. In addition, the underlying geology is crystalline rock that has no water storage capacity and, therefore, is conducive to runoff. Finally, the region is located in a hydro-climatic zone with the highest precipitation intensities in Switzerland. The runoff-promoting factors are contrasted with one of the largest proportions of forested area in Switzerland and the flood-retention effect of Lake Maggiore. Based on its catchment area (6386 km²), the lake storage capacity is around 50 mm.

In contrast to the geology and topography, land cover is variable over time. In 1868, the proportion of forest cover was lower. Ginzler und co-authors[39] report a forested area of approximately half the size, accompanied by distinctly enhanced flooding characteristics. However, lake retention was increased due to a different relationship between lake level and outflow (see p. 31).[40]

If these factors of the basic disposition are combined, the picture of a floodwater-prone region emerges today, and even more so around 1868. However, rivers and channel beds have "adapted" to these century-long higher-runoff tendencies, so that while very high runoff occurs, it does not necessarily reach the point of overflowing the stream bank. This can be clearly seen by the relatively wide riverbeds of the region. In addition, when looking at the flood event of 1868, it must be noted that the basic disposition mainly affect the catchment's short-term response to precipitation, and this becomes less important with multi-day continuous rain – as was the case in 1868.

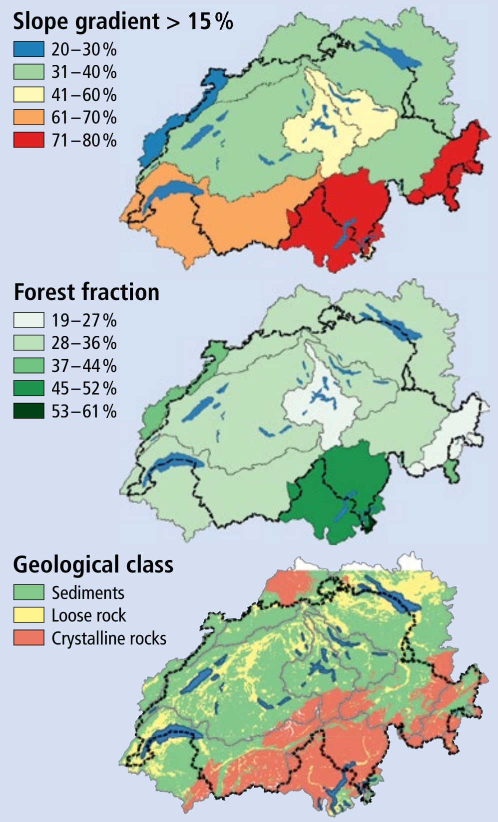


Fig. 20: *Comparison of the basic dispositions in Switzerland. Proportion of slope gradient of 15 per cent (top) and runoff-conducive crystalline geology (bottom), contrasted with a high proportion of forest cover (middle).*

Development of floods – variable disposition and flood triggers

Besides the basic disposition that do not change over time, various time-dependent factors and, in particular, the triggering precipitation are of decisive importance. Important variable dispostions include soil saturation, snowmelt, as well as the altitude of the zero-degree line. The triggering precipitation can be categorised by amount, duration, and intensity.

Complexity of floods

Floods occur due to the complex interaction between basic disposition, variable disposition, and a trigger, as illustrated by the example of the alpine catchment area of Kander (Bernese Highlands): since 1999, a cluster of large floods with greater peaks than seen previously can be observed (Fig. 21). One might intuitively assume that a single flood-related factor is responsible for this change. However, a closer analysis shows that this is not the case (see Fig. 22). The large floods occurred because of a combination of very different factors: in 1999 (see p. 8) and 2011 (see p. 10), snowmelt was a substantial contributor to the flood runoff. During the flood of August 2005 (see p. 8) – the largest since 1903 – the three-day accumulation of precipitation was immense. During the 2007 event, also occurring in August, the one-day precipitation amount was particularly high; however, due to the relatively low zero-degree line, this precipitation fell as snow at higher elevations and prevented the entire catchment area from contributing directly to the flood runoff. The flood of 1987, also seen in Figure 22, is clearly differentiated from the other floods. At the start of this event, the soil was less saturated and the triggering precipitation amount was distinctly lower. However, the zero-degree line was at a very high elevation.

Floods occur because of a complex interaction between various factors. The largest floods happen when the constellation of factors is particularly unfavourable, such as when the triggering precipitation falls on saturated soils, the zero-degree line lies at a very high elevation during the event, and snowmelt additionally contributes to the flood.

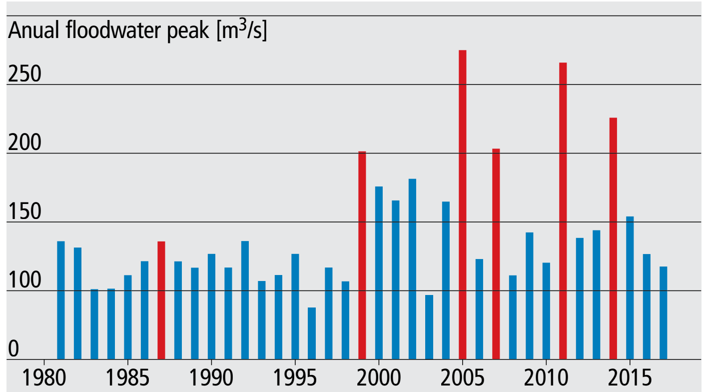


Fig. 21: *Yearly floodwater peaks of the Kander. (Red: floods analysed in Fig. 22.)*

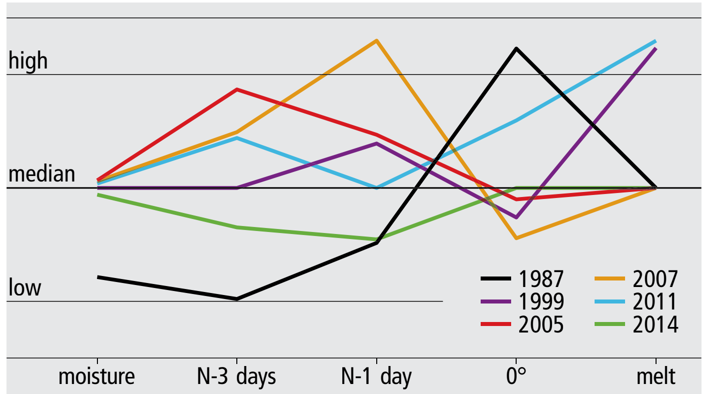


Fig. 22: *Variable characteristics and triggers of the greatest Kander floods (see Fig. 21). Moisture: soil saturation at begin of event; N-3 days, N-1 day: precipitation amount over three and one day(s); 0°: elevation of the zero-degree line; Melt: contribution of snowmelt.*

Triggering precipitation

Diezig[41] investigated and categorised the triggering precipitation of the largest floods in 39 Swiss catchment areas – a total of over 1000 events in the time period 1974–2003. Around a third of the triggering precipitation events lasted between 12 and 24 hours, and indicated a relatively high intensity [mm precipitation per hour]. These "downpours" are therefore quite important for triggering a flood. Around 20 per cent of the events were triggered by "continuous rain" or "showers". The former lasts two or more days and has very high yields. "Showers" generally have a shorter duration (minutes to several hours) and mostly occur during thunderstorms. The precipitation intensity is high to very high.

Figure 23 conveys an overview of the spatial distribution of precipitation types. In the pre-Alpine region, "showers" play an important role since thunderstorms are more common here. "Continuous rain" is very important in the central Alps, as well as in Ticino. It is remarkable that the most common type – "downpours" – is only of limited importance in the Alps. In the Jura, we find so-called "rain on snow events": when rain falls on an existing snow cover, additional water masses can be activated through the input of heat. The combination of "triggering precipitation" and "snowmelt" led to very high floodwaters in May 1999 (Fig. 24), which only occurred due to an unusual combination of different variable factors: low air temperatures until mid-April prevented the melt of most of the snowpack, and a relatively intense snowmelt started after sudden warming, leading to saturation of the soils. This combination of factors alone would have never sufficed to generate very large floods, as shown by the year 2018. Only the relatively high amount of continuous rain in May 1999 finally led to the great floodwater peaks and to the inundations by lakes (e.g. by Lake Thun). The proportion of snowmelt in total runoff varies between 15 to 30 per cent, depending on the catchment area.[42]

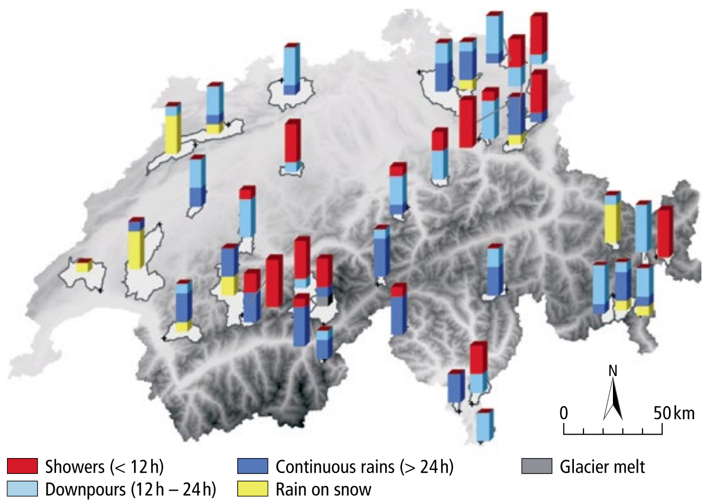


Fig. 23: *Weighted frequency of the triggering precipitation types in the selected catchment areas. In the weighting, a greater (lesser) weight is assigned to those precipitation types that lead to a larger (smaller) flood.*

Role of the zero-degree line

In the Alps, a good understanding of the underlying flooding characteristics and the triggering precipitation intensity only go so far in evaluating or predicting a flood event. A significant role is played by the altitude of the zero-degree line. This decides at what elevations precipitation falls in the form of rain and thereby generates runoff. In the Kander catchment, for example, large floods only occur when at least 80 per cent of the catchment area is exposed to rain. This occurs when the zero-degree line lies at around 2400 m above sea level.

The zero-degree line during all seasons in Switzerland has risen significantly over the time period 1961–2016. The total rise is between 200 m in autumn and 400 m in spring and summer.[43] As a result, the variable characteristics for flooding have generally intensified. With a further temperature increase, not only will the zero-degree line continue to rise, but precipitation intensity will also increase (see p. 44). With global warming, important flooding-related factors also change unfavourably. The subject of floods will therefore continue to engage us in the future.

Fig. 24: *The flood of May 1999 in Bern.*

Variable disposition 1868

A rainy September preceded the flood of 1868,[35] which exhausted the water storage capacity of the soils and considerably raised lake levels starting in mid-September (see Fig. 34). The lake level in September 1868 reached the sixth-highest level ever measured in September. No similar records exist for soil saturation, although hydrological models confirm the obvious assumption of depleted storage capacity by the end of September 1868.

During the end of September and beginning of October, two substantial rainfalls accumulated on top of these very wet conditions, with multi-day sums that exceeded the long-standing maxima for this time of year (see p. 21). Due to the consistently high zero-degree line during this period (Fig. 25), these rains could contribute fully to runoff. One mitigating factor for the flood situation of 1868 was certainly the small impact of snowmelt. Despite the high temperatures, snowmelt up to the highest altitudes only played a marginal role, as no significant snowpack remained from the previous winter, and no relevant amount of snow fell before the event.

Figure 26 shows a summary of the influences of various factors for the flood event of 1868.

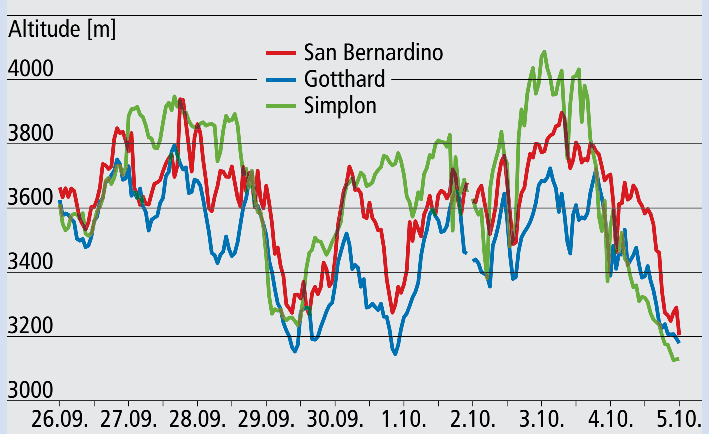


Fig. 25: *The zero-degree line reconstructed using a regional weather prediction model (see p. 26), at three selected locations,[1] showing the high zero-degree line from the end of September until the start of October 1868.[32]*

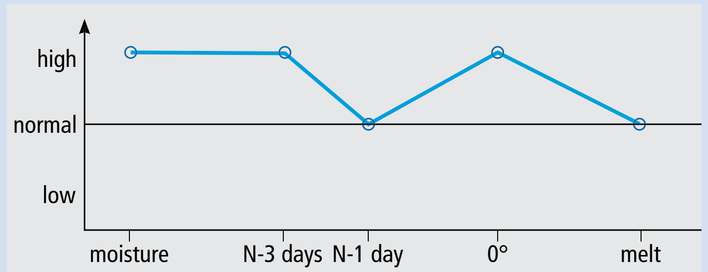


Fig. 26: *Graphic representation of the influence of variable factors (see Fig. 22) on the flood event of 1868.*

Historical documents from 1868 and other historical floods

Written and illustrated sources, including diagrams and inscriptions such as floodwater marks, belong to the most detailed accounts of historical floods. In particular, they provide information about perceptions of the affected population, as well as relief and prevention measures.

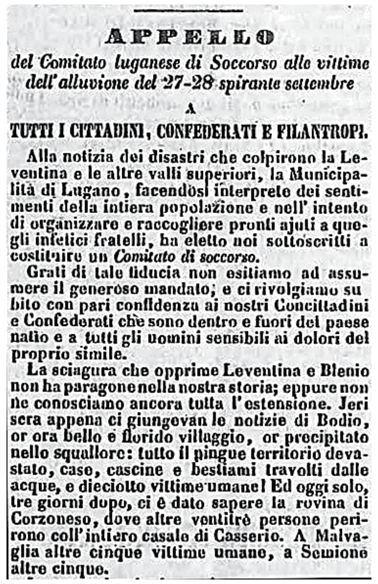
The most important flood events of Switzerland since the end of the Middle Ages can be, in the first instance, reconstructed using historical records. These sources were recorded by people without the use of measurement devices and can, in turn, de divided into several groups, depending on the context of their creation, the medium of publication, and their intended purpose. This can be understood as sources that were recorded by people without the use of measurement devices. Records, in turn, can be divided into several groups, depending on the context of their creation, the medium of publication, and their intended purpose.

On the one hand, there are individual, or rather serial, administrative sources. The first group includes individual communications in chronicles, newspapers, and personal documents, such as letters and postcards, that were recorded by a single person, based on either personal views or the processing of reports from others. These may be very short communications about the extents or consequences of events, or in part very detailed reports and even contemporary descriptions of the event in the form of a book.[3,35] In such sources, it is especially relevant to have reports on a reference point reached by a flood, damages, prevention and response measures taken by people, as well as how the causes of the event were determined. On the other hand, there are serial administrative sources that were written over a long time period and often for general bureaucratic purposes, which retained their original structure and character over decades and often even centuries. The authors were administrators who kept these accounting records over many years and found successors to continue them. In the weekly editions from Basel or the treasurer's accounts from Fribourg and Solothurn, every expenditure for the repair of bridges and protection structures was meticulously noted week by week.[44]

The sources can also be differentiated based on their publication medium: while handwritten chronicles in monasteries or cities served individuals of single groups, the first early, modern leaflets, and later news reports that existed with ever-increasing frequency in the 18th century, were directed at the general literate public from the outset. The more spectacular, dramatic, unique, and catastrophic an event was, the more likely and extensively it was reported in the newspapers. During the course of the 19th century, newspapers not only became media that reported on the events themselves, sometimes including stories of individuals, but they also turned into one of the most important platforms for charitable donation appeals (Fig. 27); some regional newspapers even published lists of benefactors who contributed aid for the relief of material damages. Politicians also quickly realised that an appearance in a disaster area could elevate their popularity and that reports in newspapers would make this widely known. Newspaper reports belong to the most important and detailed sources existing for floods of the 19th century, and in particular for the year 1868, even if the motivation for their creation must be analysed alongside their use. Particularly sensational incidents are over-represented, whereas less-spectacular events were sometimes not covered at all or just marginally included.

A further significant group of sources are legal provisions regarding the handling of floods as well as prevention measures, such as the protection of forests in mountains. These were normally developed only several years after extreme events, but can be directly traced back to the event (see p. 38). Regional regulations created during these events can be included, serving the purpose of on-site disaster management, the regulation of provisional ferry services when bridges were washed away, or for the provision of clean drinking water.

Not only written reports, but also drawings of all kinds are included in historical records. With the onset of river corrections in the 18th and 19th centuries, as well as exact land-mapping in the form of so-called land registers, old and new river courses were recorded, cross sections of rivers were made, and exact construction designs for bridges were prepared. This, in turn, was a significant step for enabling precise hydrological findings about average flow volume relevant to peak flow



APPELLO

del Comitato luganese di Soccorso alle vittime dell'alluvione del 27-28 spirante settembre

A

TUTTI I CITTADINI, CONFEDERATI E FILANTROPI.

Alla notizia dei disastri che colpirono la Leventina e le altre valli superiori, la Municipalità di Lugano, facendosi interprete dei sentimenti della intiera popolazione e nell' intento di organizzare e raccogliere pronti ajuti a quegli infelici fratelli, ha eletto noi sottoscritti a costituire un *Comitato di soccorso.*

Grati di tale fiducia non esitiamo ad assumere il generoso mandato; e ci rivolgiamo subito con pari confidenza ai nostri Concittadini e Confederati che sono dentro e fuori del paese natio e a tutti gli uomini sensibili ai dolori del proprio simile.

La sciagura che opprime Leventina e Blenio non ha paragone nella nostra storia; eppure non ne conosciamo ancora tutta l'estensione. Jeri sera appena ci giungevan le notizie di Bodio, or ora bello e florido villaggio, or precipitato nello squallore: tutto il pingue territorio devastato, case, cascine e bestiami travolti dalle acque, e diciotto vittime umane! Ed oggi solo, tre giorni dopo, ci è dato sapere la rovina di Corzoneso, dove altre ventitrè persone perirono coll'intiero casale di Casserio. A Malvaglia altre cinque vittime umane, a Semione altre cinque.

Fig. 27: *Appeal for aid by the newly founded Aid Committee of Lugano for the support of flood victims in Leventin and Blenio valleys, merged with a status report from the worst-hit region. It should be noted that even three days after the event, the extent of destruction was only gradually coming to light. Gazzetta Ticinese from the 1st October 1868: p. 897.*

times or debris.[45] Floods and their damages were recorded in drawings as well as in newspapers and copper etchings (Fig. 28), with the latter increasingly used in newspapers in the late 19th century. The technology of photography had already emerged in the late 1830s, but was initially not suitable to reproduce movements, such as raging waters during floods, because of the required long-exposure time. The first photographs from the flood of 1868 (see Fig. 1) are therefore almost arranged in a studio-like fashion. The shutter speed of professional cameras only increased dramatically in the mid-1880s, allowing moving water or people doing clean-up work to be portrayed in sharp focus. Printers were able to integrate photos into newspaper articles shortly before 1900.

High-water marks provide a reference limit for the instrumental measurements of water levels and heavy precipitation (see p. 21), and have, over centuries, been affixed by people to private and public houses, churches, city gates, and bridges. Due to the numerous anthropogenic interventions in the river courses themselves, as well as changes in land use of the catchment area, high-water marks are only of limited importance for pure hydrological calculations today, but they may be interpreted as a sign of an active culture of remembrance. They were an everyday reminder for the population about the potential risk of life near a river or lake. In the 20th century, such high-water marks increasingly disappeared, or rather were often not renewed during the renovation of houses; in some cases also probably to prevent a decrease in the real estate value. The heavy floods in Switzerland in the last quarter of the 20th century and the beginning of the 21st century clearly show that a remembrance culture is very likely still of importance. Today, this lives on in the form of blogs46 or the recently installed platform "Collective Flood Memory", where experts as well as amateurs can upload historic and current photos of flood events.

1868 in historical documents

The number of historical documents for the floods of 1868 is excellent, even if not of equal quality for all of the affected regions. We are very well-informed about the canton of Grisons by two nearly simultaneous publications by experts documenting the technical-hydrological aspects as well as the management strategies, relief efforts, and charitable donations. Johann Coaz, the forest inspector for Grisons, who later would become the leading expert on reforestation and avalanche protection in Switzerland, summarised three inspection missions in the Posterior Rhine (Hinterrhein) and Anterior Rhine (Vorderrhein), that appeared as a book in 1869.[35] The precisely described effects of the flood are also illustrated by print plates. While Coaz dealt with the hydrological questions and the state of forests in the mountains (see p. 29), Johann Arpagaus was more interested in the material damages of individual municipalities in his book from 1870.[3] He extensively depicts the relief efforts and emphasises donations from within the region, the rest of Switzerland, and abroad. Professional discussions about the events were also conducted in scientific journals (such as the "Swiss Journal of Forestry"), brochures, and printed lectures.

The regional and national newspapers from the autumn of 1868 are veritable goldmines for the reconstructions of floods and their effects; however, the research in this particular area is far from finished. For their reports, editors built upon a network of official informers and feedback from the general public. Because of the destruction of transportation infrastructure, reports of events in remote regions was often delayed by many days (Fig. 27). Due to printing technology constraints, illustrations were not common at the time.

In the Federal Archives, such as the archives of affected cantons, there are internal reports, damage reports, expert opinions, and correspondences between the responsible authorities that allow for the exact reconstruction of the administrative processes of flood management. The contribution of the Central Federal Relief Committee of 1868–1870 is a rich source, specifically generated for the relief efforts of 1868 to coordinate measures for the whole of Switzerland.[4]

Fig. 28: *The flood of 1868 by Au (St. Gallen)[1] (watercolour). On the left, the damaged train bridge is reproduced. This very reliable and modern picture is a significantly better illustration of the extent of flooding in the Rhine Valley than any written source, especially when it is combined with close-ups such as the early photography from Lustenau (Fig. 1, on the watercolour, left in the background). However, based on the start of repair works, it remains unclear if the picture reproduces the highest water levels or an already reduced water level.*

Long measurement series

Research, risk assessment, monitoring, and warning: a wide range of applications depend on measurement data of heavy precipitation and peak runoff. Switzerland now has dense measuring networks for both precipitation and runoff. To what extent can we use long-term measurements to investigate historical events?

Precipitation measurements

Precipitation varies on small scales. A high spatial density of stations is therefore important. Today's precipitation monitoring network of Switzerland is operated by MeteoSwiss. In addition to the conventional automatic weather stations, there is a dense network of automatic and manual precipitation stations (Fig. 29). In addition, there are further cantonal and private stations as well as radar data (see p. 22).

In the past, the station density was lower. The event of 1868 falls into the period before the construction of a precipitation measurement network, but after the establishment of a Swiss meteorological network. Measurements from conventional weather stations are therefore available. The construction of an additional network of precipitation stations (in addition to the climate stations) began in the 1880s. The network reached 247 stations in 1900. Precipitation was measured daily, usually around 06:00 Swiss time.

For a long time, only manual instruments were available for measuring precipitation. A precise automatic measurement is not trivial. Figure 30 shows an automatic measuring station on the left. The measured value depends strongly on the local wind field and turbulence at the rain gauge. Such measurement errors also influence the long-term stability of precipitation measurements. Even minor changes in the environment of a station can influence the measurements and, for example, lead to an artificial shift in the data. With statistical methods, for example, by comparing neighbouring stations, shifts can be corrected at least on a monthly basis. The adjusted monthly data provide the basis for reconstructing the precipitation distribution in September and October 1868 (Fig. 31).

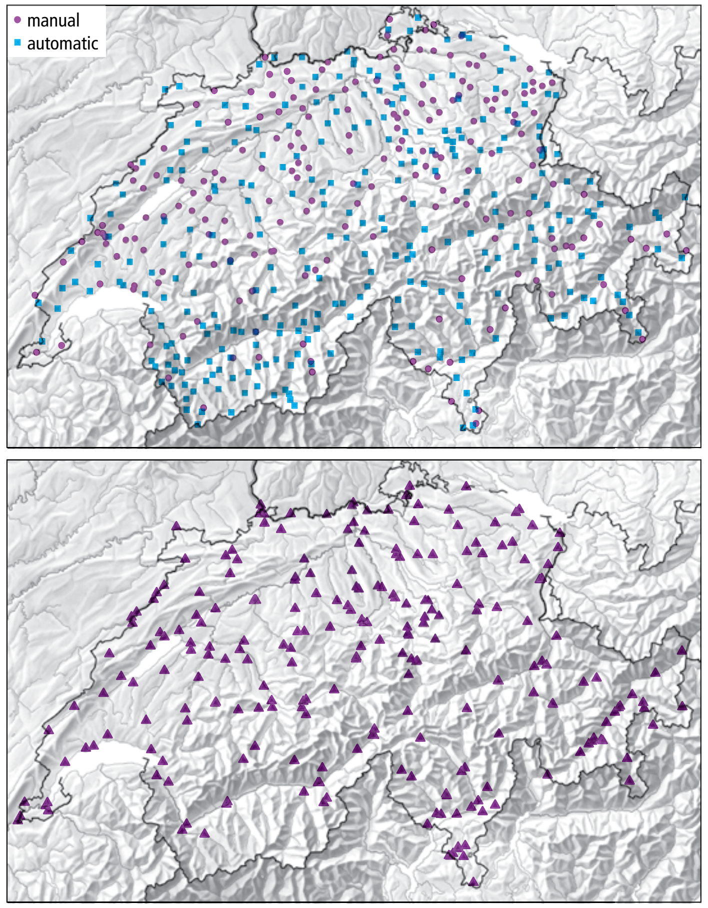


Fig. 29: *The Swiss monitoring network. Top: Manual and automatic precipitation stations of MeteoSwiss (as of 2017). Bottom: FOEN's hydrometric network.*

Fig. 30: *Left: Precipitation measurement at the meteorological station Zollikofen. Right: Liène-Tseuzier hydrometric station.*

Runoff measurement

The runoff measuring stations are operated by the Federal Office for the Environment (FOEN). The water levels are measured at around 260 locations on rivers and lakes. Systematic measurements in Switzerland date back to the mid-19th century. Long runoff series are particularly important for flood protection. The runoff stations are checked weekly and are calibrated five to six times a year.

To determine the runoff, the water level and, normally, the flow velocity of a water body are measured. The discharge is then determined via a stage-discharge relation or it can be determined directly (volumetrically) with a triangular weir (see Fig. 30). The water level is measured either with automatic level metres, pressure probes, or radar; the flow velocity with hydrometric wings or acoustic sensors.

For a long time, precipitation and runoff data were recorded and archived on paper (Fig. 32). Only in the past few decades were they registered electronically. Some, but not all, of the previous data have been digitised subsequently. Especially for past periods, a lot of data is still only available in paper form. Digitisation of these historical data would lead to significantly improved reconstructions of past extreme events. Current events could then be compared with these data. Together, the FOEN and MeteoSwiss provide a publicly available platform for the classification of extreme precipitation (*www.climate-extremes.ch*).

> ### The Hydrological Atlas of Switzerland HADES
>
> The "Hydrological Atlas of Switzerland" HADES (*hydrologicalatlas.ch*) is a joint project of Swiss hydrology and has been providing basic hydrological information, specialist knowledge, and didactic media to a broad range of users for more than 30 years. In addition to the original set of 63 printed maps, the Hydrological Atlas includes a wide range of products such as excursion guides and teaching materials.

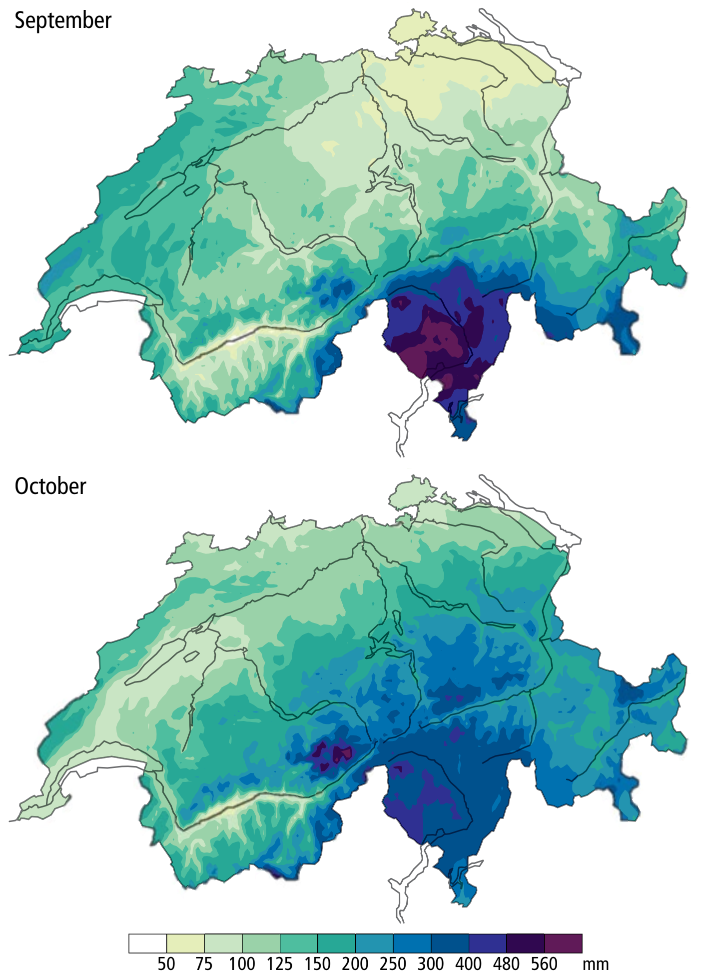


Fig. 31: *Monthly precipitation totals in September and October 1868.[47]*

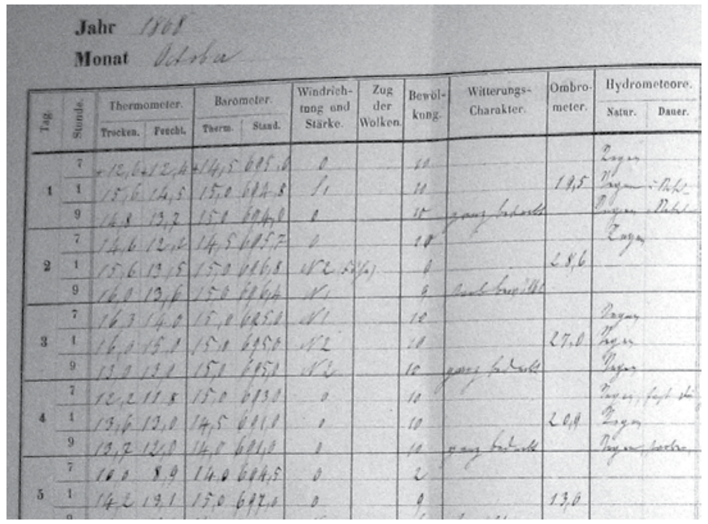


Fig. 32: *Meteorological measurements in October 1868 at the station Brusio[1] (the column "Ombrometer" indicates the amount of precipitation per day).*

The event of 1868 in measurements

Although the event took place in an early stage of the measurement networks (see p. 23), there was already a respectable number of stations with precipitation measurements (also in international comparison), so that certain aspects of the event can be analysed directly in measurement data.[12] There were two distinct episodes with extreme precipitation over several days (Figs. 33 and 34). On 28 September 1868, a daily precipitation of 254 mm was measured at the station San Bernardino Ospizio,[1] at about 2000 m above sea level. This is the highest daily value ever reached here, and also the five-day total reaches a long-term high. The maximum of the second phase was measured on 3 October with 170 mm in Platte[1] not far from the Lukmanier Pass. Over both episodes (eight days), rainfall on the San Bernardino Pass reached an incredible 1118 mm — more than the annual precipitation in Bern.

The level of Lake Maggiore[1] was also measured. Figure 34 shows how the lake level was already significantly elevated a few days before the main event. The lake-level peak lasted three weeks. The flood event of 1868 led to the highest water level ever measured.

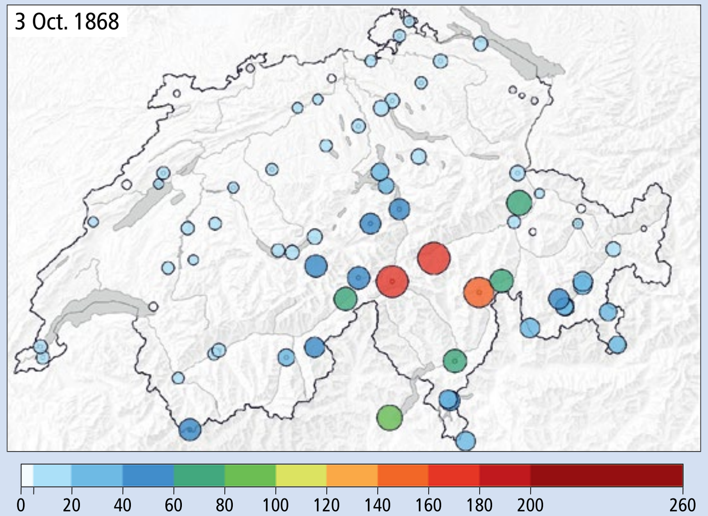


Fig. 33: *Measurements of daily precipitation (millimetres or litres per square metre within 24 hours) in Switzerland on 3 October 1868.[12,32]*

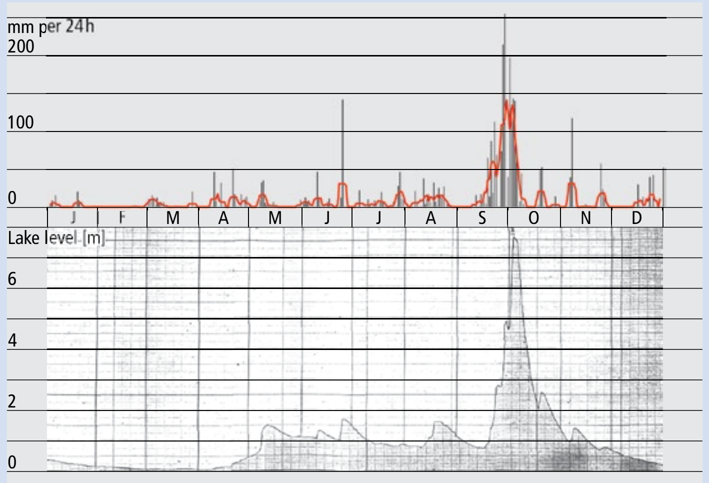


Fig. 34: *Top: Daily totals (bars) and five-day totals (red line) of precipitation for the station San Bernardino Ospizio at the top of the pass. Bottom: Level of Lake Maggiore in Verbania, 1868.[48]*

From radar image to flood warning

Real-time precipitation information at the highest spatial and temporal resolution possible is essential for short-term heavy precipitation, inundation and flood warnings.

In Switzerland, precipitation is measured continuously and automatically in real time at ground weather stations (see p. 20), and via weather radar. For ground weather stations in complex topography, these measured precipitation values are only representative for the local environment. The weather radar network of MeteoSwiss is comprised of five fully automatic radar stations with Doppler and Dual Polarisation technology, and records a detailed three-dimensional picture of all precipitation clouds and thunderstorms over Switzerland and its neighbouring areas (Fig. 35).[49,50] A map of precipitation values on the ground can be derived from this information.[51,52]

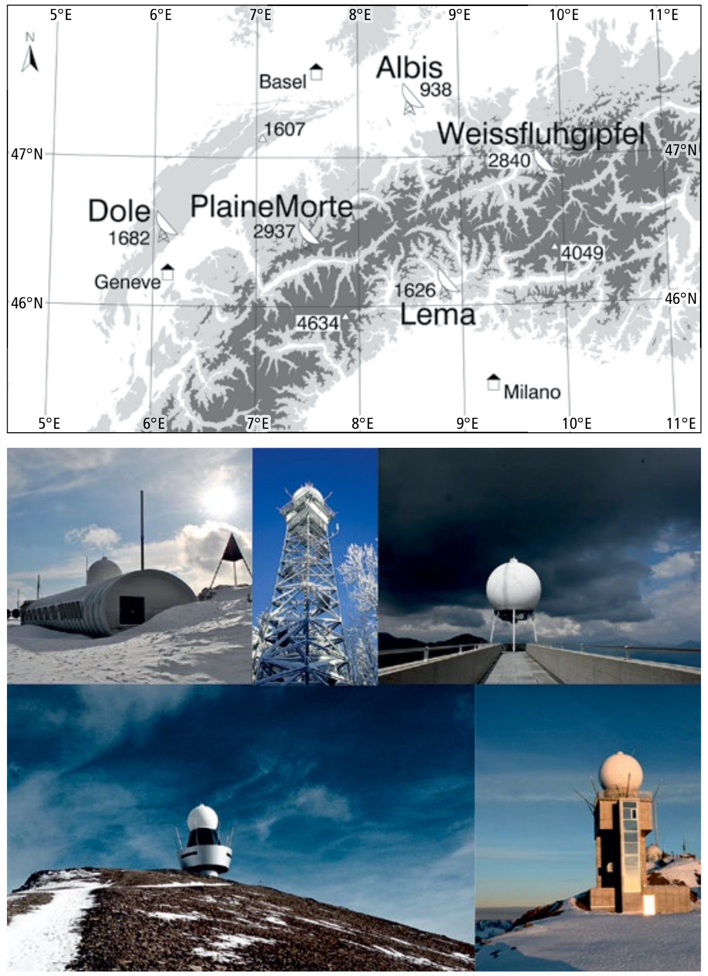


Fig. 35: *The MeteoSwiss weather radar network with its five stations on La Dôle[1] (since 1959), Albis[1] (since 1959), Mount Lema[1] (since 1993), Pointe de la Plaine Morte[1] (since 2014) and the Weissfluhgipfel[1] (since 2016).*

A radar sends electromagnetic waves into the atmosphere. These are reflected back to the radar as precipitation clouds and thunderstorms, and the radar measures the received energy as a function of distance, azimuth, and angle of elevation. The back radiation comes not only from the so-called hydrometeors of rain drops, snowflakes, hail, sleet, and ice crystals, but also from aeroplanes, birds, and insects. When the radar wave arrives at a mountain, a part of this energy is also reflected. With laborious calculation methods, such interference echoes can be filtered out. Meteorological echoes remain. Based on the ratio of emitted-to-reflected energy, precipitation intensity can be determined. The emitted radar beam is only one degree wide and allows for a fine-scaled observation of the precipitation system and thunderstorms. In order to scan the atmosphere vertically up to the height of 18 km and horizontally to a distance of 236 km, the antenna turns according to a fixed pattern and completes 20 rotations every five minutes. The data are transferred to a central computer from the five radar stations, compiled into comprehensive precipitation maps, further processed into hail and thunderstorm warnings, and sent to a variety of users. This group includes air traffic control, the service Protection Against Natural Hazards, the hydrology, insurance, and energy sectors, as well as many others. The radar products are updated every two and a half minutes, and have a spatial resolution of 1 km. A picture emerges of the changes in precipitation systems and thunderstorms over space and time (Fig. 36, upper right). Thanks to the application of Doppler and Dual Polarisation technology as well as sophisticated computer programs, radar can distinguish between the echoes of droplets, snowflakes, hail, ice crystals, insects, birds, aeroplanes, and mountains, and can even derive wind fields along with the intensity of precipitation in precipitation clouds.

For an optimal determination of precipitation amounts on the ground, radar data (Fig. 36, upper right) are statistically merged (Fig. 36, bottom left) in real time with measurements from ground stations (Fig 36, upper left).[53] The combination of radar, satellite, lightning, and modelling data create the basis for short-term weather forecasts of rain, thunderstorms, and hail: so-called "now-casting".

Precipitation forecasts for longer time periods (several hours to days) are based on the calculations of numerical weather-forecasting models. These models deliver comprehensive information about precipitation (Fig. 36, bottom right). Numerical weather-forecasting models solve the principle equations of the atmosphere and use observations through data assimilation (see p. 24) to obtain an optimal description of the state of the atmosphere for the initial conditions of the model calculations. Uncertainties remain, however, since observations are also faulty and cannot portray the state of the atmosphere in full detail. The impacts of these uncertainties on the model prediction can be quantified with the help of so-called "ensemble predictions". For an ensemble prediction, many model predictions are calculated with slightly varying initial and boundary conditions. The difference between the individual ensemble forecasts provides information about the uncertainty of the forecast.[54] The calculation of the model forecasts is conducted with the help of supercomputers; nevertheless, the necessary processing time is so high that only a limited number of forecasts can be calculated.

Heavy precipitation and floodwater warnings can be created with radar observations and information from weather models. This is how, for example, short-term warnings for heavy precipitation and flash floods depend on the combination of radar measurements of the past hours and the precipitation forecasts for the coming hours.[55,56] Ensemble models are used to estimate uncertainties.[57,58] These heavy-precipitation warnings are important for addressing local floods in cities or estimating the debris-flow risk in the mountains.

Floodwater warnings for the next few days depend on the precipitation calculations of weather-forecasting models. These calculations are passed on to numerical hydrological models (see p. 28), which calculate the transfer of precipitation water through the soil in rivers and streams (Fig. 37).[59,60] The hydrological models are coupled with hydraulic models for the calculation of inundation areas (see p. 30).[61] Hydrological models deliver better discharge forecasts if they are calibrated with outflow volumes. High-quality precipitation information (radar, CombiPrecip, and soil measurements) is essential for this.[62] Figure 37 shows how the hydrological calculations vary for a period in May 2016, depending on which rain product is used for the simulation. In this specific case, CombiPrecip performs best compared to observations.

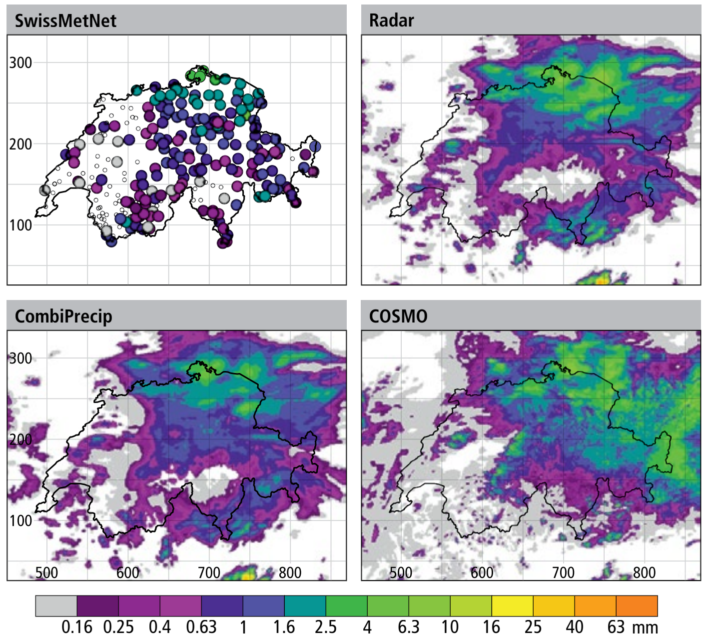


Fig. 36: *Precipitation amount [mm] from 12 May 2016, 11:00–12:00 UTC, measured at the stations of the SwissMetNet (top left), estimated with radar (top right), estimated from a combination of station and radar data (CombiPrecip, lower left) and in the analysis of the weather forecasting model COSMO.*

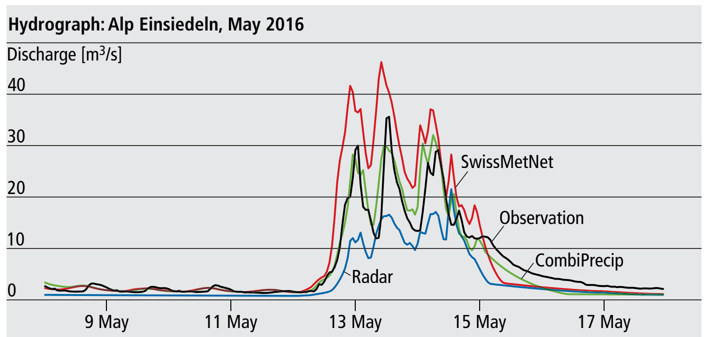


Fig. 37: *Runoff simulation of Alp at Einsiedeln [$m^3 s^{-1}$] with the hydrological model PREVAH for the period of 8–17 May 2016. Three rain products were used for the simulations: interpolated SwissMetNet data (red), radar data (blue), and the CombiPrecip product (green).*

The origins of MeteoSwiss

The history of the measurement network operated today in Switzerland begins in the early 1860s: at the time, the Swiss Academy of Natural Sciences organised meteorological observations in all parts of the country. Starting in December 1863, temperature and pressure, as well as daily precipitation and other values, were recorded at around 80 locations three times per day. The idea behind this was to be able to better describe climate with long-term means and extreme values. For the coordination of this project, an office in Zürich was arranged: the Swiss Central Meteorological InstituteSwiss Central Institute for Meteorology; the predecessor of the Federal Office of Meteorology and Climatology, MeteoSwiss.

In contrast to today, the institution was not initially responsible for issuing weather warnings. Its activities were limited to measuring the amount of rainfall, including the event of 1868. The spatial variability could only be imprecisely represented. In this context, the flood of 1868 – together with that of 1876 – provided the impetus for expanding the measurement network. In 1868, there were only 76 stations measuring precipitation; by 1900, there were 380.

More and more people began to ask whether the Central Meteorological Institute should also offer weather forecasts besides climatological data. Several countries, particularly seafaring nations, already possessed storm-warning services. Their central agencies received current weather-station data every morning by telegraph. They drew the high- and low-pressure areas onto a map of Europe and then predicted the weather development over the next hours, using past understandings of the relationship between air-pressure distribution and wind.

The first forecasts created in this way were controversial, because they lacked a solid scientific basis. However, their proponents argued that forecasts were greatly needed by agriculture and other weather-dependent sectors. The Swiss Federal Council supported this proposal, which enabled the Central Meteorological Institute to introduce its own forecasts. Starting in 1880, it published a daily weather report about current conditions and "prospects" for the following day. This new service prompted the Swiss Confederationfederal government to take over responsibility for the Central Meteorological Institute from the Swiss Academy of Natural Sciences. Starting in 1881, the climate observations as well as weather forecasts were a governmental task in Switzerland.

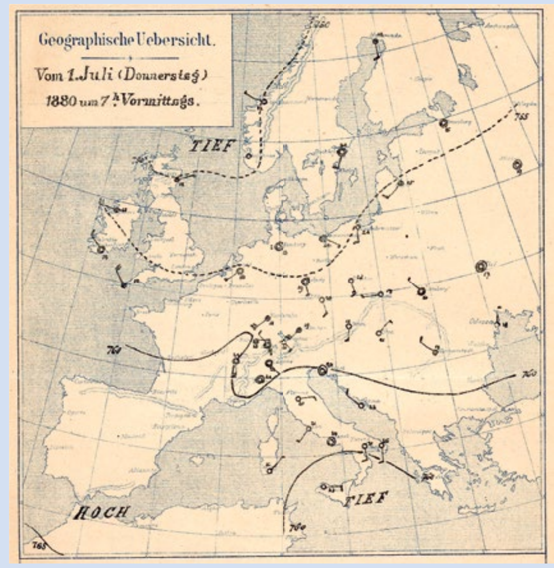


Fig. 38: *Excerpt from the first "Weather forecast of the Swiss Central Meteorological Institute" from 1 July 1880.*

Weather reconstruction

How can we reconstruct the weather of the 1868 event? There are some meteorological measurements from this period, but they do not allow a direct interpretation. Weather diaries contain additional information. Combined with expert knowledge, the weather at that time can be reconstructed qualitatively. However, there is also a quantitative approach: numerical weather reconstruction using so-called data assimilation. This method can provide accurate three-dimensional weather data of the past.

Reanalysis as time machine

Data assimilation is the combination of measured data with a numerical weather-prediction model. A model forecast is manipulated in such a way that the model reproduces all available measurements within their error range. At the same time, the model retains its characteristics such as physical consistency.[63]

The process can be imagined as a continuous slight correction, as shown in Figure 39. First, a model is used to forecast the weather over a short time period (e.g. six hours). Forecasts are usually accurate over such a short period. The forecast is now compared with the available measurements at that time. The entire three-dimensional model state is then corrected towards the observations using statistical relationships between all variables and grid cells. The technical term for this is "analysis" and every weather map is created this way. This analysis is now used as the starting point for the next forecast and the process is repeated. If this procedure is applied retroactively over a long period of time, it is referred to as "reanalysis".

Reanalysis data sets have become the most widely used data in geosciences. Most of the meteorological maps shown in this booklet are from reanalyses. Some reanalyses, such as ERA-Interim[64] of the European Centre for Medium-Range Weather Forecasts, provide data for the time after 1979, i.e. the time for which satellite data are available.

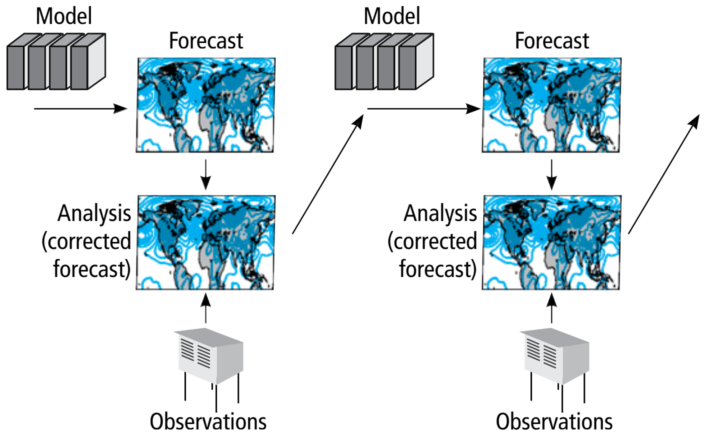


Fig. 39: *Schematic sequence of a reanalysis.*

In recent years, data-assimilation approaches have been improved to such an extent that a useful estimate of the three-dimensional atmospheric state for a certain situation in the past is already possible from several dozen measurements.[63] Air-pressure measurements are used almost exclusively. These make it possible to reconstruct the weather back to the 19th century, as air-pressure data have been available, at least for Europe and North America, since the beginning of national weather services around the mid-19th century (see p. 23). These data are spread across numerous archives worldwide, often only on paper. Therefore, large efforts are still needed to digitise these data (see p. 20). An example of a reanalysis based only on air-pressure measurements is the Twentieth Century Reanalysis Project (20CR), which goes back to 1851.[25]

As a demonstration of the potential of these new data sets, the text on the right shows meteorological fields for the event of 1868. Below we use the example of the flood of 14 June 1910 on the northern side of the Alps (Fig. 40). This flood event is very similar to that of 2005

Fig. 40: *Flood in the Mattequartier in Bern on 14 June 1910.*

(see p. 8). Since such events are rare, it is important to be able to study several individual events.

Although measurements were already quite widespread in 1910, only a small part of these data is available electronically, and was used for the reanalysis (Fig. 41). Thus, it would theoretically be possible to reconstruct the weather even more accurately. In addition to the meteorological stations on land, Figure 41 also shows particularly important data from ships, and the smooth topography of the model, which obviously only allows a large-scale reconstruction of the weather in complex terrain (see p. 26).

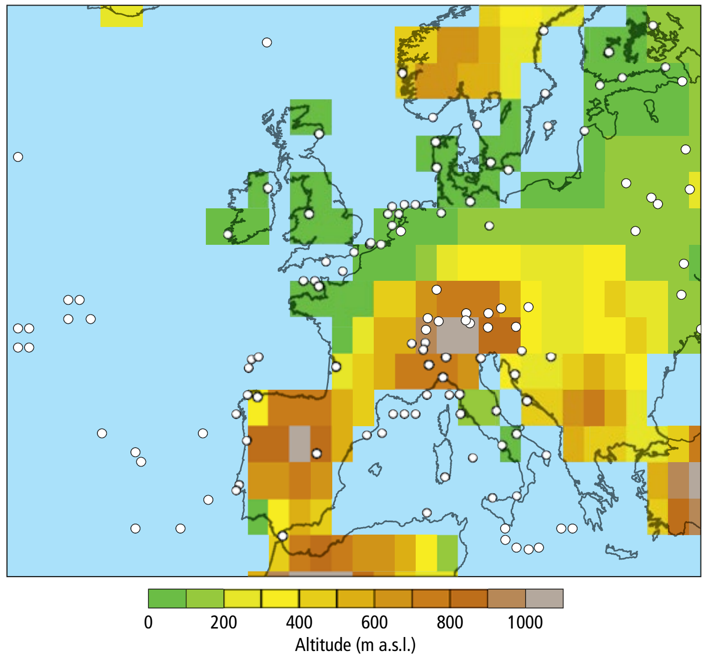


Fig. 41: *Pressure measurements used for the 20CR reanalysis[25] of 14 June 1910, 12:00 UTC.*

The weather charts obtained from these data are shown in Figures 42 (from 20CR) and 43 (CERA-20C Reanalysis[65]). The chart of the 500 hPa surface shows a low-pressure system over northern Italy at the time of the event. On its front side, the data set shows large-scale uplift. The chart of surface-level wind and temperature (Fig. 43) shows a typical Vb situation (see p. 8), in which humid air is transported

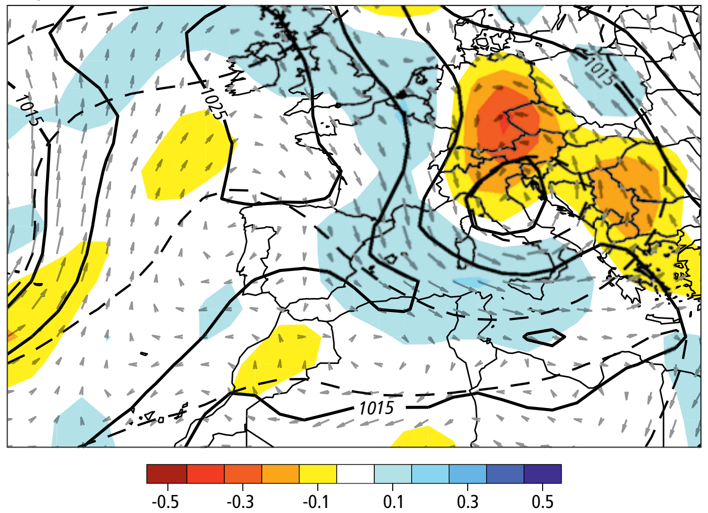


Fig. 42: *Weather map from the 20CR reanalysis[25] for 14 June 1910, 12:00 UTC: sea-level pressure (hPa, bold black lines), wind field at 850 hPa (approx. 1.5 km height, grey arrows), height of the 500 hPa surface (approx. 5 km, bold dotted lines), vertical motion at 500 hPa (negative values mean upward).*

around the Alps, where it rains out upon rising due to uplift at the Alps and upgliding onto blocked cold air.

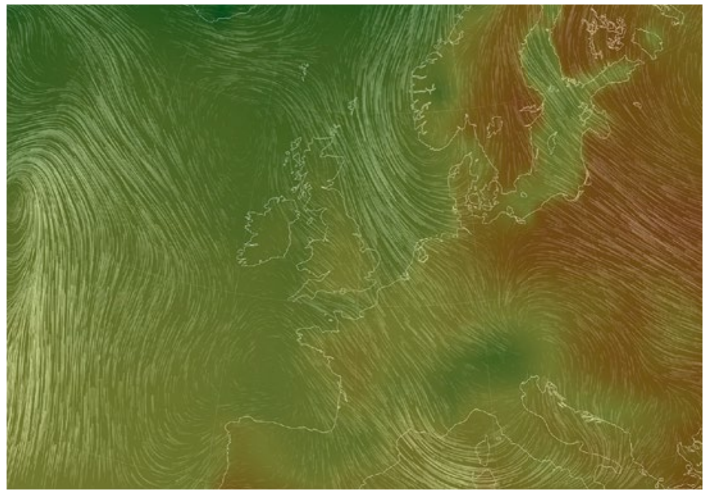


Fig. 43: *Temperature at ground level and wind streamlines on 14 June 1910 at 12:00 UTC in the CERA-20C Reanalysis (from the interactive visualisation earth.fdn-dev.iwi.unibe.ch).*

The analysis of historical extremes helps to assess current events, because the longer the reconstructed weather data sets are, the more cases they cover. Since the data are quantitative and three-dimensional, they can also be used for climate-impact research. For example, they can be downscaled using regional weather-prediction models (see p. 26) and then used for climate-impact modelling. However, the quality of other regions' reanalysis data sets is not as good as those available from Central Europe. Even here, caution is warranted when calculating trends.

Reconstructed weather for 1868

There is currently only one reanalysis data set covering the year 1868: the Twentieth Century Reanalysis (20CR). 20CR is based solely on air-pressure measurements (see main text). Although only a few pressure measurements are available for 1868 for Western and Central Europe, and much less than for 1910 (Fig. 41), they are relatively well distributed over space (Fig. 44).

The weather map from 20CR for 22 September 1868 (Fig. 44) shows a large-scale low-pressure system over Central Europe, with an extension over the Alps and a low-pressure channel to North Africa. A special feature of 20CR is that it indicates a large range of possible solutions resulting from the uncertainty of the measurements, the model, and the spatial distribution of the measurements. This range is calculated as an ensemble of 56 equally likely variants. Often only their mean value and spread are shown; in Figure 44, all 56 variants are shown for the 1008 hPa isobar line. These have only a small spread across Central Europe. The uncertainty is therefore comparatively small, while it is increasing over Africa or the North Atlantic due to the lack of station data.

20CR provides data not only for sea-level pressure but also for other variables and altitudes. For example, the reanalysis shows southerly wind at an altitude of about 1.5 km above the Mediterranean Sea, from where the flow is directed towards the southern side of the Alps. In addition, the data show a trough in the middle troposphere (at about 5 km altitude or 500 hPa) as well as strong ascent, which leads to cooling and convection. Even complex weather variables for high altitudes such as tropopause height (see p. 8) can be derived from 20CR.

The relatively small uncertainty range and the surprisingly good correspondence of surface-weather map and upper-level circulation demonstrate that 20CR is able to consistently and plausibly represent the large-scale variables for this area even back to the mid-19th century.

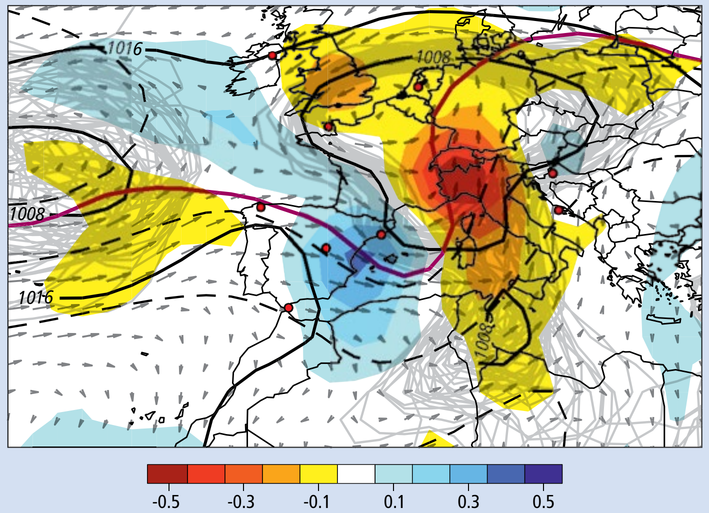


Fig. 44: *Sea-level pressure (hPa, solid black lines; grey lines for the ensemble), wind at 850 hPa (1.5 km high, grey arrows), geopotential height at 500 hPa (approx. 5 km high, dashed black lines), vertical motion at 500 hPa (negative values mean upward) and tropopause (1.5 PVU, red line) from 20CR for 22 September 1868, 12:00 UTC. The incorporated measurements are marked as red dots.*

"Downscaling": reconstructing the local weather

Global weather products are not able to resolve important features of Alpine weather and climate. This holds true specifically for historical reanalysis products. Various "downscaling" techniques are used to obtain locally relevant information from global products. Dynamical methods use numerical weather-prediction models for this purpose, while statistical methods rely on the information contained in local measurements.

Dynamical downscaling

It is remarkable that a global reanalysis realistically reconstructs the weather situation of the 1868 flood event. However, the reanalysis data have only one value every 200 km, and the Alps are represented as a single, large, smooth hill (Fig. 41). Important weather phenomena like fronts, thunderstorms, or the channelling of the wind in the Alpine valleys are too small to be reconstructed by the reanalysis.

Dynamical downscaling relies on weather models such as the WRF model.[66] The model requires initial conditions and boundary conditions for each time step. For predicting the weather of the next days, an analysis (see p. 24) and a global weather prediction are used. In order to downscale a historical event, a reanalysis is used both to initiate the WRF model and drive it at its boundary. First, the WRF model is run over a domain that covers Europe and part of the North Atlantic. Then the result of this simulation can in turn be used as initial and boundary conditions for an even finer simulation, and so on. Figure 45 shows, for the event of 2005 as an example, how a high model resolution can be achieved using four refinement steps.

The final resolution is chosen according to the smallest scale that should be resolved. For example, if historical observations indicate that thunderstorms contributed substantially to the precipitation of a historical event, the model resolution must be sufficiently fine to represent thunderstorms, i.e. the model grid cannot be coarser than a few kilometres.[67] So starting from the reanalysis with a resolution of 200 km, we can create simulations at 81 km, 27 km, 9 km, and finally 3 km. The only added information is the land surface and the topography. Nevertheless, the results of the refinements are much better than in the original global reanalysis (Fig. 45, bottom right).

Dynamical downscaling allows for the reconstruction of local weather of historical events at a resolution comparable to the best modern weather forecasts. For example, the high resolution of the topography enables investigation of how air masses penetrate into the main Alpine valleys (Fig. 46).

Of course, the results for a historical event are not as reliable as for a recent event. The main limitation is the scarcity of observations. The dynamical downscaling rather shows a proposition of what the local weather may have looked like during a historical event. In any case, dynamical downscaling facilitates four-dimensional studies of local meteorological phenomena that have probably contributed to extreme weather. Historical weather events can thereby be compared to recent ones.

Statistical downscaling

Besides the laborious numerical simulations, statistical methods can also be used. A very simple one is the analogue method. Information available from a day in the past is compared with the same information for all days in a modern time period, for which daily, high-resolution fields are available. Data from the most similar modern day – based on selected criteria – is used for reconstructing the past day. This method delivers good results if a sufficient amount of possible analogue cases is available. Several optimisation steps are required. Depending on the exact method, the reconstructed fields can be further corrected based on the measurements.

Based on data from the weather stations, MeteoSwiss has reconstructed daily fields of precipitation and temperature for Switzerland, at a resolution of 2 km, since 1960.[68,69] This represents more than

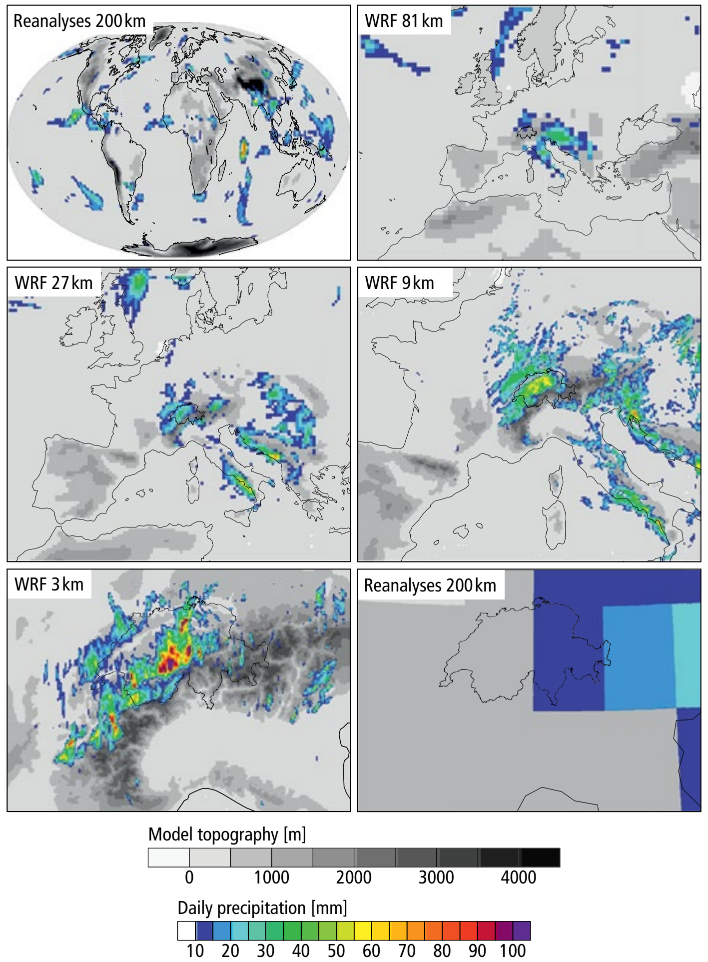


Fig. 45: Dynamical downscaling. From the 20CR reanalysis, WRF simulations are performed at 81, 27, 9 and 3 km grid sizes. Shown is the simulated daily precipitation on 22 August 2005. For comparison, the reanalysis is shown for the same extent as the 3 km WRF simulation in the bottom-right panel.

20 000 days. Thanks to this high amount of possible analogue cases, the method delivers very good results for light-to-average precipitation. The method, however, underestimates the extreme precipitation events, because extreme events are rare and the analogue cases are also often weaker. Moreover, results are inferior in regions with poor data coverage.

Downscaling the event of 1968

Dynamical downscaling

The event of 1868 was downscaled dynamically and statistically. The dynamical downscaling makes use of the WRF model. The simulated domains are comparable to the ones in Figure 45, but for the period between 26 September and 4 October 1868. The final resolution is 2 km in this case.[32] During the nine days, the model produces almost uninterrupted, widespread, and intense precipitation over Ticino that can be explained by a sustained transport of humidity from south towards the central Alps, orographic lifting, and the development of thunderstorms. In the model, as in historical observations, there was only a brief interruption of heavy precipitation on 29 and 30 September 1868 (see also Fig. 16).

In the high-resolution simulation, thunderstorms regularly develop over the Po Valley and propagate across Ticino. Figures 45 and 46 show this by snapshots. At upper levels, humid air flows over the Alps from the southwest (with a widespread cloud cover, see Fig. 47, bottom left panel). Close to the ground, humid air flows from southeast over the Po Valley. Once this air reaches the first Alpine foothills in Ticino, it is lifted by the orography. Low-level clouds form (top left). Thereby, deep convective cells are initiated, from which organised thunderstorms develop (top right). The thunderstorms move northwards with the mid-level flow and the heavy precipitations reach southern Ticino (bottom right). In the following hours, the unstable flow penetrates further into the Alpine valleys (see Fig. 46) and the heavy precipitations also reach northern Ticino. The development of the thunderstorms resembles remarkably the situations observed for recent heavy-precipitation events in the region of Lake Maggiore.[34] The local weather reproduced by the dynamical downscaling is therefore plausible.

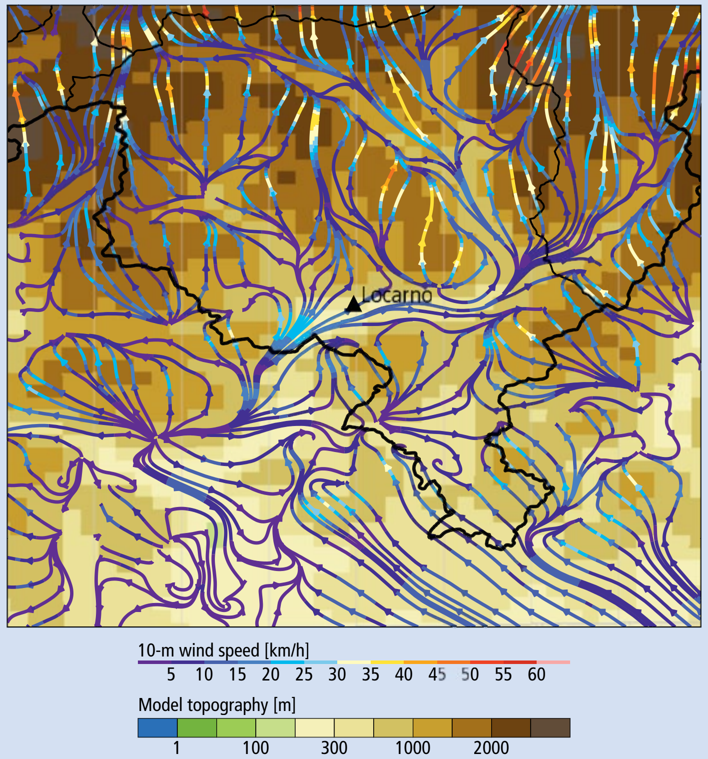


Fig. 46: The wind at 10 m above ground over Ticino on Sunday 27 September 1868 at 12:00 UTC as reconstructed by the WRF model on a 2 km grid. The topography of the model is shown in colour shade, the wind by arrows (arrow colours represent wind speed).[32]

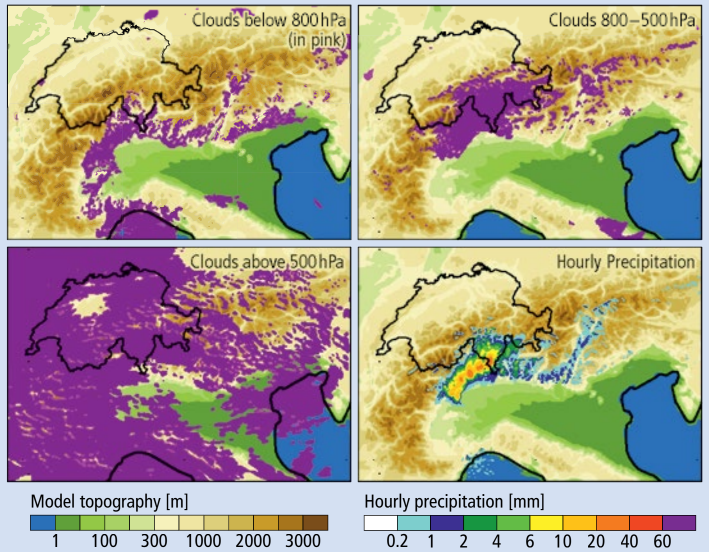


Fig. 47: Cloud cover and hourly precipitation (bottom right) in the WRF model (2 km grid) for Sunday 27 September 1868 at 03:00 UTC. The cloud cover (violet) corresponds to low-level (top left), mid-level (top right) and high-level (bottom left) clouds.

Statistical downscaling

The statistical downscaling was performed with an analogue method optimised for heavy precipitation (see left). Since Lugano[1] is the only measurement station located in the region of concern, the results can be most trusted in southern Ticino and appear more uncertain in northern Ticino. The five-day sums of precipitation over Ticino for the time windows 26–30 September and 1–5 October are shown in Figure 48.

The precipitation amounts over the entire event are almost identical in the statistical method as in the dynamical. The first episode is stronger in the dynamical method, the second in the statistical one. Single days also look similar, although the two methods are completely different.

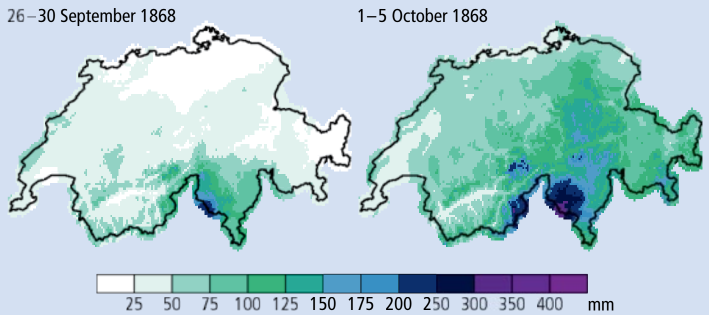


Fig. 48: Precipitation fields for Ticino and for the five-day periods of 26–30 September and 1–5 October 1868 as reconstructed by the analogue method on a 2 km grid.

Hydrological modelling

Hydrological models are used when observations are not present or not sufficient, or when forecasts, reconstructions, or a better understanding of the system are required. These models describe the process of the hydrological cycle of precipitation, water storage, runoff, and evaporation as a whole and in parts. The causal chain from precipitation to runoff is especially important. A multitude of models of varying complexity are used, depending on the question asked, availability of data, and existing computing resources.

We can distinguish deterministic from stochastic models, whereby the former calculates absolute values (e.g. runoff amounts), and the latter generates probabilities. With deterministic models, the process description is divided into three sub-types, depending on their complexity[70] (Fig. 49): so-called "black box" models, for example, only show the relationship between precipitation and runoff without describing the factors producing the runoff in detail. As a result, they primarily serve to detect empirical connections. "Grey box" models, on the other hand, describe a part of the process of the hydrological cycle on a physical basis, often in a simplified way, that partly relies on empirical evidence of connections. Finally, "white box" models simulate all processes using fundamental laws of physics. These are the most complex models.

The requirements of such complex models compete with existing observations. Whereas simple precipitation-runoff models ("black box") only require precipitation and runoff data, more complex models have a far greater data requirement: meteorological values such as temperature, relative humidity, wind speed and solar radiation, soil parameters such as root penetration depth, grain size, compactness, and land use parameters such as vegetation type and height, root depth, and leaf-area index. For these reasons, it is always important to keep in mind what data is available when picking a model. In blunt terminology, it doesn't make sense to run a Ferrari car (complex model) with a lawnmower motor (few data). Along with these differences in data requirement is spatial resolution: simple "black box" models are based on spatial averages, and "white box" models use spatially discrete raster cells or finite elements that measure the spatial variability in a catchment area.

Models for the reconstruction of historic floods

The following recommendations can be derived for the reconstruction of flood events: a) Complex models are preferable for the analysis of extreme flood events. Black box models are unsuitable, because they are often not able to capture extraordinary processes; b) The data basis for reconstructions is usually limited. Very data-intensive models are therefore excluded by this. Consequently, models that are less data intensive but nevertheless use physically-based algorithms are suitable.

The necessary calibration of a hydrological model takes place in time periods with a good data basis. The structural quality of the input data should not be substantially different from the reconstruction time period: if, for example, the reconstruction uses dynamically downscaled climate-model data (see p. 26), then the meteorological data used for the calibration have to derive from the same dataset – even if real station observation data are available for the calibration time periods. For a successful reconstruction, it is certainly important that the hydrological model can reproduce trustworthy results under extreme conditions. This can be checked with measurements as well as qualitative observations. At the same time, it is interesting whenever the model cannot reproduce certain observations. Using "what if" scenarios, the input data, background information, or process in the model can be artificially changed in order to reconstruct the flood. These necessary changes can then shed light on the real processes during the flood event.

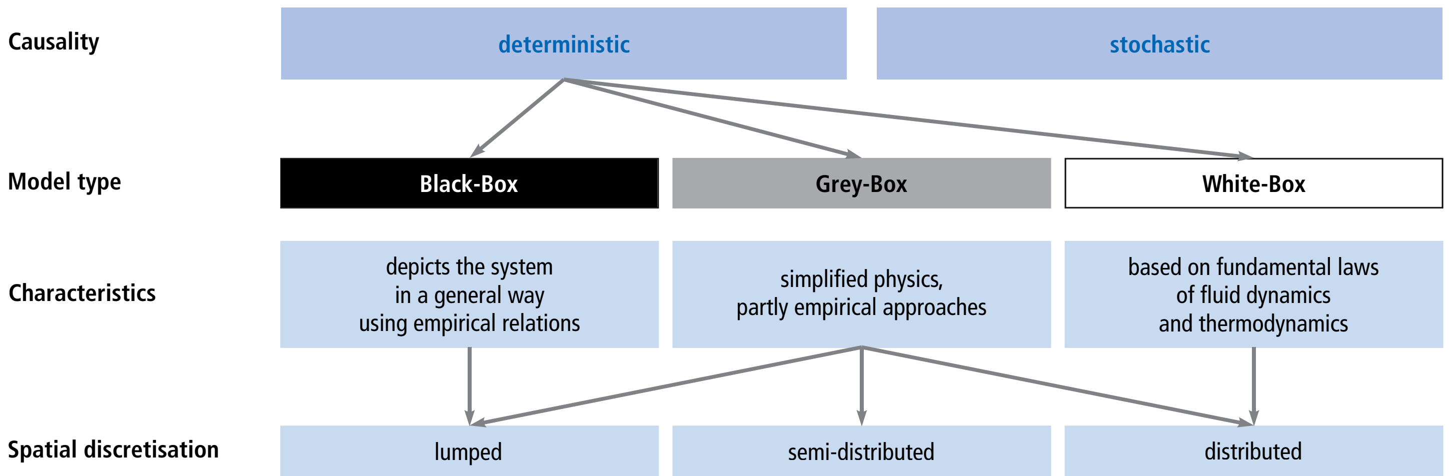


Fig. 49: *Summary of the various types of hydrological models. "Grey box" models are generally the best choice for the reconstruction of flood events.*[70]

Hydrological modelling of the flood of 1868

After having reconstructed the large-scale as well as local weather of the 1868 event, the question remains whether we are also able to accurately simulate runoff and lake level. For hydrological modelling of the flood of 1868, the "grey box" model PREVAH was used. The entire catchment of Lake Maggiore (6368 km^2) was divided into 37 sub-catchments, which were made up of 735 so-called "hydrological response units" (HRUs). HRUs are areas that hydrologically behave in a very similar. The employed model was originally developed for short-term forecasts on an hourly basis in the Lake Maggiore catchment area.[62] Todays complex routing behaviour, with many anthropogenic alterations (hydropower), was captured in this version of the model with the special "routing" model RSMinerve. As by the time of the flood of 1868, these human impacts did not exist, which is why we excluded the "routing" model for the reconstruction.

Since temperature and precipitation data were only available on a daily basis – though at a high spatial resolution – the model was adjusted accordingly. With this simplified model, runoff for the time period 1961–2010 was simulated and compared with measured data. Only a small offset from the original model was observed. Finally, a lake-level-runoff relationship was established, which was validated using the runoff measurement station below Lake Maggiore (Sesto Calende). This relationship is important to be able to correctly simulate lake level. It describes how much water discharges at a given lake level. However, only the multi-weekly average values can be reliably determined. This is because of the strong regulation of the lake, which has the goal of withholding enough irrigation water during wintertime for summer in the Po floodplain. The exact regulation is unknown, which is why no useful model performance could be achieved on a short-term basis.

Figure 50 shows the reconstruction of the lake level for the flood of 1868 using two different climate data reconstruction approaches (analogue: orange, WRF: light blue; see p. 26), as well as the measured lake level (dark blue). The two strong-precipitation events that lead to a clear rise in lake levels in two stages are apparent. Interestingly, both precipitation reconstructions are practically identical in their sum (278 and 279 mm), although very different in their timing. However, both reconstructions clearly lead to an underestimation of lake level in their hydrological simulation. Various "what if" scenarios were tested, including a rather unlikely blockage of the outflow of the lake. The most-likely reason for the large underestimation is an altered lake-level-outflow relationship, which occurred from erosion of the lake outflow during the flood of 1868.[40]

So, were the floods of 1868 really caused by deforestation, as claimed by contemporary experts (see box)? A scenario that takes into consideration the decimated forest area of 1868 (50 % decrease) in comparison to today,[39] calculated using WRF climate data, shows a nearly indistinguishable change in lake level. This is because the soils were already saturated and the general storage capacity of the tree crowns (5–8 mm) is minimal compared to the amount of fallen precipitation (280 mm).

The deforestation paradigm

The connection between deforestation in the mountains and flooding in the valleys was already occasionally recognised in the 16th century, when the heyday of mining in the eastern Alps and Germany's lower mountain ranges led to large-scale deforestation. In the 18th century, the emerging sector of forestry became increasingly more interested in sustainable forestry. At the end of the century, French forest engineers established the relationship between forest clearings and floods in the Pyrenees. In 1825, Alexandre Moreau de Jonnès emphasised that deforestation leads to warming and drying of soils, and thereby also erosion:[71] "As soon as the trees no longer shield the soils from the influences of the atmosphere and do not inhibit the interaction between the two, heat can rise from the refraction off surfaces, through the heat uptake capacity of their mineral components, … and finally because the evaporation of the forested areas is completely lacking; for all of these reasons, a great amount of heat is set free into the atmosphere instead of remaining bound."

The ensuing discussion, first only in France, became popular in Central Europe through the translation of the study into German, and was taken up by the Swiss Forestry Association, founded in 1843. Since the state of Swiss mountain forests was miserable due to centuries of deforestation and resource conflicts with the farming population, making the connection to the floods of 1834, 1852, or 1868 was straightforward for the forest engineers. Proponents of the forestry association, especially Karl Kasthofer (1777–1853) and Elias Landolt (1821–1896), tried to mobilise the public and politicians with this issue, which finally succeeded after the floods of 1868.[7]

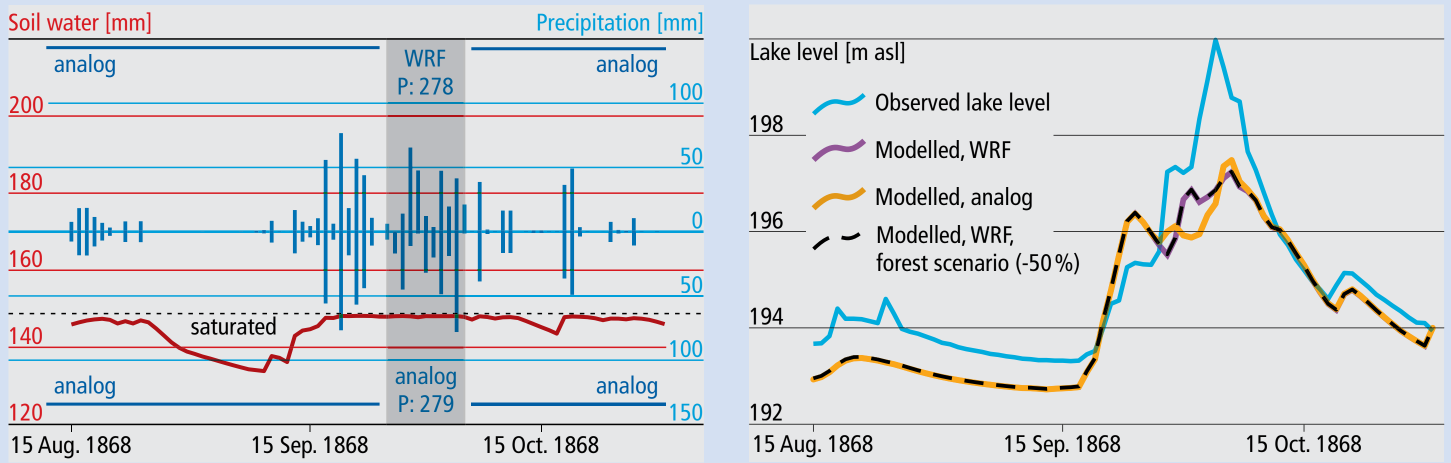


Fig. 50: *Reconstruction of precipitation and soil saturation (a regional average in each case, left), as well as lake level on the right. Bars going upwards show precipitation from the WRF simulation (grey background), and the bars extending down and bars outside of the grey area are based on the analogue method (see p. 27).*

Reconstruction of historic floods with hydrological and hydraulic models

Heavy runoff does not always lead to floods. The deciding factor is the hydraulic simulation. With an exact site reconstruction, past flood events can be simulated using hydrological and hydraulic models. However, such estimates come with many uncertainties. Precisely this information is of great importance for flood risk management.

Reconstruction of historic extreme events

The reconstruction of historic flood events can supplement records from the instrumental measurement period, and can therefore produce important findings for the assessment of extreme events. Extreme events are an important input variable for the sizing and planning of protection structures[72,73] as well as for land-use planning. On the one hand, extreme events allow us to study the processes leading to catastrophes. On the other hand, well-documented flood events reduce uncertainties in the evaluation of dangers and risks.

Past flood events leave traces that are visible on the ground as erosion marks and sediment layers,[74,75] in annual tree rings,[76] in historic documents (see p. 18), or as high-water marks on buildings.[77] Based on these sources, past floodwater events can be reconstructed. This generates great potential for the analysis of regional climate variability and for the expansion of records from the instrumental measurement period. Accordingly, many research groups work on the reconstruction of past flood events, with very different methods and data.[78–81]

Historic flood events are comparatively well-documented in Switzerland. Besides documents and high-water marks, there were already early measurements and good cartographic sources.[82] In the course of making large stream corrections, surprisingly accurate drawings were made, including measurement surveys, historical topographic maps, river cross sections, and water-level measurements (see p. 20). Compared to other regions, this abundance of historical records allowed for a relatively detailed analysis of historical events.[83]

Caution should be used when transferring reconstructed historical runoffs, water levels, and flooded areas to the situation and landscape of today. Besides climatic fluctuations and land-use changes in the catchment areas,[84] humans have from early on directly altered the water system: river diversions, dams, and floodwater protection projects have direct impacts on the hydrological state of the entire water system, and particularly on the local hazard situation. Typical examples of an altered state are bed degradation or aggradation due to lateral dams, which change the river profile and thereby the stage-discharge relationship.[85] Floodwater-protection structures in the headwaters can increase the floodwater peaks downstream.[86] Before a high-water mark can be considered in further statistical analyses and risk assessments, the hydraulic situation of this time must be reconstructed.[87] In particular, if the impact of climate change on the frequency and magnitude of flood events is being analysed over a long period, then the change of the hydraulic situation must be considered.[88]

Demonstrating changes over time

In current research projects at the Institute of Geography at the University of Bern, historical archives containing measurements and surveys from the early 19th century were digitalised and georeferenced. These data, in combination with newly available high-resolution digital terrain models that reveal visible traces of past floodwater processes, allow for a detailed reconstruction of the historical ground surface. This is portrayed in the form of a digital terrain model, and can be used for hydraulic simulations. With the simulation models available today, which resolve the shallow-water equations two-dimensionally, robust information about the corresponding floodwater runoffs can be derived from high-water marks. With these simulations, historical, generally qualitative, sources can be turned into plausible, quantifiable interpretations. A further advantage of reconstructions of past ground surfaces is that this enables a comparison with the current state. This comparison allows us to isolate the influence of changed river morphology from other runoff-influencing factors, in order to analyse only the individual effect[89] (*www.risikodynamik.ch*).

Reconstructed flood events hold a further advantage for risk management in general; in other words, for the holistic consideration of all measures to prevent and reduce flood risk. Flood risk can be impressively described at a local level when historical documents and pictures are available. This facilitates awareness within the general population (*www.ueberschwemmungsgedaechtnis.ch*).

Fig. 51: *View of the river by Giubiasco[1] and on the Magadino Plain. Photo from the 1880s. The corrections had already been started at this point, but the original river course is still visible.*

The flood event of October 1868 in a hydraulic-model experiment

Based on previous work,[62] a hydrological model (see p. 28) was used to reconstruct lake level in the region of the upper Lake Maggiore and the flood runoff in the Magadino Plain, which was then used in a hydraulic-model experiment in order to simulate the difference between flooded areas. The hydraulic model includes the digital terrain model in its natural state (ca. 1864) and in its modern state (ca. 2003). The observed lake level was also used alongside the simulated lake level.

The modelling experiment shows that the high lake level observed in the past cannot be attained with today's lake-level-runoff relationship at the outflow of Lake Maggiore. At the time of the event, the riverbed at the lake outflow deepened significantly, which increased the outflow considerably.[40] Today, this means that the lake cannot be dammed to the same extent as in the past. The modelling experiment also shows that the river corrections strongly reduced the flooded areas in the Magadino Plain. The example convincingly shows how different the effects of the same runoff event can be, and that changes in river morphology need to be considered in the interpretation of historical sources.

Effects of the flood of 1868 in the past and today

Since 1868, the settled area as well as the river course and the lake outflow have changed. In October 1868, 436 buildings stood below Bellinzona[1] and along the Swiss shoreline of Lake Maggiore in the reconstructed flood area of the measured lake level and of the simulated runoff. When looking at the existing buildings in 2016, the same flooded area (historical terrain model) would affect 3934 buildings. This means that the settled area has increased by a factor of nine. If today's river course is taken into account (current terrain model, simulated lake level and simulated runoff in Bellinzona), the impact includes 944 buildings. This shows the effectiveness of the floodwater protection measures and the enlargement of the lake outflow due to riverbed erosion during the event of 1868. Today, 2990 buildings benefit from these planned and unplanned changes in the water system. Reconstructions of past flood events can thereby represent an important foundation for the assessment of flood frequency and magnitude. Furthermore, they can provide a basis for the analysis of the spatial and temporal dynamics in the development of flood risks.

Fig. 52: *Comparison of the floodplains from the reconstructed flood event of 1868 (top) and the simulated effects of the same event under today's conditions (bottom).*

Mountain torrents and floods: searching for traces on the ground

Large flood events do not only lead to inundations. They are accompanied by landslides, debris flows (in the smaller and steep catchment areas), and changes along the river course through bank erosion and deposition of the suspended sediments. The erosion and deposition of suspended particulates through various processes thereby changes the landscape as we know it, and creates great damages to buildings, infrastructure, and agriculture. The flood events in August 2005 or the debris flows in the Lötschen Valley[1] in October 2011 clearly demonstrated this.

Processes

Streams and rivers transport boulders, gravel, sand, mud, and often also wood. The material ends up in the waterways through landslides, debris flows, eroded riverbanks or channel erosion, and then gets deposited in the flatter and wider river sections. While water runs off after a certain time during a flood, the sediments stay behind either in the form of gravel banks or as scree deposits on fields or settled areas. On large plains, rivers would often change their direction and erode new beds as a result of such deposits during floods. Today, this is practically impossible with channelised river courses; however, the old structures are still recognisable on the ground (Fig. 53).

Fig. 53: *Traces of old river watercourses in the Alpine Rhine (by Trübbach).*

During large flood events with heavy rainfall, such as 1868, 1987, 2005, or 2011, small catchment areas were also affected: large landslides occurred in saturated slopes and debris flows or intense sediment transports took place in the steep torrents. The accompanying sediments were deposited and left typical features: scree mounds and alluvial fans, channels and gullies, or other typical features. Debris flows are particularly effective for the formation of a landscape. These are a rapidly flowing mixture of water, stones, and fine material.[90] They are able to transport large amounts of sediments, along with large boulders, over long distances; they therefore belong to the dangerous mountain-torrent processes.

While sediment transport of rivers was already scientifically researched, and described with the corresponding formulas in the 1940s, debris flows in Switzerland were hardly considered by science until the late 1980s. The large events in the summer of 1987 strikingly demonstrated the need for research. With the documentation and analysis of these events, an intense period of research activity started.[91] Questions about debris-flow dynamics, the triggering conditions of landslides and debris flows (also in the context of climate change82), or the simulation of these processes,[93,94] moved to the forefront of research, particularly to provide tools for practical purposes.95,96 Since the flood events of the spring of 1999 and August 2005, with countless destructive landslides and debris flows (in Sörenberg,[1] Glarus,[1] Guttannen,[1] and Brienz[1]), the term "debris flow" caught on in the media and is now considered a standard term, e.g. for warnings.

Zavragia (Zignau[1], GR), where debris flows had already occurred during countless earlier flood events, was also affected. Particularly strong debris flows took place in 1868 (see right) and 1987 (see Fig. 54).

Measures

The large flood events of 1868, 1987, 1999, and 2005 each influenced hazard and risk strategies with floods or sediment transport by water (see p. 36). Whereas the emphasis was put on stability of the catchment areas and construction measures for channelling streams and rivers after 1868, the protection strategy after 1987 concentrated on an integrated approach with planning measures (avoiding hazardous areas), biological (reforestation), construction (protection structures), and organisational measures. After the flood events of 1999 and 2005, the emphasis was placed on warning the population.

Construction measures for flood protection are based on three fundamentally different concepts to manage water and especially sediments: retention, diversion, or passage. In the second half of the 19th century, it was recognised that the behaviour of mountain torrents was critical for the flood state,[97] and that these streams needed to be controlled accordingly. At the time, the poor state of the forest and the lack of protection structures on water bodies were blamed for the repeated damages from mountain torrents, including by the expert commissions which analysed the flood of 1868.[98] The suggestions for mountain-torrent constructions aimed to reduce erosion in the headwaters and increase sediment transport capacity in the lower reaches. With these considerations in mind, a change was made from tackling symptoms to addressing the root causes.[99] Besides reforestation, large consolidation and retention barriers as well as correction works in steep streams were built (Fig. 55), including in Zavragia.

Simultaneously with the stabilisation measures in the smaller catchment areas, actual canals and gullies were constructed in the valleys on top of scree riverbed channels and streambeds, in order to channel the flood runoff or sediments to areas downstream or into less-developed areas. The small streambed in Zavragia was also fully channelled in the 1960s. This may have prevented substantial damages in the village of Zignau during the flood of 1987. In the last few decades, many smaller and also some very large sediment collectors were constructed so that sediments wouldn't end up as bank deposits.

Today, the lifetime of many protection structures has been reached or exceeded. Especially with large retention structures in the catchment area (e.g. correction works), the question arises whether these structures should be replaced, or if other strategies would be more sustainable. Instead of retaining sediments in the catchment area, sediments today are managed on the banks, drainage channels, or diverted to areas of minimal use.[100]

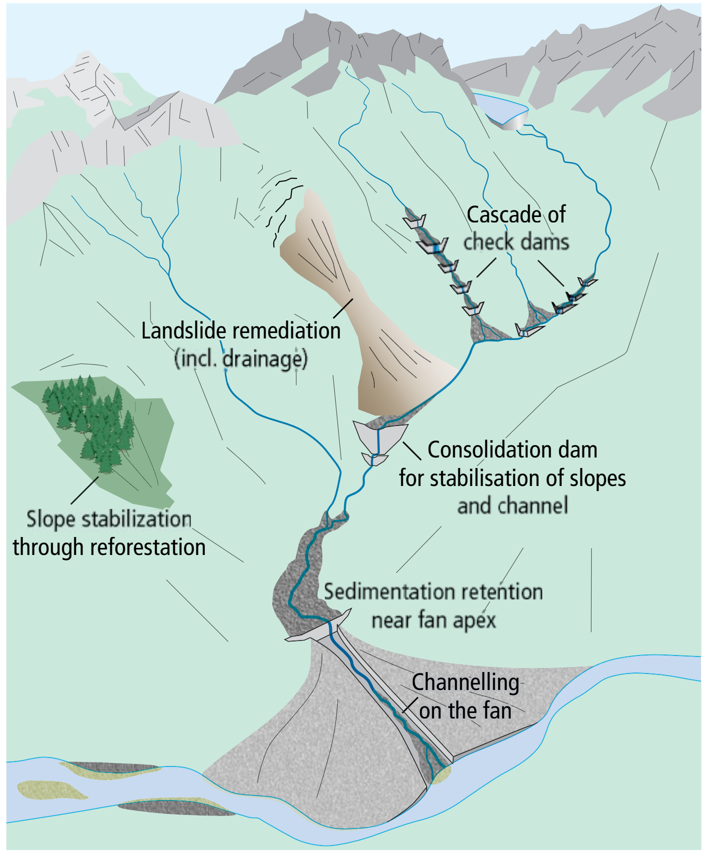


Fig. 55: *Various measures conceptualised for mountain-torrent catchment areas.[100]*

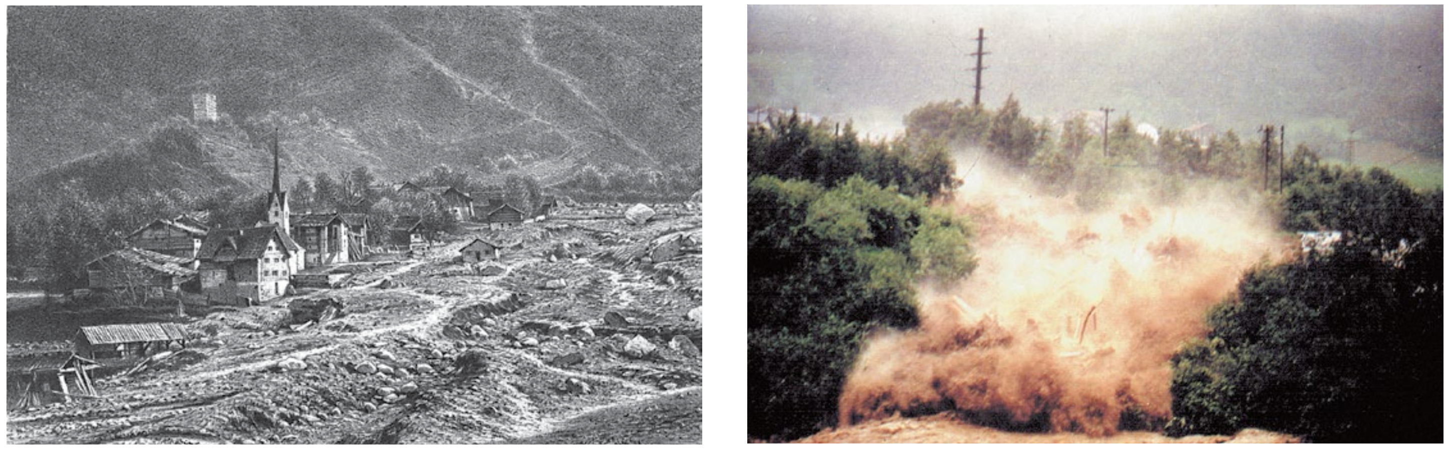


Fig. 54: *Floods and debris flows in Zignau (left) in 1868[35] and 1987 (right).*

Traces of the 1868 event

Precipitation in the fall of 1868 led to great inundations in the valley plains of the Rhine, Reuss, and Ticino; banks were partially eroded and rivers changed course. According to the Grisons daily paper from 1 October 1868, the posterior Rhine, Glenner, and Nolla in particular caused great damages to the banks and adjacent areas. The water in these rivers eroded banks, carried away weirs (longitudinal structures for the protection of the bank), and destroyed some bridges.

Not only the large river valleys were affected. The heavy and persistent precipitation caused numerous landslides, debris flows, and mountain-torrent outbursts in smaller rivers and streams. According to the report of the expert commission,[98] "the mountain waters grew to streams and, not hindered sufficiently by dams and forests, carried with them such debris, stone falls, and boulders that mountainous terrain was torn down, valleys were flooded and covered in silt, entire villages were destroyed or buried, and many of their inhabitants were buried under them." The role of sediments carried by streams and rivers is emphasised. With entrained sediments, the Peiler stream in Vals burst out of its streambed: "All nightlong, landslides fell into the Valser ravine, which dammed the water; the ravine emptied the debris down the mountain into the Glenner River seven times."[98]

Probably the most well-documented event is the debris flow (landslide) in the Zavragia valley (12 km^2) (see Fig. 54): "With a terrible thundering, a mountain of debris rolled through the middle of the street. In the pitch black night, one had scarcely set out to flee northwards to the goods and gardens as usual, that debris broke out here as well."[3] Johann Coaz captured this massive devastation with one description. Although large floods and debris flows were already documented in Zavragia in 1748 and 1834, the alluvial fan was still densely populated (Fig. 56).

The commission of experts, called in after the events of September and October 1868, discussed the question of preventative measures. Landolt, Culmann, and Escher, experts from the Linth River area, found it to be most effective if the greatest possible amounts of money were spent on construction works in the side valleys. They noted that river corrections in the plains would certainly not suffice if measures were not also undertaken in the area where the floods and sediments originated. The new laws (forestry – or rather, hydraulic-engineering acts) explicitly required the prevention of floods, particularly of mountain-torrent events.

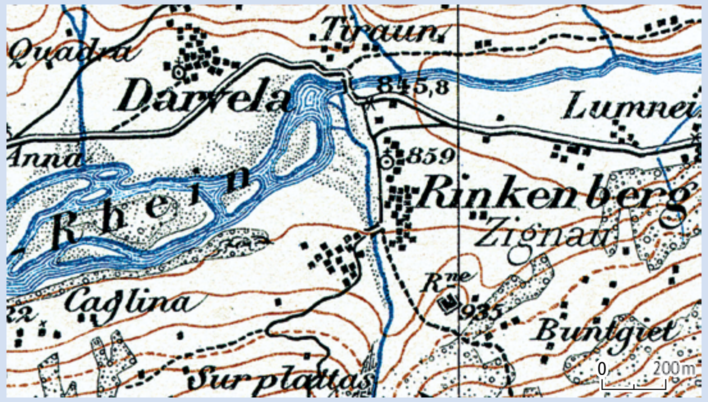


Fig. 56: *Zignau in the Topographic Atlas of Switzerland in 1881 showing sediment deposits from the event.*

Flood damages

Floods and their accompanying processes have diverse impacts on humans and their habitats. Positive effects such as nutrient inputs and irrigation are of secondary importance in modern Switzerland. Of considerably greater importance are the negative impacts – the damages.

Statistics from insurance companies and public authorities, as well as from media reports and event documentation, allow us to estimate that floods in Switzerland have caused damages costing around 300 million CHF per year in the past 50 years.[101] These estimates include direct monetary damages to buildings and their contents, vehicles, infrastructure, and civilisation.

Damages occur because of the static and dynamic pressure effects of the water and its suspended sediments, through terrain and channel modifications (see the previous chapter), as well as because of moisture and dirt.[102,103] The amount of direct monetary damages is calculated from the costs of repair or replacement of the damaged properties.

Over the past 50 years, there has been an increase in these damages, although the increase is primarily related to the development and increase in value of the built environment. Figure 57 shows an example of the timeline of reimbursed flood damages and insured building values from 18 cantonal building insurance companies between 1959 and 2015. In addition, we can see that an increasing number of new residential constructions have been built in potential flood zones over the past decades (see Fig. 58).[104] Of 110 000 residential buildings built between 1971 and 1980, for which a hazard map exists today according to the provisions of the federal government, 14 per cent are located in risk zones. For subsequent building periods this proportion rises consistently, and is around 16 per cent for the most recently examined time period (2001–2012).

The negative effects of a flood, however, encompass more than the described direct monetary damages. The costs for replacement or repair are often of secondary importance. The indirect costs of disruption are of foremost importance for infrastructure, production chains, or communication networks. A bakery affected by a flood, for example, will of course have considerable costs for the replacement of flour, ovens, and delivery vehicles. The indirect costs of interrupted operations, particularly lost profits, are disproportionately higher. These not only occur during the flood event, but also afterwards, if the customers instead go to buy their bread at a competing store. The amount of these indirect damages is often difficult to estimate. It is even more difficult to estimate damages that can hardly by expressed in monetary value, such as loss of life or cultural assets destroyed by the water.

Floods result in monetary and non-monetary and direct and indirect damages. Current research attempts to find ways of measuring the very diverse kinds of damages in a comparable way, and use them to produce a clear basis for decision making. With society on its persistent growth track, these bases for decision making help us assess flood risk appropriately.

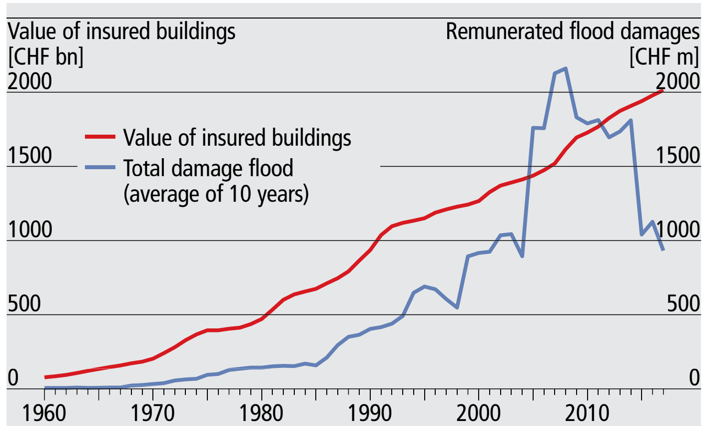


***Fig. 57:** Value of insured buildings (in billions of CHF, left axis) and remunerated flood damages (average of the last 10 years in millions of CHF, right axis) 1960–2016, from 18 cantonal building insurance companies, who insure around 70 per cent of the existing buildings in Switzerland.[105]*

Finally, there is an assumption that potentially flood-prone properties, particularly buildings, are built and used in a more flood-sensitive way today. Elevated building entrances with two or three steps in a dirt-and-water-resistant entrance area have given way to step-free thresholds from the garden sitting area directly into the living room. Heating oil is now stored in basements instead of potatoes and apples, and storage rooms have turned into control centres for domestic facilities.

It is a great challenge to quantify the flood sensitivity of buildings and other vulnerable properties in order to be useful for estimating damages of future events. The results of the limited amount of research in this long-neglected area of flood-related risk research show considerable uncertainties,[106,107] and demonstrate the need for further research.

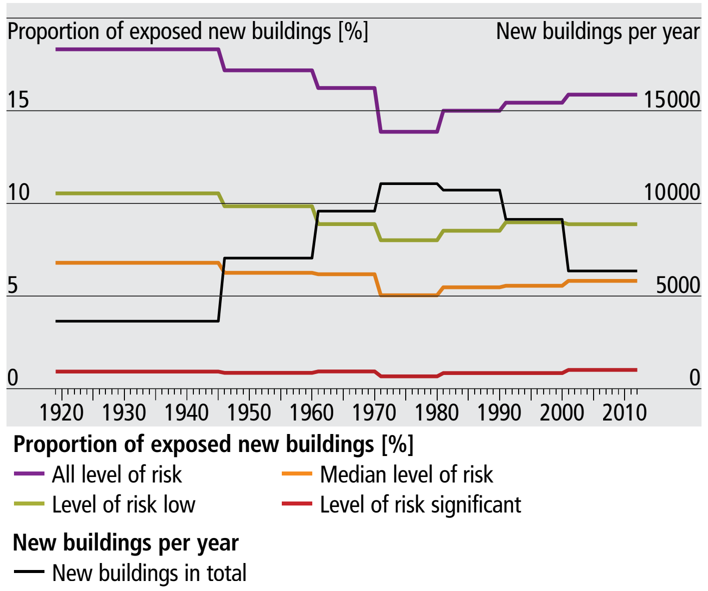


***Fig. 58:** Newly erected buildings with residential use by period of construction. The proportion of exposed new buildings (left axis, in per cent) corresponds to the ratio of newly constructed buildings in flood-risk areas of the corresponding level of risk to all newly constructed buildings, for which a hazard map exists according to the provisions of the federal government. The latter are additionally shown in absolute numbers per year (right axis).[104]*

The distribution of damages in 1868

The flood of 1868 brought exceptional damages particularly to the southern side of the Alps.[3,32,35,108] As there were still no systematic procedures for surveying the damages, an appraisal committee was specially appointed by the federal government to create a detailed survey of the damages in the months after the floods in the five affected cantons of Ticino, Grisons, St. Gallen, Valais, and Uri.[4]

The total costs in the territory of Switzerland amounted to 14 million CHF, of which 6.5 million CHF were in the canton of Ticino (Fig. 59). Adjusted to the year 2000, this would be 915 million and 425 million CHF, respectively.[109] The prolonged and intense precipitation moreover resulted in the highest-measured lake level in Lake Maggiore.[108] It is therefore not surprising that the canton of Ticino was most severely affected. The greatest damages occurred in Blenio Valley[1] and Leventina,[1] with a total of 4.1 million CHF; additionally, these regions mourned the loss of 41 of a total of 51 fatalities.[3] In the canton of Grisons, nearly every canton along the Rhine was affected by the flood, and several debris flows increased the damages considerably. For example, the village of Vals[1] (VL in Fig. 59) was covered by a layer of sand with an average thickness of 45 cm (Fig. 60). The village of Zignau[1] suffered a similar fate (ZI in Fig. 54).[35] Further downstream, four temporary lakes formed because of the water masses. In the canton of Valais, costs were incurred primarily along the Rhone, and in the canton of Uri along the Reuss.[32,108]

The previously mentioned appraisal committee surveyed the damages in a detailed manner, categorising them by type of damage, as well as by the injured party. In total, private households carried the greatest proportion of damages, with approximately 59 per cent, whereas around a third fell to municipalities and corporations, and only about 8 per cent to the cantons. The type of damages explains this distribution: 55 per cent of the damages affected agricultural areas and to some degree harvests, thereby impacting the fundamental livelihoods of the victims in the five primarily agriculturally-oriented cantons. Approximately a quarter of the damages occurred on bridges, roads, and especially to hydraulic works. From today's perspective, it is therefore surprising that the cantons were not more severely affected. In contrast to today, the cantons were historically only responsible for roads

***Fig. 60:** Photo of the sand-covered valley plain near Vals shortly after the flood and the following debris flows[3] (see p. 32).*

and bridges and a few transregional river engineering projects (e.g. along the Rhine and Rhone), whereas the remaining infrastructure of this kind was financed by municipalities alone. When considering that many of these works were accomplished by voluntary labour of inhabitants from the community, it becomes apparent that many private citizens were doubly affected. Besides the damages to agricultural areas and infrastructure, the minimal damages to buildings and so-called chattels – including mainly movable assets, livestock, and supplies – shows that the settlement of hazardous areas was still hardly an issue in 1868.

In total, the appraisal committee counted over 18 000 injured parties – more than 8000 of those in Ticino – and more than half of those had an annual income less than 1000 CHF, and belonged to the needy group or "the poor". These impoverished victims carried a third of the private damages, without being safeguarded by today's insurance system. Only the extremely successful collection of donations could ease at least some part of their hardship (see p. 37).

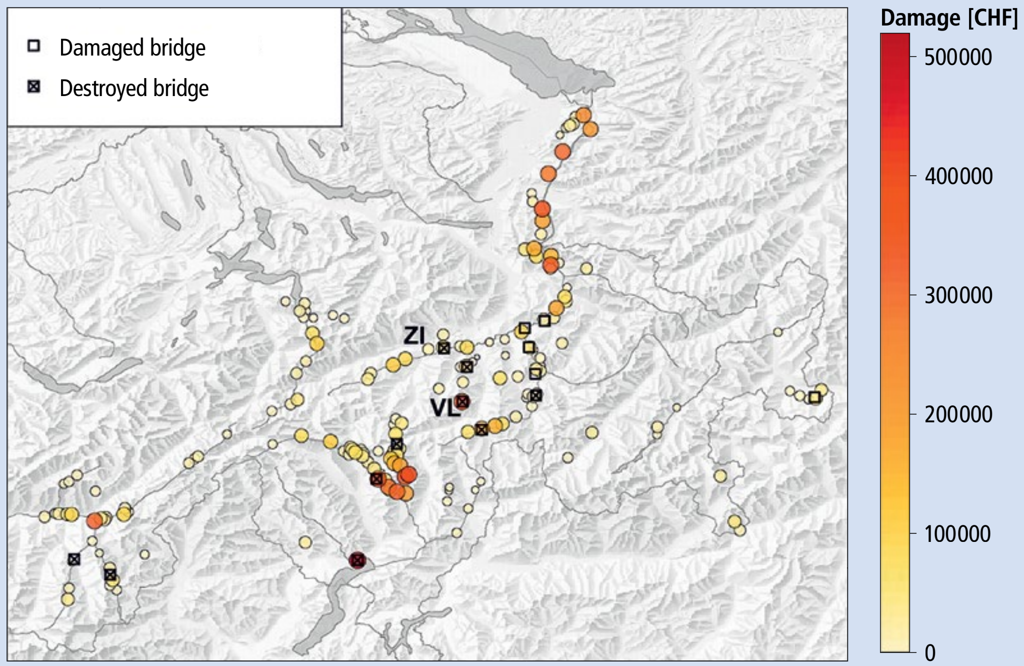


***Fig. 59:** Sum of damages (in CHF) per municipality according to modern investigations in the five affected cantons of south-eastern Switzerland. Rectangles show damaged bridges, rectangles with crosses show destroyed bridges. VL = Vals, ZI = Zignau.*

Societal impacts: coping and prevention

Transregional flood events have always shaped societal adaptation and transformation processes, for example in the areas of flood protection and risk management. They can initiate or accelerate learning, and thereby also innovation and optimisation processes, in tackling and preventing catastrophes. Preconditions for such innovations include that new strategies and solutions must build upon the current range of experience.

Extreme events also occurred in the 19th century: their extent and repercussions exceeded the coping and regeneration capacities of the local communities and cantons. The young state intervened in addressing catastrophes for the first time in 1868 (see right). Military troops from the cantons were deployed for the first time in 1868 and again in 1876 and 1910 (Fig. 61).[110] The solidarity between the regions of Switzerland grew during this time because of these unified efforts in handling catastrophes.

These three flood events, as well as thunderstorms and avalanches, also increased the local pressure on building insurance companies to expand their coverage, which had previously been limited to fire damages. In 1926, the public-law property insurance of the canton of Vaud was the first institution to include selected natural hazards into their coverage.[111] Within three decades, every building and chattel insurance provider in Switzerland followed suit. The ad-hoc solutions of donations, state contributions, and voluntary insurance benefits until the mid-1950s developed into the comprehensive, heavily regulated insurance systems known throughout Switzerland today.[112] In 19 cantons, all buildings need mandatory insurance from a cantonal institution against fire and natural hazards. In the remaining cantons, the federal government prescribes the inclusion of natural hazards in every fire insurance, covering close to 100 per cent. Damages to building structure and contents from floods and other natural hazards are covered by insurance providers in Switzerland. The costs for repair or replacement are refunded to their original value and the deductible of the insured party is minimal.[113,114]

Large flood events play an important role for innovation even today. On the local level, they are still the most common trigger for the establishment of emergency plans and prevention measures.[115] After the flood event of 2005, the weather forecasting and early warning systems, as well as emergency planning and communication strategies for crises, were extended. Overall, there has been a paradigm shift from averting natural hazards to a risk-based approach since the 1990s: technical measures are combined with organisational and spatial planning measures. So-called "integrated risk management" tries to implement a combination of the most effective measures. Internationally, the approach of strengthening resilience against the negative effects of natural hazards is increasingly followed, and quantitative uncertainties in the foundations and predictions are increasingly taken into consideration in the decision-making process. The aspects of resilience, regenerative capacity, and adaptive capacity are also supported by the new strategies of the National Platform for Natural Hazards, PLANAT, for the handling of risks from natural hazards. This extra-parliamentary commission coordinates activities of risk management in Switzerland and promotes the implementation of new approaches. Solidarity and learning from natural events thereby still play a large role today.

Today, the Swiss population benefits from the innovations of the past 200 years: with land-use planning, the settlement of vulnerable regions and its associated risks are avoided (hazard-zone planning). The building codes ensure that property protection measures are installed in buildings in not only high but also low-risk areas, which reduces damages in the case of a flood. In many hazard zones, construction measures protect residential areas and infrastructure. If an event exceeds the capacity of the protection structures, then local intervention teams such as the fire department or civil protection forces protect the most important properties with mobile safeguards. They are based on a well-functioning early warning (weather and hazard forecasts) and communications system. Furthermore, an in-depth emergency planning system with situation-adjusted strategies for event responses was compiled in many locations. Damages to buildings and chattels are covered by basic insurance. The population thereby carries only a small share of risk in the form of individual responsibility.

Fig. 61: *When tackling the flood of 1927, federal troops also provided aid in Liechtenstein, which resulted in the issuance of a series of postage stamps. At the top, Pontonier Siegrist from Schaffhausen carries boys, Oskar and Martin, to land; below, the postage stamp depicting this scene.[116]*

The collection of "charitable alms" in 1868

Concern in the country was great when the Swiss Alpine range was engulfed in floods in the autumn of 1868.[4,109] Just two days after the floods there were offers of assistance from all over the country, and the federal government dispatched a council member to the affected areas to show its concern in this "national calamity". The federal government lacked a fitting constitutional role, but it established a meeting to organise the aid work and "lend spirit and support, unity and cohesion" based on the motto "extraordinary situations and circumstances require extraordinary means of preventing distress". Thereby, the government took on the initiative of tackling a catastrophe for the first time since its formation, even though it was not its first opportunity. Held on 12 October 1868, this meeting motivated the federal government to create a national appeal for donations, appoint a central aid committee, and establish a commission of experts to estimate damages. A similar approach had already been tried and tested in 1834.[117]

The resulting collection of donations invigorated the "age-old love and eternal loyalty" of the Swiss citizens, and, with the slogan "one for all and all for one!", turned into probably one of the most successful collections in Swiss history, eclipsing even the campaigns of today's Swiss Solidarity organisation: 3.63 million CHF were donated, and together with food aid this totalled around 4 million CHF.[118] The food aid included around 3160 tonnes of foodstuffs, with 2560 tonnes of this being potatoes.[4] The monetary donations came from private citizens, benefit events, and company, church, school and community collections, as well as from well-known persons such as Emperor Napoleon III, the Prussian King William, and Pope Pius IX. Zurich, Bern, and Basel were the most-generous donor cantons, and the population of western Switzerland was particularly active in Vaud, Geneva, and Neuchâtel, despite the spatial and cultural distance (Fig. 62).

The central aid committee was the cornerstone of the entire relief campaign. Its monopoly on information and the governmental mandate secured its authority. It also battled with difficulties: the masses of foodstuffs and clothing led to an enormous administrative and logistical effort, mainly regarding storage, transport, and packaging. For example, goods such as potato bags were soon scarce; the food aid, especially, did not meet the demands of recipients, who were rather preoccupied with securing their long-term livelihoods; and above all, after some time, citizens from the affected cantons pleaded for no more potatoes.

Today's relief campaigns deal with the same problems:[119] aid supplies do not always correspond to the needs at the destination, and may be rather cumbersome because of the complex management involved with food aid. At the location, aid supplies furthermore often lead to a price decline of corresponding products. As in 1868, local infrastructure and administrations today are still overwhelmed by offers of assistance. Relief agencies seldom have full control over the distribution of aid because, as in the past, distribution systems receive less attention than collection systems.

Fig. 62: *The image "Appel de la patrie" (call to the Fartherland) was sold in Geneva in 1868 to benefit the victims, and its dichotomy mirrored the central elements of donation collection: on the left, a woman with two children extending her begging hand towards Helvetia, and in the background floods are tearing away houses, trees, and people. On the right, a farmer and townsman are hurrying towards Helvetia, the farmer carrying bread and clothes, and the townsman bringing money. In the centre, Helvetia is pointing out the way, crowned with the slogan "one for all, all for one".*

Swiss flood protection in transition

When the Swiss federal state was founded in 1848, flood protection was no novelty: for centuries, floods have been a constant in the history of what is now Switzerland. Already two decades after its foundation, the federal government took on an active role in flood protection which it has gradually expanded since then. Extreme flood events were always a driving force in politics and are often at the turning point, if not the origin, of new approaches in flood protection.

Anchoring the infrastructure regime (1848–1877)

Until the start of the 19th century, flood protection was characterised by solely local measures. With the correction of the river Linth (1807–1816), a first supra-regional project was initiated that the Federal Constitution of 1848 based its infrastructure article upon (Art. 21 BV), providing the foundation for correcting the Jura rivers, Rhine, and Rhone[109,120–123] in the 1860s (see Fig. 63, left). These major projects were considered "works in the interest of the Confederation", and were prestigious infrastructure constructions that the young federal government could use to shape the Swiss landscape and to establish strong ties to the cantons through the provision of financial resources.

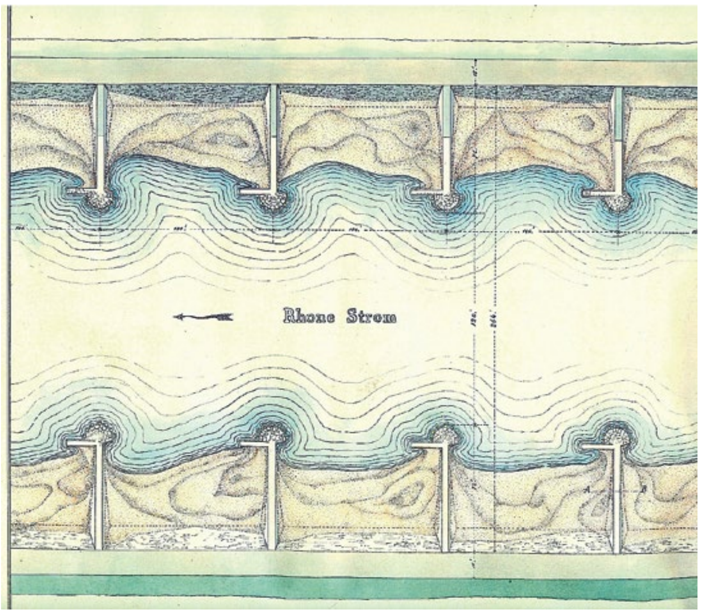
Flood protection itself, however, stayed in the hands of the cantons. The early infrastructure regime was therefore limited to the main rivers, without considering tributaries and headwaters. As early as the 1850s, some experts desired to solve this shortcoming and anchor flood protection as a federal task. They based their opinion on the debate of the causes of floods since the 1820s, and increasingly after the floods of 1834, which concluded that deforestation in the high mountain regions led to floods in the plains (see p. 29). As a countermeasure, experts demanded the modification of mountain torrents and reforestation. The demands from the experts – first and foremost the representatives of the Swiss Association of Forestry founded in 1843 – gained little attention from political decision makers. Only the floods of 1868 led to a re-evaluation of the situation, transferring hydraulic engineering and forestry policy from the cantons to the federal government with the constitutional revision of 1874. On the one hand, the 1868 floods contributed significantly to entrench flood protection as a duty of the Confederation, and on the other hand, the new policies broadened the infrastructure regime from a sectoral to a holistic regime, which took into account the entire catchment area of a river.

The long pathway towards a land-use planning regime (1950s until 1991)

The Hydraulic Engineering Act of 1877 remained the reference text for Swiss hydraulic engineering until 1991. This is partly explained by the so-called "disaster gap", during which intense flood events are missing between 1882 (or 1910) and 1976.[5] However, the thesis of a "disaster gap" underestimates the impact of local events, such as, for example, the series of floods in the 1920s in Valais as the impetus for the second correction of the river Rhone, or the frequent events in alpine mountain torrents such as shown for the Gürbe[1] south of Bern.[109,115,121] The reason that flood protection at the start of the 20th century remained unaltered after such events can be mainly attributed to the fact that the hydraulic-engineering law of 1877 was a very flexible legal framework. In addition, Switzerland was impacted by the global economic crisis and world wars. And, finally, an extensive discussion about the causes of flooding, to lay the groundwork for new solutions, was missing.

This changed, starting in the 1950s, with the environmental-protection debate, in the course of which the protection of water bodies (1953), regional planning (1969) and environmental protection (1971) were incorporated into the Federal Constitution.[109] Under this influence, the water management article was included in 1975, which for the first time saw water in its entirety as an own policy area.[109]

These developments created fertile ground for new administrative practices in hydraulic engineering. Flood protection should now also be made compatible with environmental protection. This harmonization culminated in the guidelines of 1982 "Flood Protection Along Water Courses", propagating sustainable water protection using land-use planning elements (see Fig. 63, right). New legislation was not necessary, but the existing law offered the responsible federal agencies a great deal of creative leeway. Hydraulic engineering was again discussed by the legislature only in the framework of fiscal discussions about the redistribution of tasks between the federal government and cantons. In the middle of these political discussions, the flood year of 1987 occurred, with a truly catastrophic summer. The same Swiss parliament that had previously regularly reduced flood protection funding as part of austerity measures now criticised the low allocations. The new Hydraulic Engineering Act, proposed in 1988 and adopted in 1991, attained maximum attention under the impression of the 1987 floods, anchoring the already widely applied land-use planning regime in law.[125]



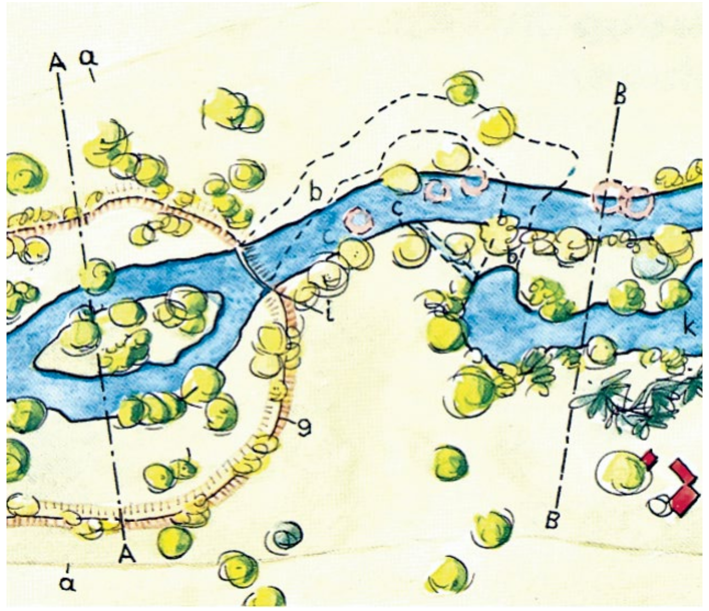


Fig. 63: *The depiction of a narrow-embankment protection system, applied in the 19th century along the Rhone (picture left), and the concept of "more space for water courses" based on guidelines from "Flood Protection Along Water Courses" in 1982 (picture right), clearly show the change of flood protection from the 19th century until today.*

The integrated regime at the turn of the millennium

The step from land-use planning to an integrated regime was a small one in comparison to the previous changes. The recent floods of 1993, and their high-cost damages, showed very impressively that it is not necessarily the hydrological features that turn an event into a disaster, but rather the use of space by people. With the slogan "more space for water courses", attempts have since been made to create an integrated regime that also considers residual risk and allows water courses more space in order to fulfil their diverse functions in the realms of flood protection and nature conservation, water use, and recreation. An important stage was, on the one hand, the foundation of the National Platform for Natural Hazards (PLANAT) in 1997, and, on the other hand, the new guidelines for flood protection in 2001, involving the Federal Office for Water and Geology and three other federal offices, which granted priority to the differentiated protection aims and spatial requirements for water bodies. The catastrophic year of 2005 further promoted this course of action – just as the floods of 1868 and 1987 had done at their time.[109,126]

A political science study from 2016 used the 12 biggest flood events between 1868 and 2015 to analyse under which conditions floods led to policy change.[126] Through this systematic approach, only the floods of 1868, 1978, 1987, and 2005 were identified as trigger events. Neither the spatial extent nor the damages, number of fatalities, or media presence could clearly explain why these flood events in particular were so formative for policymaking and new regulations in flood protection. The deciding factor is not only how severe an event is, but rather in which context it occurs: new paradigms don't arise overnight, but rather, solutions develop long in advance beyond any political pressure. If such policies are available, then a flood event can be a catalyst of political change by creating an arena of attention that allows various actors to push through their agendas.[127]

Policy transitions around 1868

In their reports[97] about mountain forests and mountain torrents, both experts, Elias Landolt (1862) and Carl Culmann (1864), suggested broadening the competences of the federal government in the domains of torrent regulation and reforestation. They further emphasized the harmonization of the cantonal laws and found that a national forestry or hydraulic engineering act was not possible due to cantonal sovereignty.[109] This changed after the 1868 events: the call for a vigorous intervention by the federal government and a shift of competences from the cantonal to the national level grew louder and louder. The floods of 1868 were instrumentalized for this purpose, and federalism was challenged. While the debate about the origin of floods revolved around the deforestation paradigm for decades (see p. 29), the policies enacted after 1868 represented a sudden change: the catastrophic events of this year brought flood prevention to the forefront of the interests of political decision makers. This event conferred the necessary public and political attention to the claims of experts, and gave their demands the corresponding vehemence. While the careful suggestions of a transformation in flood protection pronounced by experts of the early 1860s still had no chance in parliament, the floods of 1868 enabled quite far-reaching demands to be adopted.

The heated debate about the use of charitable donations was an important intermediary step for this change: the highly-acclaimed intentions of the donations were diametrically opposed to the wishes of the affected cantons. The affected cantons and experts wanted the lion's share of the donations to be used sustainably for prevention efforts. The donor cantons in turn stressed that the donors wanted to help the impoverished victims rather than taking over responsibility from the state for building dams and protection infrastructures. As a compromise, the so-called "Wuhrmillion" (referring to money dedicated to hydraulic engineering) was finally created to secure at least a quarter of the donations to be sustainably used for protection structures. This discussion, led by representatives from all cantons, clearly showed that prevention had meanwhile gained potential as a task for the Confederation. It is therefore natural that the Wuhrmillion was followed by a subsidy in 1871, in which the federal government allocated 100 000 CHF annually for torrent regulation and reforestation in the entire high mountain region.

During the 1870s, these new federal tasks were anchored in the Swiss Constitution, though centralists and federalists struggled for amendments since 1865. While many of the new debatable federal tasks were eliminated through compromise with the federalist opponents, hydraulic engineering and forestry was centralised without any notable opposition in Article 24 of the Swiss Constitution of 1874, followed by the Federal Forestry Act in 1874 and the Federal Hydraulic Engineering Act in 1877.

The paradigm shift long-proposed by experts, away from the focus on large river corrections and towards torrent regulation and reforestation, had a political breakthrough after 1868. Not only were there changes in regard to the values and standards, such as relevance, ascribed to the topic, but there were also changes in the legal standards, administrative structures, and agency practices.

Long-term dynamics: lake sediments as flood archives

Flood layers are deposited in lake sediments as a result of events with high river discharge and high loads of transported sediment. These flood layers can be precisely dated; thereby, lake sediments are natural climate archives that can be used to reconstruct the frequency of floods for over thousands of years in the past. Reconstructions show that the frequency of floods in the Alpine region have been particularly high in phases of cool and wet summers over the last 10 000 years. In the southern Alps and in Engadin, the event layer from the flood of 1868 is clearly visible.

Lake sediments record past floods

Heavy precipitation in the catchment area of a lake leads to surface runoff, erosion, mobilisation, and transport of sediments into tributaries. Once in the lake, the transport energy of the turbid inflows decreases and the lithic particles are deposited on the lake floor in the form of flood layers. In this process, the larger and denser particles sink more quickly than the small, light ones. Flood layers typically have a thickness of a few millimetres to several centimetres, and are deposited very rapidly within hours (Fig. 64). Flood layers are recognisable because they generally have a larger grain size than "normal sediments" and display grain size sorting: coarse sand grains deposit more quickly in the lake than fine silt and clay. Flood layers are also distinguished from the normal (calm) sedimentation by their chemical composition, by their higher density, and often with a lower amount of organic carbon.

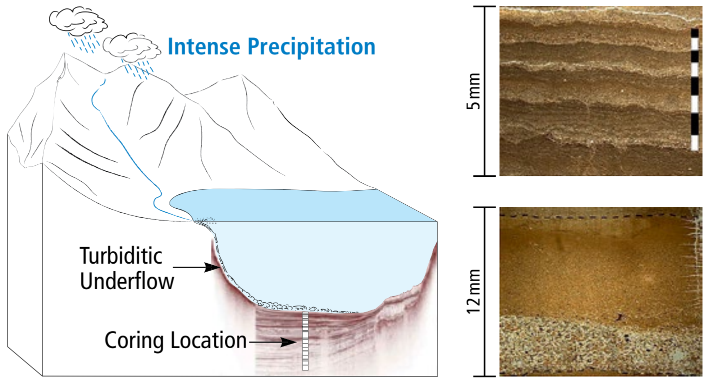


***Fig. 64:** Diagram of a catchment area with the deposition of a flood layer and its position in a sediment core (diagram left);[129] lake sediments from Lake Oeschinen[1] show (top right) normal, calm sedimentation with four annual layers (the light layers always represent spring with snowmelt) and (bottom right) a 12-mm-thick flood layer with coarse sand grains at the base and a fine silt/clay cap.[128]*

Long lake-sediment cores with embedded flood layers can be precisely dated using radionuclides (^{14}C, ^{210}Pb) or the counting of annual layers (varves). In this way, it is possible to establish a chronology of floods in respective catchment areas for thousands of years, and calculate the frequency of floods over a very long time period. It should be noted that lakes in low-lying areas (Swiss Plateau and Po Plain) can record floods in all seasons, whereas lakes in the Alpine region can only record floods in the warm seasons when they are ice-free. Since precipitation can also vary locally and regionally, and the formation of floods is determined by the specific characteristics in the given catchment area of a lake (size, geology, topography, vegetation cover, etc.), it may also be expected that the flood chronology varies from lake to lake. Lake Maggiore, for example, records even small floods with a return period of ca. two years. Lake Oeschinen records floods with a return period of five to 10 years, and Lake Silvaplana records floods with an average return period of 10–20 years. Large regional floods are generally reproduced well. In the pre-Alpine lakes and those in the southern and northern Alpine foothills, flood reconstructions go back 10 000 years. If several lakes in a region independently show increased flood activity, one can assume that the reasons behind this are climatic in nature. The connection between the thickness of a flood layer and the size of the flood is not conclusive, and is often not statistically significant. Thick flood layers, however, generally indicate large floods.

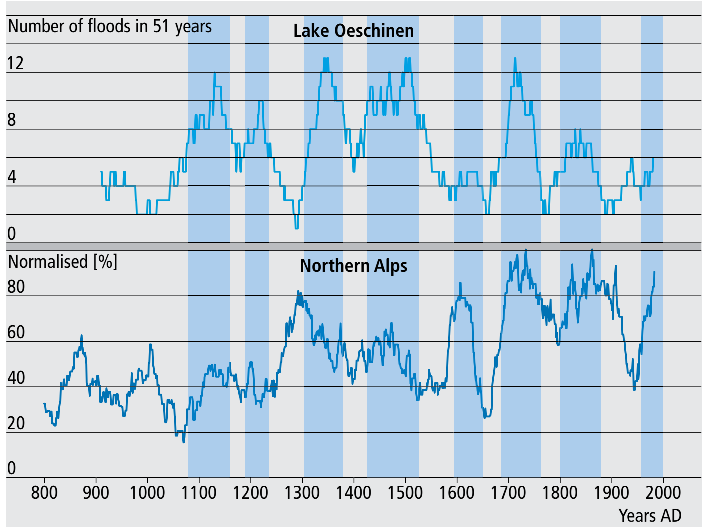


***Fig. 65:** Flood frequency in the last 1000 years in Lake Oeschinen[122] and in the northern Alps (mean from 10 lakes).[129]*

The long-term dynamics of floods in the Alpine region

In the western and central Alpine region, there are around two dozen detailed flood reconstructions using lake sediments that extend more than 1000 and even until 10 000 years into the past. The frequency of floods (number of floods per 50 or 100 years) over the last 1000 years shows a distinct multi-decadal variability. The 20th century, overall, was a relatively calm period. The reconstructions consistently show that floods in the Alpine region and the northern and southern Alpine foothills were most frequent during periods with cool and wet summers. This is particularly clear during the Little Ice Age, with peak values of flood activity in the 14th, 15th, and 18th centuries. The 19th century also had a very high frequency of floods. In the French Alps, there are scattered indications that floods were more infrequent but more intense in the warm and dry periods. In Lake Oeschinen, a period in the first half of the 13th century is well-documented as showing exceptionally frequent flood layers during a phase with generally warm and dry summers. This flood peak at the start of the 13th century is missing in reconstructions from the foreland lakes and the eastern Swiss Alps, which indicates that Lake Oeschinen may be presenting a case of local flood features due to convective summer thunderstorms in the high Alps. Based on model calculations, future climate scenarios in the Alpine region may feature similar processes.

Caution should be used when examining the past 10 000 years, since anthropogenic effects such as deforestation and grazing, and thereby the related changes in land-use and vegetation cover, can also influence flood frequency.[130] Massive land-use change in the Bronze Age often overlaps with climatic changes to wetter and cooler conditions with glacial advances in the 2nd millennium BC. The causes for increased flood frequencies are, therefore, very complex and difficult to disentangle. We are still able to conclude, however, that floods were more frequent in the southern Alps as well as in the northern Alps during cool climate phases of the Holocene.

A quantitative investigation with 2000 varve years (Bronze Age until the end of the Roman period) from Lake Silvaplana,[1] in the Engadin, showed that a 1 °C long-term cooling of average summer temperatures led to a fourfold increase in frequency of flood layers.[131] For the southern Alps, it can be shown that flood frequency was very low in the early and mid-Holocene, and quickly and significantly increased around 4000 years ago (Early Bronze Age). Peak values were reached around 2600 years ago, in the 10th century, as well as during the Little Ice Age. In the northern Alps, flood frequency decreased from the early Holocene until the mid-Holocene Warm Period. The reconstructions show a gradual but distinct increase since the Late Bronze Age, with more maxima during the Little Ice Age. Even with the perspective of the last 10 000 years, there is a strong multi-decadal and centennial variability in flood activity. Various authors have connected the former to solar cycles, and the latter with changes in Earth's orbital parameters. Other authors suspect that the multi-decadal variability in flood frequency on the northern side of the Alps rather relates to sea-surface temperatures in the North Atlantic (Atlantic Multi-decadal Oscillation, AMO, see p. 43), or the North Atlantic Oscillation (NAO).

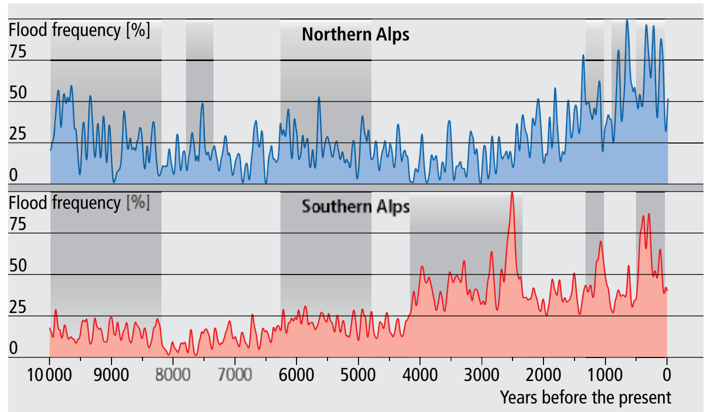


***Fig. 66:** Flood frequency in the northern Alps (10 lakes) and southern Alps (five lakes) during the last 10 000 years.[130]*

The flood of 1868 in lake sediments

The October flood of 1868 is clearly depicted in the sediments of the Pallanza Basin of Lake Maggiore and in Lake Silvaplana in the Engadin. In Lake Maggiore, the 12-mm-thick flood layer of 1868 is the thickest flood layer of the instrumental period. It can be found at approximately 71 cm depth in the sediment. The lake level was 6.94 m higher than average, and the source of sediments points towards the main origin of the flood in the Toce River and the Ossola Valley.[132] In Lake Silvaplana, the flood layer of 1868 is only 2 mm thick, and thereby clearly smaller than those of the floods of 1888 (4 mm) and, especially, the strong transregional flood of August 1834 (12 mm thick). There are also smaller floods recorded in Lake Silvaplana's sediments, including 1850, 1860, 1871, and 1874 (a total of nine floods between 1850 and 1900). These are all corroborated by local historical documents.[133] The transregional floods of February and September 1862 are missing in Lake Silvaplana, because – according to the documentation – precipitation fell as snow in the higher altitudes and thereby did not lead to high runoffs in the Fex Valley (main tributary to Lake Silvaplana).

On the northern side of the Alps, there are negative results for a flood layer of 1868 from southern Germany (Lake Ammersee), as well as from Toggenburg (Schwendi Lake), the Bernese Highlands (Lake Oeschinen), and the French Alps (Lac Blanc by Grenoble). In contrast, Lake Oeschinen has a strong record of the large floods of 1834, 1852, and 1860. The year 1868 is not exceptional.

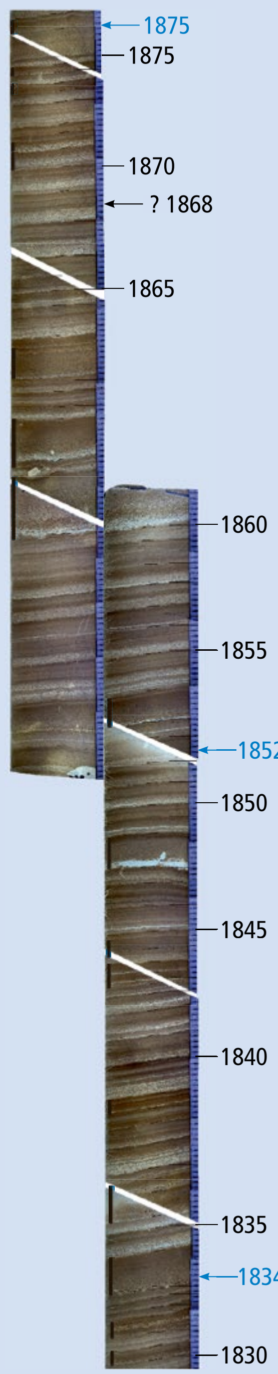


***Fig. 67:** Flood layers in Lake Oeschinen, 1830–1875.[128]*

Heavy precipitation and flooding since the start of measurements

The factors that contribute to the generation of flood events as outlined in this booklet can change over time. Water, land use, soil, and vegetation are changing, and settlement areas are expanding. Last but not least, the climate is changing. In the last 100 to 200 years, i.e. since systematic measurements have been carried out, changes in these factors have overlapped.

Changes in flood frequency

The long series of the maximum annual discharge of the Aare in Bern (Fig. 68) shows high peak discharges especially in the past 20 years. The five highest values – (in order) 1999, 2005 (see p. 8), 2015, 2007, and 2004 – all occurred in the past 20 years. Is this due to the influence of global warming? In fact, alpine rivers in particular are experiencing an increase in annual peak flows,[134] which can be attributed to higher temperatures and the resulting higher zero-degree line. European studies, in contrast, show that although the flood season has changed,[135] there was no general trend towards more floods.[136]

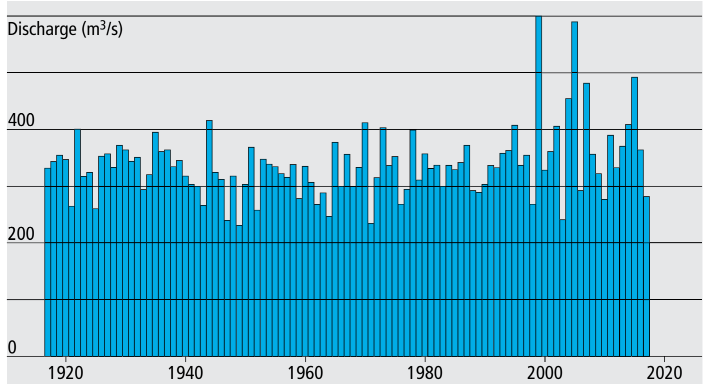


Fig. 68: *Annual maximum discharge of the Aare in Bern (Schönau): Trend or not? (Data: FOEN).*

Changes in heavy precipitation

How does climate change affect discharge peaks? In Switzerland, the temperature has increased by about 1.5 °C since 1900.[137] This directly affects the snow melt, which occurs earlier, and the snow-to-rain ratio (less snow and more rain in winter). Depending on the flow regime, this tends to dampen the annual course of the runoff.[138] For floods, however, this change plays only a minor role. Rather, the fact that warmer air can hold more water vapour than colder air, namely about seven per cent more per degree Celsius warming, becomes important. If all other factors remain constant, this should lead to stronger precipitation events. Although average precipitation in Switzerland has not increased significantly since 1901, the maximum annual rainfall increased at more than 90 per cent of Swiss stations between 1901 and 2014, typically by five to 20 per cent (Fig. 70). This corresponds well with the relationship expected from theory.[139] Heavy rainfall not only became more intense between 1901 and 2014, but also more frequent, at most sites by 10 to 50 per cent (Fig. 70). This means that events that occurred about three times a year at the beginning of the 20th century now occur about four times a year.

Decadal changes

In addition to long-term change, the climate also shows fluctuations on the scale of decades (see box). These are particularly pronounced for temperature. For instance, in Switzerland the 1940s were warm and the 1960s were cool. The frequency of flooding also shows fluctuations on a scale of decades (see p. 40). Flood-rich and flood-poor phases alternate. The cause for this variation is still unknown.[82] Particularly, floods were more frequent in the 19th century (cf. text on the right), which also led to political discussions, not only in Switzerland.[142] In contrast, the period between about 1920 and 1980 was rather poor in floods.[5] The post-war economic boom, suburbanisation and the expansion of settlement areas, and the construction of large infrastructure facilities also fell into this period.[143] Thus, during a period that was important for shaping present-day Switzerland, only a few floods occurred. With the floods of 1978 and 1987, a period of more frequent flooding began again (see p. 38).

Multi-decadal variability

Why are there fluctuations in the climate system over multiple decades? The reason for this is often sought in the ocean. On the one hand, oceans provide a huge heat storage, which smoothes short-term temperature fluctuations but returns the smoothed signal to the atmosphere over an extended time. On the other hand, the ocean itself is in motion and transports heat. Sea-surface temperatures fluctuate on time scales of decades and thus influence global climate. The two most important modes of sea-surface temperature variations are the Pacific Decadal Oscillation (PDO) and the Atlantic Multi-decadal Oscillation (AMO).

The PDO is closely linked to the El Niño phenomenon in the Pacific. If El Niño events occur frequently over a period of 20 or so years, this is the expression of a positive PDO. The AMO is nothing else than the average temperature of the North Atlantic, which shows pronounced multi-decadal fluctuations (Fig. 69). PDO and AMO influence global temperature. A negative PDO phase in the 2000s was largely responsible for the fact that global warming proceeded somewhat more slowly – and then abruptly accelerated again around 2015.

The AMO has an impact on Atlantic hurricanes, African and Indian monsoons, and also on heat waves and droughts in Europe.[140] The maximum phase of the AMO in the 1940s was accompanied by hot summers and devastating droughts in Central Europe – temperature records that were broken only in 2003.[141] Whether the AMO and PDO also affected heavy precipitation is not known. In general, decadal modes of variability can impact risk assessments. Observations from the past 30 years are often used as the basis for estimates for the next 30 years. Doing this with the AMO index, we would be systematically wrong (Fig. 69). This shows that one should either take decadal fluctuations into account or consider longer periods.

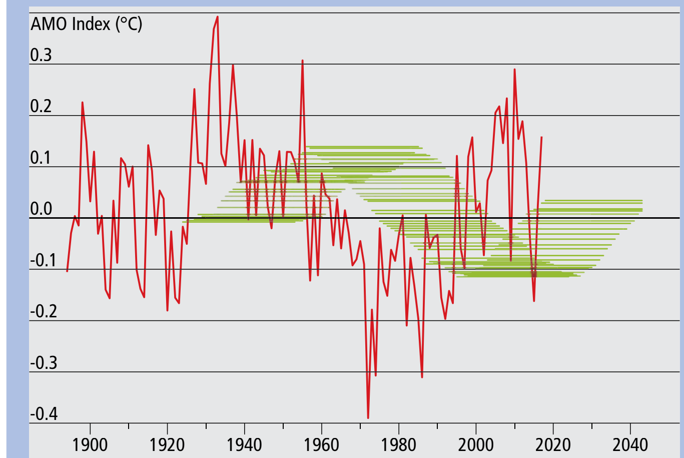


Fig. 69: *The AMO index (North Atlantic sea-surface temperature after subtracting the global mean, grey) and forecasts thereof (green), each using the mean of the previous 30 years as a forecast for the next 30 years.*

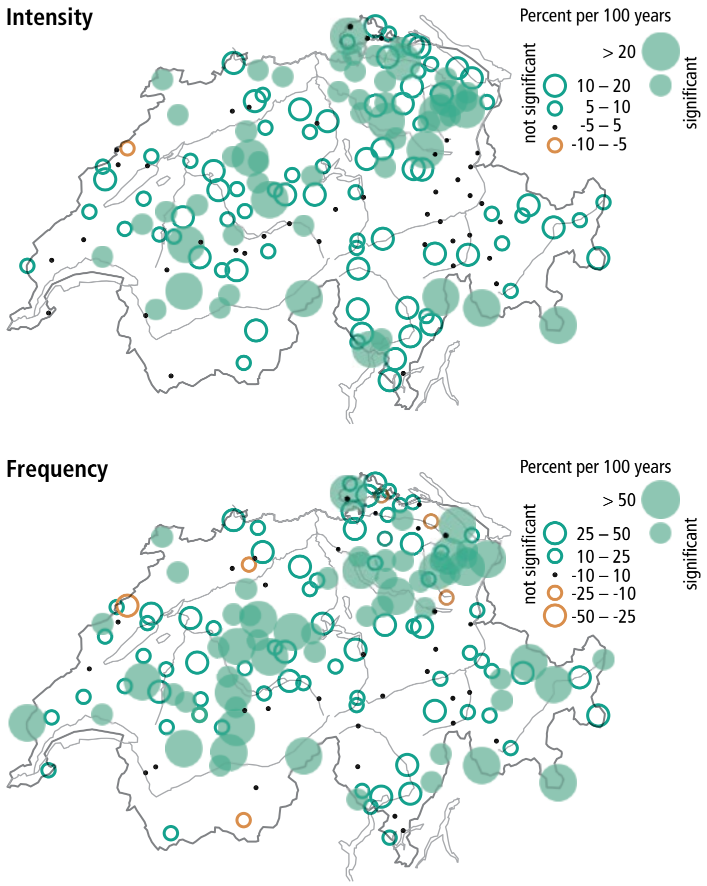


Fig. 70: *Trend (percentage per century) of intensity (top, annual maximum daily precipitation) and frequency (bottom, days exceeding the 99th percentile of daily precipitation) at MeteoSwiss stations, 1901–2014.*[139]

Fig. 71: *Concurrent with the 1950s economic boom, floods became rarer. A new lifestyle began, illustrated here with a photo of a campsite. Campsites were often built on areas at risk of flooding.*

Increasing frequency of floods in the 19th century

In 1834, the cantons of Valais, Graubünden, Ticino, Uri, and Glarus were hit by severe floods. In 1837, the Emmen Valley witnessed a centennial flood (see p. 13). In 1852, the Aare River reached its highest-ever level. Already after the floods of 1868, the notion spread that floods had become more frequent. Then further floods followed in 1876 (Fig. 72), 1881, and 1886.

What is the state of research on this question today? Was there an increased frequency of floods at all, or is this due to contemporary perception? And what was the cause? These questions are still relevant today, not only for the interpretation of past floods, but also for the assessment of future floods. If the frequency of floods has fluctuated in the past, it will likely continue to do so in the future.

The increased frequency of floods in the 19th century is a fact, although individual floods often only affected individual catchments (Fig. 73 shows peak discharge of the Rhine in Basel and the maximum lake levels of Lake Constance and Lake Maggiore).[32] This is at least partly due to atmospheric circulation changes. Flood-prone weather types (see p. 8) were more frequent in the 19th century than in the 20th century (Fig. 73). However, the cause for this remains unknown.

Fig. 72: *Flood in Schaffhausen, 1876.*

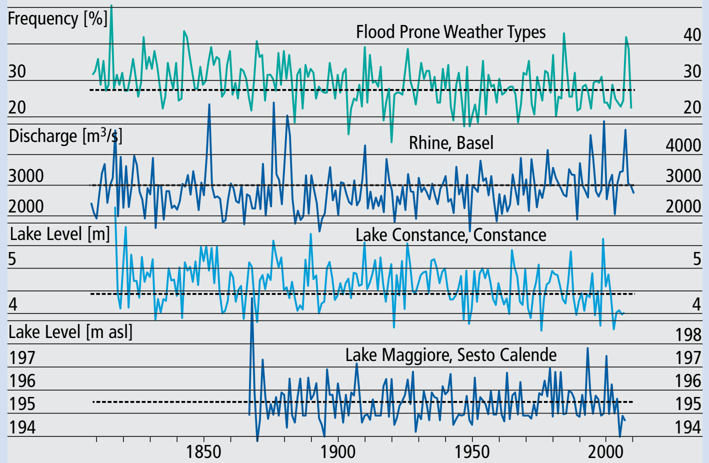


Fig. 73: *Annual maximum discharge of the Rhine in Basel and maximum lake levels of Lake Constance and Lake Maggiore.*[32] *The top line shows the frequency of weather types*[14] *"North, cyclonic" and "Westerly over Southern Europe, cyclonic" (May–October), which are typical for floods on the northern side of the Alps (dashed: mean 1951–2000).*

Flooding at the end of the 21st century

The change in the various factors influencing floods will continue, and flood frequency and damage will change. The extent to which these changes manifest themselves will depend on how people deal with the flood hazard in the future and intervene in river beds. It also depends on how land use develops, and on natural processes affecting soils and vegetation. The climate will certainly change fundamentally. Can we assess the consequences?

The future development of anthropogenic greenhouse gas emissions will play an important role. Depending on the political decisions we take, the additional warming will be stronger or weaker. In the event of strong global climate protection efforts, the global temperature rise at the end of the 21st century could be stabilised at 1.5 to 2 °C compared to the pre-industrial climate. In the event of a further increase in global greenhouse gas emissions, the global temperature is likely to increase by around 3.5 °C (compared with 1986–2005).[144] In the following, we will look at this latter scenario of a strong warming (IPCC scenario RCP8.5). What effects would a global rise in temperature have on precipitation and runoff in Switzerland?

On a regional scale, estimates of future climate developments are subject to great uncertainty. This applies in particular to precipitation, the correct simulation of which is also made difficult by an inadequate understanding of processes, for example in clouds. Although the rapidly increasing model resolutions enter an area that allows the explicit representation of convection and cloud formation, this development has is only just begun.[145]

Nevertheless, some of the changes can be predicted with greater certainty as they are closely linked to temperature. According to the Clausius-Clapeyron relation, saturation humidity will also increase sharply with a higher temperature. We have already established (see p. 10) that extreme moisture transport will be much stronger in the future. At the same time, the zero-degree limit will rise even further. This means, firstly, that more moisture will be available in the future for heavy precipitation, secondly, that precipitation will increasingly take the form of rain instead of snow, and thirdly, that snow will melt earlier in spring. In addition to these direct consequences of an increase in temperature, there are indirect effects of climate change, such as changes in atmospheric circulation (including changes in the frequency of flood-prone weather conditions). As a consequence, in Switzerland longer periods of drought are likely to be followed by short but heavy precipitation.

The most intense precipitation will continue to increase. As an example, Figure 74 shows the change in the maximum five-day precipitation over Europe in summer and winter, based on current regional climate simulations. The figure shows that maximum winter precipitation will become more intense in large parts of Europe. For the Alps, this increase is around 15 per cent. The maximum daily precipitation event per year will also increase. Figure 75 shows this for the Aare catchment area, determined here with statistical downscaling of global models (CMIP5). All simulations show a clear increase. At the same time, the seasonality of heavy precipitation will change. While the maximum daily precipitation in today's climate often occurs in late summer, the models project a shift into early summer or early autumn. Models that predict summer drying for the future show this effect more strongly. According to simulations, Vb cyclones, which today often occur in June and July, will shift into the months of May and September towards the end of the 21st century.[146] Furthermore, the climate simulations show that the number of such Vb events will decrease in the future and thus the frequency of this weather situation will be reduced in summer.

What does this mean for runoff and flooding? The runoff of the Rhine in Basel (Fig. 76) will be somewhat higher in winter in the future, while summer runoff will be lower due to summer drought. Peak discharges, which often occur in June, could be slightly stronger, while

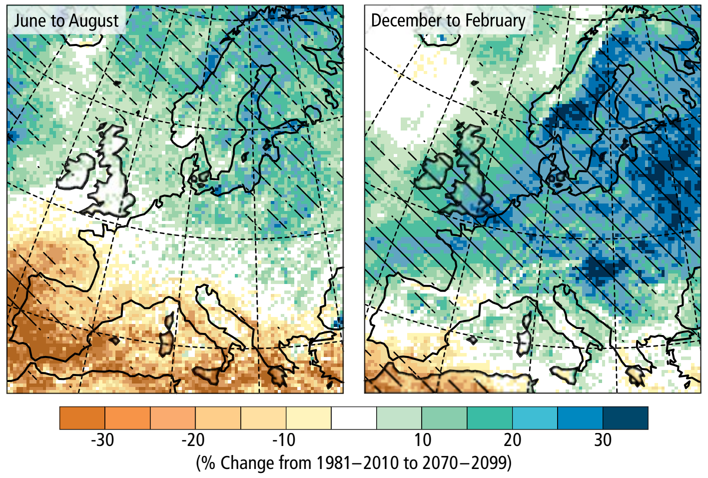


***Fig. 74:** Changes in the maximum five-day precipitation over Europe (in per cent) for winter and summer around 2070–2099 compared to today (1981–2010). Shown are the median changes over 15 regional climate models of Euro-CORDEX at a resolution of approx. 12 km.[147]*

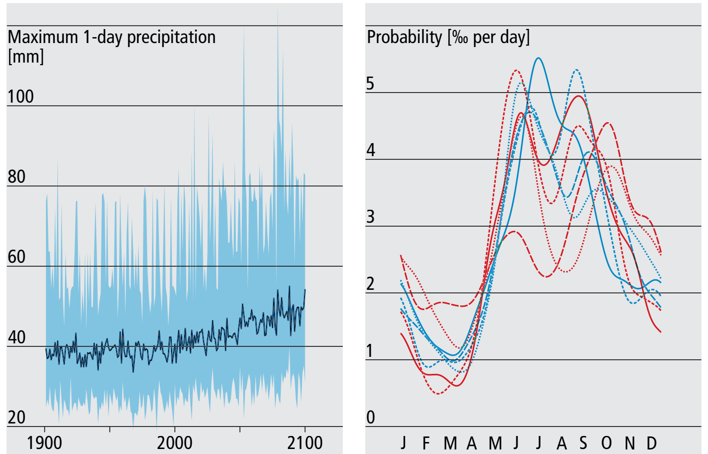


***Fig. 75:** Development of the maximum daily rainfall per year for the Aare catchment from the CMIP5 simulations (dark blue: mean value of all simulations, light blue: maxima and minima) (left). Calendar day of the maximum daily precipitation of a year in the present (1971–2005, blue) and the future (2065–2099, red; different lines represent different model ensembles) (right).[148]*

high-runoff events become significantly rarer in late summer. In catchments strongly influenced by glacier melting, the increasing melt will temporarily increase the runoff – until the glaciers have almost completely disappeared and the runoff caused by their melting decreases.

The National Centre for Climate Services (NCCS) is currently developing new climate scenarios for Switzerland (CH2018, *www.klimaszenarien.ch*). These will be published at the end of 2018 and form the basis for a series of climate impact studies. Based on this, new hydrological scenarios are also produced (Hydro-CH2018). In particular, these will also shed light on climate-related changes in the floods.

However, as we have seen in this report, many other factors contribute to floods and flood damage. In addition to the climate, the land surface will also change. Land use will continue to develop, and anthropogenic interventions in river beds and lake discharges are likely.

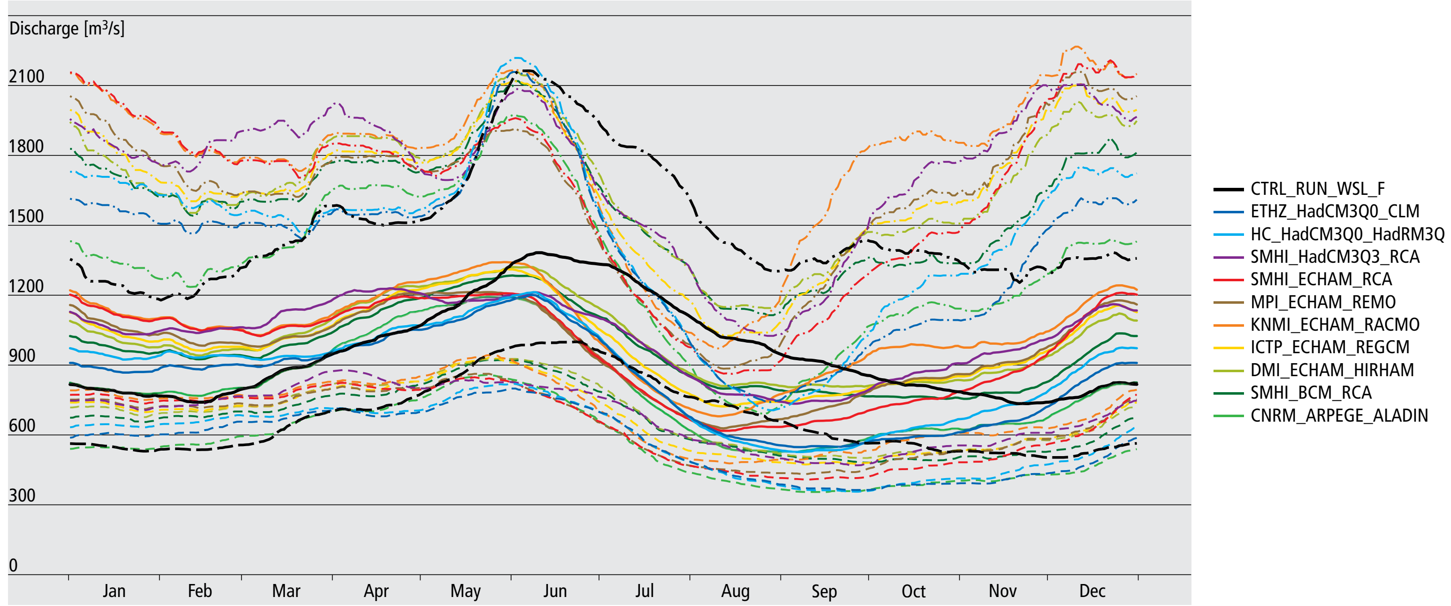


***Fig. 76:** Change in the runoff of the Rhine in Basel. Shown are the 10 per cent (dashed), 50 per cent (solid) and 90 per cent quantiles (dotted) for the control period (1980–2010, black) and for 10 climate scenarios (coloured) for the period around 2085.[149]*

Changes in the cultural landscape and its management, as well as the increasing ground sealing which is changing the runoff behaviour, must also be taken into account. Finally, the potential for damage is also changing.

As a simple illustration of possible future socio-economic changes and their effects, Figure 77 shows three scenarios for population development in Switzerland. The permanent resident population will increase to 9.4–11.0 million by 2045. This also increases the area required; depending on how contracted urban development takes place. Figure 78 shows one of four scenarios for settlement development in Switzerland; the outcome of a National Research Programme. In this scenario, the percentage increase in settlement area will be even higher than the increase in population.

At the same time, foresighted planning, careful mapping, and better designation of danger zones could counteract the spread of the settlement area into hazard areas. River engineering measures could improve the situation in some hazard areas. Damage could be reduced through better prevention and forecasting, but also through warning systems and better property protection. The knowledge is there. We have the future flood situation in Switzerland partly in our own hands. It is quite possible that – as in 1868 – individual flood events will trigger these necessary steps.

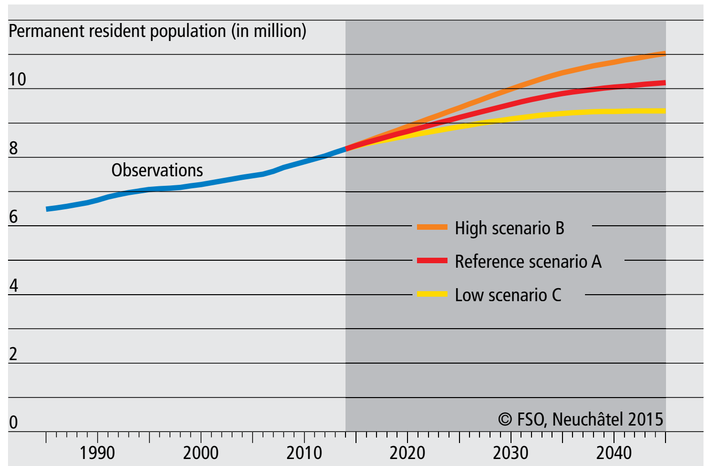


***Fig. 77:** Scenarios of population development in Switzerland up to 2045.[150]*

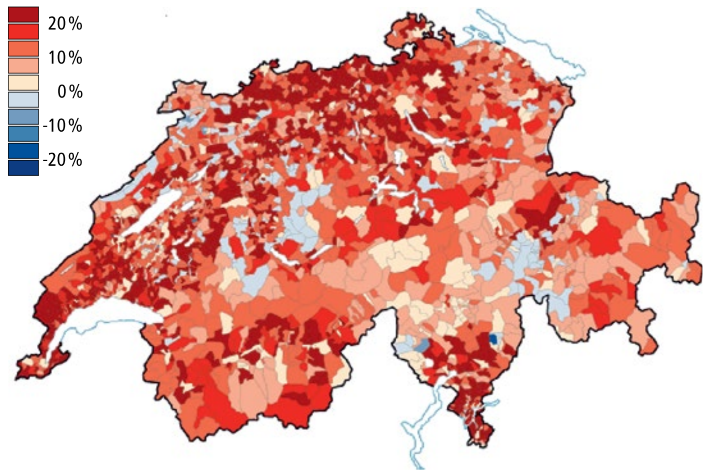


***Fig. 78:** Increase in settlement area from 2000 to 2030 according to Scenario B (metropolitan expansion) of settlement development in Switzerland.[151]*

Conclusions

In autumn 1868 – exactly 150 years ago – parts of Switzerland were affected by severe floods. Two phases of heavy rainfall on 27 and 28 September and from 1 to 5 October caused numerous rivers and lakes to overflow their banks. Coping with the enormous damage, managing the extensive donations, and finding a procedure of how to prevent such events in the future were a major challenge for the young nation. The discussions at that time set the course for the management of natural disasters during the 20th century, affecting today's landscape.

Today, new methods allow the detailed reconstruction of precipitation events and floods, while, from a historical point of view, flood management and the socio-political effects can be evaluated. An interdisciplinary research project (of the Oeschger Centre for Climate Research at the University of Bern and the Mobiliar Lab for Natural Risks, in cooperation with MeteoSwiss, Meteotest and the Swiss Federal Institute for Forest, Snow and Landscape Research) has investigated these questions over the past two years. The meteorological background of the event is understood and can be reconstructed quite well on a large scale. The local weather situation and the embedded thunderstorms can also be depicted. Natural-hazard research today often uses model chains to reproduce natural events and their consequences. If successful, the role of individual factors can then be addressed. This is also possible for the flood that occurred 150 years ago. The hydrological modelling shows that due to the erosion that occurred during this event, such a high level of Lake Maggiore as in 1868 could no longer be reached today. Finally, hydraulic modelling is able to depict the flooded area and the endangered buildings, with and without river construction, for historical and present day building distributions. Such simulations are important and instructive to assess triggering factors and to better understand the flood event using "what-if" scenarios. The assessment of damage shows that long-term effects must also be taken into account. Analysis of flood management and of the consequences of floods show how the Confederation and the cantons had to organise themselves, and how further measures were initiated. It is particularly important to account for the social and political environment in which a flood event fell, such as that of 1868. Depending on this environment, a flood event can trigger a rethinking or even paradigm shift at the political level and set a new course for flood management in the long term.

The severe floods of 1868 continue to have an effect today on settlement areas, river constructions, and mountain forests – Switzerland would look different without this historical event. At the same time, those floods allowed society to prepare for the future and how to deal with new types of floods. With the increase in precipitation intensity as a result of climate change, we will probably face new challenges. Probably it will again be individual future events that will lead to the adoption of approaches to flood protection, and thus contribute to shape Switzerland's landscape of the future.

Fig. 79: *Flooding at Lake Lucerne, 2005.*

Endnotes

1 Map of the locations mentioned in the text.

2 The research underlying this report was funded by the Oeschger Centre for CLimate Change Research, University of Bern, the Swiss National Science Foundation (projects EXTRA-LARGE and CHIMES) and the Federal Office for the Environment (project EXAR).

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Fig. 63: Expertenbericht von Leopold Blotnitzky und Friedrich Wilhelm Hartmann, Juni 1863, in Schweizerisches Bundesarchiv, Signatur E 19 1443 (left); Bundesamt für Wasserwirtschaft (Hg.): Hochwasserschutz an Fliessgewässern. Wegleitung 1982. Bern 1982, 18 (right).

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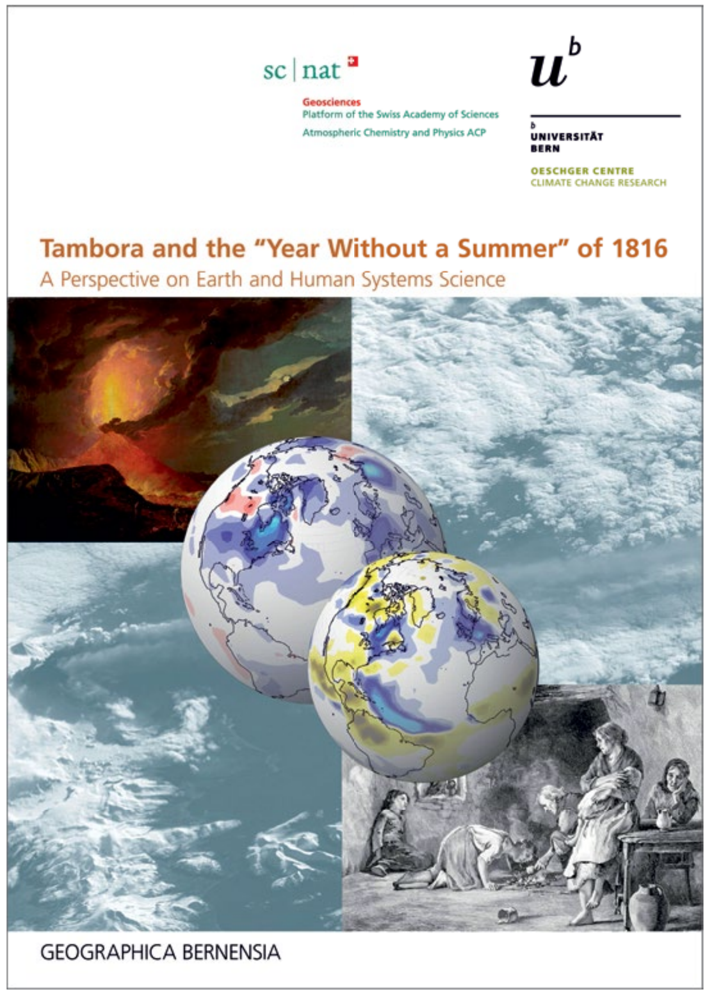

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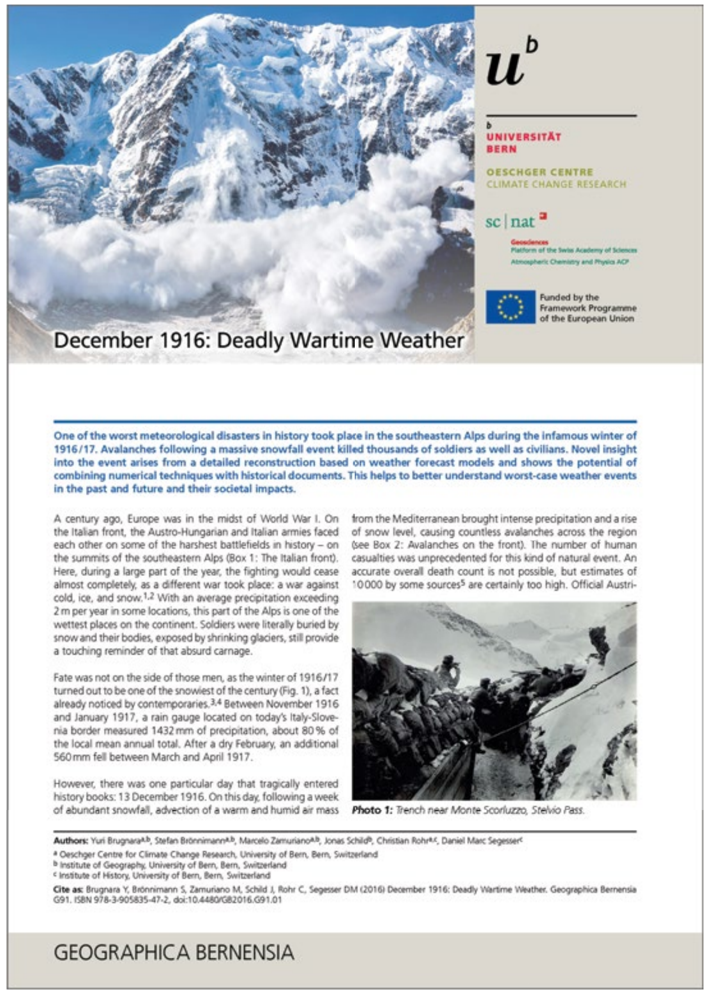

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December 1916: Deadly Wartime Weather

One of the worst meteorological disasters in history took place in the southeastern Alps during the infamous winter of 1916/17. Avalanches following a massive snowfall event killed thousands of soldiers as well as civilians. Novel insight into the event arises from a detailed reconstruction based on weather forecast models and shows the potential of combining numerical techniques with historical documents. This helps to better understand worst-case weather events in the past and future and their societal impacts.

A century ago, Europe was in the midst of World War I. On the Italian front, the Austro-Hungarian and Italian armies faced each other on some of the harshest battlefields in history – on the summits of the southeastern Alps (Box 1: The Italian front). Here, during a large part of the year, the fighting would cease almost completely, as a different war took place: a war against cold, ice, and snow.[1,2] With an average precipitation exceeding 2 m per year in some locations, this part of the Alps is one of the wettest places on the continent. Soldiers were literally buried by snow and their bodies, exposed by shrinking glaciers, still provide a touching reminder of that absurd carnage.

Fate was not on the side of those men, as the winter of 1916/17 turned out to be one of the snowiest of the century (Fig. 1), a fact already noticed by contemporaries.[3,4] Between November 1916 and January 1917, a rain gauge located on today's Italy-Slovenia border measured 1432 mm of precipitation, about 80 % of the local mean annual total. After a dry February, an additional 560 mm fell between March and April 1917.

However, there was one particular day that tragically entered history books: 13 December 1916. On this day, following a week of abundant snowfall, advection of a warm and humid air mass from the Mediterranean brought intense precipitation and a rise of snow level, causing countless avalanches across the region (see Box 2: Avalanches on the front). The number of human casualties was unprecedented for this kind of natural event. An accurate overall death count is not possible, but estimates of 10 000 by some sources[5] are certainly too high. Official Austri-

Photo 1: *Trench near Monte Scorluzzo, Stelvio Pass.*

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