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How is the hazard landscape changing in Swiss cities and how do they adapt: The case of Basel

GEO 511 Master's Thesis

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Abstract

Compared to preindustrial times, global surface temperature has increased, in Switzerland more pronounced than in other countries with the strongest increase since the 1980s. Previous research showed that as a result of climate change, both individual natural hazards and compound risks will increase in Central Europe, especially in relation to water bodies. Swiss waters will be subject to changes in the quantity and pattern of runoff that can lead to either hydrological droughts or floods, thus an increase of frequency and persistence of related hazards has to be expected. Simultaneously, urban population is growing but also changing, for example towards higher life expectancy, which results in an increasing exposure and vulnerability. While this means a greater overall future risk for the urban population and infrastructure, adaptation measures are all the more important. As these must be tailored to local conditions and risks, within this thesis past and future hazards, impacts and adaptations are examined on the basis of the Basel case study. This is achieved by using multiple methods, which subsequently lead to a more complete picture of the complex urban interdependencies using the triangulation approach. The methods include a literature review, surveying the situation especially in Central European cities and an examination of the SFLDD (WSL) and reported impacts of the two focus events in 2018 and 2021 in newspapers. Furthermore, measured (FOEN, MeteoSwiss) and modelled (Hydro-CH2018) hydrological and meteorological data are statistically examined, especially with regard to long-lasting extreme events. Lastly, semi-structured interviews with experts from relevant fields contribute to an even more holistic view. The results showed that extreme high flow events on the Rhine in Basel have moderately increased since 1900, but their number will remain stable at a slightly higher level in future. Resulting impacts of the focus event 2021 as well as adaptation measures mainly refer to the direct watercourse area. Extreme low flow events used to occur mainly in winter and show a clear decreasing trend since 1900. Hydro-CH2018 indicates a reversal of this development towards an increase, the extent of which depends on the scenario, and at the same time a seasonal shift of these events to summer and autumn. The impacts occurring during the focus event 2018, a year hit by severe hydrological drought, were already under the simultaneous influence of heat and therefore not limited to the watercourse area but present in the entire city. An intensification, interconnection and larger spatial spread of the impacts of drought due to the simultaneously occurring hazard of extreme heat can be assumed for the city of Basel in the future. As a result of the opposing, not mutually exclusive but alternating risks of flood and drought, adaptations are necessary in particular those covering several risks. The canton of Basel-Stadt is already implementing or planning numerous adaptation measures, including some addressing multiple risks, but focusing on the areas of physical infrastructure and nature-based solutions. Therefore, for the future development of adaptation in the city of Basel, there is a potential in the inclusion of social measures, such as communication strategies or the promotion of adaptation at the individual level. As policy in Basel has been more responsive to flood focus events, it is important to continue to raise awareness of the alternating and increasing occurrence of droughts. This could be supported with a similar database on drought impacts and damages as it already exists on floods and mass movements (SFLDD, WSL).

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- My family and friends for their motivating words.

List of abbreviations

AG	Aktiengesellschaft
BAFU	Bundesamt für Umwelt (Engl.: Federal Office for the Environment FOEN)
BS	Canton of Basel-Stadt
°C	Degrees Celsius
CHF	Swiss Francs
CI	Confidence Interval
CMIP5	Coupled Model Inter-comparison Project Phase 5
DSI	Drought Severity Index
EEA	European Environment Agency
EUR	Euros
FDFA	Federal Department of Foreign Affairs
FOEN	Federal Office for the Environment
HQ_{10}	Ten-year flood
HQ_{100}	One-hundred-year flood
HQ_{300}	Three-hundred-year flood
IPCC	Intergovernmental Panel on Climate Change
IWB	Industrielle Werke Basel
MHD	Maximum Historical Drought Severity Index
NA	Not available
NCCS	Swiss National Centre for Climate Services
RCP	Representative concentration pathway
SFLDD	Swiss flood and landslide damage database
UN-Habitat	United Nations Human Settlements Programme
UTC	Coordinated Universal Time
WG	Working Group
WSL	Eidgenössische Forschungsanstalt für Wald, Schnee und Landschaft (Engl.: Swiss federal Institute for Forest, Snow and Landscape Research)

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1. Introduction

1.1. Motivation

Urban areas are home to a large proportion of people, this is also true for Switzerland where 85% of the population lives in cities (Federal Department of Foreign Affairs FDFA, 2021). At the same time, weather and climate-related extreme events are increasingly observed and projected to be more frequent and intense in the future (NCCS (Publ.), 2021b; Ranasinghe et al., 2021 in press). These natural hazards also affect urban areas, which are even more exposed and vulnerable to them due to factors such as population growth, urban densification, soil sealing, and concentration of assets and economic activities (Skougaard Kaspersen et al., 2017). In the case of lack of adaptation to changing climate thus not only results in all the greater risks, but also costs. Or to put it in the words of John F. Kennedy: "There are risks and costs to action. But they are far less than the long-range risks of comfortable inaction" (cited in Nicklin et al., 2019, p. 15).

While Europe's south will have to expect an increase in heat waves and dry periods in the future, heavy rainfall and consequently flooding will increase in the north (Guerreiro et al., 2018b). Switzerland, lying in between, will be affected by both extremes (NCCS (Publ.), 2018). These trends have already been observed in recent years: In 2017, southern Europe was affected by extreme heat, 2018 was extreme hot near the arctic circle, and in 2019 occurred a record-breaking heatwave over western Europe, all of which would occur much less frequently without climate change. Conversely, there was the wettest December in the United Kingdom in 2015, rainstorms over France in 2016, and most recently heavy rainfall and severe floods in Germany and throughout Western Europe in 2021, all of which have increased in frequency since pre-industrial times (World Weather Attribution, 2021). The economic losses from climate-related extremes in Europe in the last decade (2011-2020) amounted to EUR 14.5 billion. While the costs vary greatly from country to country, Switzerland recorded the highest costs per capita and per area (European Environment Agency, 2022). Without measures, further increases in costs are predicted (Nicklin et al., 2019).

The city of Basel has also been affected by extreme events in recent years, in particular a long dry and hot period in 2018 and prolonged flooding in 2021, both attributed to climate change (World Weather Attribution, 2021) and predicted to occur more frequently in the future (NCCS (Publ.), 2021b). These two events not only show that climate change is already having an impact on the city of Basel, but also that many systems are interlinked in urban areas, making impacts all the more complex and request for more widespread adaptations.

To explore this in greater depth, the NCCS provides climate projections for Switzerland, with the Hydro-CH2018 dataset incorporating the latest climate scenarios to evaluate the effect of climate change on Swiss hydrology (NCCS (Publ.), 2021b)

Within the framework of a three-year research project, the FOEN, together with the University of Fribourg and the University of Zurich, is investigating combined extreme events, analysing their process chains and possible impacts, and evaluating them with a view to adaptation measures. The thematic focus is on long-lasting and large-scale heat periods and drought in summer, which is investigated on the basis of the case study of the city of Basel (Muccione et al., in prep.).

The present thesis deepens the study of dry periods in Basel on the basis of the year 2018 and with regard to hydrological droughts of the river Rhine. The analysis is supplemented by the flood event of the year 2021, thus the thesis sets a second focus on river floods and considers both, extreme high and low flow events on the Rhine at Basel. By using several methods, it contributes to the adaptation to these contrasting, but not mutually exclusive natural hazards driven by river discharge and amplified by climate change.

1.2. Study area

The city of Basel is located in the northwest of Switzerland, bordering Germany and France. In addition to the city itself, which makes up two-thirds of the cantons area, the two municipalities of Riehen and Bettingen also constitute part of the canton Basel-Stadt (Statistisches Amt des Kantons Basel-Stadt (Publ.), 2021a). The Rhine flows through the middle of the city of Basel. Its catchment area is complex, consisting of one third each of the tributary of the Aare and that of Lake Constance, with the remaining tributary divided between the Reuss, Limmat and Thur rivers (Scherrer et al., 2006). In the city area, the smaller rivers Birs, Birsig and Wiese flow into the Rhine (see Figure 1).

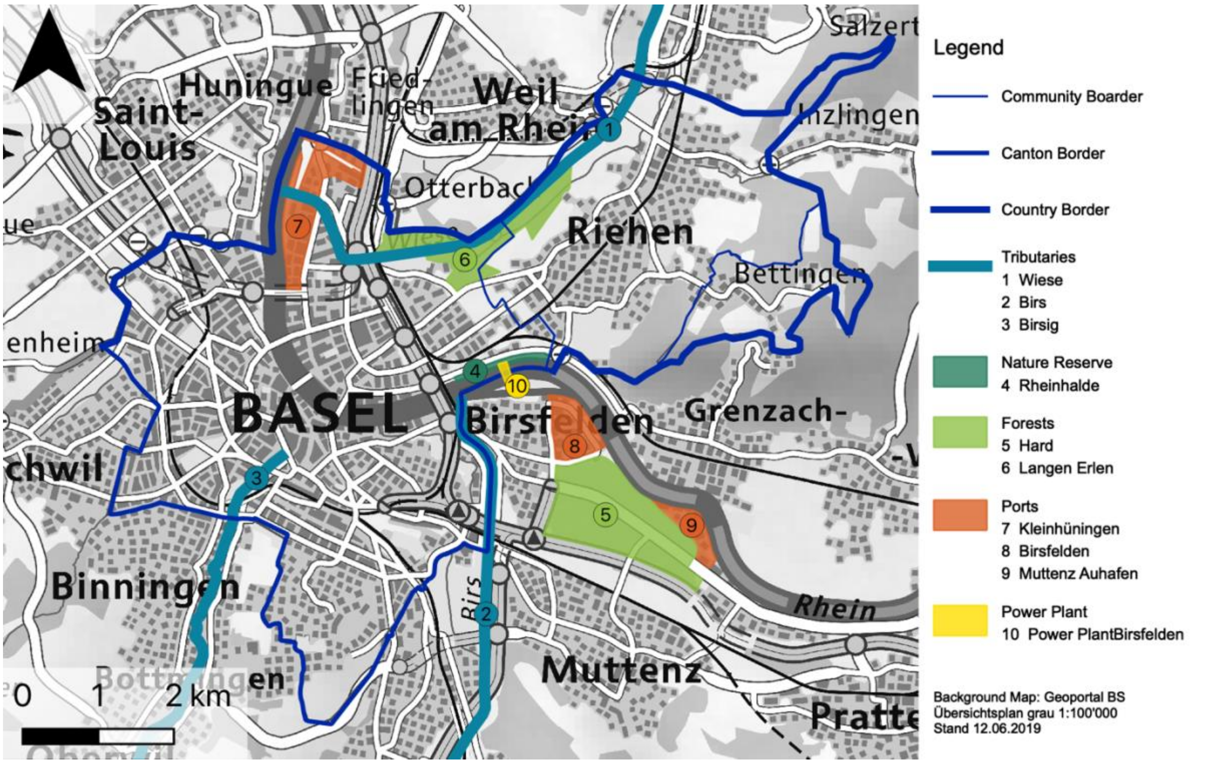


Figure 1 Overview map study area Basel (own illustration based on Grundbuch- und Vermessungsamt Kanton Basel-Stadt (2019))

The Rhine fulfils important economic, ecological and social functions both at the local level and with national impacts. For the drinking water supply of the Basel region, the Rhine water is treated in several steps including sand filter, forest ground and activated carbon filter at two locations, in the Hardwald and in the Lange Erlen (Industrielle Werke Basel IWB, 2020). Furthermore, the Rhine with its three ports Basel-Kleinhüningen, Birsfelden and Muttenz Auhafen is relevant for cargo handling. Around 10 percent of Swiss imports and one third of the mineral oil for Switzerland are trans-shipped in Basel (Port of Switzerland, 2018b). Basel's water bodies as well as their banks and the adjacent Hardwald and Lange Erlen forests provide a habitat for numerous species and contribute to biodiversity and the urban climate (Baudepartement des Kantons Basel-Stadt, 2008). This also makes the water space attractive, both as a tourist destination and as a local recreation area for the population, which has a strong connection to the river. Meeting on the Rhine, being involved in water sports clubs or swimming down the Rhine in summer are among the important cultural practices (Inauen & Kuhn, 2016). Thus, the Rhine in Basel is an intensely used water body and central element for a wide range of ecosystem services, the maintenance of which is elementary for life in the city.

So far, climate change in the canton of Basel-Stadt has been similar to that observed for Switzerland as a whole, with a temperature increase of 2.1°C compared to preindustrial times, which is minimally higher than the 2°C warming in Switzerland (NCCS (Publ.), 2021a). Based on the emission scenario RCP8.5, a temperature increase of +2.3°C is assumed for the canton of Basel-Stadt until the period 2060 (see Figure 2). At the same time, it is assumed for this scenario at the meteorological measuring station in Binningen that the dry periods will increase by +2.1 days especially in summer, the temperature on the hottest day of the year will be +3.5°C higher, and one-day precipitation will increase strongest in winter but overall by +8.9% (NCCS (Publ.), 2021a).

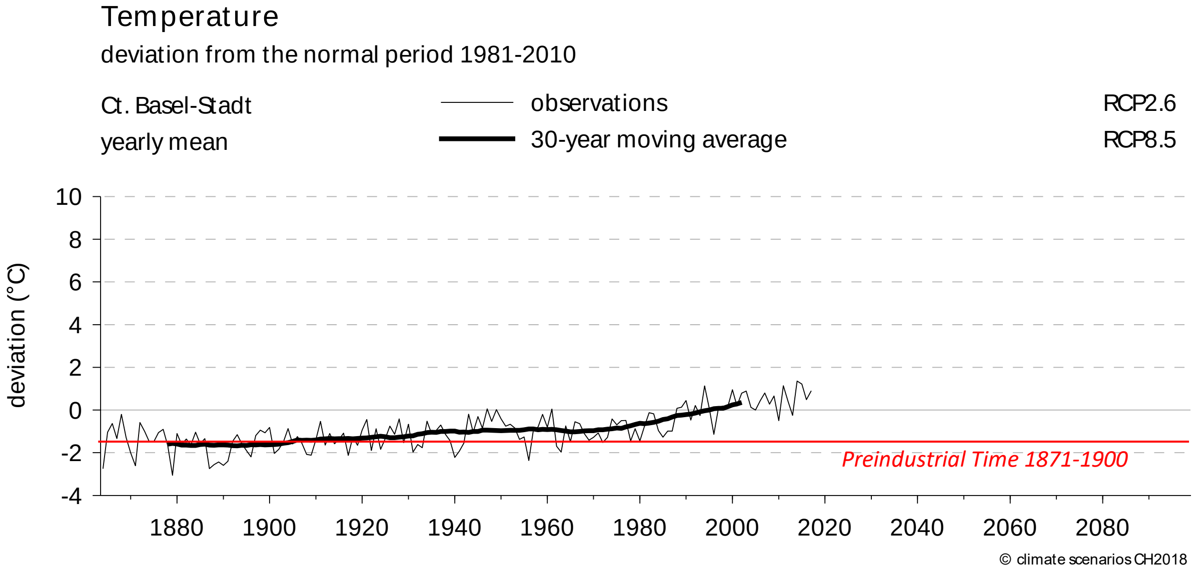


Figure 2 Observed and expected temperature trends in the canton of Basel-Stadt. The temperature is indicated as deviation from the mean of the standard period (1981-2010), from which on the projections for two emission scenarios (RCP2.6 blue and RCP8.5 red) including uncertainty range are shown. The preindustrial (1971-1900) temperature in Basel is added in red, illustration from NCCS (Publ., 2021a, 2021c).

More people are likely to be affected by these future changes, as according to the canton's development scenario, the population will increase by 11% (medium scenario) and 29% (high scenario) respectively by 2045, with the strongest increase taking place in the "Kleinbasel" quarter in both scenarios. The medium scenario assumes a continuation of the development observed in the past years. The high scenario is related to a clearly positive economic development, high attractiveness of the city for employees and employers as well as strong construction activity. New areas will be developed for living space, as well as existing areas will be used more condensed. According to Statistisches Amt des Kantons Basel-Stadt (Publ., 2021b), many construction projects are foreseeable for the next ten years. The low scenario with slightly decreasing population figures is assigned a low probability of occurrence (Statistisches Amt des Kantons Basel-Stadt (Publ.), 2021b).

According to the scenarios of Statistisches Amt des Kantons Basel-Stadt (Publ., 2021b) the population structure will also change. All three scenarios assume increasing life expectancy, with both the number of people over 65 and over 80 increasing. Despite a rising old-age dependency ratio and more people over 65 in absolute numbers than today, Basel will still be one of the youngest cantons in Switzerland in 2054. While living space consumption per person is stagnant or increasing, depending on the scenario, international migration is positive in all three scenarios (Statistisches Amt des Kantons Basel-Stadt (Publ.), 2021b).

1.3. Problem description and research questions

In the report "Climate-related risks and opportunities" (Köllner et al., 2017), the FOEN formulates the goal of closing knowledge gaps. This is to be done beyond the development of the climate and to help identify risks earlier, to better understand possible event progressions and options for action, and to be able to take targeted countermeasures. There is a particular need for research into the impact of climate change and extreme events on natural and socioeconomic systems. Thereby, so-called wildcards are difficult to quantify with current methods, since they occur surprisingly and have potentially far-reaching consequences. Wildcards are closely linked to systemic risks. These are "chains of effects of other processes, activities and events in nature, society and the economy" (translated according to Köllner et al., 2017, p. 104) whose probability of occurrence and extent of damage are difficult to assess. It is possible that their processes occur non-linearly, have cascade effects or lead to secondary and tertiary damage in other, linked systems (Köllner et al., 2017), which are numerous in the closely interconnected urban area.

In order to understand the multiple and interconnected process chains, to identify interrelationships and potential hazards, a multi-method approach was chosen to study high and low flow events of the Rhine at Basel. The aim of the thesis is to combine the results of different methods with a triangulation approach to gain a more holistic picture of the potential risks of extreme events and possible adaptation measures and thus also to uncover previously unrecognized or uncertain connections, so-called blind spots. Combining knowledge from other European cities with impacts in Basel of the events 2018 and 2021, expert knowledge on these events, current adaptation strategies and conceivable future impacts, and historical and future data allows to expand the boundaries of the individual methods and to develop a scenario-like thinking to describe plausible development paths and to identify associated risks and evaluate adaptation options.

In the canton of Basel-Stadt, the question, to what challenges arise for this area, which is characterized by urbanity and strong interaction with the water space was processed and answered with a report on local adaptation to climate change (Departement für Wirtschaft Soziales und Umwelt (Publ.), 2021), which on the one hand identifies many problem areas and proposes adaptations, but on the other hand does not address extreme events, combined risks and interactions, which are however predicted to increase in the future (NCCS (Publ.), 2018, 2021b) and identified as research gaps (Köllner et al., 2017).

Based on this research gap of existing and future extreme events, their impacts and possible adaptations in the urban area of Basel, the following research questions arise, which will be answered within the framework of the present thesis:

I. What is the current state of knowledge on climate change and water extremes in European cities?
II. What can we learn from recent water extremes, especially 2018 and 2021, in Swiss cities and Basel in particular?
III. What are the current risk management strategies?
IV. How do flow regimes change under future climate change and how can the city adapt to it?

2. Theoretical background

2.1. Climate development and Swiss water bodies

Compared to pre-industrial times, global warming driven by emissions from human activities can be observed. Comparing the period 2011-2020 with 1850-1900, global surface temperature has increased by 1.09°C, with a greater temperature increase over land than over the ocean (IPCC, 2021). The average annual temperature in Switzerland has increased by 2°C from 1864 to 2021, with the largest changes occurring since the 1980s (Federal Office of Meteorology and Climatology MeteoSwiss, 2022). Switzerland is thus more affected by climate change than the global average, whereby this can only partly be explained by land-ocean contrast and polar amplification (Bundesamt für Meteorologie und Klimatologie MeteoSchweiz, 2016).

In order to assess the consequences of climate change for Switzerland, the NCCS has developed the CH2018 climate scenarios, based on 21 different computer models. Whereas the starting point of the simulations was the reference period 1981-2010, the simulated data reach up to the year 2099 and cover the three different climate scenarios described in Table 1 (NCCS (Publ.), 2018).

Table 1 Overview of the climate scenarios in CH2018. The number of the RCP scenario indicates the expected radiative forcing in W/m² in the year 2100 compared to the year 1850 (NCCS (Publ.), 2018a, 2018b).

RCP	Mitigation Measures	Impacts
RCP2.6	Immediate reduction of emissions to virtually zero.	The increase in greenhouse gases will be halted in about 20 years, this enables the global warming to be kept to 2°C compared to pre-industrial times.
RCP4.5	Limited mitigation measures lead to a decrease in greenhouse gas emissions.	Greenhouse gas emissions increase over another 50 years, the 2°C limit target is not achieved.
RCP8.5	No implementation of mitigation measures.	Climate-influencing emissions and therefore global warming continually increase.

The national trend across all scenarios shows a development towards drier summers, heavier precipitation, more heat days and winters with less snow. Switzerland is under the influence of both the Mediterranean region, which will experience increasing summer drought, and northern Europe, which will be affected by an increase in heavy and extreme precipitation and floods. For Switzerland, stronger extremes are predicted in both directions (NCCS (Publ.), 2018).

These climate changes will also affect Swiss water bodies. With the reduced relevance of snowfall and glaciers as reservoirs for precipitation, the runoff in summer will decrease, and the one in winter will increase. While the annual runoff will decrease only slightly, the pattern of the runoff will change in particular. This and the more frequent and longer dry periods result in water shortages in summer. These are further aggravated by the higher evaporation and the increased water consumption of the population. the hazard potential will also increase in that precipitation events will become more frequent and heavier. High water-levels, landslides, and flooding are the consequences. Especially in summer, aquatic life will be at risk due to raised water temperatures and low water levels (NCCS (Publ.), 2021b).

With a worldwide reduction of greenhouse gas emissions, half of the climate changes could be avoided in Switzerland by the middle of the 21st century and two-thirds by the end of the 21st century (NCCS (Publ.), 2018), thus also reducing the pressure on Swiss water bodies (NCCS

(Publ.), 2021b). Nevertheless, temperatures would continue to rise – in Switzerland more than the global average (NCCS (Publ.), 2018) – and thus cause implications for the human use of the waters. In order to ensure that Swiss waters can continue to perform their multiple functions such as drinking water abstraction, electricity generation or cooling without the conflict of an overloaded ecosystem, the federal strategy is to make the waters more resilient (NCCS (Publ.), 2021b).

2.2. Definition of Drought and Flood

In literature droughts are defined as a temporary water deficit (van Loon et al., 2016) and thus as a period of reduced water availability (Paton et al., 2021) compared to normal conditions (Forzieri et al., 2014; van Loon et al., 2016). On the one hand, dry periods occur naturally in the water cycle and reflect the complex interactions of meteorological anomalies, climatic factors, and land surface processes (Forzieri et al., 2014; van Loon et al., 2016). At the same time, these processes are increasingly dependent on humans, for example through changes in inflows, outflows, and storage changes (van Loon et al., 2016). Regardless of whether the drought is due to single causes or multiple drivers (van Loon et al., 2016), they are associated with negative impacts on vegetation and agricultural production and are characterized by reduced streamflow, low groundwater recharge rates, and therefore water supply problems (Paton et al., 2021). Since society is strongly intertwined with the natural process, their feedback may have further effects on the water deficit and propagate or even cause droughts in the absence of natural drivers. Therefore, van Loon et al. (2016) recommend not to consider this exclusively as an external natural hazard and consequently not to consider the consequences separately from the causes (van Loon et al., 2016).

According to Paton et al. (2021) and van Loon et al. (2016), droughts are classified into the following three categories, based on natural processes:

- **Meteorological droughts**: These describe periods of rainfall deficit and thus below-average precipitation.
- **Hydrological droughts**: They are characterized by periods with below-average runoff in surface or subsurface waters.
- **Agricultural or soil moisture droughts**: They take place during the growing season and are characterized by below-normal soil moisture availability in agricultural areas combined with high evaporation levels. This form of drought leads to crop losses.

The normal or average value is usually understood as a quantile of the corresponding variable. From this, the magnitude of the drought in terms of the deficit volume or its duration can be calculated (van Loon et al., 2016). In this subdivision of droughts related to natural processes, human processes can be included by studying the cause of the dry period and thus distinguishing between climate-induced and human-induced drought (van Loon et al., 2016), as done by World Weather Attribution (2018) (see Chapter 2.4.1). To account for the potentially large influence of humans on the emergence and modification of drought, (van Loon et al., 2016, p. 3635) additionally suggest the term "human-modified drought”, whereby anthropogenic processes can not only aggravate but also alleviate the drought. For this extended definition, van Loon et al. (2016) leave out anthropogenic influence in the form of climate change but refer to direct human influence on the hydrological cycle, such as water abstraction, irrigation or land use change.

Analogous to the definition of drought, floods are also divided into types (Nicklin et al., 2019) on the basis of natural conditions as follows:

- **River or fluvial floods**: Caused by extreme river discharges (Rojas et al., 2013).
- **Pluvial floods**: Caused by meteorological events of severe rainstorms, they are characterized by unpredictable locations and extent. When these intense and highly localized rainfall events occur very rapidly, urban flash flooding can result, especially in landscapes with steep topography (Penning-Rowsell & Korndewal, 2019).
- **Coastal floods**: Caused by high sea levels and increased by storm surges and tidal changes, this type of flood occurs along the coastline (European Environment Agency, 2021).
- **Groundwater floods**: This flooding is characterized by the rise of groundwater to the earth's surface at a spatial distance from perennial river courses, where groundwater can also infiltrate buildings and other infrastructure (MacDonald et al., 2012).

Nicklin et al. (2019) emphasize that these different flood types require different techniques to cope with and to be prepared. Here, too, a distinction can be made in the cause of the event between climate-driven physical causes and socio-economic factors (Rojas et al., 2013). Van Loon et al. (2016) suggest adding anthropogenic influence on the definitions in the typology of floods as well – analogous to their extended definition of drought. Again, leaving anthropogenic climate change aside, direct influence on the (urban) hydrological cycle, such as soil sealing or drainage systems, could be mentioned here as a human influence (Skougaard Kaspersen et al., 2017).

2.3. Definition of Risk and Adaptation

In the context of the sixth IPCC report the concept of risks from climate change was expanded and refined. **Risk** is defined as “potential for adverse consequences for human or ecological systems, recognizing the diversity of values and objectives associated with such systems” (Chen et al., 2021, p. 64 in press). Risks arise not only directly from climate change impacts, but possibly also from human responses to climate change (Chen et al., 2021 in press), called maladaptation (IPCC, 2022 in press).

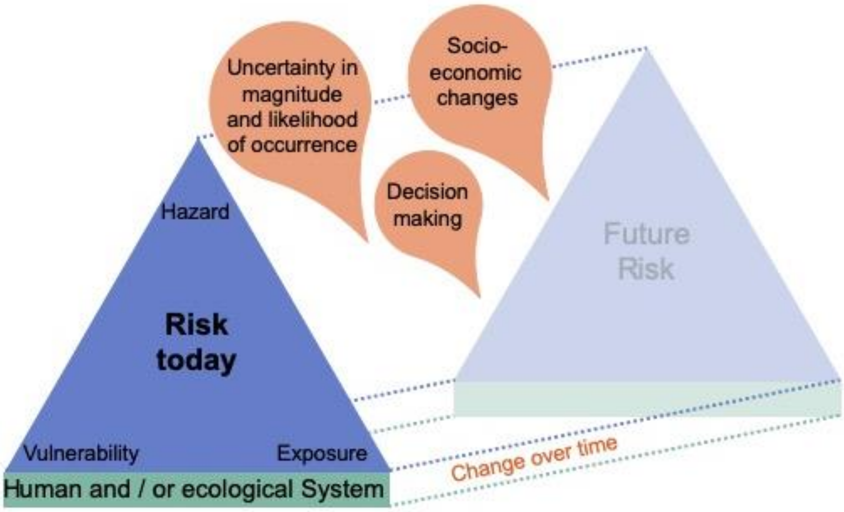


Figure 3 Concept of risk due to climate change impacts. Visualization according to Chen et al. (2021 in press).

To define risk due to climate change, the following concepts are relevant:

- **Exposure** is defined as “the presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected” (Chen et al., 2021, p. 64 in press).
- **Vulnerability** is defined as “the propensity or predisposition to be adversely affected” (Chen et al., 2021, p. 64 in press), where “susceptibility to harm and lack of ability to cope and adapt” (Chen et al., 2021, p. 64 in press) are also meant. Vulnerability differs “within communities and across societies, regions and countries, also changing through time” (IPCC, 2022, p. 5 in press).
- **Hazard** is defined as “the potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources” (Chen et al., 2021, p. 64 in press).
- **Impacts** are “the consequences of realized risks on natural and human systems” (Chen et al., 2021, p. 64 in press).

Risks, as illustrated in Figure 3, “result from the interactions of climate-related hazards (including extreme weather and climate events), exposure, and vulnerability” (Chen et al., 2021, p. 64).

The **response** to climate change includes two approaches: While **mitigation** of climate change means “the efforts to limit climate change” (Chen et al., 2021, p. 5 in press), with **adaptation** the “efforts to adapt to changes that cannot be avoided”(Chen et al., 2021, p. 5 in press) are meant. This is not only about adjusting to the current climate, but also to the expected climate change and its effects (Cardona et al., 2012). Adaptative strategies that reduce exposure and vulnerability will increase resilience and adaptive capacity. While resilience refers to disaster risk management, adaptive capacity means reducing socio-ecological and economic impacts (Cardona et al., 2012). This improved ability to adjust to climate change results in a reduction of impacts as moderating damages or cope with consequences (Aguiar et al., 2018; Seneviratne et al., 2021 in press). It is important to note that adaptation to climate change does not replace mitigation but complements it (Aguiar et al., 2018).

The term **Climate Resilient Development** is even more holistic, as it includes besides climate mitigation and adaptation also sustainable development and social justice (IPCC, 2022b).

2.4. Climate Change and Event Attribution

Whenever weather extremes occur, media and decision-makers ask the question to what extent it was triggered by climate change. With the emerging field within climate science called Extreme Event Attribution it became possible to answer this question. However, these scientific results appear with a delay of a year or more due to peer-reviewing and publishing. In the meantime, the public had to find solutions without taking the scientific perspective into account. In order to overcome this dilemma, climate scientist from institutions all over the world started the World Weather Attribution Initiative in 2014. While their method is peer-reviewed and published, the attributions are published without this procedure promptly online and thus make the results available to the public, media, and decision-makers (World Weather Attribution, 2021).

The following two chapters 2.4.1 and 2.4.2 use the results of the World Weather Attribution to show the extent to which the two events studied, 2018 and 2021, were amplified by climate change.

2.4.1. Heatwave in northern Europe, summer 2018

The heatwave in summer 2018 mainly affected northern Europe with high temperature anomalies and drought from May to July. The clearest extreme was reached over Scandinavia. In the same period, southern Europe was unusually wet. This dichotomy was also evident in Switzerland where the Alpine ridge marked a division between the dry and hot north and the humid south (interpretation of Figure 1 in World Weather Attribution, 2018).

The results of the Event Attribution show that within the whole region of the heatwave in summer 2018 the probability of such an event to occur has doubled due to climate change. The temperatures in summer 2018 were not very extreme and therefore the return time is small. This is a general observation since due to the overall rise in temperatures heatwaves are less extreme but more frequent. Therefore, heat waves like these will be less exceptional in the future. Exceptional in summer 2018 was the persistence of the heatwave, which is strongly linked to global warming (World Weather Attribution, 2018).

As this assessment of the World Weather Attribution is dated to the end of July 2018 and no new results have been published since then, an assessment of the following months remains open.

2.4.2. Heavy rainfall and flood in western Europe, summer 2021

In the summer of 2021, the low-pressure system “Bernd” caused heavy rainfall from 12 to 15 July (Figure 4). Wet conditions prevailed throughout Western Europe in the weeks before, resulting in nearly saturated soils. The following high-pressure system “Diana” caused further heavy rainfall events in Germany. While the entire large region between the north of the Alps and the Netherlands was affected, the catchment areas of the Ahr and Erft rivers in Germany and the Belgian part of the Meuse (Figure 4, Figure 5) exceeded historically observed precipitation values by far. Assumed return values of 100 years and more were exceeded too. This resulted in major property damage and over two hundred deaths (Kreienkamp et al., 2021).

The Event Attribution focuses on heavy rainfall as first-order driver, while river discharge and water levels are the effects of it. A direct analysis of these parameters was not possible, as some hydrological measuring systems were destroyed during the flood. To reduce the signal-to-noise ratio, the assessment was extended with a pooling region (Figure 5). Nevertheless, the challenge of specific local extremes with high variabilities, limited data and time series remained. This results in large ranges of values. The authors emphasize that these are not to be understood as absolute but merely indicate the direction of change (Kreienkamp et al., 2021).

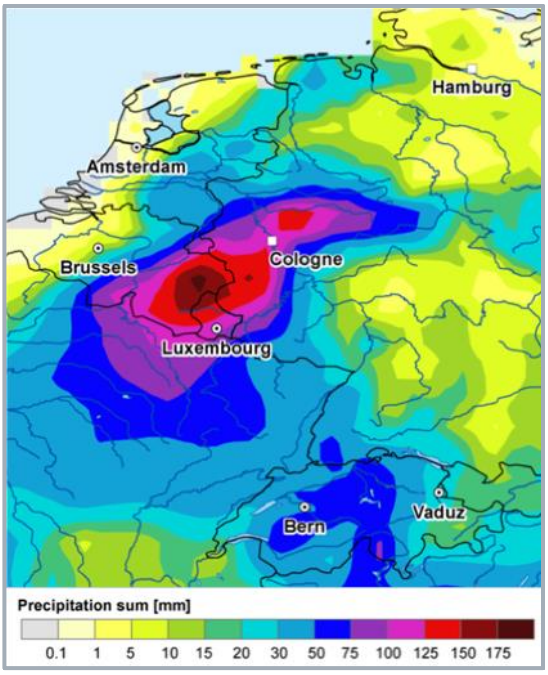


Figure 4 Precipitation sum over 48h in 2021 (13 July 0:00 UTC - 15 July 0:00 UTC) (Deutscher Wetterdienst in Kreienkamp et al., 2021).

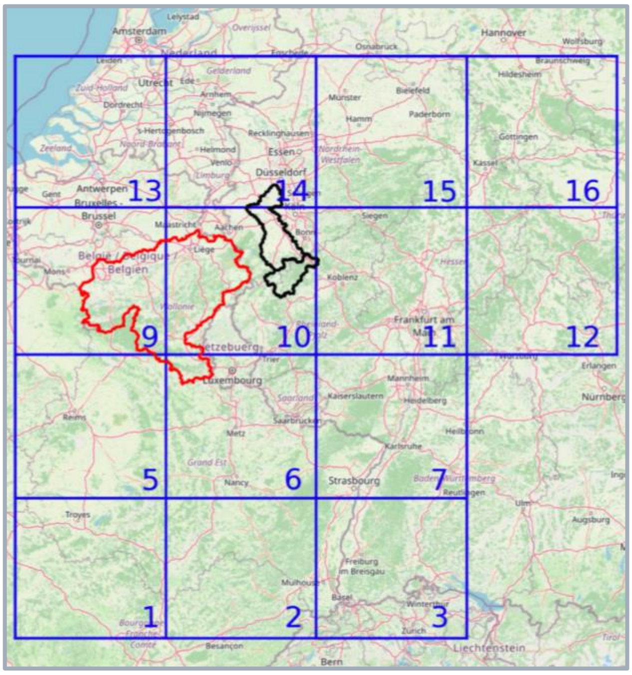


Figure 5 Pooling region of the World Weather Attribution, 2021. Meuse catchment in red, Ahr and Erft catchment in black and grid of the pooling region in blue, including Basel in the quadrant number three (Kreienkamp et al., 2021).

Observational data of the most affected catchments result either in return periods that are longer than the time series (Ahr and Erft) or in a natural variability that is too high compared to the signal (Meuse). These data neither indicate a trend nor its absence. From the observational data of the extended pooling region, a return period of 400 years can be inferred, which means that in each of the 16 tiles of the pooling region such a 1-day precipitation event will take place in 400 years (Kreienkamp et al., 2021).

Table 2 Observational analysis of return time and trend within the pooling region. 95% confidence intervals are given in brackets (Tabular representation according to Kreienkamp et al., 2021: 20).

	Δ Intensity	**Δ Probability**	**Return Period**
1-day precipitation	22% (6.7 – 34%)	7.7 (2.0 – 52)	400 years (170 – 2500 years)
2-day precipitation	24% (7.7 – 30%)	5.9 (1.6 – 12)	300 years (130 – 1200 years)

Table 2 illustrates the result of the significant increase in probability and intensity of extreme 1-day precipitation of 64mm/day and 2-day precipitation of 45mm/day within the pooling region.

For the final attribution statement, the models were evaluated by using the observational data. Overall, the observations (Table 2) show more significant positive changes than the models. As a result, the unweighted synthesis of model and observation shows a trend of increasing intensity and probability too, but with extended values in the upper range (Table 3) (Kreienkamp et al., 2021).

Table 3 Attribution of the intensity and probability change of 1- and 2-day precipitation events within the pooling region. Past-to-present equals a comparison with a climate 1.2°C cooler than today, present-to-future describes the additional model-based changes of the current climate with a total warming of 2°C (Tabular representation according to Kreienkamp et al., 2021: 32-35).

	Past-to-present		**Present-to-future**	
	Δ Intensity	Δ Probability	Δ Intensity	Δ Probability
1-day precipitation	3% – 19%	1.2 – 9	0.8% – 6%	1.2 – 1.4
2-day precipitation	2% – 17%	1.5 – 7	0.2% – 5%	1.1 – 1.4

Table 3, which provides an overarching attribution statement, also highlights the major uncertainties associated with this study. While these were even more pronounced in the individual studies of the catchments of Ahr, Erft and Meuse, an attribution was possible due to the extended data set of the pooling region. Within this large region, climate change caused an increased intensity of 3-19% and increased probability of a factor 1.2-9 of the maximum 1-day-rainfall event of the summer season, with a similar increase of the 2-day-rainfall event. With high confidence the authorship concludes that the increase of intensity and likelihood of such an event is not only increased by climate change to date but will continue to increase as temperatures rise (Kreienkamp et al., 2021). Nonetheless, the authors repeatedly emphasize that “the detection and attribution of trends is challenging for events occurring on such a small scale as the ones which are investigated here” and thus their study pushed “the limits of what current methods of extreme event attribution are designed for” (Kreienkamp et al., 2021: 36).

3. Methods

A combination of several research methods (Figure 6) was chosen to capture the multiple interactions of urban life with riparian habitat and to elicit challenges and adaptation strategies related to the changing climate and its impact on the water bodies in Basel. While in science quantitative and qualitative methods can be combined in different ways (Bryman, 2012), those of “different research questions” and “triangulation” (Bryman, 2012, p. 633) are used here. The term triangulation is used differently in the literature, here it refers to the inclusion of different perspectives and sources to maximize the understanding of a research question and gain a more complete picture (Longhurst, 2016; O’Cathain et al., 2010).

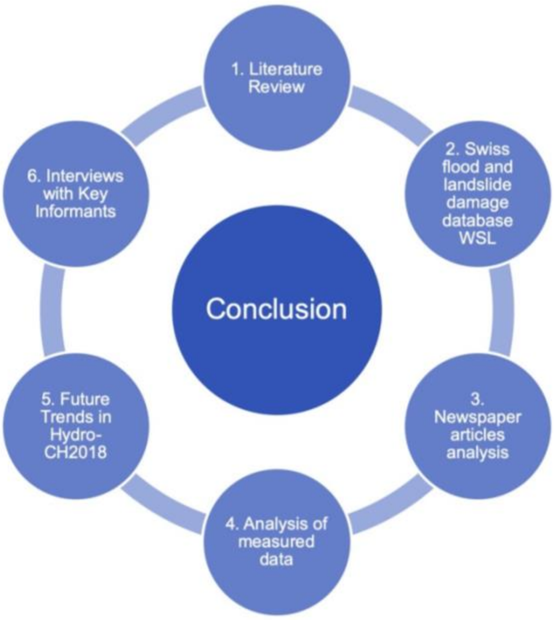


Figure 6 Triangulation of Methods (own Illustration).

For the evaluation of the different methods being part of the triangulation the approach “following a thread” according to O’Cathain et al. (2010, p. 3) is used. At the beginning of this approach are themes or research questions, which are used to start with in one component or method and then followed by all other components – this is called the thread (O’Cathain et al., 2010). On some research questions, certain methods are more obviously answer-generating than others. Therefore, the approach of “different research questions” was mentioned too, which states that different methods serve to answer different questions (Bryman, 2012). For the discussion, therefore, the associated methods were determined per research question, which mainly answer the questions. Then, stepwise according to the approach “following a thread”, it was proceeded through the other methods to obtain information that contribute to a more complete answer of the research question.

3.1. Literature Review

As recommended by Healey & Healey (2016), the methodical procedure of the literature review was divided into the three steps of defining the key terms, specify a range of sources, and evaluating the references found.

The selected key terms were grouped (Table 4) and combined in different ways. The list of key terms was continuously expanded and refined on the basis of the scientific articles found and the key words noted there.

Table 4 Key terms of the literature review.

Space, Context, Time	Process	Implications
Europe, Central Europe Switzerland, Swiss Urban, urbanization City, cities Recent Future	Extreme events, Compound events Water extremes Flood, river flood, pluvial flooding Drought, hydrological / streamflow drought Heat, heatwave Land use change, urban growth Climate change, Global warming	Damage Risk Impacts Vulnerability Adaptation Measures, Management

Of the search tools proposed in Healey & Healey (2016), those representing the most current knowledge were chosen, hence databases, scientific journals, and the web. For the search in databases Web of Science and ScienceDirect were chosen as both cover several scientific disciplines and journals. This search was supplemented with Google Scholar to go beyond the boundaries of individual publishers. Finally, the search was supplemented by websites of intergovernmental (IPCC, EEA) and governmental (NCCS, FOEN, WSL, Swiss cantons) organizations.

The evaluation process was carried out according to Healey & Healey (2016): The references were listed in tabular form based on the criteria year of publication, covered region and processes, methods, and main findings (Appendix 9.1). References published in 2010 or later, covering study sites in Central Europe and reasonable processes were classified as relevant. This ensured the relation in terms of space and process to Switzerland and Basel. Consequently, papers on processes such as coastal flood were excluded due to the lack of relevance for Switzerland. In particular, comparative studies such as Alfieri et al. (2015) at the country level and Guerreiro et al. (2018b) at the city level allow the individual papers to be related to Switzerland and Basel.

This method of literature review described here is not a linear but an iterative process that becomes increasingly refined (Healey & Healey, 2016).

3.2. Swiss flood and landslide damage database WSL

From the Swiss flood and landslide damage database, the flood events of the cities of Bern, Zurich, Geneva and Basel were presented in tabular form and compared. For the city of Basel, the damages of the largest floods recorded in the damage database were compared with regard to monetary losses and description of the damages. In addition, the damage caused by the water process in 2018 in the same cities was compared. The choice of cities was based on the paper by Guerreiro et al. (2018b), which included these Swiss cities, with the exception of Basel. Due to the lack of an analogue database on drought damage, literature was consulted to evaluate this.

3.3. Newspaper articles analysis

Similar to Vogel et al. (2019) newspaper articles with information about resulting impacts of climate extremes were collected and mapped. This was done for the 2018 drought and the 2021 flood. Record breaking temperatures or water levels were not searched for, but rather the impacts of these events on the city of Basel, it’s population and infrastructure.

The search was carried out on Swissdox Medienbeobachtungsstelle. This database covers the whole of Switzerland with 400 sources, both online and offline (Swissdox AG, 2021). The result of the search is not exhaustive media overview but collection of impacts of the events 2018 and 2021. This as well as the presentation of the results follows Vogel et al. (2019).

The drought in 2018 lasted from May to at least July (World Weather Attribution, 2018). The heavy rainfall and flooding in 2021 were most pronounced in July (Kreienkamp et al., 2021). To standardize the time intervals, it was searched for newspaper articles published between May 1 and October 31, 2018 and 2021, respectively.

Since Basel is a German-speaking region, only articles in German were searched for. The spatial limitation of the search was achieved with the supplementary search words “Basel” and/or “Rhine”. To reflect the focus on impacts in the search, the keywords (see Table 5) were combined with keywords such as impact, effect, or consequence. Due to the repetition of content, the search was limited to regional and national dailies.

Table 5 Combination of keywords for the search on Swissdox. The German words searched for are given in italics in parentheses.

Location	Event	Impact
Basel Rhine *(Rhein)*	Natural Hazards *(Naturgefahren)*	Impact *(Auswirkung)* Effect *(Effekt)* Consequence *(Folge/Konsequenz)*
	Flood *(Hochwasser)*	
	Flooding *(Überschwemmung)*	
	Surface flooding *(Oberflächenabfluss)*	
	Flood damage *(Hochwasserschäden)*	
	Heat *(Hitze)*	
	Low flow *(Niedrigwasser)*	
	Drought *(Trockenheit)*	

The results were summarized in a table (Appendix 9.2). In particular, the effects of the extreme events and their localization were important, so that they could subsequently be presented cartographically.

3.4. Analysis of measured hydrological and meteorological data

Measured hydrological (FOEN, 2021a) and meteorological (Federal Office of Meteorology and Climatology MeteoSwiss, 2014) data were chosen for data analysis. The mainly analysed interval starts with 1981 consistent to the beginning of the reference period of the Hydro-CH2018 data (CH2018 Project Team, 2018; Zappa et al., 2021) and ends with 2021, the second focus event assessed. For individual analyses, the time series was extended further back in time to 1900. Of the available measuring stations, those were selected that are spatially related to the city of Basel and measured the required values over a sufficiently long period of time (Chapter 4.2, Figure 7).

For data analysis, the Jupiter Notebook environment was used, including the python programming language and the pandas library. During pre-processing, the data was cleaned, saved as a DataFrame and the time information was set as an index with datetime format. The libraries NumPy and Matplotlib were used to process, visualise and plot the data.

In accordance with the recommendation for the evaluation of continuous data by Field (2016), first descriptive statistics were applied (summary table, measures of variability) and the distribution of the data was examined (boxplots). Relationships between data were shown by representing the values of the years 2018 and 2021 at the mean value or the variance of the period. Resolutions of calendar year, hydrological season, month, and day were chosen to show boxplots and hydrographs, the latter being supplemented with the reference to precipitation data (implementation inspired by Leskovar (2020)). For the hydrological seasons, December to February are summarized as winter, March to May as spring, June to August as summer, and September to November as fall.

Trends in the available data were examined in that consecutive days of an extreme event were identified. For this, first the threshold was defined, secondly all values which exceeded this threshold were marked with 1, the others with 0. Then the number of consecutive days was added up, these were periods marked with the number 1 without interruption. To these events also the start and end date were given (implementation inspired by buzzphp.com (2021) and Data to Fish (2021)). As a further result, the number of days per year exceeding the threshold was output. The results were plotted as a bar, line, or scatter plot, with a trend line where appropriate. The extreme event is defined as values above or below a threshold expressed as quantiles (van Loon et al., 2016) of the reference period 1981-2021. Especially over larger time series, the number of days above or below a threshold value per year was displayed instead of the consecutive days per event for better readability.

3.5. Identification of future trends with Hydro-CH2018

The analysis of the modelled data of Hydro-CH2018 (CH2018, 2018; CH2018 Project Team, 2018; Zappa et al., 2021) is based on the method of measured data (Chapter 3.4) whereas the data of the individual models were read in as in Muccione et al. (in prep.). In order to keep both analyses comparable, not only the same method for analysing consecutive days was chosen but also implemented with identical thresholds. This implies that the analysis of the upper and lower quantiles of the modelled data refer to the corresponding quantile of the measured data of the same variable of the period 1981-2021.

Due to the longer time period of 2022-2099, these data have been presented as a line plot. For better readability, the mean of all models has been plotted additionally, as well as a trendline.

Since the models vary considerably in their predictions, one third of the models were presented separately, with the mean number of days being decisive for the classification into the upper, middle or lower class of the models. This classification was made anew for each analysis. Additional subplots were created based on hydrologic seasons to determine changes within the year.

The notebooks produced in the context of the methods described in Chapter 3.4 and Chapter 3.5 are freely available upon request.

3.6. Semi-structured interviews with key informants

The objective of the interviews was to better understand the relationship between the extremes in low and high flow and the interviewee's area of expertise, both in relation to the 2018 and 2021 events and for flood and drought in general. In addition, the aim was to find out which dimensions and combinations of extreme events are conceivable, what they mean for the respective area and which adaptation measures have already been taken or are planned.

As the method of semi-structured interviews is suitable for data collection in a wide range of subjects (Longhurst, 2016), it was chosen for the in-depth study of the events of 2018 and 2021, respectively flood and drought extremes in Basel in general, which have impact on a wide variety of topics too (see Chapter 5.3). Lying in the middle of the continuum between structured and unstructured interviews, semi-structured interviews are characterized by some predetermined questions and the opportunity given to the participant "to explore issues they feel are important" (Longhurst, 2016, p. 143) within the conversation. These open-ended responses in the interviewee's own words enable additional interrelationships to be captured and blind spots to be eliminated. Furthermore, semi-structured interviews allow the linkage between a selection of other methods (Longhurst, 2016), which makes it appropriate for this multi-method research.

The **selection** of the interviewees was taken based on their expertise in relation to the research questions (Longhurst, 2016) and the impacts of the 2018 and 2021 events determined as part of the newspaper articles analysis (see Chapter 5.3). From the possible options to **recruit** people for the interviews, the contact via email (Longhurst, 2016) as well as the so-called "snowballing" was used for this thesis. The latter stands for contacts that help to get in touch with further persons suitable for an interview (Longhurst, 2016). Also, existing contacts of the research project of Muccione et al. (in prep.) could be made use of and invited for a second interview. The following Table 6 provides an overview of the experts interviewed, their institution and field of expertise.

Table 6 Date of semi-structured interviews, institution and field of expertise of interviewees.

Date	Institution	Field of expertise
2021-12-15	Canton of Basel-Stadt	Environment and energy
2022-01-03	IWB and Hardwasser AG	Water supply
2022-01-10	Hardwasser AG	Water supply
2022-01-22	Canton of Basel-Stadt	Waters and natural hazards
2022-02-03	IWB	Energy supply

Since the interviews are not based on strict rules but on social interaction, each interview required its own individual preparation and realization (Longhurst, 2016). Based on the interviewee's area of expertise and in relation to the extreme events, a set of **questions** including follow-up questions was prepared. Across all interviews factual (about their view on the events 2018 and 2021), descriptive (about interactions of their field with flood and drought in general) and thoughtful (what might be the consequences of even more frequent and intense extremes) information were asked, as well as their combination. As recommended by Longhurst (2016) it was started with a question that the interviewee was likely to feel comfortable answering while the more sensitive and difficult questions were asked towards the end. The fact that within this method the questions do not have to be asked in an orderly sequence allowed to discuss the topics in the order of the interviewee and to go more in-depth on the topics that are particularly important to them. All the more important was to ensure towards the end of the interview that all questions had been covered (Longhurst, 2016). In the following Table 7 the main questions are given, whereby the general questions and those about the outlook were asked of all interviewees, supplemented with selected specific questions about the interviewee's field of expertise. Depending on the answer, in-depth questions were asked.

Table 7 Main and supplementary questions of the semi-structured interviews.

Event	Impacted field	Question
Low-Flow (2018)	General	– To what extent was the extreme low water in 2018 problematic for your field, what areas did it affect and how were the problems solved? – Assuming a 10-fold more extreme drought in terms of discharge values and duration occurs, what would be the impacts and how is your institution preparing for it? – Assuming a situation like 2018 occurs for several years in a row, what additional impacts would occur?
	Water supply	– Is there a lower discharge limit below which water withdrawals are critical or impossible? – At what low discharge levels is drinking water quality reduced and are there additional factors that negatively impact water quality? – Are measures planned with regard to the use of drinking water?
	Transport and Economy	– How do you assess the impact of low flow on the economy and transport, what solutions are available?
	Energy supply	– To what extent does the lower electricity production during low water have an impact, and what effect does it have on the electricity supply of the city of Basel?
	Natural Hazards	– What does prolong or extreme low water mean for the environment and how are negative impacts prevented? – To what extent is the population affected by extremely low water?
	Outlook	– Are there other contexts and impacts of low flow and drought in Basel that have not yet been addressed but could become important in more extreme events in the future? – Considering the changing climate: what challenges do you see in Basel in the future in connection with low flow and which measures do you consider important? – What additional risks could cause a problem in combination with low flow?
High-Flow (2021)	General	– To what extent was the prolonged high-water situation in 2021 problematic for your field, what areas did it affect and how were the problems solved? – What effects would an even longer flood situation or consecutive floods have on your field, what measures could conceivably be taken to counteract this? – What impact would higher peak flows have, is your field prepared for this or which measures would be necessary?
	Water supply	– Are there flood situations in which the pumps have to be suspended for water extraction, why and how is the drinking water supply ensured in such situations?
	Transport and Economy	– How do you assess the impact of the flood on the economy and transport, what solutions are available?
	Energy supply	– Did the Birsfelden power plant have to be shut down or reduced in the summer of 2021 due to the flood? – To what extent was the driftwood a problem for the Birsfelden power plant? – How does the lower water gradient during floods affect the city's power supply?
	Natural Hazards	– How do you assess the flood situation of last summer 2021? – What is more problematic for Basel: short intense rainfalls or enormously long-lasting ones? – Where are the hotspots in Basel that are affected by flooding and what measures are currently being implemented or planned? – What does prolonged flooding mean for the environment and how are negative impacts prevented? – What is the impact of this natural hazard on the population?
	Outlook	– Are there other contexts and impacts of flooding and heavy rainfall in Basel that have not yet been addressed but could become important in more extreme events in the future?

		– Considering the changing climate: what challenges do you see in Basel in the future in connection with flooding and which measures do you consider important? – What additional risks could cause a problem in combination with high flow and flood?

As the interview can take place in person as well as **online** (Longhurst, 2016), the latter was chosen as it accounts for the limited time resources and the working from home of the experts. Other advantages of this mode of implementation were that the interviewees were in a comfortable, quiet, and easily accessible location (Longhurst, 2016) and that the interview could be recorded in most cases with the option included in the selected software. This allowed as recommended by (Longhurst, 2016) to fully concentrate on the interaction in the interview without the pressure of taking notes. Nevertheless, after the interview the most important topics and aspects mentioned were recorded in writing, as well as surprising or new results.

The most important **ethical issues** in semi-structured interviews include confidentiality and anonymity. Also, the possibility that the result of their interview is not included in the work must be left open to the participants at any time. To ensure this, a summary of the interview (Appendix 9.5) and the description of the interviewee used in the thesis was provided to the participants with the option to apply corrections, thus following standard research practice (Longhurst, 2016).

In order to **evaluate** the information from the expert interviews in a careful and systematically way, a procedure according to Nicklin et al. (2019) was chosen. The paper distinguishes between tangible and intangible as well as direct and indirect flood damage. While direct damages are characterized by their immediate physical proximity to the floodwater, indirect damages have spatial or temporal distance to it. The criterion of easily monetizable assets with a market price is used to distinguish tangible from intangible flood losses. Aspects that do not have a clear market price, such as health or environmental damage, are therefore referred to as intangible (Nicklin et al., 2019). This approach was applied equally to the low water situation. Since the expert interviews went beyond the impacts and included adaptation strategies, the matrix proposed by Nicklin et al. (2019) was duplicated, with adaptation strategies listed in the copy (see Figure 40 and Figure 39). While the information of these illustrations is mainly based on the interviews from Table 6, with regard to individual aspects of the topics forest, electricity and navigation on the Rhine, expert interviews were used which were conducted earlier in the context of the research project of Muccione et al. (in prep.) and were used as secondary data.

4. Data

4.1. Swiss flood and landslide damage database WSL

The SFLDD, produced by the WSL, is a systematically collection on reports of flood and mass movement damage since 1972 with the goal to improve hazard mapping, land-use planning, and protection from natural hazards. Press articles as main sources of information are used to estimate the direct monetary damages. In addition, fatalities and injured people are documented. Besides this the information includes locality and date of an event, the type of the damage-causing process, triggering weather conditions, and the description of the event including affected objects and estimated costs (Hilker et al., 2009; WSL, 2021).

4.2. Measured Data FOEN and MeteoSwiss

The FOEN operates 260 monitoring stations on Swiss surface waters, at 200 of which discharge is determined. The longest time series go back to 1863 and thus also document rare flood events and dry periods. At the measuring station "Rheinhalle" in Basel, existing since the year 1891, both water level and discharge are measured, respectively the discharge data are calculated from the water levels. The other measuring stations in Basel "Klingentalfähre" and "Weil, Palmbrücke" (Figure 7) only go back to the year 1995, the latter measuring only the water temperature (BAFU, n.d.; FOEN, 2021b). With the criteria of a sufficiently long time series (at least back to 1981), values on the flow characteristics (level, discharge) and available data in the Hydro-CH2018 data set for the same location (Chapter 4.3), the station "Rheinhalle" was chosen for the data analysis. The corresponding data with minimum, maximum and mean values and the resolutions annual, monthly and daily could be obtained from the FOEN Hydrological Data Service for watercourses and lakes whereby it is important to note that the data are validated until 2019, those after are provisionally released (FOEN, 2021a).

Figure 7 Hydrological and meteorological measuring stations at the Rhine in Basel (Federal Office of Meteorology and Climatology MeteoSwiss, 2014; FOEN, 2021b; Grundbuch- und Vermessungsamt Kanton Basel-Stadt, 2019).

MeteoSwiss Data portal for teaching and research provided rainfall data from the Binningen weather station with daily resolution (Federal Office of Meteorology and Climatology MeteoSwiss, 2014). In the precipitation measurement, the sum of rainfall is given per day. For reasons of comparability with the hydrological data, the sum of 0:00 UTC - 0:00 UTC and thus the measuring station "Binningen" was selected, although these data only go back to 1981. Since the measuring station "St. Chrischona" does not provide the mentioned data set, it was not considered further (Figure 7).

4.3. Hydro-CH2018

To explore the consequences of climate change, the CH-2018 scenarios were chosen as it is the most recent dataset for Switzerland and “an important source of data for impact research and for the definition of adaptation strategies” (CH2018, 2018, p. 11). With hydrology being one of the priority themes within these scenarios, the Hydro-CH2018 dataset provides modelled mean runoff changes (absolute and relative) for the emission scenarios RCP2.6, RCP4.5, and RCP8.5 by the end of the 21st century in monthly, seasonal and annual resolution (NCCS (Publ.), 2022).

For the Basel location, the only station available is "Rheinhalle", whereby discharge values in daily resolution from (Zappa et al., 2021), which modelled the mean discharges of large catchments within the framework of Hydro-CH2018, were used. Zappa et al. (2021) consider a total of 39 model chains across the three emission scenarios. The modelled rainfall data of the Binningen station with daily resolution also originate from CH2018 (CH2018, 2018; CH2018 Project Team, 2018), considering 12 models for RCP2.6, 25 models for RCP4.5, and 31 models for RCP8.5.

5. Results

5.1. Literature review

The most recent IPCC report of Working Group I states with near certainty that "hot extremes (including heatwaves) have become more frequent and more intense across most land regions since the 1950s" (IPCC, 2021). The same is found for frequency and intensity of heavy precipitation events. Both changes are attributed to climate change with high respectively likely confidence and also apply to the Western and Central Europe region. This highlights the fact that climate change with its extreme and compound events and their impacts is not a future scenario but already a reality today. The following chapters explore the state of knowledge about the trend of climate change driven water extremes in Europe (Chapter 5.1.1) and which adaptation strategies exist in Central European cities (Chapter 5.1.2).

5.1.1. Evidence on climate change and water extremes in Europe

Changes in the hazard refer to developments in temperature, droughts, precipitation, streamflow, and floods. These factors can also occur simultaneously and lead to multiple risks (Guerreiro et al., 2018b).

Changes in flood, heatwaves, and drought were investigated by Guerreiro et al. (2018b) under a unified approach and the RCP8.5 scenario for 571 European cities. It should be noted that local variabilities are not detected in global models (Alfieri et al., 2015). Within the RCP8.5 scenario spatially differentiated patterns of **temperature** development are evident within Europe. A dichotomy is predicted between the south of Europe and south-central Europe. Southern Europe is affected by a higher increase of mean temperatures and therefore shows an increase in the number of heat-wave days. South-central Europe shows a higher increase of the variability and therefore higher maximum temperatures (Fischer & Schär, 2010; Guerreiro et al., 2018b). Whereas Fischer & Schär (2010) find the highest increase of the daily temperature variability at 45°N, (Guerreiro et al., 2018b) see the maximum temperatures of heatwaves even further north. Under the high impact scenario, the maximum increase of 14°C is found in Innsbruck, Austria (Guerreiro et al., 2018b). For the Swiss cities a temperature increase of ~6°C to ~12°C for the low and the high scenario respectively are predicted (Guerreiro et al., 2018a). The change in the number of heat-wave days shows a clear north-south gradient, whereas it ranges from an increase of 4% in Trondheim (Norway) to an increase of 69% in Lefkosia and Lemesos (Cyprus) (Guerreiro et al., 2018b).

In southern Europe, **droughts** are projected to become more frequent and longer. Future water consumption will exacerbate this situation by another 10-30% (Forzieri et al., 2014). The development of droughts in central and northern Europe depends on the scenario. While northern latitude cities are only affected of a higher intensity of droughts under the high impact scenario, the mid latitude cities show already an increase of drought under the medium impact scenario (Guerreiro et al., 2018b). Similarly, it is found that the discharge decreases in southern Europe whereas it increases in northern Europe. In Central Europe, the projections show no clear trend (Forzieri et al., 2014), respectively different, strongly scenario-dependent trends (Guerreiro et al., 2018b). This finding is also supported by Paton et al. (2021), which studied the development of drought since 1950 in 31 German cities and found a high heterogeneity between the cities. Nevertheless, a spatial pattern could be observed in which southern and central German cities showed a significant increase in the number of drought months while northern cities showed an increase or absence of a trend (Paton et al., 2021).

Analogous to the changes in temperature and drought, **precipitation** in southern Europe will experience a reduction of up to 30% per year. North-eastern Europe, on the other hand, faces an increasing trend, with the largest increases in annual precipitation occurring in Scandinavia and Iceland (Alfieri et al., 2015). For Central Europe, which lies between these two clear trends, it is difficult to make a prediction as the spread of precipitation per year is large compared to the mean change (Alfieri et al., 2015; Guerreiro et al., 2018b). The maximum precipitation values, on the other hand, show a significant and mostly positive change for the future, with the largest increase up to 40% in northern and western Europe (Alfieri et al., 2015).

Identical to the trend of the mean annual precipitation, the **streamflow** also decreases in Southern Europe and increases in Northern and Eastern Europe, while no clear trend is evident in Western and Central Europe. 73% of the rivers studied show an increase in streamflow by 2080, 38% show a significant increase in maximum streamflow. The mean increase of the streamflow of 8% is due to the significant decreases in southern Spain, the Baltic countries and partly Scandinavia. The fact that Scandinavia shows a contradictory picture of increase and decrease of the streamflow is due to the future reduced snow accumulation (Alfieri et al., 2015).

Assessing the changes in river **flooding** in the near future until 2035, Alfieri et al. (2015) find a decrease in low return periods such as 20-year events. In the further future, the period 2052-2100 compared with the baseline (1951-2000), high flows of a return period of 10 years find again a strong north-south gradient. The British Isles, but also Norway and northern Iberia are facing the worst projections whereas most cities of Southern Europe see no change or a decrease of 10-year floods (Guerreiro et al., 2018b). Also, by the middle and end of the century, extreme events with a return period of 100 years will increase strongly, by 126% and 176%, respectively. Smaller-scale events will also increase considerably (Alfieri et al., 2015). By the end of the century (time slice 2066-2095), all countries studied by Alfieri et al. (2015) show significant positive changes in 100-year extreme events (refer to Table 8).

Table 8 Future change of HQ_{100} of river floods on country level. The change is indicated in percentages between the baseline (1976–2005) and the future time slices, based on RCP8.5. Changes in italics are not significant at 1 ‰ (excerpt from Alfieri et al., 2015).

	Country	**ΔHQ_{100}**		
		2006–2035	2036–2065	2066–2095
Minimum	Finland	18 %	*-3 %*	18 %
Switzerland and neighbouring countries	Germany	110 %	91 %	139 %
	Austria	152 %	276 %	362 %
	Switzerland	238 %	254 %	518 %
	France	127 %	154 %	245 %
	Italy	48 %	170 %	276 %
Maximum	Iceland	193 %	695 %	982 %

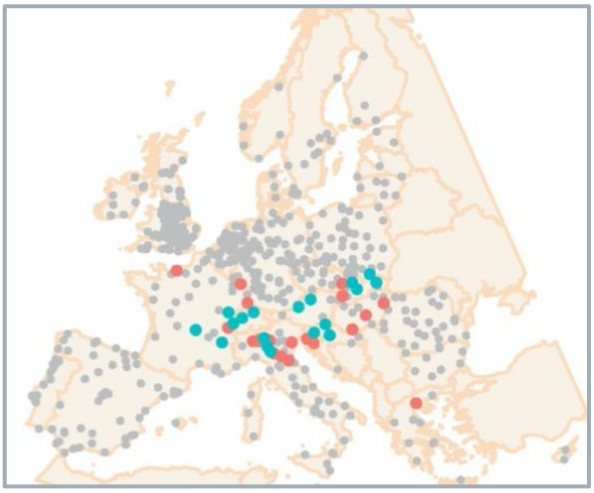


Figure 8 Top 25% European cities affected by combined risks. These cities will be affected by the largest changes in floods and heatwave maximum temperatures between the reference period (1951-2000) and the future period (2051-2100) under the high impact scenario. Green dots indicate cities with rivers, red dots those without rivers (Guerreiro et al., 2018b).

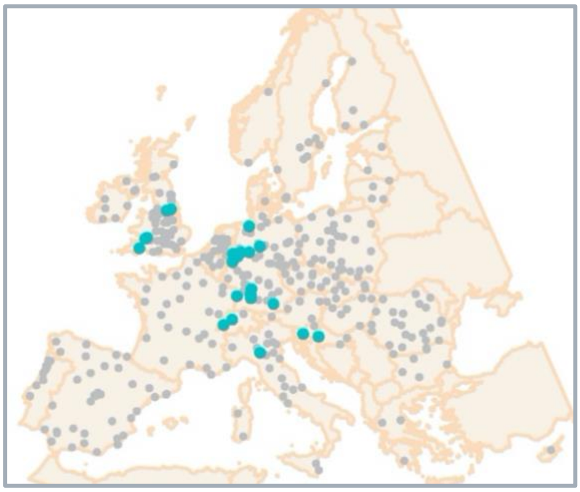


Figure 9 Top 50% European cities affected by combined risks. These cities will be affected by the largest changes in floods, number of heatwave days, maximum heatwave temperatures, and drought severity between the reference period (1951-2000) and the future period (2051-2100) under the high impact scenario. Green dots indicate cities with rivers (Guerreiro et al., 2018b).

Especially for Central Europe, which has unclear trends for some risks (Alfieri et al., 2015; Guerreiro et al., 2018b), it is important to look at the probability for **multiple risks**. If two or more climate variables occur simultaneously, also known as a compound event, the impact on society can be expected to be greater than if the risks were to occur individually (Sedlmeier et al., 2016). Data from the past decades were examined in particular for the simultaneous occurrence of heat and drought. It was found that the likelihood of simultaneous exceedance of the 95-percentile of heat and drought values increased across Europe between 1950 and 2013. The change – except in south-eastern Europe – is not so much in the length of the events, but rather in their temperature increase. Therefore, the general temperature increase in Europe is assumed to be the driver of this trend (Manning et al., 2019). An increase in the compound events of drought and heat was also observed within German cities, with this being described as a strong increase within the last two decades (Paton et al., 2021).

With a view to the future, Sedlmeier et al. (2016) found that cold and wet extremes in winter will become longer and more frequent in France and Germany. The future occurrence of floods across Europe show, as intuitively expected, a negative correlation to the simultaneous occurrence of drought, heatwave days, and the maximum temperatures of heatwaves (Guerreiro et al., 2018b). For the compound events of hot and dry summers, Sedlmeier et al. (2016) find a more frequent occurrence and longer duration of the extremes in Spain and Bulgaria. Splitting heat up into two variables and making a pronouncement about the whole of Europe, Guerreiro et al. (2018b) find a low negative correlation of the increase of the maximum temperature and the number of heatwave days. The reason for this is seen in the spatial dichotomy of these variables between South and Central Europe. However, Guerreiro et al. (2018b) also find a positive correlation between the number of heatwave days and the occurrence of drought.

Interestingly, the cities in Switzerland and around Basel (see Table 9) are within the 18 European cities of the top 50% for all indices (heatwave days, maximum temperature, drought, and flood with a return period of 10 years) for the high impact scenario (Figure 9) in the study of Guerreiro et al. (2018b). The cities Bern and Geneva, seen in Figure 8, are in the top 25% for flood and maximum temperature of heatwaves for the high impact scenario as well (Guerreiro et al., 2018b).

Table 9 Future change in climate indicators of cities around Basel. The indicators denote (i) the difference of summer (May-September) heatwave days in percentage, (ii) the difference in the maximum temperature of heatwave days in °C, (iii) the future maximum DSI-12 (Drought severity index DSI over 12 months) divided by historical maximum DSI-12, (iv) the probability for any given month in the future being above Maximum historical DSI (MHD), and (v) the future HQ_{10} divided by historical HQ_{10}, cities without a river (with at least 500 km^2 of catchment area) within their boundary are not applicable (NA) for this index (Excerpt from Guerreiro et al., 2018a).

City	**Scenario**	**Δ % of Heatwave Days** (i)	**Δ Max (Temp)** (ii)	**DSI change factor** (iii)	**P(DSI-12>MHD)** (iv)	**HQ_{10} change factor** (v)
Zurich	High	41.1	12.9	3.00	18.1	1.35
	Low	10.3	5.6	0.42	0.0	0.81
	Medium	23.9	9.3	1.30	2.4	1.15
Bern	High	41.6	12.4	2.94	19.2	1.43
	Low	15.9	5.8	0.59	0.0	0.90
	Medium	24.3	8.8	1.30	1.8	1.14
Geneva	High	41.1	12.1	3.84	31.8	NA
	Low	13.5	6.8	0.58	0.0	NA
	Medium	26.9	9.6	2.23	10.6	NA
Besancon	High	40.4	11.6	2.96	19.6	1.38
	Low	11.9	6.1	0.44	0.0	1.05
	Medium	22.6	8.9	1.37	3.8	1.20
Stuttgart	High	36.4	11.9	2.32	16.9	1.40
	Low	8.4	5.5	0.34	0.0	0.93
	Medium	19.4	9.1	0.96	0.0	1.17
Innsbruck	High	43.6	14.2	2.62	14.0	1.29
	Low	9.9	5.1	0.33	0.0	0.81
	Medium	25.3	8.9	1.19	1.7	1.07

In addition to changes in hazard, **changes in exposure and vulnerability** are key determinants of future risk (see Figure 3). While Chapter 5.1.1 looks at the risk in Europe mainly from the perspective of climate and weather events, it is equally crucial to look at exposure and vulnerability to these hazards (Cardona et al., 2012).

Exposure is increasing in European cities within the growth of imperviousness surfaces. Other contributing factors are the densification of assets within cities, the general expansion of urban areas, population growth, and human-driven transformation of hydrological systems (Skougaard Kaspersen et al., 2017). For the future, there is a trend towards further urbanization, so that the current 75% of the population living in cities will increase to 82% by 2050 (UN-Habitat 2011 cited in (Guerreiro et al., 2018b; Tapia et al., 2017)).

Analyses of trends over the past 30 years show that the exposure of cities to pluvial flooding has increased by 6% for 10-year events and by 26% for 100-year events due to urban land cover change and soil sealing. It is estimated that this exposure will increase by 40% (RCP4.5) and 100% (RCP8.5) by 2100. This highlights the relevance of land cover changes within cities (Skougaard Kaspersen et al., 2015), even if there are considerable differences between the cities, due to soil infiltration properties or historical trends in urban development (Skougaard Kaspersen et al., 2017). To what extent the effect of urbanization is comparable to that of climate change and extreme precipitation varies between cities. For some cities studied (Odense, Vienna, and Strasbourg), the contribution of urbanization and increased precipitation are nearly identical, while in others (Nice) climate change is the much larger contributor to future risk (Skougaard Kaspersen et al., 2017).

Vulnerability refers to the negative impact of hazard events on the livelihoods and assets of exposed people (Cardona et al., 2012). Tapia et al. (2017) showed that climate vulnerability is very unevenly distributed in European cities. Although vulnerabilities to flood, drought and heatwaves are high, no spatial pattern is evident. The reason for this, according to Tapia et al. (2017), is that intrinsic vulnerabilities of individual cities are crucial and also depend on the hazard process. As crucial for the vulnerability of cities on floods Tapia et al. (2017) mentions the socio-economic profile, which consists among other things, of demographic distribution, level of education and income, and unemployment rate. Also, the awareness of the population to climate change related hazards influences the vulnerability. The vulnerability to droughts was determined by whether the city is already accustomed to this climate extreme, but also by the diversification of economies, population development, and performance of the water management system (Tapia et al., 2017).

5.1.2. Adaptation and water risk management in Central European cities

Adaptation to climate and weather impacts is essential to maintain the safety of the citizens but also to protect the economy, health, environment, and cultural heritage (Priest et al., 2016). This is particularly important for cities which have a high concentration of elements at risk. Additional to the high population size, these are critical infrastructure and buildings (Carter, 2011). Combined with the recognition that climate change has different local impacts, this not only means that an adaptation strategy is particularly important for cities, but also that it must be adapted to local conditions (Aguiar et al., 2018; Carter, 2011). Despite the recognition that it seems difficult for local politicians to understand the long-term consequences of climate change, Aguiar et al. (2018) found a rapid increase in local and national adaptation strategies in Europe over the past decade.

Adaptation strategies of Central European cities focus mainly on reducing exposure and vulnerability, as these factors are contributing to the increasing hazard losses in cities (Cardona et al., 2012). Since the majority of extreme climate events in Europe are floods, storms, heatwaves and droughts, water, including its availability and quality, has a particularly important role in local adaptation strategies (Aguiar et al., 2018).

In urban areas, **land cover change** mainly means additional sealing. While this exacerbates the problem of surface runoff during heavy rainfall, unsealing is a measure to reduce flood exposure (Skougaard Kaspersen et al., 2015, 2017). Land use planning is needed to create and preserve additional unsealed land in urban areas. Possible implementation measures are green infrastructure, increased vegetation in densely built-up areas or roof top greening (Carter, 2011). These measures have the advantage that they not only mitigate the risk of flooding, but at the same time prevent overheating through insulation and passive cooling through shading and are therefore a measure against the urban heat island effect (Carter, 2011). Further flood protection measures are **protection structures** such as hard infrastructure, waterproof membranes on buildings and the development of the urban drainage system (Carter, 2011). It is important to develop the urban drainage system in a sustainable way (Carter, 2011), because the mere expansion of the drainage system compensates for the additional sealed surfaces, but only to a lesser extent in extreme events for the changed intensities of the rain due to climate change (Skougaard Kaspersen et al., 2017). Another measure to reduce exposure is to **prevent** further and increasing **economic**

development, **asset value increase** and further **densification** of human settlement on floodplains (Kreibich et al., 2017; Priest et al., 2016). Instead, Rossano (2015) proposes a **restoration of flood plains**. This **integrated water management** should bring back the natural fluctuation and replace permanent and rigid infrastructures. This trend is toward controlled inundation rather than complete exclusion and would result in a paradigm shift away from a total protection strategy to an accepted and thus well-controllable disaster (Rossano, 2015).

Vulnerability can be reduced with a flood warning system, especially for flash flooding, but also with the raised risk awareness which is necessary to ensure that early warning is taken seriously by the population. Risk awareness as well as preparedness and improvements of organizational emergency management generally increase after so-called "focusing events" (Kreibich et al., 2017, p. 954). These exert strong pressure to act and trigger risk mitigation and management. Land use planning can also reduce vulnerability (Kreibich et al., 2017).

The fact that measures are only taken after focusing events also applies to heat and drought, as Mücke & Litvinovitch (2020) describe that the extremely hot summer of 2003 was stimulating for the development of a national adaptation strategy in Germany, including measures to improve human health under heat. As a response to the extreme hot summer of 2003, the German Meteorological Service developed a **heat health warning system**. This was later supplemented with special recommendations for particularly vulnerable groups which are elderly people, outdoor workers, children, but also people with certain diseases or people living in densely populated areas (Mücke & Litvinovitch, 2020). Switzerland has a similar warning system, also with behavioural recommendations, since 2005 (Federal Office of Meteorology and Climatology MeteoSwiss, 2021). To complement the early warning, several European countries have developed **heat health action plans**. In Germany these should include measures concerning communication, reduction of exposure, and care for vulnerable people, which are implemented by the individual regions so that locally tailored adaptation is possible. Besides these short-term measures, long-term adaptation such as **improvements to housing and urban planning** are further possible measures (Mücke & Litvinovitch, 2020). Reductions in sealed surface area, increased green space, and inner-city ventilation channels can not only make urban populations more resilient to health impacts of future heat, but also reinforce adaptation measures by other sectors to climate change (Mücke & Litvinovitch, 2020). Since greening cities is an important measure against urban heat, but at the same time drought can occur, tree species more resistant to water scarcity are being searched for (Stratópoulos et al., 2019). Species from warmer regions are particularly suitable for this purpose, although it is important for sustainable adaptation in Central Europe that these species are resistant to cooler temperatures. Therefore, Stratópoulos et al. (2019) recommend **tree species selection** tailored to local conditions such as water availability and drought susceptibility.

In addition to these measures by government agencies and urban planners, there are also adaptation strategies that are implemented bottom up by the population itself. While in high income societies these are often technological and costly measures, Ferenčuhová (2021) argues that there are also strategies at the household level that are not associated with energy and material consumption and are implemented more intuitively. In the survey of Ferenčuhová (2021), individual adaptation strategies to heat and drought were mentioned, such as staying home of elderly people and families with children, getting used to the situation and being psychologically prepared, a shift of the daily schedule to avoid the exposure to extreme heat and for that getting up earlier. With regard to drought, water conservation was mentioned in particular, and in connection with this, the teaching of this practice to children.

Further individual strategies mentioned were the usage of grey water in combination with new technologies or accepting a lower level of comfort and hygiene (Ferenčuhová, 2021).

With this it is already indicated that for a holistic approach to adapt to future climate extremes in cities, the behavioural dimension is important in addition to urban planning, building regulations and water management (Aguiar et al., 2018; Carter, 2011). The behavioural dimension refers to awareness of potential impacts, landowner commitment, willingness to pay for resilience measures, and personal responsibility for action (Carter, 2011). Also, adaptation should be integrative, consisting of researchers, practitioners, policy makers, stakeholders and the general public (Aguiar et al., 2018; Carter, 2011). This prevents maladaptation and conflicts between different interests and adaptation measures (Aguiar et al., 2018).

The most important barriers to adaptation strategies in Europe are insufficient resources, technical capacity, political commitment, and financial resources. Inadequate communication and information, beliefs that influence people in their way of thinking about climate change, and uncertainties about future climate scenarios also hinder adaptation (Aguiar et al., 2018). The high potential for adaptation is often not realized as long as the extreme events do not occur (Kreibich et al., 2017). For this reason, adaptation strategies in Europe have increased after experiencing extreme climate events such as heat waves and droughts, storms and increased precipitation (Aguiar et al., 2018). While these costs of adaptation are immediately visible, their benefits will only become apparent in the future. Therefore, the focus of decision makers is often put on more urgent issues and it needs the trigger of research, case studies and national legislation for local adaptation strategies (Aguiar et al., 2018).

5.2. Recent water extremes in Swiss cities based on SFLDD

Extremes associated with climate change are climatic impact drivers that correspond to “unusual events with respect to the range of observed values of the variable” (Chen et al., 2021, p. 65 in press). In its reports, the IPCC uses the neutral term "climatic impact driver" instead of "hazard", since the latter has a negative connotation, whereas changes in the physical system caused by climate can also have positive impacts (Chen et al., 2021 in press). In relation to the extremes in the area of water, however, both high and low flow have problematic impacts (refer to Chapter 5.1.1) and are therefore hazards. In order to classify **recent** events, such as the drought in 2018 and the flood in 2021 in Basel, "a range of observed values" (Chen et al., 2021, p. 65 in press) is needed, as described above.

High flow and flood events

The Swiss Federal Research Institute WSL provides data on flood and mass movements back to 1972 (Hilker et al., 2009). This data is used in the following to compare the high flow events of Basel, Zurich, Bern and Geneva (Table 10).

*Table 10 Hazards on the process water 1972-2021 in the Swiss Cities Basel, Zurich, Bern, and Geneva. Dark orange revers to high or catastrophic damage (>2 million CHF), light orange revers to medium damage (0.4-2 million CHF), data not yet available in the database are marked with * (own illustration based on excerpt of the Swiss flood and landslide damage database (WSL, 2021)).*

City	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996
Basel							▨			▨															
Zurich																	■		▨			■	▨		
Bern						▨				▨															
Geneva								▨							▨										

City	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Basel			■						▨		▨														*
Zurich			■		▨	▨	▨		■		■					▨	▨		▨						*
Bern			■	▨				▨	■	▨							■								*
Geneva	▨										▨						▨						■		*

In the period 1972-2007, 89% of the damage costs were caused by floods and inundations. Long-lasting rainfall caused 75% of the total losses and triggered all six major events in the period 1972-2016 (Andres & Badoux, 2019b; Hilker et al., 2009). Five of these six major events (1987, 1993, 1999, 2000, and 2005) caused medium to catastrophic damage in one or more of the cities listed in Table 10. 80% of the damage caused by floods and debris flows affected material assets (Hilker et al., 2009).

In the analysis of the Swiss flood and landslide damage database, no statistically significant trend in the increase of damage costs in the period 1972-2016 and thus no potential influence of climate change on the damage processes investigated has been detected so far (Andres &

Badoux, 2019b). However, in addition to climate, the loss potential and the effectiveness of protection structures have also changed during this period (Hilker et al., 2009). Especially in cities, the extent of damage depends not only on the hazard but also on exposure and vulnerability (see Chapter 2.2). In addition, these major events in particular have led to better adaptation and thus to a reduction in damage costs for subsequent events. Overall, it must be assumed that the events registered in the database were not unique but will occur again in the future in a similar form (Hilker et al., 2009).

The enormous increase in the extent of damage in cities due to value accumulation in the last century is shown by the example of the city of **Zurich**. The last time Sihl and Limmat overflowed their banks was in 1910, and statistically this could happen every 100 years. In contrast to 1910, the potential damage is many times greater today, due to the high level of construction activity in the city and is estimated at three to five billion CHF. The floodplain would cover 1500 to 3600 buildings, with only 5% of the buildings having 50% of the damage due to the large accumulation of value. The analysis of the weather situation in 2005 showed that Zurich only narrowly escaped a flood disaster. If the centre of precipitation had been in the Sihl catchment area, large parts of the city of Zurich would have been flooded. With the knowledge of this event, a longer-term flood management as well as immediate measures were implemented in the city (Stadt Zürich Tiefbau- und Entsorgungsdepartement, 2022).

Bern also took adaptation measures after the serious floods in 1999 and 2005. In addition to emergency measures during the events, a long-term management system was set up to protect in particular the most densely populated neighbourhoods from flooding (Stadt Bern Bevölkerungsschutz, 2021).

Geneva was particularly affected by a major event in 2019. In mid-June, a thunderstorm moved across Switzerland from the southwest and caused major damage in the city canton of Geneva, among other places. Particularly in the city of Geneva, the damage was due to surface runoff (Liechti et al., 2020).

Going further back in time, the city of **Basel** was affected by extreme flooding in 1480. Other cities such as Bern, Fribourg, Olten and Aarau were also affected by this event. Along the Rhine, several bridges were destroyed, and the city was flooded via the “Schifflände” all the way to the marketplace, the latter due to backwater of the Birsig. The cause is believed to have been heavy rainfall over three days following on exceptionally warm temperatures. These probably caused additional melting of the snow, which had fallen abundantly the previous spring (Pfister & Wetter, 2011). Despite its enormous scale, however, the event has little relevance for the city's recent flood situation, as various hydraulic engineering projects were implemented in the Rhine catchment area in the 19th century, including the Jura water correction. The discharge behaviour of the Rhine has changed as a result, so that discharges of over 5000 m^3/s hardly ever occurred in the 20th century (Scherrer et al., 2006).

The following Table 11 compares the two flood events of the 21st century in Basel with the floods of the 20th century which exceeded a discharge of $4000m^3/s$ and the historical extreme event of the year 1480.

This compilation of floods in Basel (Table 11) shows that the resulting damage around the turn of the millennium was higher than before, although no trend can be concluded from this short time series also due to the social, economic and structural changes that took place in the meantime but were not included in the evaluation.

While nationwide 50% of the damages in the period 1972-2007 were registered in the month of August (Hilker et al., 2009), this agrees with Table 11, which shows a second flood focus for Basel in the month of May.

Table 11 Comparison of the floods in Basel in 20th and 21st century with the historic one from 1480. Estimated extent of damage from WSL Swiss flood and landslide damage data base in italics (in million CHF: low <0.4, medium 0.4-2, large/catastrophic >2 or death (WSL, 2021)).

Date	Discharge max [m³/s]	Weather conditions	Damage from flooding	Damage costs (SFLDD)	Source
1480-07-29	6000 – 6400	Wet and snowy spring, warm days with snowmelt before 3 days of heavy precipitation.	Floods up to marketplace, backwater on Birsig.	NA	(Pfister & Wetter, 2011)
1910-07-16	4300	Precipitation up to 25mm/day in Basel and Aargau, up to 32mm/day in Bern within the 10 days before (Federal Office of Meteorology and Climatology MeteoSwiss, 2014), large inflows from the Thur (Scherrer AG, 2004).	Riverbank floods on the Rhine in Basel, floods on the Birs and damage to industry there (regionatur.ch, 2020).	NA	(Pfister, 2006; Scherrer et al., 2006)
1978-07-31 – 1978-08-08	4150	Extensive precipitation in the catchment area over 2 days, up to 90mm/d	31.7.: Water damage in cellars, halls and apartments, flooded streets, especially in Kleinbasel (medium). 6.-7.8.: Flooding, overflow of the Birs at Birskopf due to backwater from the Rhine, Rhine shipping suspended, 1 freighter sunk.	Low	(Scherrer et al., 2006; WSL, 2021)
1994-05-18	4640	Large amounts of precipitation in the triangle Basel-Lucerne-Lake Constance, within 15h 60-100mm.	Minor floods, Flooding in Kleinbasel due to blocked sewage system.	Low	(Scherrer et al., 2006; WSL, 2021)
1999-05-12	5090	In the area of Bern, Central and Eastern Switzerland in 3 days between 80 and 130 mm, in 5 days up to 180 mm precipitation, previously high base flows from the lakes due to snowmelt. In Basel, over 100mm of rain fell between 7. and 13.5., in the night of 12.5. alone over 40mm.	Flooding on the Kleinbasel side, cellars on both sides of the Rhine under water, also due to groundwater infiltration, backwater of the Birsig and in the sewage system of the inner city, despite sandbags the Rhine promenade and some cross streets were flooded, a transformer station had to be switched off and led to power failure in one neighbourhood, interruption of shipping for 36 days, high damage in the port of Kleinhüningen.	Large / catastrophic	(Scherrer et al., 2006; WSL, 2021)

2005-08-22	3400	Heavy precipitation in the Alps, lower precipitation below the lakes.	Damage to private property.	Medium	(Scherrer et al., 2006; WSL, 2021)
2021-07-15	3448	See Chapter 5.4.1	See Chapter 5.3	NA	(FOEN, 2021a)

Low flow and drought events

While events and damages caused by water and mass movements are systematically recorded in Switzerland (WSL, 2021), there is no analogous database on events and costs of low water and drought events. However, on the occasion of the extreme summer drought in 2018, which affected the whole of Switzerland, the "WSL Drought Initiative 2018" (WSL, 2020) was established to answer specific related questions, particularly related to impacts and damages in the forest. The 2018 summer drought is classified as "the longest and most severe period with no precipitation since the start of systematic weather records in 1864" (WSL, 2020). At the same time, answering the severity of a drought event depends heavily on the perspective of the person asking the question and what measurements are used to make the assessment. However, surprisingly little is known about the consequences of earlier comparable weather extremes such as those that occurred in 1911, 1921, 1947, 1976, 2003 and 2015 (WSL, 2020).

With regard to the water discharge of the Rhine near Basel, historical reports can be referred to. Whereas in the 18th century discharges of less than 300 m^3/s were quite frequently recorded in the Rhine near Laufenburg in the months January to March, such low flows have not been documented since 1910 (Pfister, 2006). This development is considered to be a consequence of the increasing winter precipitation and temperature in the 20th century (Kohn et al., 2019; Pfister, 2006). In addition, the increasing winterly discharges on the Rhine were influenced by the effects of the hydropower plants from 1945 onwards. It is assumed that this reservoir management and the climate-driven trend, which is not expected to reverse in future, amplified, so that the winter stream flow in the Rhine in Basel increased (Kohn et al., 2019). The last winter low flow in Switzerland in 2016/17 resulted from a combination of low precipitation in autumn and winter and winterly freezing conditions. While in the 18th century low flows near Basel were documented exclusively in the winter months, summer droughts have also been described since 1962 (Kohn et al., 2019). Neither report Kohn et al. (2019) on low flow events in other Swiss cities, nor on costs caused by these events.

Although little is known about the impacts and costs of low-flow events themselves, damage caused by process water during low-flows and droughts is also registered in the WSL damage data base. An overview of the damage caused by water and flooding during the last low flow event 2018 in the Swiss cities of Basel, Bern, Zurich, and Geneva is given in Table 12.

Table 12 Damage due to water and debris flow in 2018 in the Swiss cities Basel, Bern, Zurich, and Geneva. Data and estimated extent of damage from WSL Swiss flood and landslide damage data base (in million CHF: low <0.4, medium 0.4-2, large/catastrophic >2 or death (WSL, 2021)).

Date	City	Weather conditions	Damage from flooding	Damage costs
2018-05-31	Zurich	Heavy thunderstorms over Switzerland in the evening with heavy rain.	Five fire brigade responses in the city.	Low
2018-06-08	Zurich	Strong thunderstorms over Switzerland.	Several fire brigade responses.	Low

2018-06-04	Basel	Thunderstorms over the Switzerland in the evening.	Flooded streets.	Low
2018-06-13	Basel	NA	The Birs floods a construction site.	Low
2018-07-03	Bern	Thunderstorm with lightning and hail.	Water had to be pumped out of cellars several times.	Low
2018-06-12	Geneva	44 mm of rain fell that day, 12 mm within 10 minutes.	30 fire brigade responses due to flooded buildings.	Low
2018-08-06	Geneva	Thunderstorm in the evening.	A total of 50 fire brigade responses due to flooding of cellars, garages, and apartments.	Low

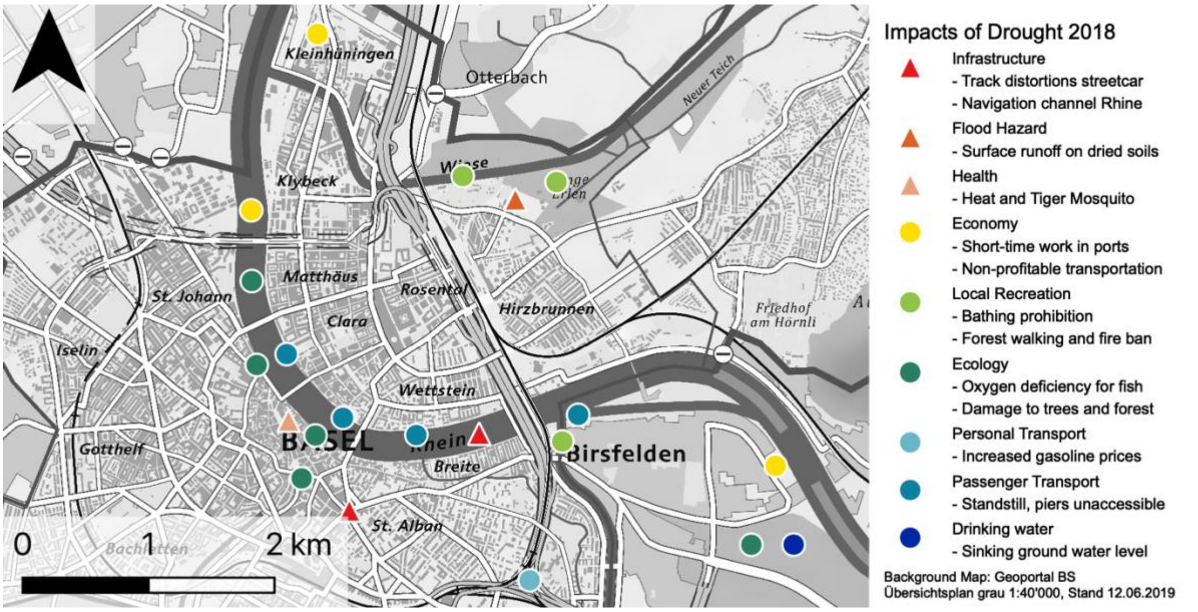
The year 2018 caused losses from landslides, debris flows, floods and fall events that were below the inflation-adjusted average from 1972-2017. After a precipitation-rich January, the year was very dry throughout Switzerland from April onward. Nevertheless, damage resulted, 79% of which was due to flooding, surface runoff, and debris flows. Of the damage in 2018, 69% was triggered by thunderstorms, with the Basel area only affected by flooded cellars in the Baselland region (Andres & Badoux, 2019a).

5.3. Impacts reported in newspaper articles

Both events, 2018 and 2021, were covered in the newspapers. The most coverage was in Basler Zeitung and Basellandschaftliche Zeitung, which was to be expected when looking for local impacts, which was limited to regional and national dailies. However, it is noticeable that in the case of the 2018 drought, more articles were published in national dailies about the effects than in the case of the 2021 flood.

Beyond the fact that the 2018 drought was a particularly prolonged event (World Weather Attribution, 2018), the newspaper articles published over a period of more than three months also reflect a wide spatial extent of impacts. In comparison, the coverage of the 2021 flood occurred over a much shorter period of three weeks and mainly described impacts that occurred directly linked to the water bodies.

The local dimension of the drought 2018 is illustrated in Figure 10. Both heat and low water led to hazards and damage to the ecology. While aquatic animals suffered from the high temperatures and decreasing oxygen in the water, damage was reported mainly to those trees that did not reach the groundwater with their roots. Branch breaks, cracks in the trunks and death of trees were described. In order to protect the cooler water sections as a retreat for the fish, but also to prevent the population from falling branches in the forest and the danger of forest fires, corresponding bans were imposed, thus limiting the possibility of local recreation for the population. The low water conditions further lead to ships navigating with a small cargo. As a consequence, a lack of economic efficiency of transport and increased gasoline prices were reported. Some port companies applied for short-time work. The deepening of the navigation channel to counteract these effects was already planned in the years before but implemented exactly in the summer that highlighted the necessity of the measure. Unaffected by the navigation channel, both ferries and passenger shipping were temporarily unable to reach the piers and had to be suspended.



Background Map: Geoportal BS
Übersichtsplan grau 1:40'000, Stand 12.06.2019

Figure 10 Approximate locations and categorization of heat- and drought-related impacts 2018 (own illustration based on Grundbuch- und Vermessungsamt Kanton Basel-Stadt (2019))

The heat caused distortions of the streetcar tracks on the one hand, and health problems on the other. Tiger mosquitoes were found, whereby it was critically questioned whether the dryness would not counteract a spread. The drought further led to falling groundwater levels, with reports of increased infiltration of Rhine water to compensate and no drinking water shortage occurred. In reports on intermittent short and intensive rainfalls it was emphasized that this did not lead to a relaxation of the situation but to an additional danger of surface flood due to the dry soils.

Figure 11 illustrates the spatial extent flood-related impacts as reported by news agencies in 2021. Over days, they described the flood situation in Basel as tense. As precaution, sandbags and other mobile flood protection measures were positioned at the Rhine and for smaller rivers in Riehen. There, the rakes were regularly cleaned of driftwood and the grass besides the Wiese was cut to improve the runoff. However, several reports emphasize that more important than flood defence at the Rhine had been the protection of the population. As the high water implied the danger of drowning due to the speed of the river, turbid water and driftwood, the popular recreational area along the watercourse was closed off by grids. At the Rhine no floodings of the riverbanks were reported, but the long duration of the flood led to undermined banks in the area of Rankhof and subsequently to a landslide with several fallen fishing piers and damage to the Rheinhalde nature reserve. Although immediate measures were taken to stabilize the bank, the neighbouring road had to be closed to private motorized traffic for several days. Traffic on the Rhine, both passenger and cargo shipping, were suspended too. The elevated water level further led to lower power production at the power plant in Birsfelden where at the same time additional work and costs were incurred due to time-consuming manual cleaning of the rakes from driftwood. Due to the turbidity of the water, IWB suspended the pumping of Rhine water into the Lange Erlen, nevertheless the drinking water supply was still ensured. Reports about impacts on surface runoff were not found.

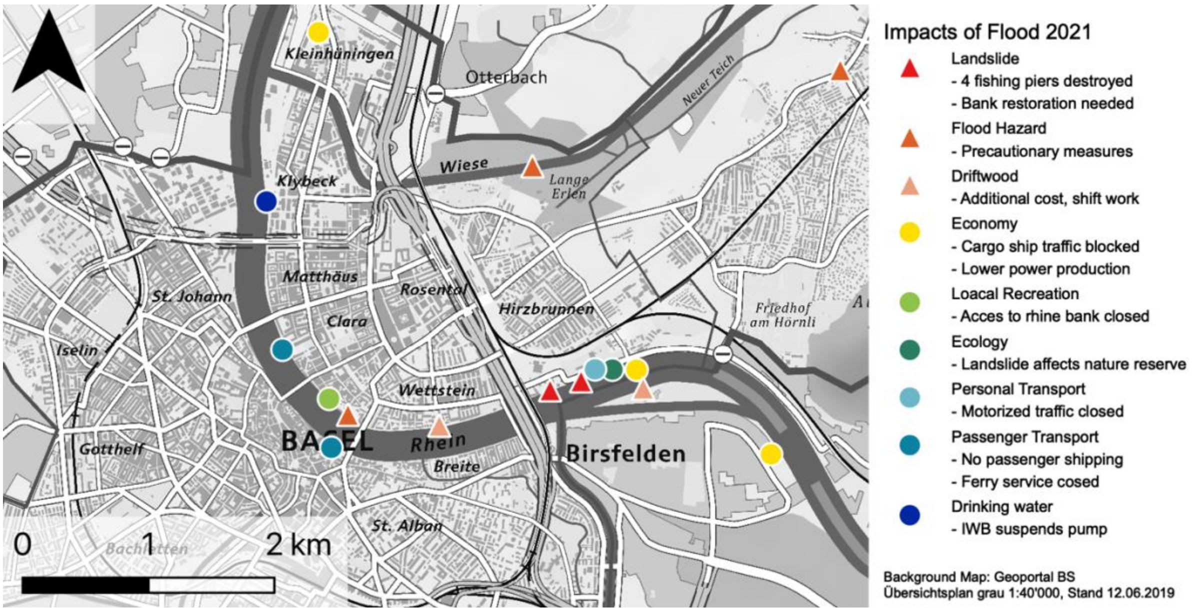


Figure 11 Approximate locations and categorization of high flow- and flood-related impacts 2021 (own illustration based on Grundbuch- und Vermessungsamt Kanton Basel-Stadt (2019))

5.4. Analysis of measured hydrological and meteorological data

In the following, discharge and water levels of Rheinhalle as well as precipitation data of the meteorological station in Binningen are analysed and presented. An overview of the data is given in Table 13 in which the upper and lower 2.5%-quantiles are highlighted, as these are used as thresholds for subsequent analyses of extremes (Figure 19-Figure 25).

Table 13 Descrptive statistics of discharge and level at Rheinhalle and precipitation in Binningen, daily data 1981-2021.

1981 – 2021	**Rheinhalle Mean daily discharge [m³/s]**	**Rheinhalle Maximum daily level [m]**	**Binningen Daily sum of precipitation [mm]**
count	14972	14973	14961
mean	1061.328	6.015	2.287
std	447.451	0.693	5.130
min	366.771	4.908	0.000
2.5%	476.860	5.105	0.000
5%	520.686	5.169	0.000
10%	583.000	5.265	0.000
25%	730.426	5.489	0.000
50%	971.816	5.872	0.000
75%	1284.176	6.375	2.200
90%	1654.904	6.962	7.300
95%	1923.301	7.362	12.200
97.5%	2178.401	7.740	17.700
max	4583.997	10.580	87.600

5.4.1. Analysis of the events of 2018 and 2021

Across the annual data, the median discharges in 2018 and 2021 were at the lower and upper quartiles, respectively, of the 1981-2021 period. However, the boxplot (Figure 12) also shows that there were also maximum discharges at the upper quartile boundary in 2018 and minimum discharges around the median in 2021. The data set shows outliers of high outflows, but none of low outflows.

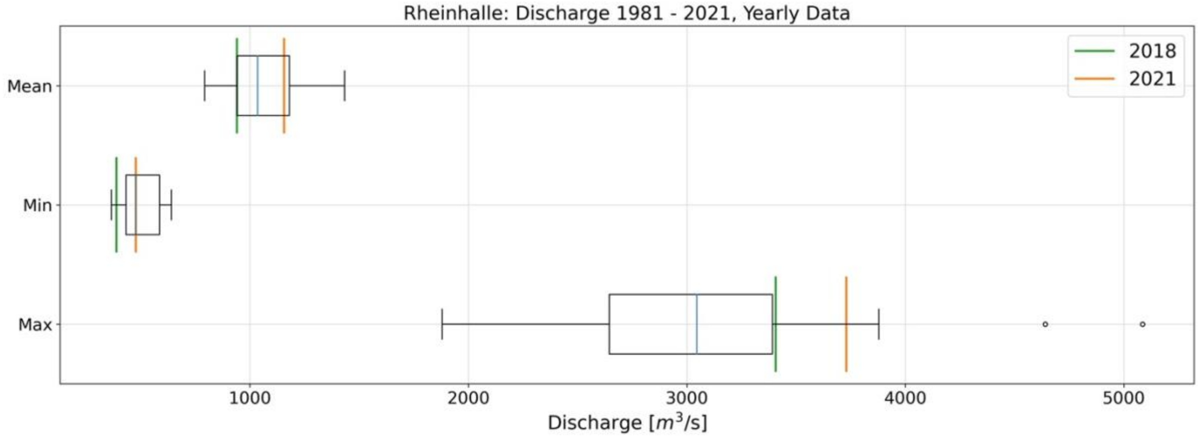


Figure 12 Boxplot of yearly mean, minimum, and maximum discharge, 1981-2021, Rheinhalle.

The hydrographs with monthly resolution (Figure 13) show that the patterns of the two events in 2018 and 2021 are markedly different and place them in relation to the mean of the 1981-2021 period. The 2021 flood affected two months, with the following fall having remarkable low discharges, as did the preceding April. The 2021 flood is thus situated between two rather dry periods. The 2018 event was significantly longer as the low water lasted six months, with slightly higher discharges before and after this period. During the 2021 flood event, the minimum measured values also exceeded the average for the 1981-2021 period. Likewise, the maximum values measured, especially in late summer and autumn in 2018, fell below the average of the reference period 1981-2021.

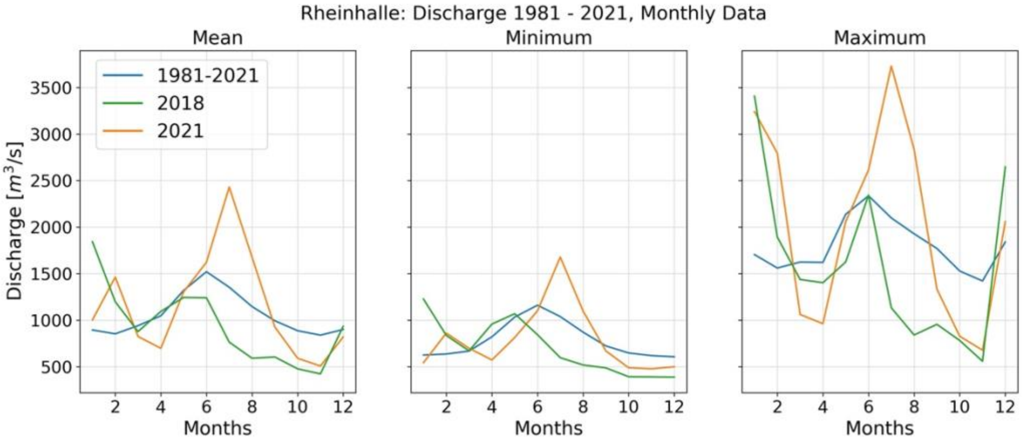


Figure 13 Hydrograph of monthly mean, minimum, and maximum discharge, 1981-2021, Rheinhalle.

The boxplot with monthly data (Appendix, Figure 41) and its subdivision into hydrological seasons (Figure 14) provide more information on the dispersion of monthly data from 1981-2021. In Figure 14, the references to 2018 and 2021 each combine the three single monthly mean values per hydrological season, displayed as one mean. The plot shows that both winters tended to be wet and both springs were relatively close to the median. The major difference between the 2018 and 2021 events is visible in the summer, with both years followed by a fall with low runoff.

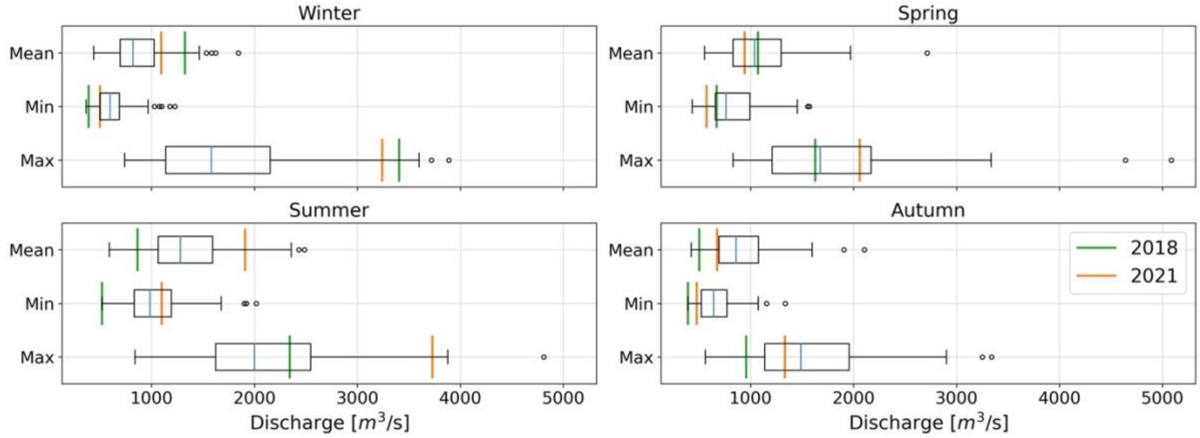


Figure 14 Boxplots of monthly mean, minimum, and maximum discharge data with subdivision into hydrological season, 1981-2021, Rheinhalle.

Figure 15 shows in monthly boxplots the means of 2018 and 2021, respectively, compared to the longer period of 1900-2021. Since the same analysis was also performed in relation to the reference period 1981-2021 (Appendix, Figure 42), some differences can be identified. In particular, because the monthly discharge data from 1900-2021 show greater variability compared to those from the shorter 1981-2021 period, they provide a different reference to the mean data from 2018 and 2021 that are drawn in the boxplot. While mean discharge values from July, August, October, and November 2018 are each at the lower whiskers of the

1981-2021 period, they are within the whiskers of the period beginning in 1900. Compared to the larger time period, the months mentioned appear to be less extreme. Since the spread of the 1900-2021 period is much larger, especially in August, the mean value of August 2021 lies in the middle of this whisker, but at the outer end of the whisker for the period 1981-2021. Compared to both time periods, July 2021 is a clear outlier. Moreover, the plot shows well how opposite the months of July and August were in 2018 and 2021, respectively. Also, the different dynamics of the events is again illustrated: while 2021 showed high outflows over a short period of time, 2018 showed low outflows over a long period of time.

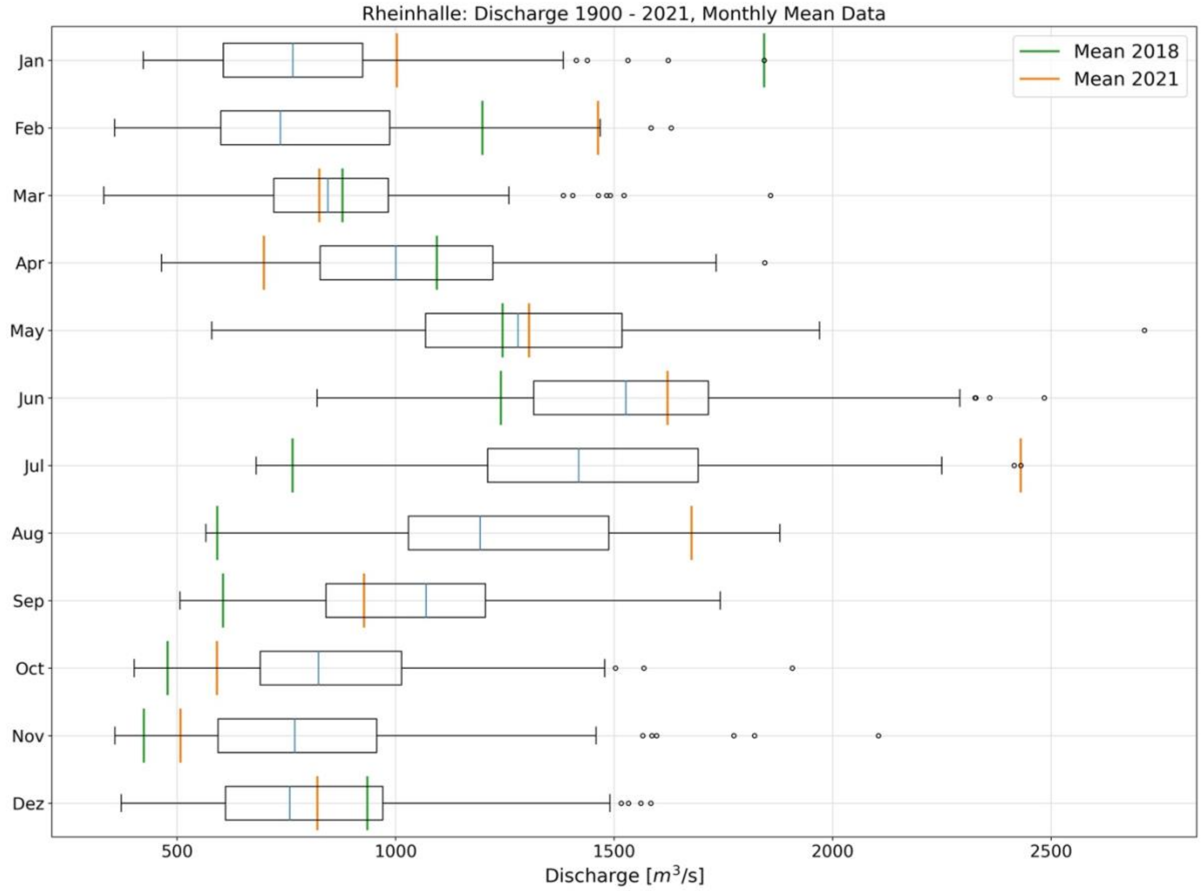


Figure 15 Boxplots per month of monthly mean discharge, 1900-2021, Rheinhalle.

The following hydrographs (Figure 16 and Figure 17) show runoff in daily resolution and daily total precipitation from 2018 and 2021, both compared to the 1981-2021 period mean. They indicate the relation of precipitation and discharge at the Rheinhalle measurement station, whereby it must be mentioned that the discharge of the Rhine is mainly determined by precipitation over the cantons Aargau and Bern (compare Appendix 9.5.4 and Scherrer et al. (2006)), and not primarily by those over Basel. Therefore, it is understandable that the individual precipitation peaks in the following graphs raise the discharges only slightly and with a delay.

In 2018, an enormous heavy precipitation on a single day in May stands out, followed by dry summer and autumn with single heavier precipitations (Figure 16). These single heavy precipitation events are hardly able to raise the discharge of the Rhine, or only if they occur several times in a row.

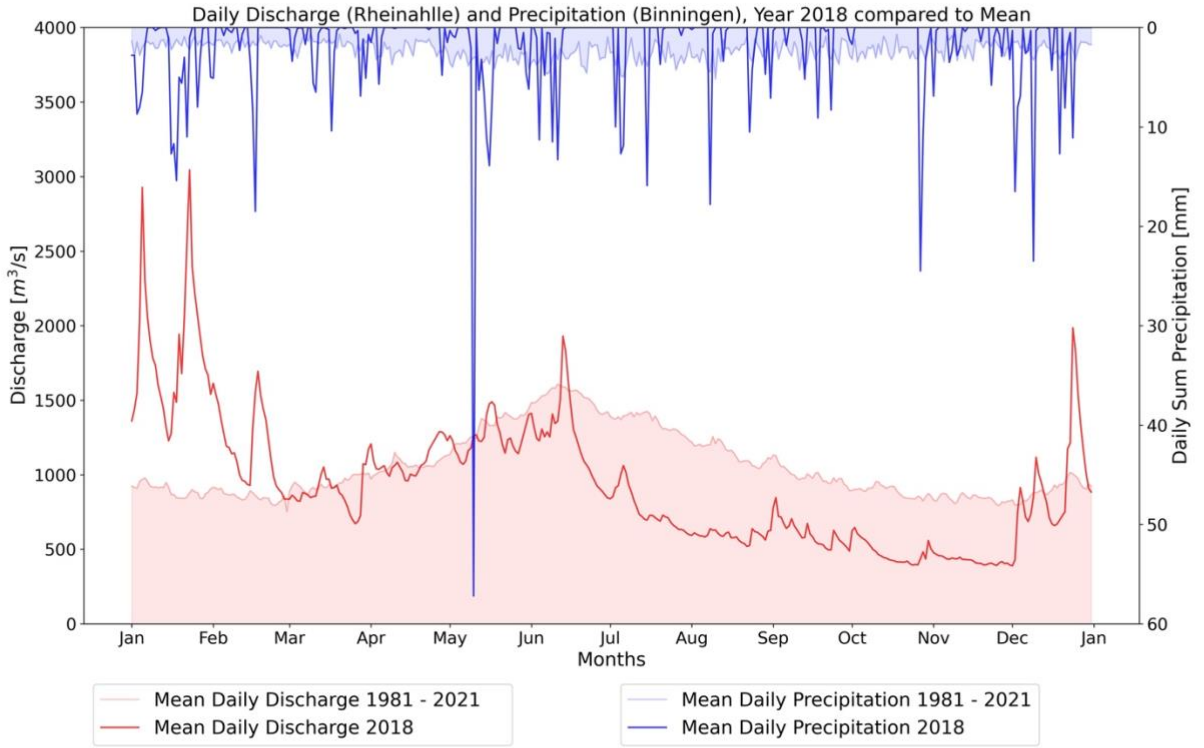


Figure 16 Hydrograph of daily mean discharge and sum precipitation data, 2018 compared to mean of 1981 - 2021, Rheinhalle and Binningen.

The year 2021 shows higher precipitation from May to August, with a prominent peak of high runoff in July (Figure 17). This is also clearly reflected in the newspaper coverage, which focuses on a few days in July (see Section 5.3 and Table 19). Remarkable are also the high discharges in February 2021, although their duration was much shorter. These two periods in 2021 with peak flows were separate from a spring with rather below-average flows.

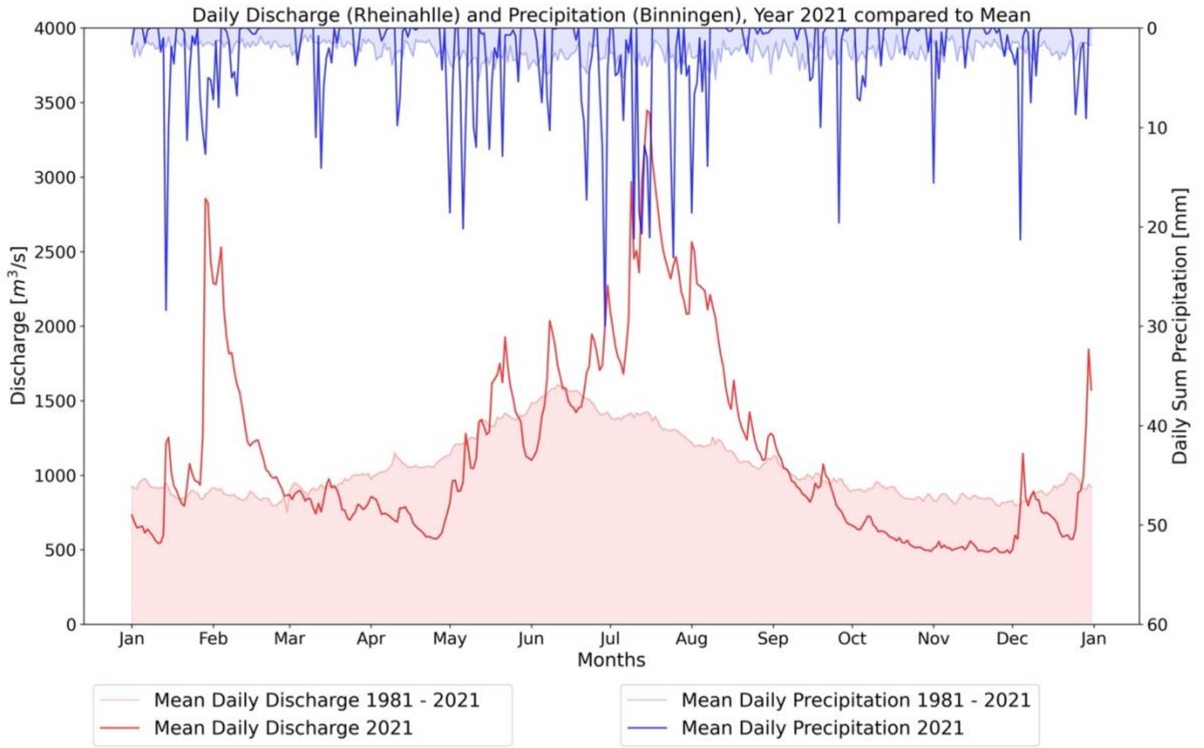


Figure 17 Hydrograph of daily mean discharge and sum precipitation data, 2021 compared to mean of 1981 - 2021, Rheinhalle and Binningen.

Since the months of July to October 2018 and 2021 are particularly relevant for the extremes, a corresponding month-by-month presentation is shown in the Appendix (Figure 43). In it, August 2021 clearly shows the change from high to low water.

To test the hypothesis that the years preceding 2018 were also exceptionally dry, particularly 2016 and 2017, these years are compared in the following plot. Figure 18 shows again precipitation and runoff data in daily resolution. The graphs show a tendency towards low outflows from September 2016 onwards, which – with an interruption in winter 2017/18 – continued until the end of 2018. The period of May until June 2016 shows a similar pattern to summer 2021 (Figure 17) in terms of precipitation and runoff, but less extreme.

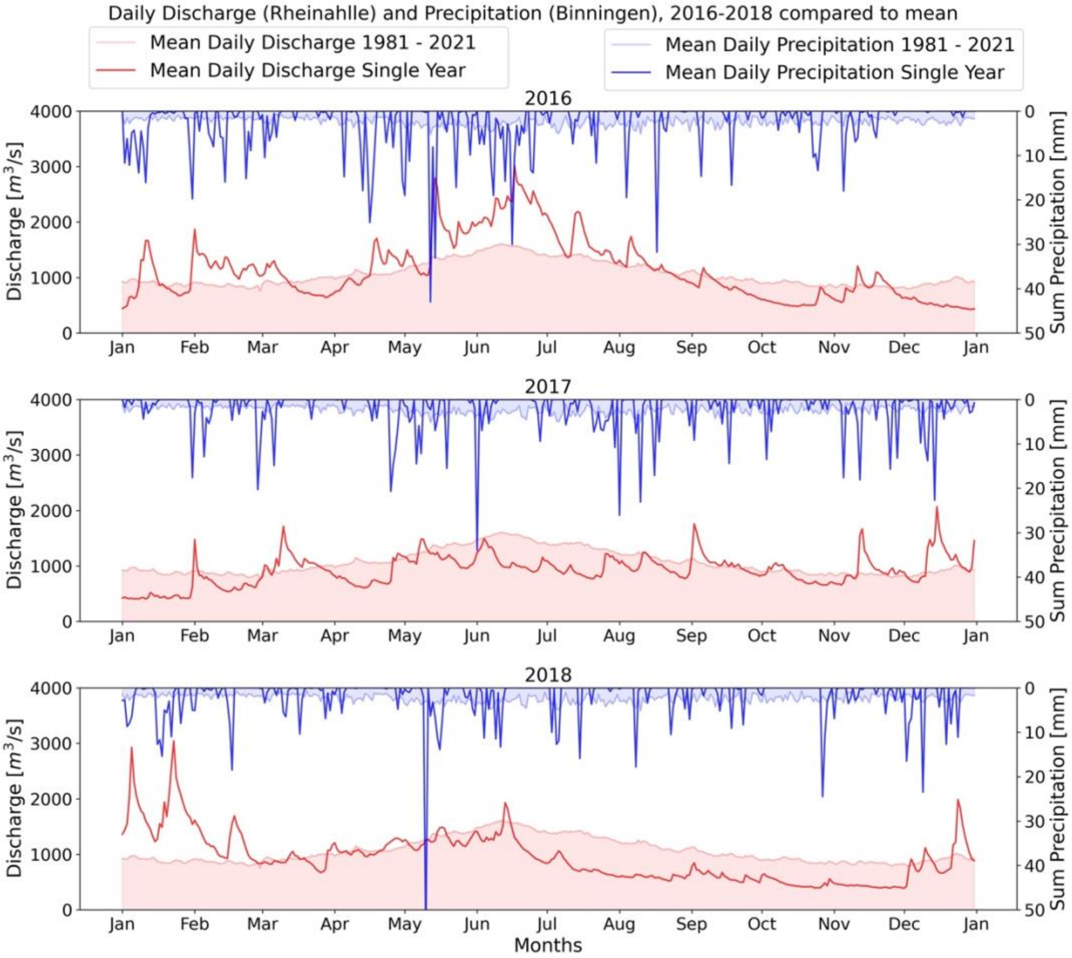


Figure 18 Hydrograph of daily mean discharge and daily sum precipitation data, 2016-2018 compared to 1981 - 2021, Rheinhalle and Binningen.

The extreme one-day precipitation event in May 2018 is visible in full extent in Figure 17. Similar precipitation events also occurred in May and July of the other two years, 2016 and 2017.

5.4.2. Analysis of extreme discharge

The duration of the event is also decisive for the extent of the impacts, both in the case of high and low water (compare Chapter 5.3 and Chapter 5.6). The next plots therefore show the number of days with discharges above or below a threshold. The scatterplots show individual events with the number of consecutive days above or below the limiting value. In contrast, the histograms summarize the number of days above or below the threshold per year to allow a better readability of the data. In order to detect a possible shift of the events into another hydrological season, the data points of the scatterplots are coloured accordingly.

The upper and lower 2.5% of the data for the period 1981-2021 were chosen as cut-off thresholds (Table 13), these values correspond to the 0.975-quantile and the 0.025-quantile, respectively. All analyses in this subchapter refer to measured data from the hydrological measuring station Rheinhalle in Basel.

The number of days per year of the upper 2.5%-quantile (Figure 19) does not show a trend within the period 1981-2021, but clearly outstanding years. In addition to the years 1987 and 1999, the year 2021 is also one of the top three years with the most days with extremely high discharges.

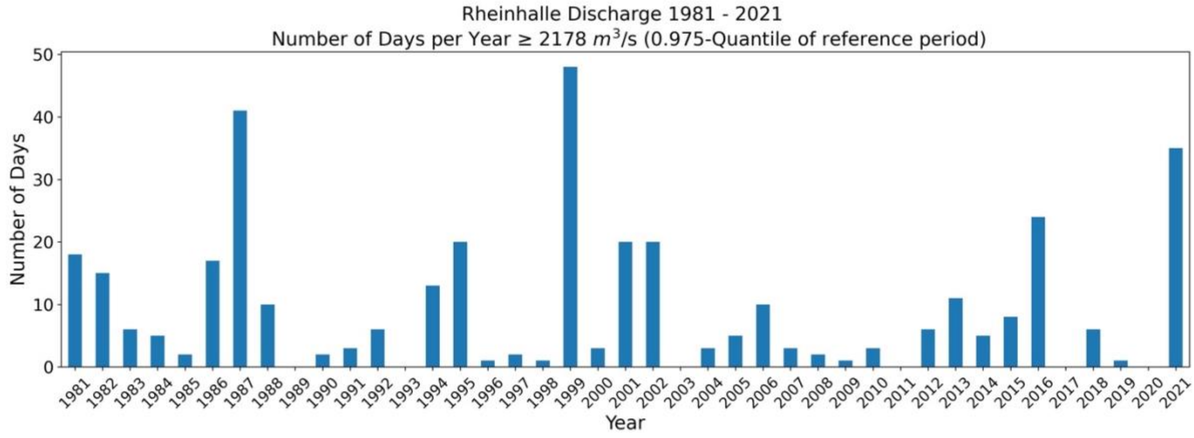


Figure 19 Discharge Rheinhalle, upper 2.5% of the events, number of days per year, 1981-2021

Considering the individual events, divided by hydrological season (Figure 20), no tendency towards longer events is visible. According to this graph, the longest periods of discharges above 2178 m^3/s clearly occur in spring and summer. A significant change of these events towards another season cannot be derived.

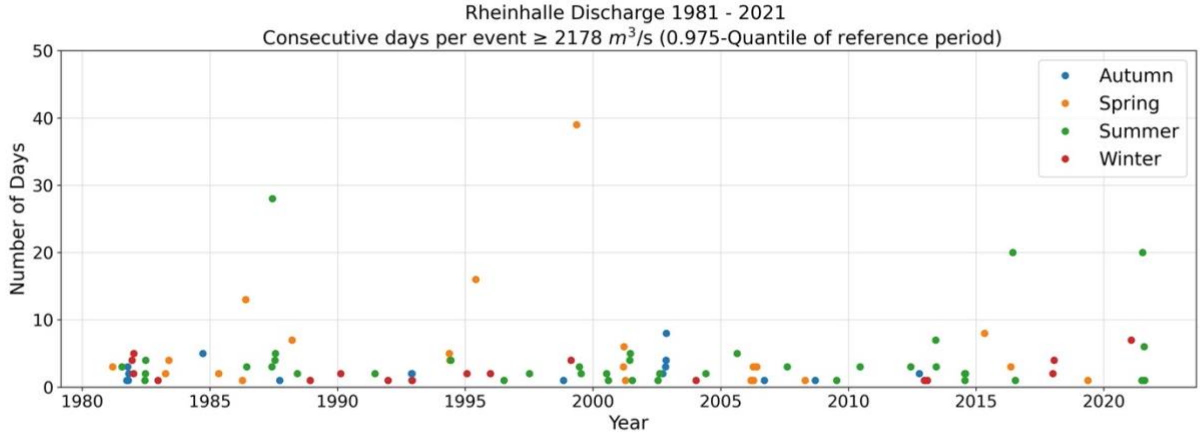


Figure 20 Discharge Rheinhalle, upper 2.5% of the events, number of days per event, 1981-2021

With regard to the impacts of high runoff and floods on navigation in Basel, the same analysis as above was carried out with the data of water levels (Appendix Figure 44 and Figure 45). This because water levels are decisive for the navigability of the Rhine. From a water level of 7.9m, major navigation is suspended, from a water level of 8.2m, all navigation is prohibited (Port of Switzerland, 2018a) – therefore these two numbers were chosen as threshold values for this analysis. The results do not show a clear increase or decrease in the number of days above these thresholds over the period 1981-2021. The years 1999 and 2021 again stand out clearly. An analogous analysis of the levels at low water was not carried out, as there are no clear legislative thresholds for this case.

However, low water was studied in terms of discharges below the 2.5%-quantile (Figure 21) analogous to the analysis of high outflows. While no increase or decrease in the number of days can be seen over this period, it is noticeable that between 2003 and 2006, as well as between 2015 and 2018, there was an accumulation of the number of days per year below this threshold over each of the four years.

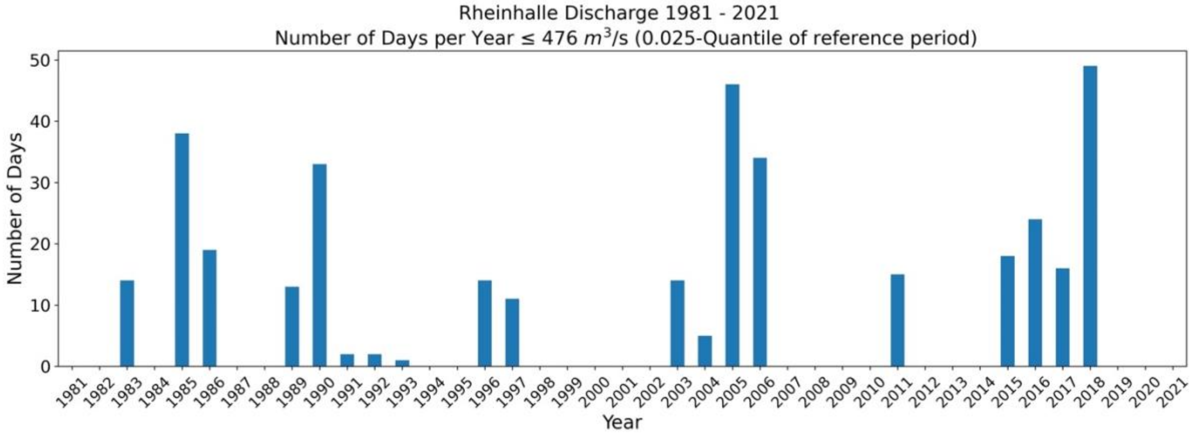


Figure 21 Discharge Rheinhalle, lower 2.5% of the events, number of days per year, 1981-2021

An examination of the individual events, broken down by hydrological season shows that most low-water periods occur in autumn and winter (Figure 22). In summer, discharge rates of the bottom 2.5% of all values have not occurred in the last forty years at all. In the spring, such events took place only sporadically, with a noticeable concentration in the 1990s.

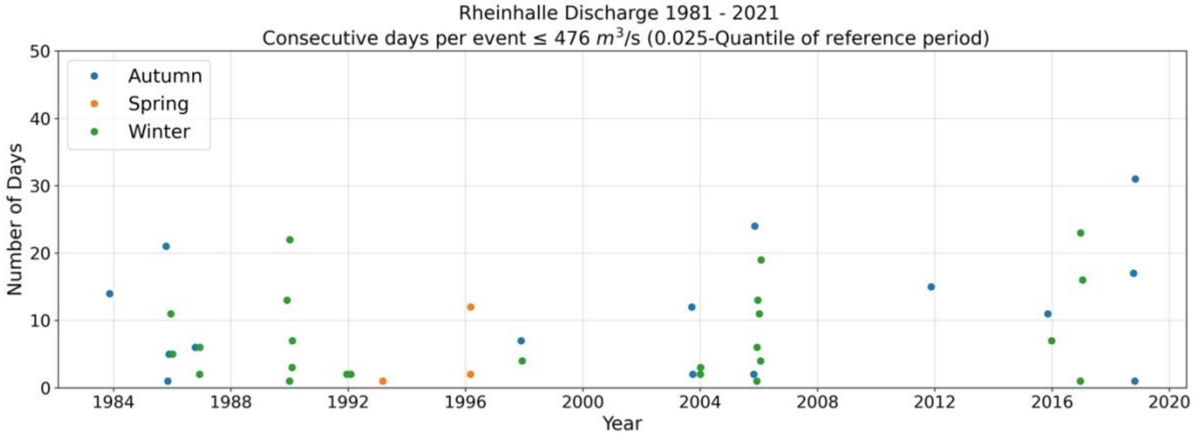


Figure 22 Discharge Rheinhalle, lower 2.5% of the events, number of days per event, 1981-2021

Since hardly any trends are evident in the rather short time period from 1981-2021, the analogous analysis of the longer period from 1900-2021 follows in Figure 23 and Figure 25. For both extremes, the number of days per year above and below the threshold were plotted in histogram, line plot and scatter plot. The histogram summarizes the data in 5-year periods, for which data from 1902 onwards were considered.

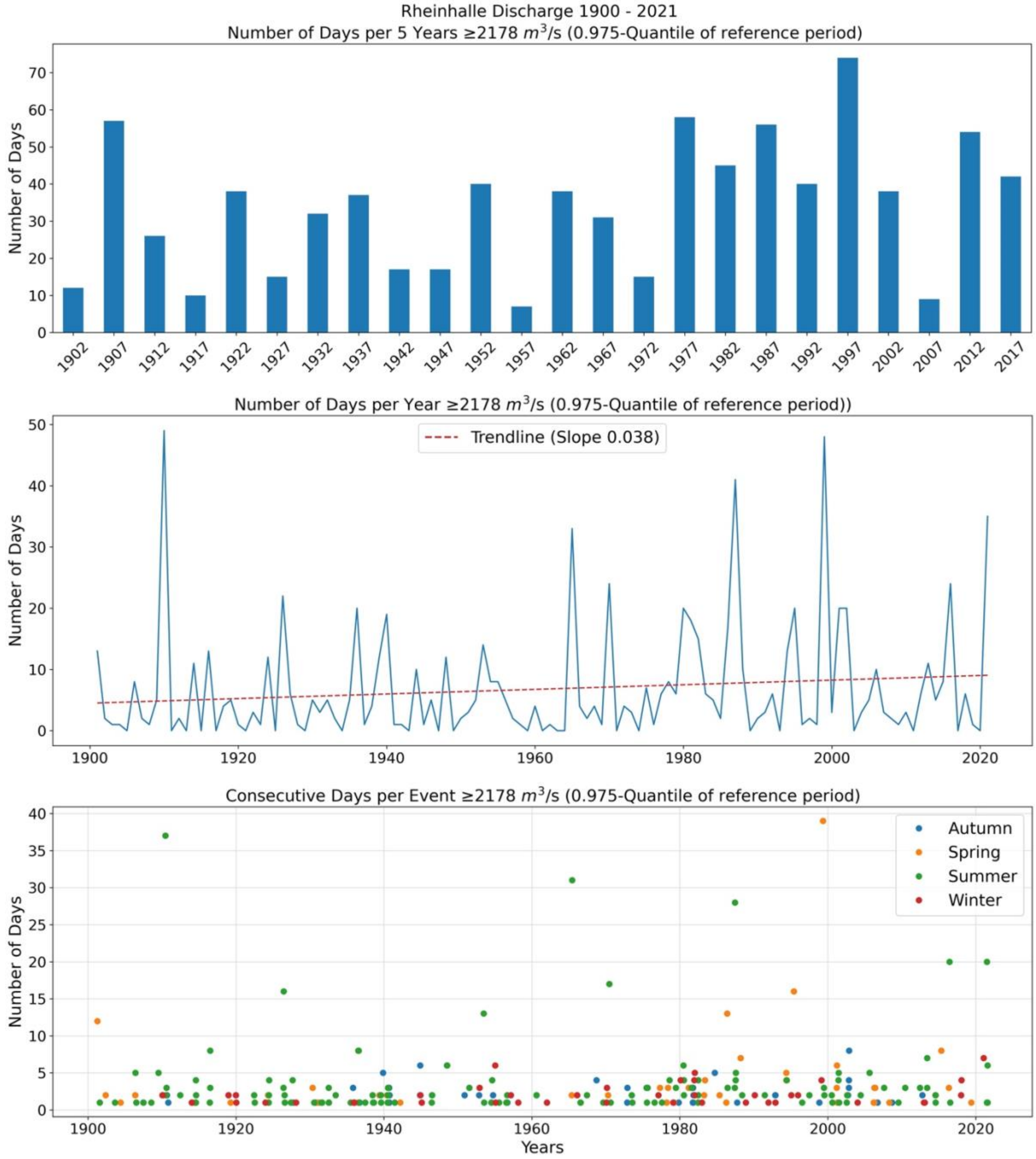


Figure 23 Discharge Rheinhalle, upper 2.5% of the events, number of days per five years, year and event, 1900-2021

The above histogram of the flood and high flow events shows a slight increase in the number of days, which is confirmed by the positive trend (slope of 0.038) of the line plot. In the consideration of the first and even more clearly the second plot of Figure 23 it is noticeable that the first and the second halves of the last century differ significantly in terms of discharge behavior at Rheinhalle. This becomes even clearer in the calculation of the average number of days above the threshold value of 2178 m^3/s discharge over the entire period and over the following sub-periods:

Top 2.5% high-flow events (refers to Figure 23):

– Single year 1910:	49 days / year
– Mean 1900-2021:	6.73 days / year
– Mean 1911-1964:	4.44 days / year
– Mean 1965-2021:	8.32 days / year

The above list refers to the number of days per year that the discharge exceeded the 0.975-quantile of the reference period (1981-2021). It shows that in the last 55 years the number of days per year was almost twice as high as in the previous period of the same length. The year 1910 shows the largest number of days above this threshold in this time series from 1900 onwards.

The breakdown into events per hydrological season (third plot in Figure 23) shows a similar picture as for the shorter study period 1981-2021 – in both cases spring and summer are the dominant seasons for high discharge events. However, in the analogous analysis from 1981-2021 (Figure 20), 0.975-quantile events appear to increasingly play a role in fall and winter as well, although with shorter durations.

The same analysis was also carried out with the much higher threshold of 3553 m^3/s, since this corresponds to the lower confidence interval of HQ_{10} (BAFU, 2021). However, the results (Figure 24) showed that since 1900, these events have occurred sporadically, at about the expected 10-year interval, and have lasted only single days. The only outlier of this analysis was the year 1999, in which these high discharge values lasted over four consecutive days and one single day. A shortening of the intervals between these events towards the turn of the millennium can hardly be concluded on the basis of the few events. These HQ_{10}-events occurred in all hydrological seasons.

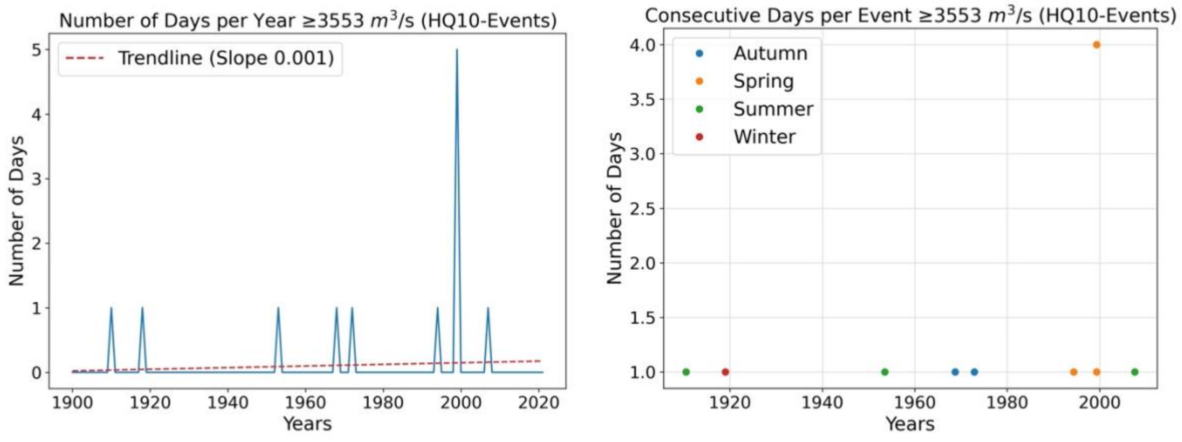


Figure 24 Discharge Rheinhalle, events of ≥HQ_{10} 1900-2021. Days per year (left) and events (right) coloured by hydrological season.

While a slight trend towards longer extreme flood periods can be observed, the duration of low water periods has clearly decreased over the past century (Figure 25). Analogous to the shorter investigation period 1981-2021, no low flow extreme events of this magnitude are found in summer in this extended time series either. The hydrological seasons autumn and winter are about equally dominant in this evaluation. The graph shows that low flows of the 0.025-quantile played a role in the last century only sporadically in spring, and then they were rather short events.

Again, a dichotomy of the past century can be observed. The average number of days of this event per period varies as follows:

Bottom 2.5% low-flow events (refers to Figure 25):

- Single year 1921: 132 days / year
- Mean 1900-2021: 18.94 days / year
- Mean 1900-1972: 26.26 days / year
- Mean 1973-2021: 8.24 days / year

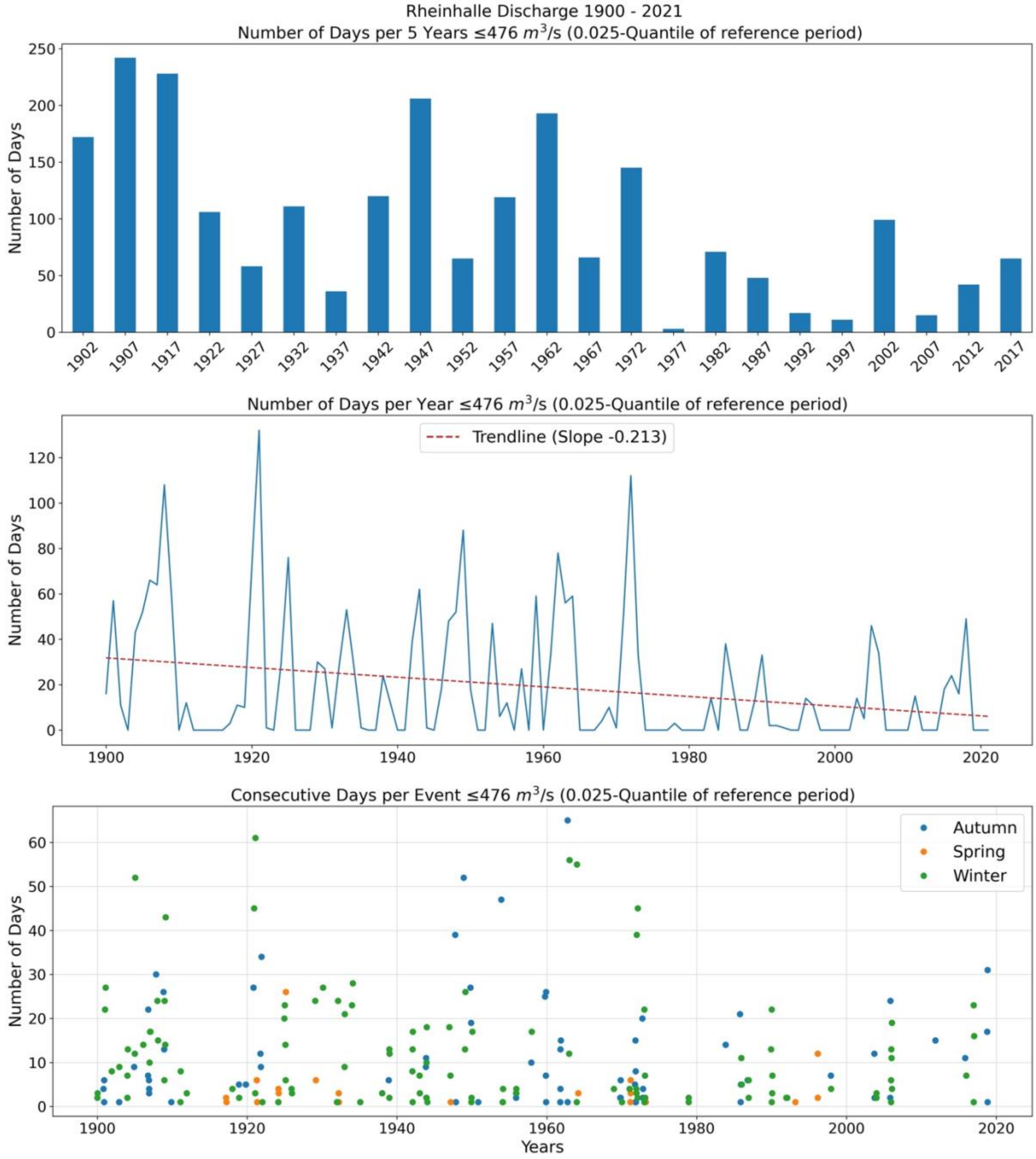


Figure 25 Discharge Rheinhalle, lower 2.5% of the events, number of days per five years, year and event, 1900-2021

Compared to the duration of the flood events, it is noticeable that during the 20th century low-water periods last significantly longer than high water periods.

5.4.3. Analysis of extreme precipitation

The following plot shows the number of days per year on which precipitation at the Binningen measuring station reached or exceeded the 0.975-quantile (Table 13) of the reference period 1981-2021. Since this measuring station only provides daily precipitation measurements from 0:00 UTC - 0:00 UTC from 1981 onwards, it was not possible to carry out analyses going further back.

The individual events over this threshold mostly lasted only one day, in a few cases up to three days. Events of longer duration were not recorded. Also, the events are equally distributed across all hydrological seasons.

Figure 26 shows no trend in the number of days of these events per year. Around the turn of the millennium, an increased variability of the values is evident. The highest number of days took place in 2002, the lowest in the year 2003.

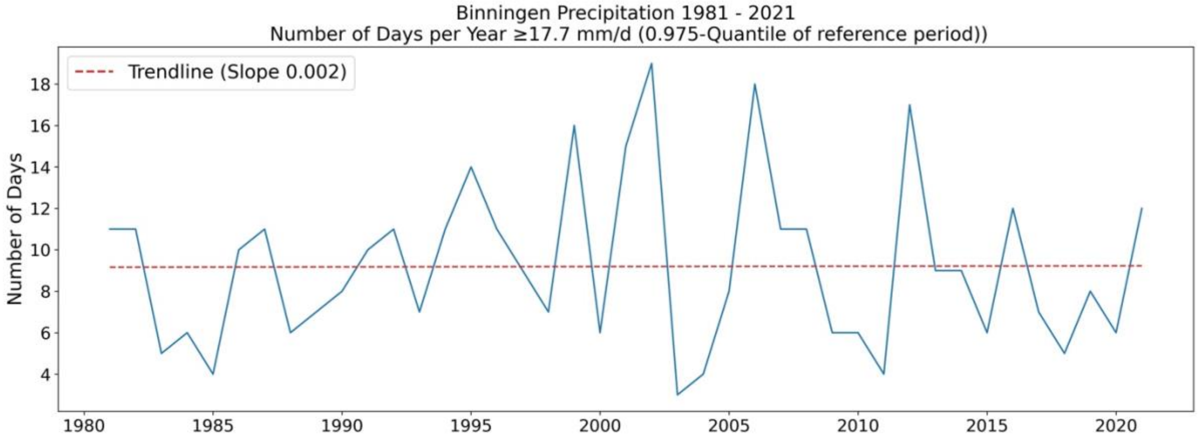


Figure 26 Precipitation Binningen, upper 2.5% of the events, number of days per year, 1981-2021

5.5. Identification of future extremes with Hydro-CH2018

All the plots in the Chapters 5.5.1 to 5.5.5 refer to Hydro-CH2018 data of the station Rheinhalle in Basel (Zappa et al., 2021). Chapter 5.5.6 shows similar analysis for the precipitation data of the station Binningen (CH2018, 2018; CH2018 Project Team, 2018). The period 2022-2099 is shown in each case, with all thresholds referring to the quantiles of the reference period 1981-2021 (Table 13). In addition to the RCP scenario, for each graph the selected threshold is given as an absolute value and as a quantile.

The aim of these analysis is to show how the extreme events, defined as the upper and lower 2.5% of the reference period, will develop by the end of the century.

5.5.1. Discharge RCP2.6 scenario

The RCP2.6 scenario subsumes eight different models. These show a minimum increase of +2.3% by 2099 in the analysis of the top 2.5% of events of high runoff (Figure 27). The daily means across all models in number of days above this threshold varies as follows:

Top 2.5% high-flow events (refers to Figure 27):

- Minimum of mean values: 2.62 days / year
- Maximum of mean values: 25.0 days / year
- Mean of mean values: 11.51 days / year

The eight models were divided into two subgroups for analysis, with the four models with the lower mean values showing a greater increase. The four upper models show a smaller increase in the number of days, but their level is slightly higher. If this analysis is carried out per hydrological season, there is a small increase or decrease of ±1.7% across all seasons and thus no trend in a single season.

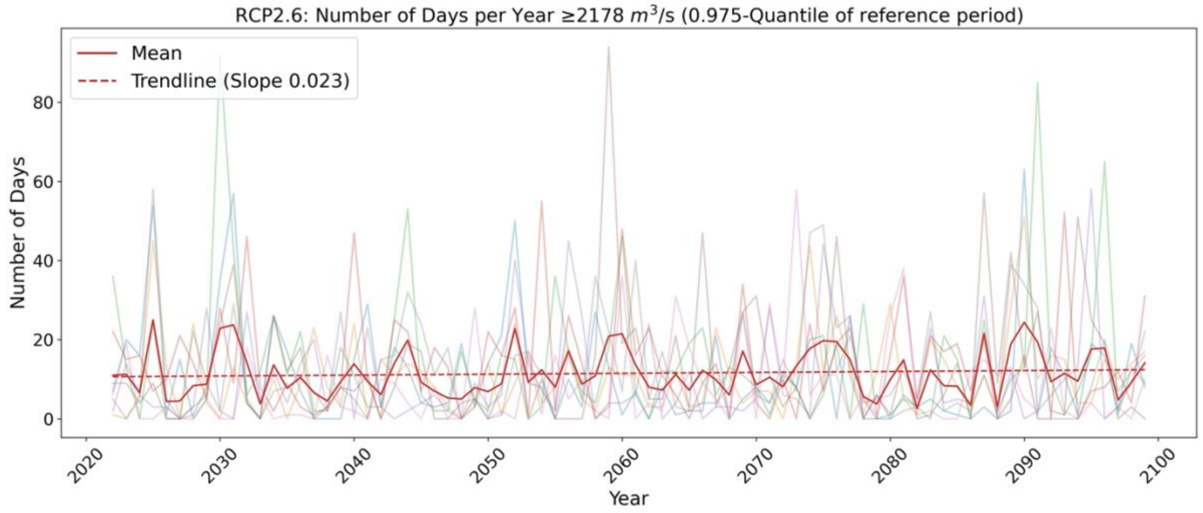


Figure 27 Expected future number of days per year above the 0.975-quantile of the reference period discharge (1981-2021) according to Hydro-CH2018, RCP2.6. The 8 models of the scenario are shown in pastel colours, their mean and trend line in red.

A trend in the number of days below the 2.5%-quantile is slightly present under RCP2.6, with the trend line indicating a slope of +5.6% (Figure 28). A subdivision of the models by mean into two groups shows that their development of the trend line varies barely. The subdivision into hydrological seasons shows that in winter the 0.025-quantile is only undercut on a few days, in spring there are hardly any such events. For these two seasons there is also no development under this scenario until 2099. The level of low water days in summer and autumn is higher, with a slightly decreasing trend in summer (-2.5%) and an increasing trend in autumn (+5.4%). A comparison of the two graphs (Figure 27 and Figure 28) shows that there are significantly more days below the 0.025-quantile than above the 0.975-quantile.

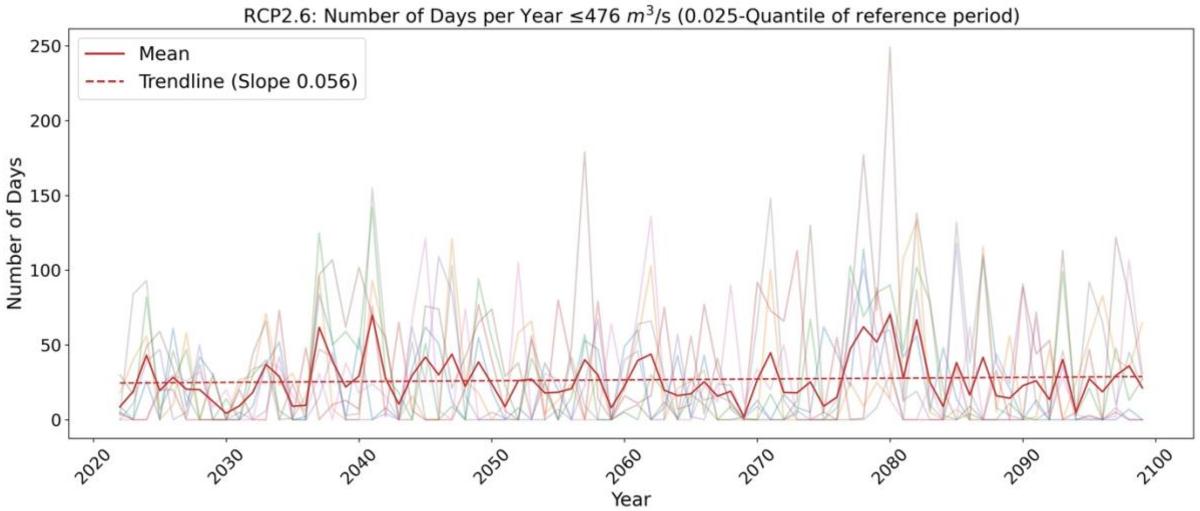


Figure 28 Expected future number of days per year below the 0.025-quantile of the reference period discharge (1981-2021) according to Hydro-CH2018, RCP2.6. The 8 models of the scenario are shown in pastel colours, their mean and trend line in red.

The mean of all models in the RCP2.6 scenario varies for the extreme low flow events between 2022 and 2099 as follows:

Bottom 2.5% low-flow events (refers to Figure 28):

– Minimum of mean values:	1.88 days / year
– Maximum of mean values:	70.38 days / year
– Mean of mean values:	26.67 days / year

5.5.2. Discharge RCP4.5 scenario

The RCP4.5 scenario comprises 13 models (Figure 29) and, at +2.2%, indicates a comparable increase in days of the top 2.5%-events of discharge as the RCP2.6 scenario. The mean value over all models of RCP4.5 shows the following minimum, maximum and medium number of days per year:

Top 2.5% high-flow events (refers to Figure 29):

– Minimum of mean values:	3.69 days / year
– Maximum of mean values:	24.23 days / year
– Mean of mean values:	11.33 days / year

The four models with the highest mean values indicate the strongest increase in days above this threshold, with the middle five models predicting no development but at a slightly higher level than the bottom four models, which again indicate a slight increase in the number of days of this event. The subdivision into hydrological seasons also shows a comparable picture with RCP2.6. Under RCP4.5, no significant increase or decrease in the number of days of this event is evident in any season up to 2099. However, the maximum peaks of the single models in this graph are higher than under RCP2.6.

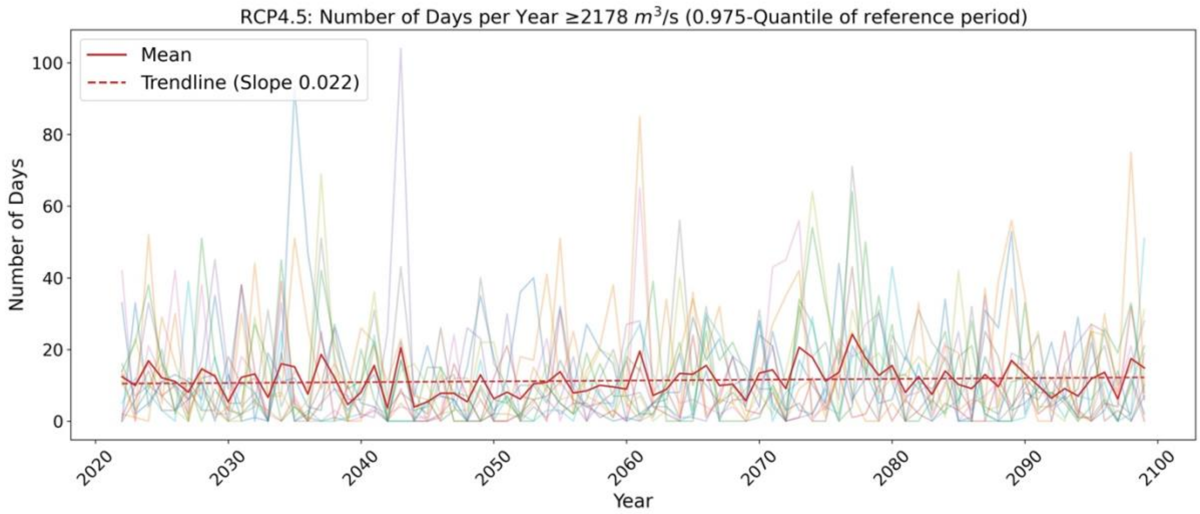


Figure 29 Expected future number of days per year above the 0.975-quantile of the reference period discharge (1981-2021) according to Hydro-CH2018, RCP4.5. The 13 models of the scenario are shown in pastel colours, their mean and trend line in red.

On the other hand, RCP4.5 already shows a more pronounced average increase in events of the lower 0.025-quantiles than RCP2.6. The average increase of +16.3% (Figure 30) is most pronounced in summer (+8.9%) and autumn (+6.1%). For winter and spring, no development is expected under this scenario. Compared with the same analysis under RCP2.6, it is noticeable that overall more individual models of RCP4.5 indicate a high number of days under this threshold, but the maximum number of days of this event per year is smaller than under RCP2.6.

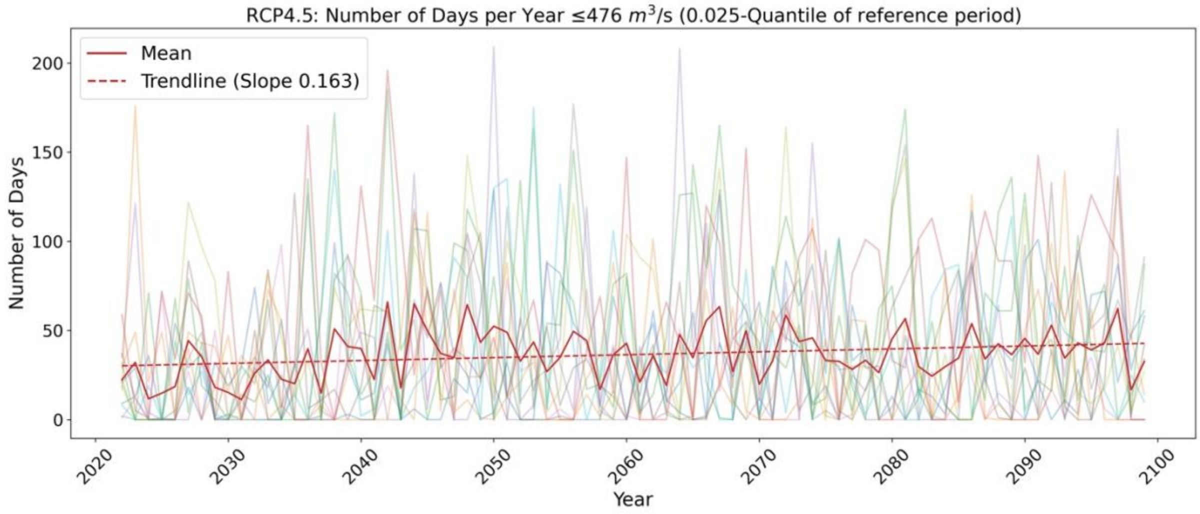


Figure 30 Expected future number of days per year below the 0.025-quantile of the reference period discharge (1981-2021) according to Hydro-CH2018, RCP4.5. The 13 models of the scenario are shown in pastel colours, their mean and trend line in red.

The mean of all models in the RCP4.5 scenario varies for the extreme low flow events between 2022 and 2099 as follows:

Bottom 2.5% low-flow events (refers to Figure 30):

– Minimum of mean values:	11.23 days / year
– Maximum of mean values:	66.0 days / year
– Mean of mean values:	36.47 days / year

5.5.3. Discharge RCP8.5 scenario

The analysis of the top 2.5% of the events (Figure 31) shows that the models differ in the number of days of this event per year. The average over all 18 models of RCP8.5 varies as follows:

Top 2.5% high-flow events (refers to Figure 31):

- Minimum of mean values: 3.94 days / year
- Maximum of mean values: 25.28 days / year
- Mean of mean values: 11.75 days / year

The trend line across all models in Figure 31 shows no change until the end of the 21st century. If the 18 models are considered in three groups, the lower and middle six models show a slightly decreasing trend (both with a slope of -0.032) and the top six models show a trend line with a minimally positive slope (0.006), whereby this is negligibly small. Also, when divided by hydrological season, no trends are visible in these top 2.5% of events (Appendix Figure 46).

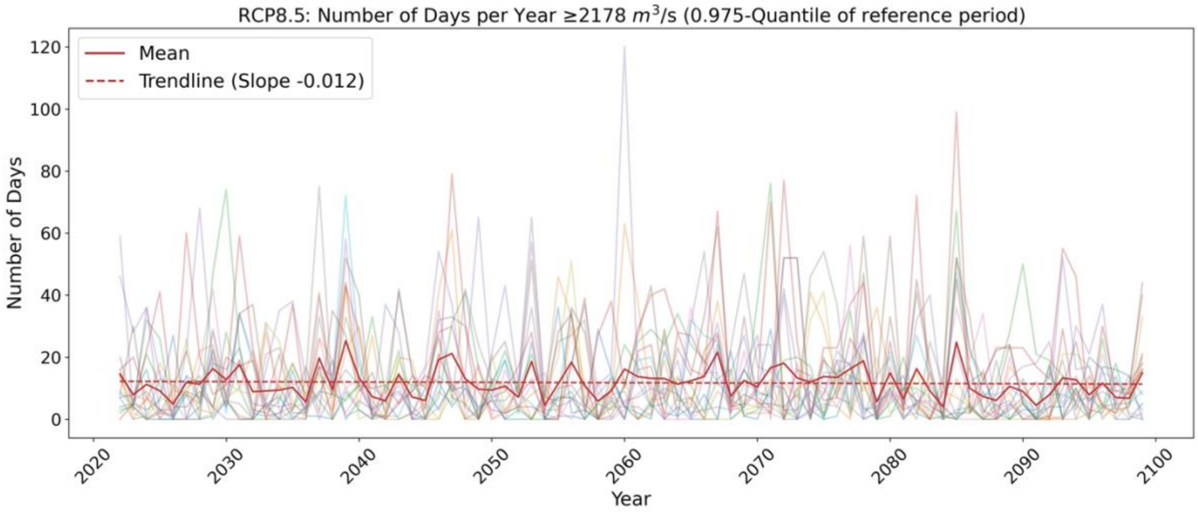


Figure 31 Expected future number of days per year above the 0.975-quantile of the reference period discharge (1981-2021) according to Hydro-CH2018, RCP8.5. The 18 models of the scenario are shown in pastel colours, their mean and trend line in red.

The same analysis was done for the top 10% of events, which means all days with discharges ≥1654 m^3/s and thus also including significantly fewer extreme discharges. This analysis showed a small decrease of discharges over the entire year (slope of the trendline of -0.043). However, when subdivided into hydrological seasons, an increase in the number of days of these events in winter (+5.4%) and spring (+2.9%) was observed. In summer (-10.5%) and autumn (-2.1%), however, discharges tend to decrease according to this analysis.

The analysis of the lowest 2.5% of events under the RCP8.5 scenario shows a clear trend towards more days per year with very low discharge (Figure 32). Dividing the 18 models into three subgroups, a clear increase concerning the trend was observed from the lower six models (+45.5%), to the middle six (+50.7%), to the top six models (+111.0%). Subdividing the bottom 2.5% of events into hydrological seasons shows clear differences between them (Figure 33): While the number of days with low discharges in spring is hardly expected and those in winter stagnate, there is a clear trend in summer (+35.2%) and autumn (+33.2%) towards more days with low discharges.

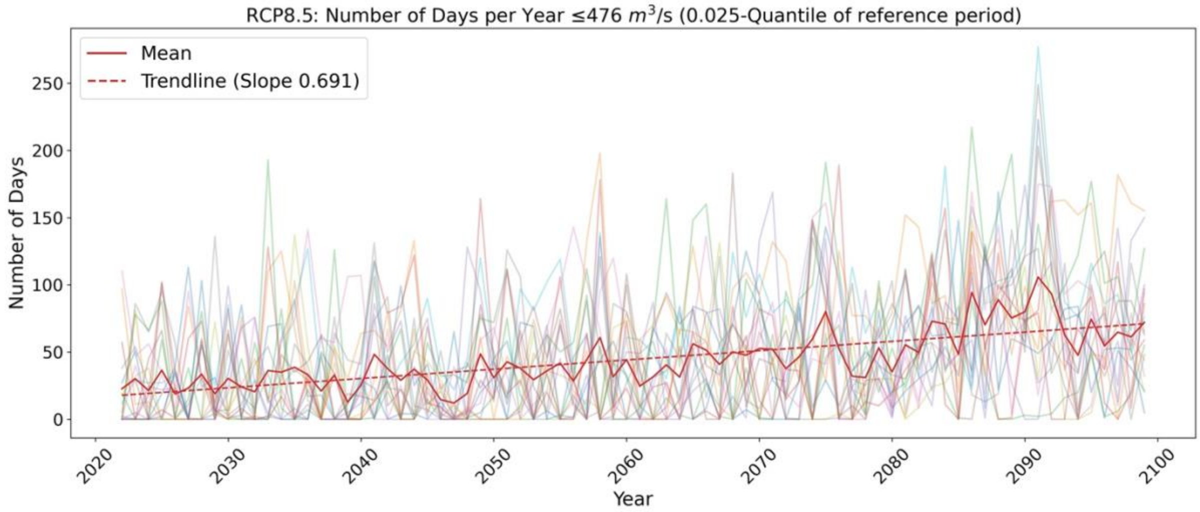


Figure 32 Expected future number of days per year below the 0.025-quantile of the reference period discharge (1981-2021) according to Hydro-CH2018, RCP8.5. The 18 models of the scenario are shown in pastel colours, their mean and trend line in red.

The mean value across all models in Figure 32 varies as follows:

Bottom 2.5% low-flow events (refers to Figure 32):

- Minimum of mean values: 12.06 days / year
- Maximum of mean values: 105.78 days / year
- Mean of mean values: 44.44 days / year

The analysis of the bottom 10% of events shows a similar pattern: Here, an increase of 74.3% by the end of the 21st century is indicated across all models under RCP8.5. The subdivision into seasons also shows the same pattern as the top 2.5% of events, whereby the increase in the number of days in summer is even higher at +44%.

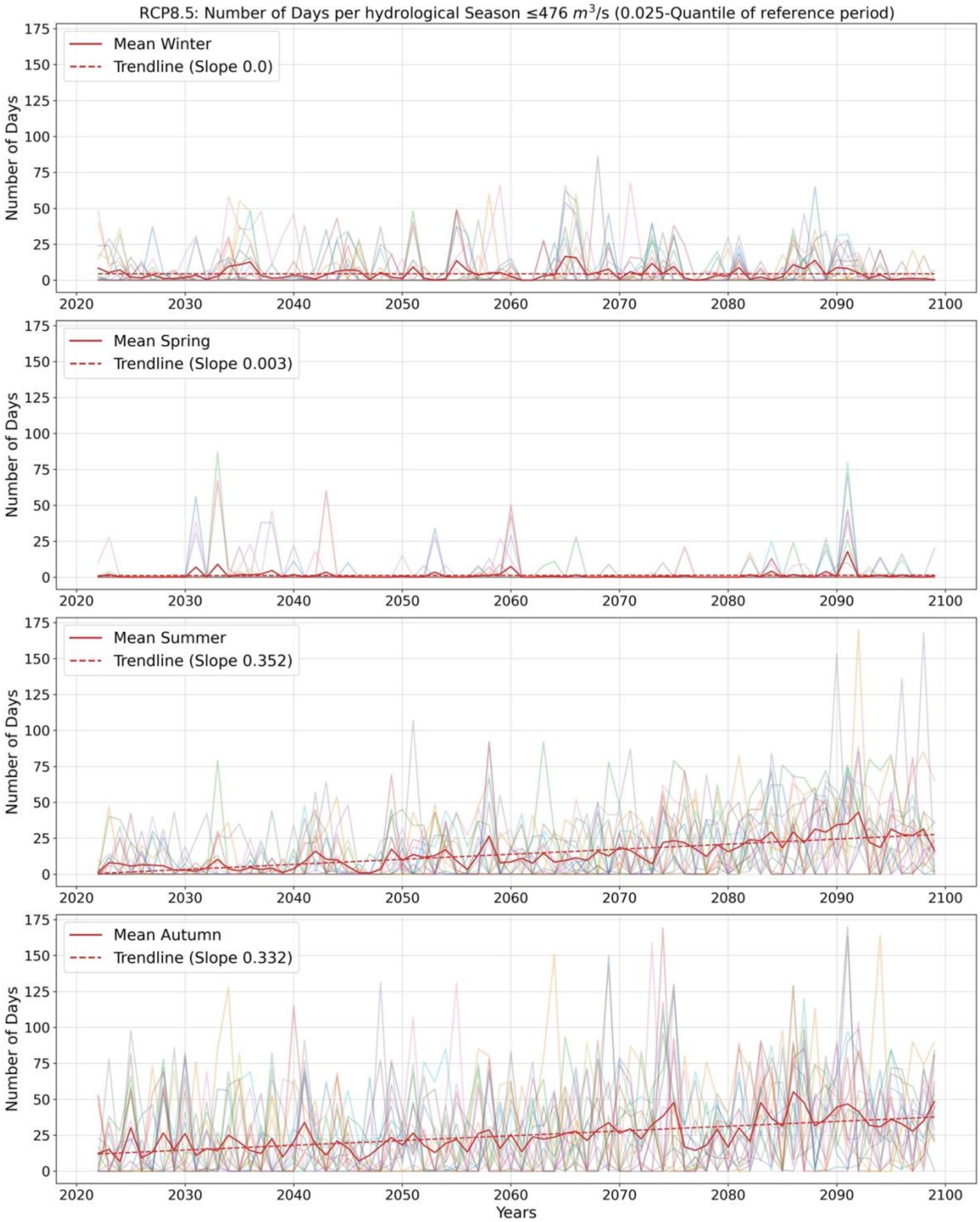


Figure 33 Expected future number of days per hydrological season below the 0.025-quantile of the reference period discharge (1981-2021) according to Hydro-CH2018, RCP8.5. For each season, the 18 models of the scenario are shown in pastel colours, their mean and trend line in red.

5.5.4. Summarizing discharge trends of 2.5% of extremes

Since the difference between the individual scenarios is particularly relevant, they are compared in the following Table 14 and Table 15, broken down by hydrological season. The slope of the trend line of the analysis on the number of days above the 0.975-quantile and below the 0.025-quantile serves as a comparison value. In the tables, both positive (blue) and negative (red) trends with regard to this trend line are highlighted in colour.

The overview clearly shows that – according to Hydro-CH2018 – discharges in Basel greater than 2178 m^3/s (0.975-quantile) will change little. Only under the RCP8.5 scenario, a minimal shift of these events from summer to winter takes place.

Table 14 Comparison of RCP2.6, RCP4.5, and RCP8.5 concerning the trend in the number of days of the top 2.5% events.

Season	Changes in 0.975-Quantile		
	RCP2.6	**RCP4.5**	**RCP8.5**
Winter	0.001	0.015	0.014
Spring	- 0.009	0.007	0.009
Summer	0.017	0.004	- 0.027
Autumn	0.014	- 0.004	- 0.008
Year	0.023	0.022	- 0.012

In contrast, changes are expected in the analogous studies of the lowest 2.5% of events representing discharges below 476 m^3/s. Across all scenarios, the number of days with particularly low outflows will increase in the fall, with the number of days increasing with the emissions scenario. In summer, the picture is mixed: under RCP2.6, the number of days is still slightly decreasing, but under RCP4.5 and RCP8.5 it is clearly increasing. Little change is expected in spring and winter.

Table 15 Comparison of RCP2.6, RCP4.5, and RCP8.5 concerning the trend in the number of days of the bottom 2.5% events.

Season	Changes in 0.025-Quantile		
	RCP2.6	**RCP4.5**	**RCP8.5**
Winter	0.019	0.004	0.000
Spring	0.008	0.007	0.003
Summer	- 0.025	0.089	0.352
Autumn	0.054	0.061	0.332
Year	0.056	0.163	0.691

5.5.5. Discharge trends in HQ_{10}, HQ_{30} and rarer floods

Since the upper 2.5%-quantiles of the discharges in Basel do not yet represent extremely high values, a further analysis was made using the limit values of the HQ_{10} and HQ_{30} discharges valid today (BAFU, 2021). Figure 34 and Figure 35 show the results of this analysis in relation to the RCP8.5 scenario. It is evident that discharges above these thresholds will not become more frequent until 2099, so the discharges associated with HQ_{10} and HQ_{30} today are expected to remain stable. The same analysis was performed for the two lower scenarios RCP2.6 and RCP4.5, with comparable results and likewise no trend.

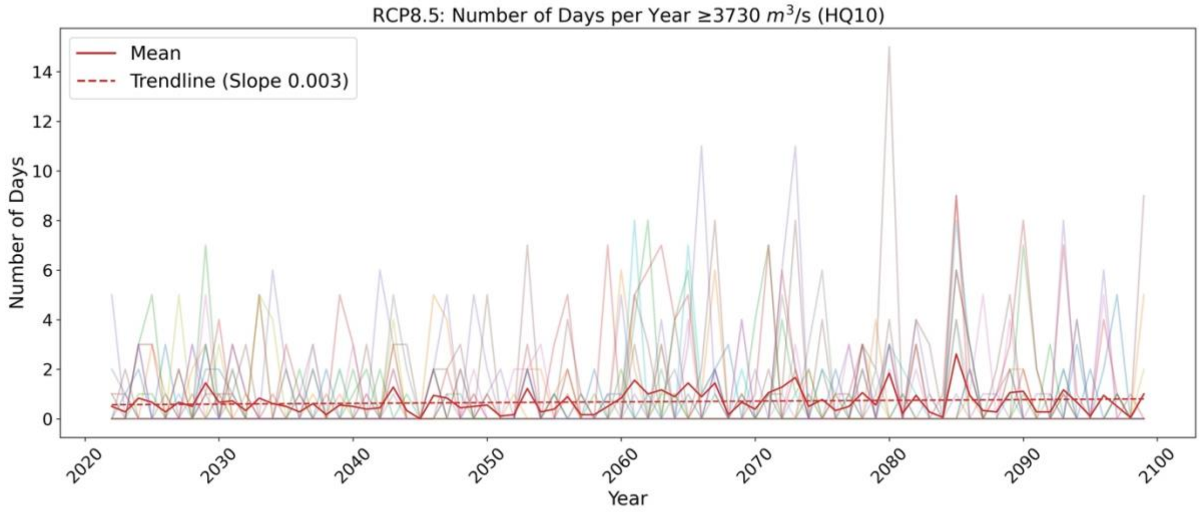


Figure 34 Expected future number of days per year above HQ_{10} according to Hydro-CH2018, RCP8.5. The 18 models of the scenario are shown in pastel colours, their mean and trend line in red.

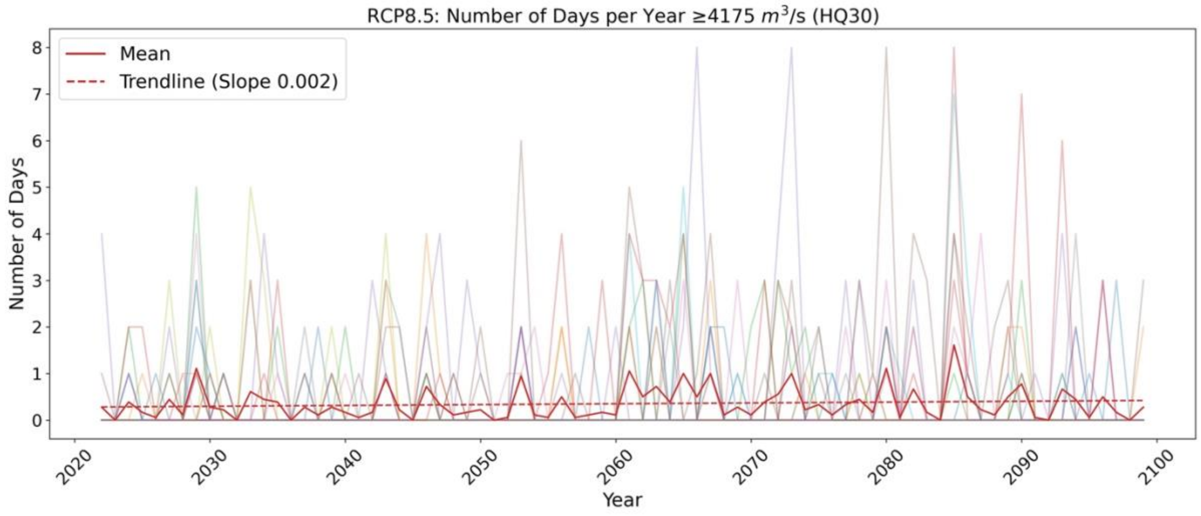


Figure 35 Expected future number of days per year above HQ_{30} according to Hydro-CH2018, RCP8.5. The 18 models of the scenario are shown in pastel colours, their mean and trend line in red.

To determine the development of even more extreme events, the same analysis was chosen with the threshold of the discharge greater than 5500m^3/s (Figure 36). While some of the models do not foresee such events until 2099, in others there are up to a maximum of three days per year when this discharge is exceeded. The mean number of days of this event remains low and shows neither an increasing nor a decreasing trend.

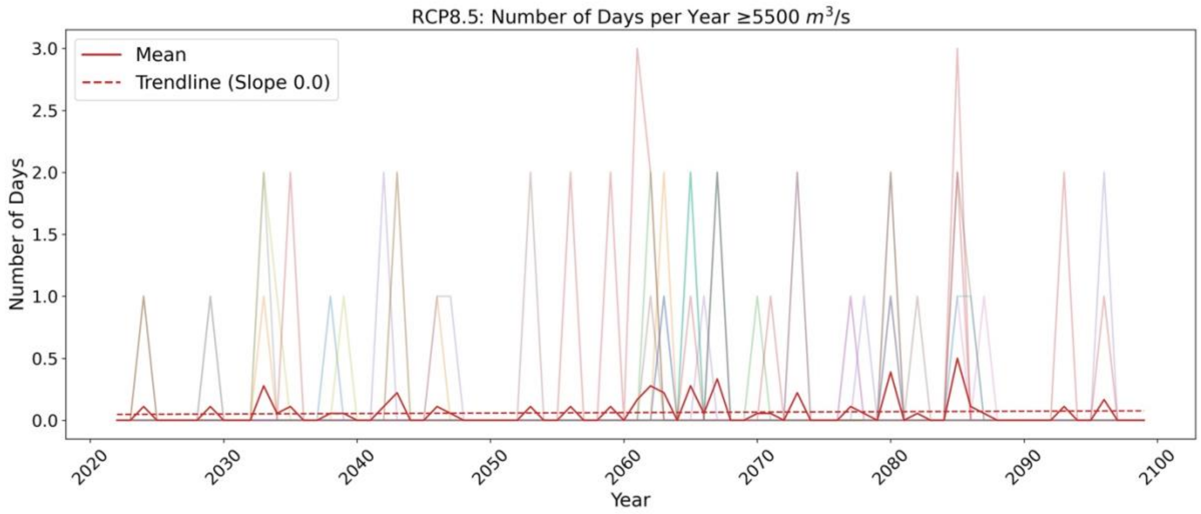


Figure 36 Expected future number of days per year above a discharge value of 5500m³/s, according to Hydro-CH2018, RCP8.5. The single models of the scenario are shown in pastel colours, their mean and trend line in red.

5.5.6. Precipitation trends of 2.5% of extremes

To analyse the development of heavy precipitation events, again the threshold of the reference period 1981-2021 was chosen (Table 13). The number of days per year above this threshold was first calculated individually for each model in each RCP scenario, the graphical representation of which can be found in the appendix (Figure 47 - Figure 49). The following Figure 37 shows the mean values of the number of days above the threshold per RCP scenario. In this illustration, it is clear that the increase in the number of days of this event is strongly dependent on the scenario. With a higher scenario, the number of extreme precipitation events also increase.

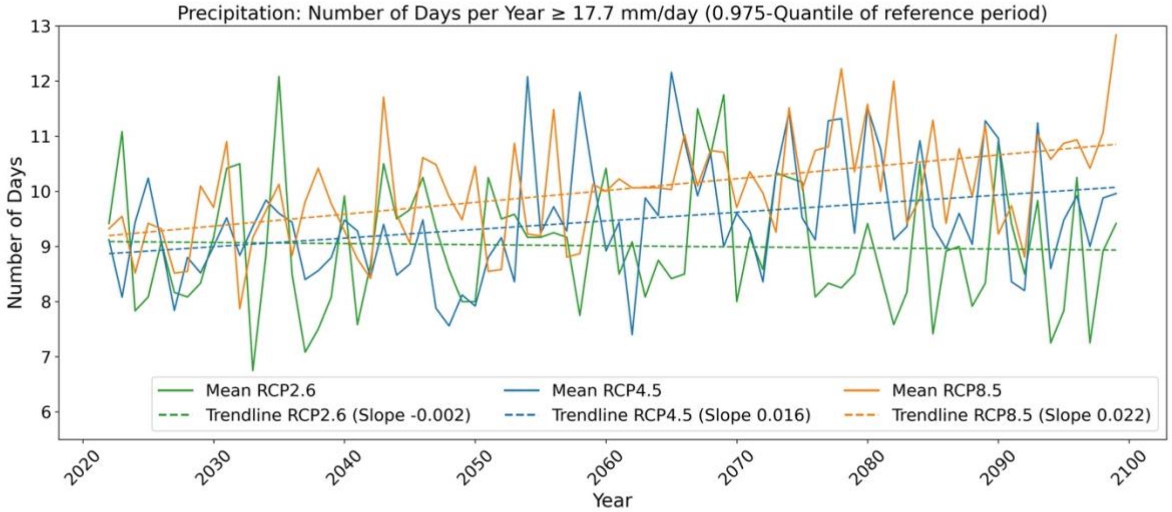


Figure 37 Future extreme precipitation in Binningen, RCP2.6, RCP4.5, and RCP8.5, illustrated as expected number of days per year above the 0.975-quantile of the reference period (1981-2021) according to Hydro-CH2018.

For the scenario RCP8.5 which shows the most significant changes, the events were split up into the four hydrological seasons (Figure 38). While the seasons spring, summer and autumn show no or negligible trends, it is clear that the increase in the number of days of this event occurs exclusively in winter. In the winter season, not only an increase in the number of days is visible, but also that the mean starts at a higher level and the individual models show significantly larger outliers up to more than 20 days.

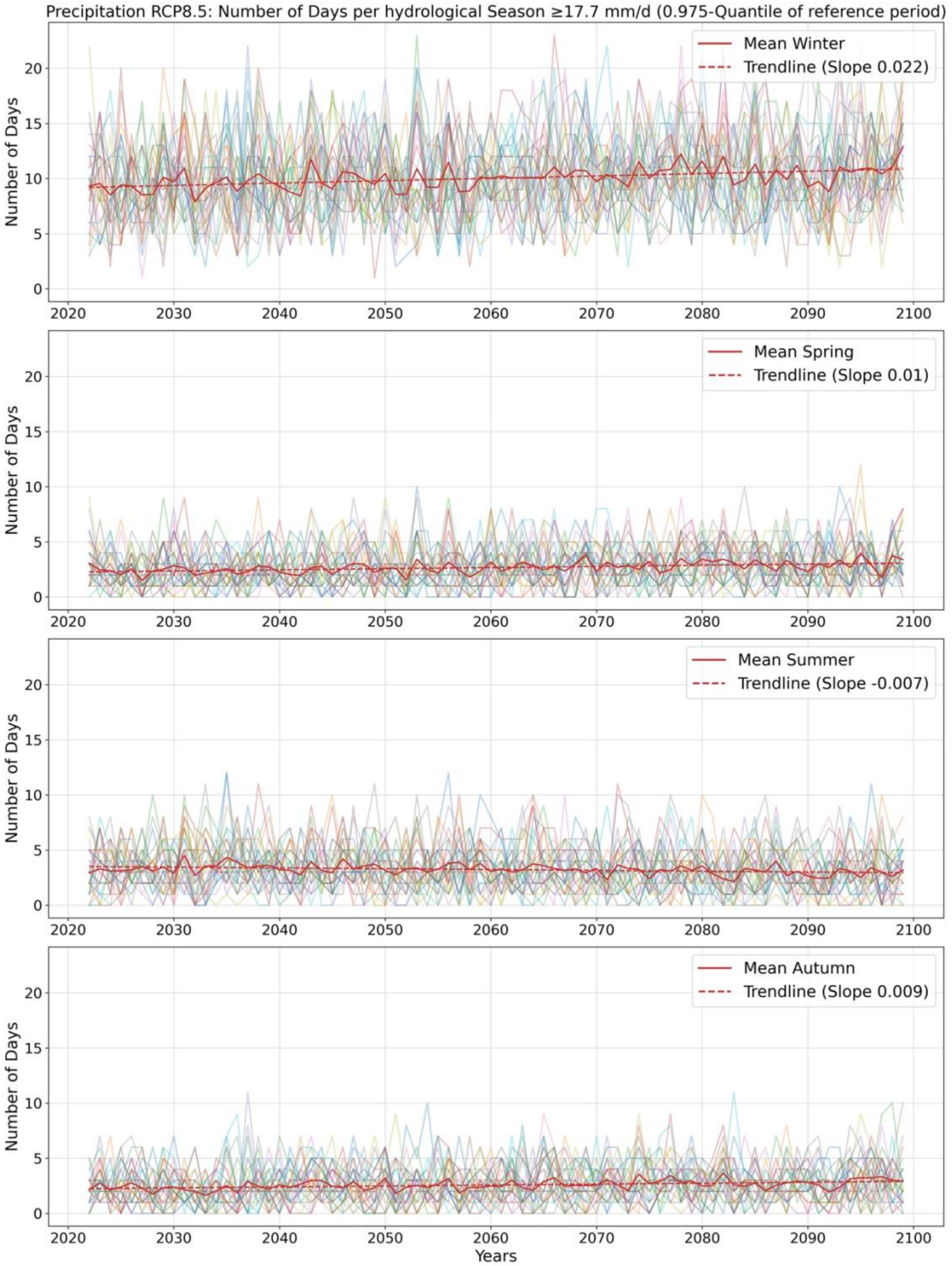


Figure 38 Future extreme precipitation in Binningen, RCP8.5 per hydrological season, illustrated as expected number of days above the 0.975-quantile of the reference period (1981-2021) according to Hydro-CH2018. For each season, the 31 models of the scenario are shown in pastel colours, their mean and trend line in red.

5.6. Interviews with key informants

Similar to the analysis of the newspaper articles, the evaluation of the interviews also shows that the effects of flood are more strongly bound to the watercourse, whereas the effects of low flow and drought are spatially wider spread. This is also reflected in the two graphs: While in Figure 40, which summarizes the interview statements on the topic of flood, the quadrant with the direct and tangible impacts and adaptations is clearly larger, in Figure 39, which summarizes the results on the topic of low-flow and drought, the quadrants are more balanced in size and content. In both illustrations (Figure 39 and Figure 40), the left part shows impacts that have occurred as well as possible future impacts, while the right part combines planned and possible adaptations.

Based on 2018, extremely **dry years with low runoff** are expected to cause direct and monetizable problems in the drinking water supply, industrial, and transportation sectors. The importance of Rhine shipping in terms of national supply, especially of petrochemical products, was emphasized among others by the expert for waters and natural hazards and also made itself visible in 2018 in the form of rising oil prices. However, the adaptation measure carried out in 2018 in the form of deepening the navigation channel has been able to reduce this problem. For the guarantee of navigation, the objective was that the Rhine should not be unnavigable for more than 10 days per year, as reported by the expert for waters and natural hazards. For the industry, the water temperature is more of a problem; as a measure, another groundwater well was built. However, according to the experts for water supply, this is not a long-term adaptation, as the number of wells in the region has almost reached its maximum. For the drinking water supply, the low discharge of the Rhine is not limiting according to the respective experts. A water supply expert explained that while pollutants double when the flow rate is cut in half, but at the same time there is less contamination in the summer months because sewage-treatment facilities operate more efficiently at high temperatures. If the groundwater level drops in the Hardwald as a result of drought, this will imply increase water runoff in the periphery of the groundwater table and therefore the need for higher infiltration. As consequence in such a situation, the pumps in the Hardwald should not have to be shut down, if possible. However, according to a local water supply expert, such a combination of events is unlikely, since the reason for stopping infiltration is more likely to be the turbidity that occurs at high water, and this is not associated with low flow and low groundwater levels. If, however, low flow and low groundwater level would occur together with enormous contamination of the water in the Rhine, a longer interruption of the pumps in the Hardwald could be unfavourable. In case of the Langen Erlen the change to the infiltration of water from the Wiese could become critical if the minimum residual volumes of water in the Wiese are fall below. The expert for water supply also reports, that a corresponding framework agreement with the Office for the Environment and Energy is in the progress. Concerning the expert for waters and natural hazards, environmental damages have occurred 2018 both directly and indirectly. In the watercourse, the low water level reduced fish passage and water temperature increased even in deeper sections. In the summer of 2018, the problem became particularly acute at the Wiese. With the bathing ban, a short-term measure was taken to protect refuges for fish. Further ideas for measures such as water pumping or groundwater input existed but did not have to be taken when the precipitation came. The planned "WieseVital" project also includes a longer-term and more holistic adaptation to hotter and drier summers.

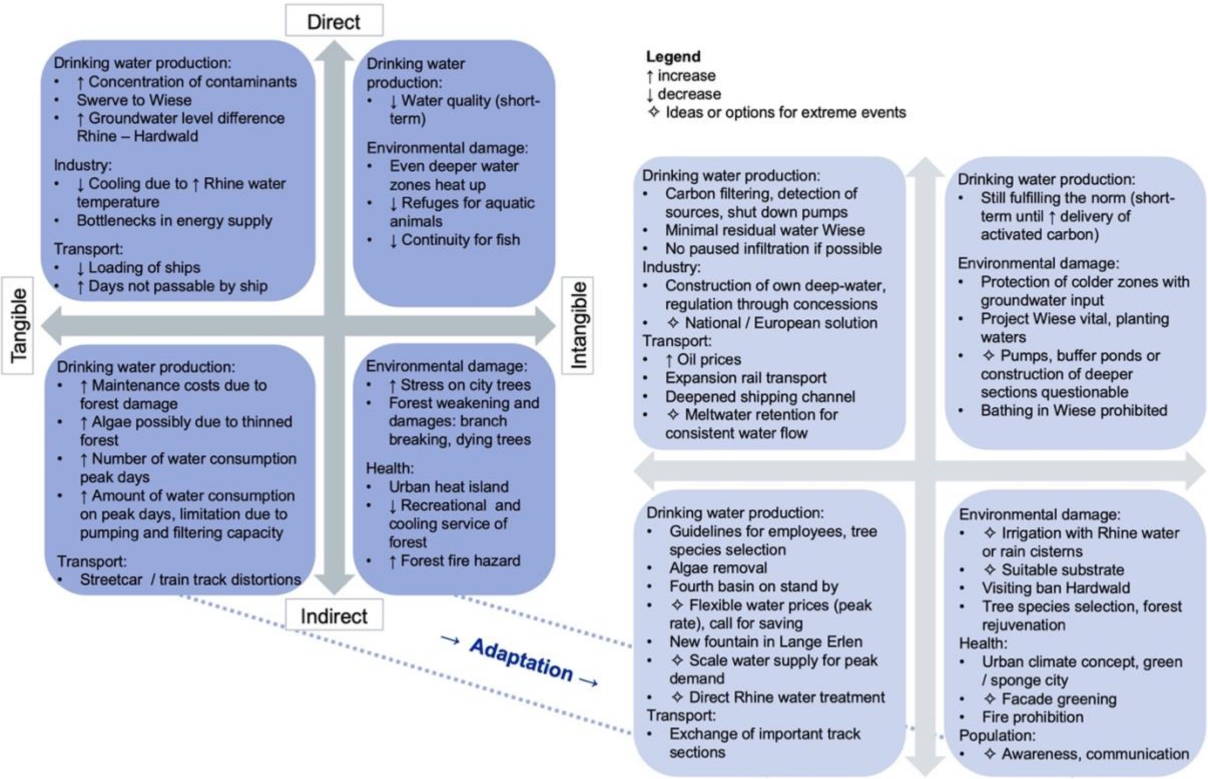


Figure 39 Adaptations to drought situations according to the semi-structured interviews, representation based on Nicklin et al. (2019)

Indirect ecological damage occurred to the urban trees and in the forest, as reported by several experts. In the case of the Hardwald, these damages can also be monetized, since according to the expert of water supply from Hardwasser AG, their maintenance costs increased in 2018 due to various safety precautions that became necessary because of the danger of breaking branches and trees. To what extent the resulting thinner forest led to increased algal growth and whether this was the cause of more algae in the later treatment step of the drinking water is not clear. In recent years and clearly in 2018, the tendency to more water consumption peak days was noted by the experts of water supply. In addition, on peak days the consumption volume has increased, so that in 2018 even a call for saving was necessary. As a concrete measure, a fourth water basin would be ready, and other groundwater wells are planned to be built in the Langen Erlen. The commissioning of this fourth basin could result in slightly reduced water quality, but it still meets the specified standard and is therefore classified as intangible in Figure 39. According to the water supply expert, this reduced quality would only be the case for a short time at maximum, until the appropriate activated carbon is supplied.

Other possible adaptations, which were mentioned by the experts for water supply, but which are not yet concretely planned, would be flexible water prices or the further expansion of the drinking water supply geared to peak consumption days. In the latter case, there would be a lot of reserve, which, according to the expert for water supply, would only be used on a few days a year and – according to the expert for environment and energy – would lead to higher water prices. By the expert for environment and energy is emphasized that the irrigation of urban trees in hot summers would be enormously important for the urban climate, but if carried out as in 2018, it could conflict with the drinking water supply in future. The interviewees mentioned potential adaptations such as the use of Rhine water, rainwater management or the search for a more suitable substrate for the trees, but their implementation is not or not yet available. There is also the question, both for the urban trees and for the forest, of what species should be planted in the future. Also, in order to ensure a stable forest in the protection zone in the Hardwald in the future, the expert on drinking water supply reports that it is relevant which tree species will be planted in future for the Hardwald AG. The fact that in the summer of 2018, the woods were temporarily closed to pedestrians and bathing was prohibited in the Wiese, severely limited the recreational spaces of the population, especially because these would be important places to cool off. The urban climate concept with possible greening of facades is intended to improve the urban climate for the future. The expert of environment and energy as well as the expert of waters and natural hazards also addressed the issue of raising public awareness, which they described as questionable. They perceive that there is little understanding among the population for extreme events and possible limitations in everyday life. The experts see potential for improvement here.

During a **flood** like the one in Basel in 2021, both river floods and pluvial floods pose a risk. Concerning the expert for waters and natural hazards the flooding of the Rhine is dependent on torrential precipitation over Bern and Aargau. Therefore, and because the Rhine is additionally buffered by the lakes, there is a lead time that allows to prepare appropriate mobile measures. In 2021, the Rhine did not overflow its banks, but if full lakes and heavy precipitation coincide unfavourably, this would be conceivable, first at the lowest point near “Kaserne”. In 2021, a combination of saturated embankments and opening of the bottom outlet at the Birsfelden power plant caused the “Rankhof” embankment to slide, as also described by the expert for energy supply. Especially during prolonged floods, as was the case in 2021, this danger also exists at other locations on the banks of the Rhine. In addition to the redevelopment of the “Rankhof” embankment, a second project is planned for the redevelopment of the “Pfalzmauer”. In the interview with both, with the expert for waters and natural hazards as well as with the expert for environment and energy, it was emphasized that the Rhine in Basel is enormously safe for flood events, even for such with a high return period. From the expert for water supply as well, little danger is seen for the drinking water treatment infrastructure on the Rhine. However, it was also said by the expert for waters and natural hazards that flood events with return periods of 2-10 years have increased and that the flood in 2021 lasted exceptionally long. While there is potential for damage to embankments and walls on the Rhine, the smaller tributaries also pose a threat to buildings and private property. The Birsig, in particular, has great potential for damage to the city centre, and a relief measure will be presented to local politicians in the summer of 2022. Despite the lower damage potential, there is also a project on the Wiese called “WieseVital”, whereby measures for adaptation to low water are equally included here as part of the integrated flood protection. Following these measures, a stepwise revision of the flood hazard map is planned. In all measures against river floods, it is noticeable that the climate scenarios and an additional safety factor are included. In several projects, the measures are combined with nature conservation and adaptation to low water. The expert on waters and natural hazard assesses that policy makers are more aware of flood protection measures, especially after events, and tend to neglect the prevention of low water consequences. According to this expert, the integrated flood protection strategy is intended to help balance this. Pluvial floods pose a risk especially for the communities of Riehen and Bettingen and also occurred in 2021. Measures are being planned in this regard, and some are already being implemented, although implementation was also described in the interviews as being too slow or delayed by politics. In the city of Basel, with limited infiltration in urban areas, adaptation measures such as the new wastewater process control system and the sponge city principle are also being planned. According to the environment and energy expert, some of the have already been implemented. However, the expert also emphasizes that the room for development in the already built city is extremely limited and at the same time measures such as requirements for new buildings and site developments are already standard. As a possible adaptation, the expert for environment and energy also mentions the protection of the property, whereby it is mentioned that this is the responsibility of the house owners.

For shipping, which is also located in the upper left quadrant in the graphic, low- and high-water levels are equally problematic. In both cases, transport is restricted and, above a certain level stopped, as it was the case in 2021. Since the bridges in Basel are the main limiting factor in the case of high water above a certain level, it is – according to the expert for waters and natural hazards – much more difficult to take measures against this than in the case of low water. The new boat acquired by the Rhine ports can extend the limit from which non-navigability applies to 7.9 meters.

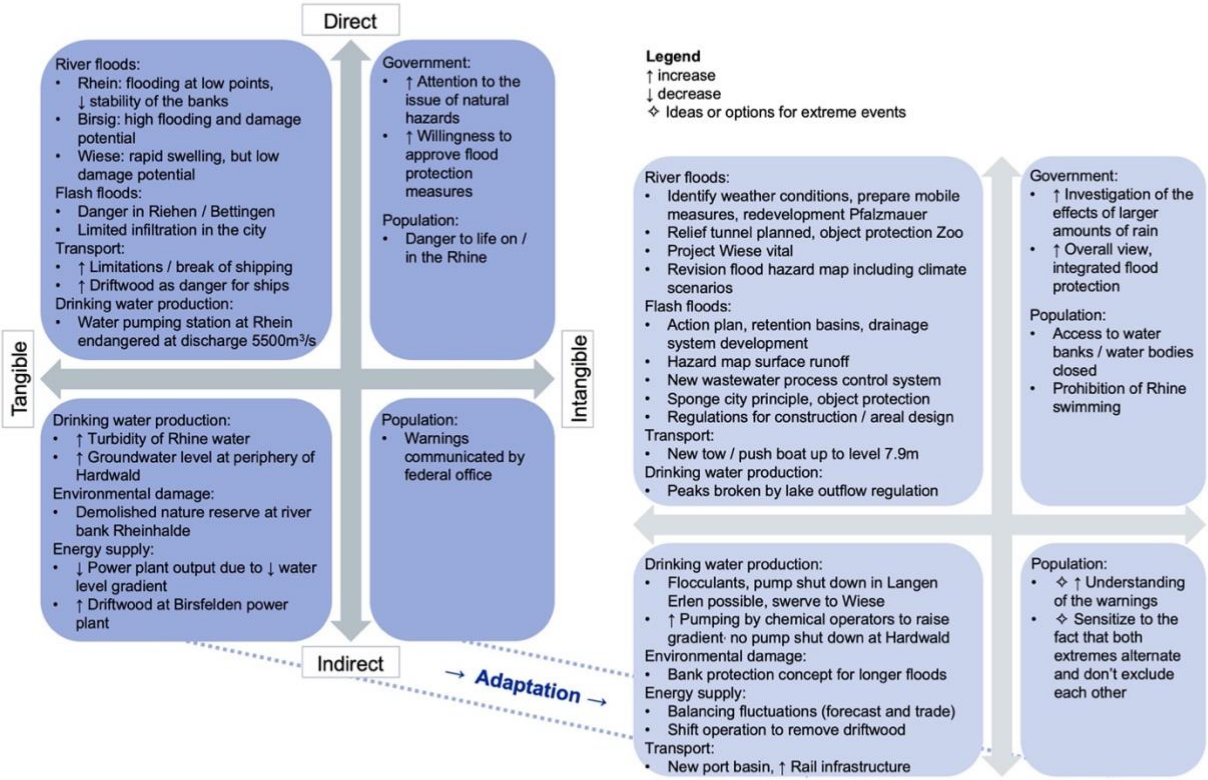


Figure 40 Adaptations to flood situations according to the semi-structured interviews, representation based on Nicklin et al. (2019)

In the lower left quadrant describing indirect and intangible impacts, drinking water production is also listed for floods. While floods can make extra measures necessary, the interview with the experts for water supply described that this is part of normal operations and so far, not an additional cost due to climate change. It is known that turbidity can be a problem during floods, also in other rivers. Against this, additional flocculants are used, at Lange Erlen the pumping of Rhine water can be stopped and water from the Wiese can be used. In the case of high water, there is no problem that the minimum residual water quantity in the Wiese would be undercut. In addition, the Feldberg groundwater flows in through the

Wiese plain and forms a natural groundwater mountain, so that a complete shutdown of the pumps would be possible. This is different in the Hardwald, since its groundwater mountain is artificially generated, the pumps should not have to be shut down here if possible. Generally, flood situations are not accompanied by peak consumption of drinking water, so these impacts are less accentuated than for low water and drought.

Environmental damage occurred in the summer of 2021 in the “Rheinhalde” nature reserve, this area just above the “Rankhof” was also affected by the landslides there. The redevelopment of the embankment, which is according to the expert for waters and natural hazards also to be oriented to long-lasting floods, also includes the nature reserve.

With regard to energy supply, the corresponding expert revealed that the Birsfelden power plant is regionally significant, but that neither high nor low water is critical for the city's energy supply. Both water extremes reduce the output of the power plant, which has its optimal performance at a river discharge of 1500 m^3/s, but this is compensated with the national and international trade of electricity. For this, it is not so much the extreme events that are critical, but their accurate forecasting that is important. If the city's energy supply is questioned, the expert sees a national or even international problem rather than one caused by local water extremes. In the case of the 2021 flood, increased driftwood occurred at the Birsfelden power plant, but its removal was negligible in terms of costs and, if long-lasting, only critical in terms of personnel planning as shift work will be needed. According to the expert of energy supply, this could be solved with temporary employees.

As in the case of low water, heat and drought, the promotion of communication with the population is also seen as an important adaptation measure in the case of floods. Although warning messages are issued by the federal government, the expert for waters and natural hazards question the extent to which the population is sensitized to understand them. This assessment is supported by the description of the expert that bans and access restrictions imposed were only partially respected by the population in past. It is assumed that it is difficult for the public to understand that in the future both dry and flood extremes will be a problem and that they are not mutually exclusive but alternate. With the assessment of the same expert that the climate scenarios of the federal government were little registered by the general public, a clearer communication strategy of the canton is desired.

The interviews showed that among all experts interviewed great awareness of the need for adaptation to the future climate is available. Specific measures on **combined risks and wild card events** were less addressed. The reason for this given by the expert for environment and energy is that these risks are difficult to assess and that they are subject to major uncertainties. In view of this uncertainty, adaptation measures would not be politically acceptable or economically efficient. Reference is made to the FOEN investigations and consequently resulting guidelines.

Regarding **future challenges** due to climate change, the increasing number of heat days is mentioned by the experts for water supply, which will cause more tree losses and make related measures necessary. It is also mentioned, that the drinking water supply of the agglomeration is increasingly linked to the one of the cities. This is because the water supply system there is based on springs and groundwater and is therefore more vulnerable to periods of heat. In the past, rivers in Baselland have dried up in extreme summer and the water was brought to the villages in tanker trucks. Since the city's drinking water supply is more independent due to the infiltration of Rhine water, the surrounding communities of Baselland are also supplied with drinking water in the event of extreme drought. This shows that in terms of adaptation measures, it is necessary to think beyond the city limits and involve the region. With regard to flood protection and concerning the respective expert, structural measures are already planned larger than necessary today in order to take future development into account, also because this is more cost-effective than having to invest in the same infrastructure again in a few years.

Across several interviewees, an overarching framework for addressing the issue of future natural hazards and adaptations was named as missing. A stronger coordination and a guideline from the federal government is desired.

It is important to emphasize that the results of these interviews reflect not the absolute truth but the views of the experts (Longhurst, 2016), some of whom have already dealt with climate scenarios in addition to their area of expertise. Nevertheless, semi-structured interviews hold an important role in geographic research, especially when it comes to complex contexts that link politics, knowledge, and power (Longhurst, 2016). As can be seen from the two resulting graphs (Figure 39, Figure 40), this complexity exists for both, low- and high-water extremes.

6. Discussion

The present thesis supports the research project of the Universities Zurich and Fribourg on behalf of the FOEN (Muccione et al., in prep.). This case study examines low water, drought, and compound events within the urban area Basel in the context of climate change. The project examines three of the four key future risks considered by the (IPCC, 2022a) to be fundamental to Europe, including health risks from heat, heat and drought stress on ecosystems, and water scarcity. The present thesis contributes to this research project and additionally includes the fourth main risk for Europe, namely flooding (IPCC, 2022a). This is achieved by linking risks, impacts, and adaptation, with particular focus on hydrological drought and flood events and the development of their duration in past and future. With the focus on both sides of the extreme of the water levels, on high and low water, the thesis allows a holistic view on the risks and impacts that derive from the water space of the city of Basel. In addition, links to further risks are identified. This allows a consideration of the adaptation measures in relation to different water extremes, but also to the amplification by other extremes such as extreme heat or heavy precipitation. As the IPCC points out, this is important as “the success of adaptation will depend on our understanding of which adaptation options are feasible and effective in their local context” (IPCC, 2022a, p. 2).

The importance of a case study in urban areas is shown by the statement of the IPCC, which considers cities as "crucial for delivering urgent climate action" (IPCC, 2022b, p. 1). Within cities, there is not only a concentration but also an interconnection of people, infrastructure and assets (IPCC, 2022b) which also applies to Switzerland (Federal Department of Foreign Affairs FDFA, 2021) and Swiss cities (Stadt Zürich Tiefbau- und Entsorgungsdepartement, 2022; Statistisches Amt des Kantons Basel-Stadt (Publ.), 2021b). This highlights the importance of the simultaneous consideration of hazard, exposure, and vulnerability (see Figure 3). The realization that the concentration and interconnection of population, infrastructure and assets within cities not only represent the risk, but also the solution (IPCC, 2022b) justifies the multi-method approach of this thesis. This is because the different methods not only provide a better understanding of the individual aspects, but also a deeper comprehension of the interconnections between them, whereby adaptation measures can also be reviewed from this point of view. The following discussion of the research questions also indicates that several methods contributed to the comprehensive answering of a question in each case.

6.1. Climate trends in Europe and transferability to case study Basel

Research question I (see Chapter 1.3) broadens the perspective to include climate trends in Europe, with a special focus on cities in Central Europe. The literature review shows that recent studies on all four key risks defined by the IPCC (2022a) for Europe are available. Of particular interest were papers that allow a comparison across several European countries (Alfieri et al., 2015) and cities, including even the study of several hazards (Guerreiro et al., 2018b; Tapia et al., 2017). However, most papers examined individual hazards exemplary for a city (Skougaard Kaspersen et al., 2015) or country (Paton et al., 2021), or chose a few cities to compare (Nicklin et al., 2019; Skougaard Kaspersen et al., 2017). The benefit of the European comparative papers (Alfieri et al., 2015; Guerreiro et al., 2018b; Tapia et al., 2017) for the present case study lies mainly in the fact that the development of climate-related risks in Switzerland and in Swiss cities can be put in relation to other European regions. Unfortunately, the city of Basel is not explicitly examined in these papers. However, the results for the future trends for the other major Swiss cities of Zurich, Bern and Geneva (Table 9) can be put in relation to the hazards and damages that occurred there (Table 10). This comparison is only possible concerning heavy rainfall and flood, as the other risks in Table 9 are not assessed in the SFLDD by the WSL. The comparison shows, that heavy rainfall is and will be in particular problematic for Geneva. Bern and Zurich show a similar picture, both in terms of rain and floods. Basel shows slightly lower damage than Bern and Zurich since 1972 – accordingly, a possible conclusion would be that the increase of these events in Basel in the future will also be slightly lower than in Zurich and Bern. Table 9 in particular, with its comparison of surrounding cities in Switzerland and abroad, allows conclusions to be drawn about Basel and also papers that examine individual hazard phenomena in other cities to be placed in relation to Basel.

The overall conclusion of the literature review shows a strong dichotomy between Northern and Southern Europe, with either no clear trend for the intermediate Central Europe, or one that is strongly dependent on the RCP scenario. The development of heat shows an increase for Central Europe (Fischer & Schär, 2010; Guerreiro et al., 2018b), that of drought only an increase in the medium scenario (Guerreiro et al., 2018b), and that of discharge no clear trend (Forzieri et al., 2014; Guerreiro et al., 2018b). With respect to precipitation and flood, as for example HQ_{10}, there is also a north-south gradient within Europe, with Central Europe again showing no clear trend (Alfieri et al., 2015; Guerreiro et al., 2018b). For the HQ_{100} events, however, a strong increase is also to be expected in Central Europe, as shown in Table 8, which shows that the increase in Switzerland is even stronger than in the surrounding countries (Alfieri et al., 2015).

The data analysis of this thesis did not cover an examination of the Hydro-CH2018 data with regard to HQ_{100} as the time period of this data is too short for this. From the analysis of discharges above 5500m^3/s, which would lead to major damage to infrastructures such as the Hardwasser pumping station on the Rhine or the Birsfelden power plant, it can only be concluded that such an event is not completely excluded in Hydro-CH2018, but a change in the return period of this event cannot be derived from this analysis. The comparatively smaller events of HQ_{10} and HQ_{30} did not show any significant trend until 2099 and thus showed partial agreement with the literature. Partial because on the one hand no clear trend is reported for Central Europe, on the other hand in Table 9 the cities of Zurich and Bern show an increase of these events under the high and medium scenario. With respect to hydrological drought and low flow, a strong scenario-dependent increase in the data was found, which again is in agreement with the findings in literature about Central Europe (Guerreiro et al., 2018b).

Although Central Europe often does not show a clear trend in the study of individual hazards, this is no reason to neglect adaptation measures. On the contrary, in the study of multiple hazards, Central European cities, especially those around Basel (Figure 8 and Figure 9), are the most affected (Guerreiro et al., 2018b). That Basel was affected in recent years with both extremes of low and high water, drought and heavy rain show the years 2018 and 2021 exemplary (Chapter 5.3) and further methods (Chapters 5.2 and 5.4) in general. The statement that compound events of cold and wet winters will increase in the future in the neighbouring countries of Germany and France (Sedlmeier et al., 2016) could also apply to Basel, since according to the analysis of future rainfall data in Basel, precipitation will increase especially in winter (Figure 38).

Concerning adaptation strategies, the literature review provides a collection of possible measurements which were realized by other Central European cities or suggested in scientific papers. Single strategies could be reviewed concerning their applicability in Basel, for example the search for suitable tree species (Stratópoulos et al., 2019) or the implementation of a local heat health action plan (Mücke & Litvinovitch, 2020). The semi-structured interview with the expert in environment and energy from the canton of Basel-Stadt confirms, that it is not appropriate to copy a whole adaptation strategy from another city, since the interconnections of Basel with its water course are unique. This because of the drinking water supply system or the importance of the navigation. But concerning the mentioned expert the exchange of ideas and knowledge took place for the published climate adaptation strategy of the city (Departement für Wirtschaft Soziales und Umwelt (Publ.), 2021). Furthermore, the expert reports that concerning specific strategies as façade greening or wastewater there is an exchange of knowledge with other cities within Switzerland as well as with cities of the neighbouring countries. These statements confirm the assumption, that concerning single adaptation strategies a transfer to the city of Basel is possible.

6.2. Learnings from the water extremes 2018 and 2021

The newspaper articles analysis illustrates the dimension of the two opposite events 2018 and 2021 and shows differences as well as similarities in terms of impacts. While the drought and low flow were of longer duration and revealed more widespread impacts, the flood was significantly shorter, although it was described as unusually long, and the impacts were closer to the waterbody. This observation is consistent with the literature, which describes droughts as sustained, which means lasting for at least a few days. Thus, droughts, including hydrological ones, generally occur over longer periods than floods (van Loon et al., 2016).

While the newspaper articles tended to describe short-term measures to limit the damage, the interviews with experts provided insight into ideas and implementations for longer-term adaptation strategies. An important result of these interviews is that measures regarding extreme events and compound risks like they have never happened before are politically difficult to implement. According to the interviewees, the willingness of politicians in Basel to take appropriate measures increased after the 2021 flood. The fact, that so-called focus events trigger risk management is already described in literature (Kreibich et al., 2017). According to the interviewees, however, the flood event in 2021 caused in Basel a stronger push for action than the long low flow in 2018. This despite the drought 2018 was more extreme than the flood 2021, as evident in the data analysis (Figure 19 and Figure 21).The trend towards integrated flood management in Basel thus not only takes account of the combined risks, but also makes it possible to implement low flow measures despite political limits.

The data analyses provide a more comprehensive picture of the two events in 2018 and 2021, particularly in that the combination of heavy rainfall and a dry period represents another combination of risks that can lead to damage especially due to surface runoff. However, no trend towards longer periods of high or low water could be detected in the data series 1981-2021. Going further back to 1900, a slight increase of flood-days (Figure 23) is becoming visible as well as the decrease in low-flow events (Figure 25). The absence of trends or their only weak expression may be due, among other things, to the fact that in the course of these 120 years, interventions have repeatedly been made in the watercourse area (Scherrer et al., 2006), leading possibly also to the decrease of hydrological droughts and low flow events since 1900. The long period from 1910 to 1999 without significant floods is striking (Pfister, 2006) (see also Table 10 and Table 11). This may be due to the realization of physical infrastructure projects and the regulation of alpine lakes in the 20th century, but also to the fact that adaptation measures have been implemented in recent years and may be having an effect (Hilker et al., 2009). On the other side vulnerability and exposure developed too during this time (Hilker et al., 2009; Stadt Zürich Tiefbau- und Entsorgungsdepartement, 2022).

Having a closer look on the two years of special interest, 2018 and 2021, the boxplot of yearly data (Figure 12) shows that both years were not uniformly characterized by high or low flow respectively. Figure 13 makes visible that 2018 began with higher than average outflows. Also, the flood of 2021 was followed by an above-average dry autumn. This may probably have reduced the magnitude and variety of the impacts of these events. If the flood situation had also lasted longer, it is conceivable that landslides or washed-out walls would also have led to problematic effects at other locations on the bank. This assumption is based on the fact mentioned in the interview with the expert on waters and natural hazards that bank protection measures are considered necessary at several locations, their implementation is being planned (compare to Chapter 5.6). If the spring and winter preceding the dry fall of 2018 had not been average or wetter than average (Figure 14 and Figure 15), it can be assumed that the effects on vegetation in particular would have been significantly greater. This assumption is based on the one hand on the newspaper analysis, which describes the corresponding impacts. On the other hand, it is also based on the interviews, where the water supply experts in particular emphasized that the drought that preceded 2018 had accentuated the impacts on the forest even more. A closer look at the data of these years (Figure 18) shows that the winter of 2016/17 was already characterized by below-average discharges. But the winter 2017/18 marked a break due to larger outflows. A scenario without the interruption of the low outflows in winter 2018 would be conceivable and would have correspondingly stronger impacts. In such a scenario, even higher damage to the forest and urban trees would be conceivable. In this case, the impacts on the environment in the Wiese would probably have been even greater in the summer of 2018, and the planned measures such as water intake would have had to be taken to preserve the ecosystem. Also, a prolonged non-navigability despite the taken measure and problematics in the industry with the cooling water would be conceivable.

The analysis of the precipitation-discharge relationship in 2018 (Figure 16) shows an extremely heavy precipitation in May followed by several less extreme precipitation events which, with some delay, increased the discharge of the Rhine. The days with heavy precipitation in August was reported in the newspaper as it caused surface runoff due to dry soils (Chapter 5.3 and Table 18). July through the end of November show well below average runoff, even in daily resolution, with little variation (see also Figure 43). The Swiss flood and landslide damage database does not record any damage for Basel due to the heavy precipitation in May 2018 (Table 12), possibly because it did not affect soils that had already dried out. It is conceivable that if this amount of precipitation had occurred later in the year, less infiltration could have taken place and damage due to surface runoff could have followed even in the city. There is also the possibility that, particularly during prolonged dry periods, people are less focused on the issue of (pluvial) flooding and are less likely to protect themselves and infrastructures during these times (compare Table 12).

The relationship of precipitation and discharge in 2021 shows the contrary (Figure 17). Heavy precipitation and high runoff cumulated at the end of July and the beginning of August. This shorter duration is also reflected in the newspapers, which report on the acute event for only a few days (15.07.2021 – 06.08.2021, Table 19). The following rather dry autumn brings low discharges. Thinking of a scenario like in 1999, where heavy precipitation repeatedly hit already high lake and river levels, much greater damage such as bank overtopping, landslides on banks, surface runoff and backwater would be conceivable and caused higher damage. The scenario of precipitation over Basel or the Rhine catchment area as it fell in Germany in the summer of 2021 (compare Chapter 2.4) was considered in the expert interviews (Appendix 9.5.4) and the conclusion was reached that this would also have caused far greater damage for Basel. It follows that the minor damage caused by the flood in 2021 could have been greater due to even longer floods, repeated heavy precipitation or heavier one-time precipitation.

With regard to low flows, impacts can be stronger and more diverse if the seasonality of these events changes. The investigation of the seasonality of the events in the past thirty years (Figure 22), but also in the past century (Figure 25), is consistent with the results of the literature review (Chapter 5.2), which shows that low flow events tend to occur in winter, but increasingly began in autumn. Shifting these events to the summer would have all the greater impacts, as compound risks with high temperatures then occur, leading, for example, to increased water requirements. The event 2018 has already started at the end of summer, giving an idea of the strong impacts of such a shift.

In summary, the two events in 2018 and 2021 would most likely have resulted in stronger impacts if precipitation and discharge had shown a more uniform pattern than it was the case. Both extreme events acted as so-called focus events (Kreibich et al., 2017; Mücke & Litvinovitch, 2020), which encouraged the government to take or push for adaptation measures (Appendix 9.5.4), as it became visible that the events touched the limits of some of the existing measures (compare Chapter 5.3). If the 2018 and 2021 events are viewed over a longer period of time, in this thesis from 1900 onwards, the flood seems less and the drought more extreme. However, as Figure 3 shows, the assessment of risk is not about hazard alone, but also about exposure and vulnerability. As the latter two factors have changed over this period, the impacts of these events are likely to be greater and more interconnected today (see Figure 39 and Figure 40).

6.3. Future changes according to Hydro-CH2018

High flow and heavy precipitation events

Since systematic recording of events and damages in the SFLDD of the WSL, 9 out of 10 events were caused by floods and inundations. Three quarters of the events were caused by heavy rainfall, which is also responsible for the six major events since beginning of the recording (Andres & Badoux, 2019b; Hilker et al., 2009). On the one hand, the authors found no significant increase in damage costs since 1972, from which they conclude that the influence of climate change on the damage process in Switzerland cannot be determined (Andres & Badoux, 2019b). But there are some arguments to counter this conclusion: First, the event of 2021 was attributed to climate change (Kreienkamp et al., 2021; World Weather Attribution, 2021), northern Switzerland and Basel being part of the investigation. As this study concludes with a high confidence that intensity and likelihood of such an event will increase with further climate change and rising temperatures (Kreienkamp et al., 2021), a connection between severe rainfall and water damages to climate change is likely for Switzerland and Basel as well. Second, in the past years not only climate has changed, but focus events have also triggered adaptation measures. These protection structures may have reduced the damage costs or kept at the same level (Hilker et al., 2009), while the cost of damages might have increased without these measures. Third, neither the events registered in the SFLDD (Hilker et al., 2009) nor the heavy rainfall of 2021 (Kreienkamp et al., 2021) were unique but they will occur again.

The question is whether these events will occur in future in a similar form as in past as assumed by (Hilker et al., 2009), or whether they will occur much more frequently and strongly as predicted by (Kreienkamp et al., 2021).

The more important is not only to know the future trend of heavy rainfall and flooding, but also to be able to classify these results with the help of past development, here for the city of Basel. The past has shown, that the highest discharge values, but also the greatest variability, occur in summer, especially in July. The lowest discharges occur between October and February (Figure 13 and Figure 15). The analysis of extreme flood events since 1900 has shown a minimal increase in these (Figure 23). It is interesting to note that the number of extreme events almost doubled from the period 1911-1964 to the period 1965-2021. The same analysis with modelled data from Hydro-CH2018 shows no increase in the number of days of this event per year between 2022 and 2099. However, it is noticeable that the future level of the number of days per year, seen across all RCP scenarios, is with 11.5 days per year higher than the past average of 6.73 days per year. According to this analysis, longer flood periods must be assumed in the future. There are few differences between the single RCPs, either in the average or in the development of the number of days per year (Table 14). However, the higher the scenario, the greater the maximum values of individual models. This strengthens the assumption that the stronger the climate change, the greater the individual extreme events could be at the Rhine in Basel – as already assumed for Switzerland as a whole (NCCS (Publ.), 2021b).

The examination of the rainfall data in Basel showed no trend since 1981, the number of days above the 0.975-quantile was on average 9 days (Figure 26) and thus the same value as modelled by the Hydro-CH2018 data from 2022 for the same station Binningen (Figure 37). The further development of these events until 2099 is subsequently scenario-dependent, most strongly for RCP8.5, with the increase occurring exclusively in winter (Figure 38). These findings are consistent with the NCCS statement that the extent of heavy one-day precipitation in Basel will increase by +8.9% overall (CI -0.8 to +18.3%), with the heaviest one-day precipitation of 18.5mm expected in winter (NCCS (Publ.), 2021a).

However, it cannot be directly concluded that the more frequent rainfall extremes in Binningen under RCP8.5 will directly amplify the runoff in Basel and thus increase future flood peaks even more. According to the analysis of the past floods in 1978, 1994 and 1999 of (Scherrer et al., 2006) high discharges in Basel result primarily from precipitation events of high intensity over the catchment area of the Rhine, especially over the cantons Bern and Aarau (Appendix 9.5.4). The lakes of the Central Plateau (Mittelland) can initially break the following runoff peaks but release large amounts of water over a long period of time during prolonged flood situations. These periods can be long enough that a second event of heavy precipitation can hit the same watershed at high lake levels, as happened in 1999 (Scherrer et al., 2006). This combination led to the largest event of the last 100 years not only in Basel, but also on other Swiss cities (compare Table 10). This phenomenon was also mentioned by the expert for waters and natural hazards, as it enables the provision of mobile flood protection measures in Basel if appropriate weather conditions are recognized in time (Appendix 9.5.4). However, it is described in Scherrer et al. (2006) that the rise time of the flood waves in Basel is relatively short with 14-20 hours. Scherrer et al. (2006) mention two factors that additionally aggravate the flooding of the Rhine in Basel: First, the outflow peaks of the most important tributaries Aare and Thur often overlap and second, delays in flooding due to overflows in the Thur have become rarer since the expansion of the river channel there. In the semi-structured interviews, however, the water supply expert (Appendix 9.5.3) mentioned the opposite, namely that more attention is being paid to the operation of weirs and retention volumes to achieve in consequence that peaks from the tributaries do not overlap at the same time in Basel, if possible. According to the expert, this adaptation measure was taken as a consequence of the 1999 flood – thus this flood served as a focus event. But this effect helps only to break extreme peaks and does not protect against long lasting high discharges. It is therefore all the more important that measures are taken to stabilize the banks of the Rhine in Basel, as described by the expert on waters and natural hazards (Appendix 9.5.4).

Scherrer et al. (2006), not including current climate scenarios, names peak discharges of 4500-5600 m^3/s as possible for Basel, whereby discharges between 5000 and 6000 m^3/s are described as possible but speculative, as these require an extremely unfavourable combination of runoff and precipitation events. As a prerequisite for this, persistent events or a rapid sequence of heavy precipitation are mentioned. While these cause high water levels in the lakes at the edge of the Alps, the actual flood wave is triggered by heavy precipitation on the Central Plateau (Mittelland), which overlaps with the high base flows of the lakes. Multi-day events are more likely to meet these requirements than single-day heavy rains (Scherrer et al., 2006). The examination of the Hydro-CH2018 data for events with discharges greater than 5500m^3/s showed that these events occur in individual models of the RCP8.5 scenario, but they neither increase nor decrease on average until 2099 – this analysis is consistent with the findings of Scherrer et al. (2006). The chosen limit value is relevant insofar as – concerning the experts for water supply (Appendix 9.5.3) and energy supply (Appendix 9.5.5) – the pumping station of Hardwasser AG and the Birsfelden power plant would be in danger from such a discharge. However, the significance of this analysis in Hydro-CH2018 must be limited in that, according to the FOEN (BAFU, 2021), this discharge quantity has a return period of far more than 300 years and is therefore possibly inadequately recorded in a data series of 100 years. However, since an increase of heavy rainfall (100-year single-day precipitation event) of 20% in summer and winter is expected for the whole of Switzerland under the RCP8.5 scenario by the end of the century (NCCS (Publ.), 2018), it must be assumed that these can also fall over the catchment areas of the Rhine. If, in addition, a pattern of precipitation and high lake and river levels as described by Scherrer et al. (2006) occurs, this could also have considerable consequences for Basel.

The – depending on the scenario possibly increasing – heavy rainfalls over Basel have mainly impact on river floods of the tributaries, especially the Birsig, but may also cause pluvial floods. According to the semi-structured interviews with the expert for environment and energy (Appendix 9.5.1) and the expert for waters and natural hazards (Appendix 9.5.4), adaptation measures are planned for both hazards. In the case of the Birsig, this is a physical infrastructure measure with the relief tunnel. In the case of the pluvial flood, the drainage system and the sponge city principle are particularly worth mentioning. For both cases, hazard maps are either newly drawn up or adapted after measures have been taken, taking climate scenarios into account.

Low flow and drought events

In the past, the frequency and extent of extreme low water on the Rhine near Basel has decreased, as reported in the literature on the one hand (Pfister, 2006), and as shown by the data analysis of this thesis on the other. In the literature, two independent reasons are given for this: First, during the 20th century an increasing winter precipitation occurred (Kohn et al., 2019; Pfister, 2006) and second, since the middle of the 20th century, more and more hydraulic structures and hydropower plants have been built which, with their reservoir management, have increased the winter streamflow (Kohn et al., 2019). The decline in low-water events in Basel is clearly evident in the data since 1900, with an almost abrupt decrease in the number of days with extreme low water around 1963 (Figure 25). The reason for this could be a mutual reinforcement of the causes described in the literature. While an increase in low water events in summer is reported in the literature around the same time (Kohn et al., 2019), this can only be determined to a limited extent in the extreme event analysis of this thesis, because it shows none of the lowest 2.5% of events in summer, but a slight increase in autumn (Figure 25). The drought period of 2018, which was considered separately, also took place mainly in autumn, and the year 2021 was also drier than average in autumn (Figure 14).

The rainfall data from the Binningen station do not go back far enough to verify the trend of increasing winter precipitation in the past. But the data from Hydro-CH2018 show that this trend will continue in the future, although the extent will depend on the scenario (Figure 37 and Figure 38).

The extreme event analysis of the discharge data in Basel shows that the trend towards fewer low-flow events that was evident in the past will be reversed in the future. The mean number of days per year of the lower 0.025-quantile is 26.26 days on average under RCP2.6 and thus corresponds to the value from the period 1900-1962. Under the RCP4.5 scenario the average number is 36.47 days per year. The highest climate scenario RCP8.5 indicates a mean of 44.44 days per year. All three scenarios show an increase in the number of days of this event per year until 2099, with the largest increase under RCP8.5 and in the summer and autumn seasons, with the exception of summer under RCP2.6, where there is a slight decrease (Table 15). It can thus be concluded that in the 21st century there will not only be a reversal of the trend in runoff from the 20th century, but also a shift in the seasonality of low flow events from winter to summer and autumn. This increases the risk of these hydrological droughts coming together with higher temperatures resulting in a combined risk as described in Guerreiro et al. (2018b) and Paton et al. (2021) and thus also in increasing impacts. This assumption is supported by studies of the RCP8.5 scenarios until 2060, which show that in Basel meteorological droughts will also increase by +2.1 days (CI +0 to +8.6 days) and temperatures on the hottest days of the year will increase by +3.5°C (CI +1.8 to +6.1°C) (NCCS (Publ.), 2021a). In addition, certain uses of water, such as abstraction for irrigation, have a seasonal pattern and thus a different effect on a summer drought than on a winter drought (van Loon et al., 2016). In Basel, this dynamic can have an impact on various water uses: While very low discharges are still sufficient for water withdrawal for drinking water treatment, an increased number of days with peak water consumption could occur at the same time. According to the experts of drinking water supply (Appendix 9.5.2 and 9.5.3) this would not affect the drinking water quality. However, drinking water could become scarce, necessitating today's ideas such as a savings call or flexible water pricing. This could be all the more important, as exposure will increase with the expected population growth in Basel (Statistisches Amt des Kantons Basel-Stadt (Publ.), 2021b). Flexible water pricing could also mean that the population is affected differently depending on income (Tapia et al., 2017), and possible differences in vulnerability are amplified. As the low water levels in summer and autumn are also accompanied by increased water temperatures, the cooling capacity of the Rhine water used by industry could be further impaired. According to the energy supply expert (Appendix 9.5.5), this is not a problem for the Birsfelden run-of-river power plant, but for other power plants further downstream, which also rely on cooling capacity, it could mean that they have to reduce their performance. In the summer of 2018, when the discharge was around 600m^3/s, there were already reports in the newspapers that cargo shipping would incur higher transport costs and that passenger shipping would no longer be able to reach the landing stage in Birsfelden. With a discharge of around 400m^3/s, short-time work in the port companies and the standstill of the top three ferries were also reported in 2018 (Chapter 5.3 and Table 18). These impacts from the year 2018 compared to the future development suggests an increase in such impacts in the future.

These scenarios showing an increasing number of days of extreme low flow events do not yet include the effect of adaptation measures. According to Figure 39, many measures are already being implemented or planned.

6.4. Assessment of the current adaptation measures

Basel has been working on adapting the city to climate change at a very early stage, as the canton's first climate impact report was already published in 2011, as the expert for environment and energy reported in the semi-structured interview (see Appendix 9.5.1). In addition to the fact that Basel has continuously developed the strategies since then up to today's reports "Stadtklimakonzept" (Bau- und Verkehrsdepartement des Kantons Basel-Stadt (Publ.), 2021) and "Anpassung an den Klimawandel im Kanton Basel-Stadt (Klimafolgenbericht 2021)" (Departement für Wirtschaft Soziales und Umwelt (Publ.), 2021), the city thus already has several years of experience with climate change impacts and adaptation measures.

The IPCC (2022b) confirms that adaptation measures play a decisive role, especially in urban regions. This is not least due to the increasing population in cities, a fact that also applies to Basel (Statistisches Amt des Kantons Basel-Stadt (Publ.), 2021b). The general statement that many cities have developed adaptation plans, but only a few of them are implemented (IPCC, 2022b), also applies in part to Basel. This because some of the measures are subject to political or other delays, as reported in the interview by the expert for waters and natural hazards (see Appendix 9.5.4). The IPCC also makes the general statement that "current adaptation is unable to resolve risks to current climate change associated hazards" (IPCC, 2022b, p. 1). On the one hand, this is not the case for Basel, as the two events attributed to climate change in 2018 and 2021 did not cause immense damage (see newspaper articles analysis Chapter 5.3). On the other hand, the closer examination of the two events in the previous Chapter 6.2 also shows that the existing adaptation measures reached their limits and that conceivable scenarios such as recurring heavy rainfall or no interruption of the long low-flow periods in the years 2016-2018 could have had significantly more severe impacts, which the existing measures would have been less able to mitigate. Therefore, adaptation gaps also exist in Basel.

In order to discuss the existing adaptation measures in Basel more systematically, a comparison is made to the "Contributions of urban adaptation options to Climate Resilient Development" (IPCC, 2022b, p. 2). The concept of Climate Resilient Development is appropriate in the discussion of adaptation as the related measures offer an important contribution to it, particularly in urban areas. This potential is especially present in those adaptation strategies that go beyond physical measures and also include nature-based solutions, planning and social approaches (Dodman et al., 2022 in press).

According to the expert for environment and energy (Appendix 9.5.1) and the expert for waters and natural hazards (Appendix 9.5.4), several physical infrastructure or grey measures are implemented in Basel. In some places, the embankments of the Rhine are being rehabilitated, a new wastewater management system is being planned, the river channel has been deepened with a dredger for navigation, the outflow of the Birsig is being made safer during floods and there are already technical requirements for new buildings. These measures increase safety for the population, but only apply to one hazard at a time. The expansion of the wastewater system is justified according to the literature to drain additional sealed surfaces, but according to (Skougaard Kaspersen et al., 2017) it is not sufficient to channel heavier rainfall in the future.

Both in terms of drought, heat and low flow, and in terms of flooding, it is clear from the discussions with the experts that Basel has a strong focus on nature-based solutions too (Chapter 5.6). In particular, it is noticeable that these measures address several hazards at the same time, such as the WieseVital project, which stands for the concept of integrated flood management described in literature (Rossano, 2015). Also, the implementation of the sponge city principle is a strategy that adapts to both extremes, whereby livelihood and health are enhanced, and an ecological benefit is achieved. According to the expert interviews (Chapter 5.6), the possible conflict between irrigation of the greener city during extreme droughts and drinking water availability has not yet been resolved. However, ideas are available such as suitable selection of tree species and substrates, which are also described in the literature (Stratópoulos et al., 2019) and belong to the nature-based solutions. These solutions could be strengthened by improved communication with the population and a discussion within society about prioritizing the use of drinking water (compare Appendix 9.5.1). This is also relevant due to the statement that dry periods over several weeks could become problematic for the drinking water supply, especially due to limitations in groundwater recharge and pumping capacity (Appendix 9.5.2).

Looking at the implemented and planned adaptation strategies mentioned in the interviews according to the Climate Resilient Development of the IPCC, it is noticeable that few of the existing measures can be classified under the heading "planning and social policy" (IPCC, 2022b, p. 3). The existing warning system for natural hazards is operated at the federal level and is not specifically adapted to Basel. The climate education listed under this heading by the IPCC is also mentioned in the interviews, in particular by the expert for waters and natural hazards (Appendix 9.5.4) and the expert for environment and energy (Appendix 9.5.1), and named as missing. More activity to promote a discourse on climate risks among the population is desired by the experts. On the one hand, this would promote bottom-up adaptation strategies from the population, such as described in (Ferenčuhová, 2021). On the other hand, this adaptation strategy addressing the communication could reduce the vulnerability of the population as it includes the behavioural dimension (Carter, 2011). Concerning the vulnerability, it can be observed that in the past, the greatest flood damage to buildings was recorded (WSL, 2021) in the same district where the largest population growth is expected (Statistisches Amt des Kantons Basel-Stadt (Publ.), 2021b). At the same time, the expert on waters and natural hazards doubts that the population is sufficiently sensitized to understand and implement warnings about natural hazards. Measures which not only provide a warning system but help the citizens to understand the warnings – which are also clearly desired by the expert in the interview – would be another way of reducing the vulnerability.

According to the IPCC (2022b), the preference for large infrastructure projects over social innovations is typical for financially stronger locations, which certainly includes Switzerland and Basel. However, meaningful climate governance is characterized by the involvement of all societal actors, including individuals and households, the private sector or social movements (IPCC, 2022b). The fact that not only specific local factors are important, but also supraregional, national and international networking is emphasized both by the IPCC (2022b) and the experts interviewed (Chapter 5.6). In the event of extreme drought, the surrounding communities in Baselland depend on the city's drinking water supply, this according to the experts of drinking water supply. With regard to navigation, cooperation is important too because, according to the expert on waters and natural hazards, during extremely low water navigation is limited not only in Basel. The energy supply as a whole is already international, and the corresponding expert assumes that supply bottlenecks for Basel would not result from local extreme events but from those of a more far-reaching nature affecting larger parts of Europe. The management of lake outflows during floods, as mentioned by the expert for drinking water supply (Appendix 9.5.3), already shows the importance of supraregional measures for high water.

This subdivision of the adaptation measures in Basel mentioned in the interviews shows that a number of measures are already in place to reduce exposure by means of physical infrastructure and nature-based solutions. However, there is still a residual risk, which means the risk remaining after the implementation of adaptation measures (IPCC, 2022c). This is also due to the few measures in the area of social policy such as communication strategies or climate education, which could help to reduce the vulnerability.

6.5. Future outlook: adaptation to changing risks

Although the data analysis did not show an increase in extreme flood events until the end of the 21st century, the planned adaptation measures should be maintained. First because the number of flood days could be at a higher level and therefore place a greater impact on the immediate infrastructure of the water bodies, such as the Rhine bank. Second, with the data analysis of this thesis, the occurrence of rare extreme events cannot be excluded. And third, the initially mentioned higher number of flood days combined with the increase in heavy rainfall events may lead to critical flooding in Basel, as described in Scherrer et al. (2006). Therefore, the planned measures should be further promoted, and political barriers should be reduced if possible.

The study of the development of low flow and drought showed that adaptation in Basel is elementary and should be further promoted. In particular, because a compound risk from heat and drought is likely. Especially with regard to this combination of risks, the urban climate concept (Bau- und Verkehrsdepartement des Kantons Basel-Stadt (Publ.), 2021) and the associated greening of the city is an important element. As, according to the expert for environment and energy, the associated conflict of use of drinking water for irrigation and simultaneously peak consumption of drinking water, has not yet been resolved, special attention should be paid to solutions to this problem. The approaches to solutions mentioned in Chapters 5.6 and 6.4 should be evaluated in terms of their implementability in Basel. Precisely because this is a conflict of use, all stakeholders should be involved here, as suggested by the IPCC (2022b). This includes, on the one hand, those responsible for drinking water supply, who must have knowledge of the currently known developments and their effects on consumption of drinking water. On the other hand, the population should also be involved, as they can have a significant influence on consumption.

Adaptation measures not conflicting each other, but being mutually reinforcing, should be particularly supported. This is especially the case for projects that address drought as well as floods and heavy rainfall, including the WieseVital project. This is also a forward-looking project, as the year 2018 has already shown that low water levels were more problematic in the tributaries than in the Rhine itself, and as reported by the expert of waters and natural hazards (Appendix 9.5.4), were most pronounced at the Wiese. Even though the discharge data of the Wiese were not examined, based on the year 2018 and the reports of the expert for waters and natural hazards, it must be assumed that hydrological droughts in this tributary would increase drastically in the future without measures. The planned WieseVital project is an important adaptation to that development and might reduce the negative impacts on the environment considerably. The situation and adaptation of the other tributaries would have to be examined individually.

With regard to the cargo navigation on the Rhine it seems – depending of the scenario considered – unlikely that the aim of having not more than ten days per year an unnavigable situation (Appendix 9.5.4) is achieved. All the more important it seems in the view of these scenarios important, that deepening the shipping channel stays not the only adaptation but gets accompanied by other measures as the third harbor basin and associated option to shift to train transport if necessary.

For the future, it is essential to continuously monitor the changes in hazards and their impacts. This not only includes evaluating the positive or negative effects of the individual adaptation measures, but also which other risk factors, such as vulnerability and exposure, are changing. These results must be communicated in an exchange with all stakeholders. On the one hand, this includes experts such as the interviewees (see Table 6), who should be aware of the likely changes and impacts on their field and help shape the adaptation. On the other hand, individuals at the household level should also be involved, which means that social policy has to be included in Basel's adaptation strategy. Independent of individual or combined risks, it is important not to wait for the next focusing event, but to be proactive and thus avoid costs of inaction (Nicklin et al., 2019).

7. Conclusion

According to the FOEN, Swiss water bodies are significantly affected by climate change. Without climate mitigation and adaptation measures, winter runoff is projected to increase, and summer discharges will decrease significantly, both on average throughout Switzerland. At the same time, heavy single day precipitation events and summer temperatures of water streams increase according to these projections for the whole of Switzerland by the end of the century (NCCS (Publ.), 2021b). The aim of this thesis is to explore to what extent these changes also apply to the case study Basel, which impacts result from them in the urban area and thus which adaptation measures are suitable. The thesis is guided from research questions on the knowledge of climate change and adaptation to water extremes in Europe, as well as the experiences resulting from the recent focus events of 2018 and 2021 in the city of Basel. Further it is asked about current risk management strategies in Basel and their classification in the view of changing water extremes under climate change. To answer these questions, multiple methods were chosen, the results of which, with the approach of triangulation, lead to a more complete view of the complex topic.

In contrast to the increase in high flow events predicted for Switzerland as a whole, the Rhine at Basel is relatively resilient to this hazard due to delaying and peak breaking effects of the lakes of the Central Plateau (Mittelland). Regardless, critical high flow events could arise from a generally higher number of days per year with extreme high discharge, especially in combination with more extreme precipitation events. This even though the higher number of days of extreme discharge does not show an increasing or decreasing trend until the end of the century. Also, extreme high discharges with large recurrence periods are difficult to project and thus make adaptation measures as well as their justification to politicians challenging. Furthermore, the projected changes in duration and annual distribution of heavy rainfall can lead to increased pluvial floods as well as hazards at the smaller tributaries. This all the more as they do not benefit from similar delaying factors as the larger river Rhine. For these reasons, the planned adaptation measures to future fluvial and pluvial floods should be further promoted.

In terms of climate change effects on low flow and drought a significant change in the previous trends can be expected. First, the observed decrease in extreme low water since 1900 will reverse to a renewed increase in these events, the severity of which depends on the scenario. Second, a shift of these events from winter to summer and autumn is evident in the modelled discharge data of the Rhine at Basel. This shift from low water to warmer seasons might lead to even more severe impacts due to the combined risks of heat and drought. Moreover, higher heavy precipitation events could pose a further additional risk as the dried-out soils could aggravate high surface runoff. But according to the results of this thesis, this triple combination of risks seems to play a subordinate role, as precipitation will increase in winter and dry periods concentrate more in summer and fall. The study of adaptation to heat and drought in Basel has revealed gaps, including the drinking water supply, which is not prepared for prolonged dry periods. This problem is further exacerbated by the conflict of water use due to the irrigation of a greener city. According to the data analysis of this thesis, navigation will also have to be increasingly prepared for the non-navigability of the Rhine. These adaptation gaps should be given special attention, whereby those measures that support each other and also mitigate the effects of flooding should be given priority.

As the past years have shown with the two focus events 2018 and 2021, extreme high and low flow events are not mutually exclusive but complement each other. This will continue to be the case in Basel in the future, as confirmed by the analysis of future data, with low flow events being more emphasized than floods. On the one side, this alternation can be a chance, as it mitigates to some extent the impacts of droughts on for example forests if the dry periods are preceded or followed by a period of higher precipitation and runoff. On the other hand, the co-existence of these two hazards leads to the need for Basel to adapt equally to both extremes. In Basel, however, flood hazards are perceived to be more serious and, as a result, measures tailored to them are more likely to be favoured at the political level.

The interviews with experts showed that also in Basel an increase in adaptation measures after focus events has taken place. However, with extreme events at both ends of the scale, there is a danger of neglecting adaptation measures for the risk that is not acutely prevalent in each case. This makes it all the more important to focus on measures that are suitable for several hazards at the same time. This first because space for physical infrastructure is limited in a densely built up city as Basel and second as it overcomes the bias of neglecting one side of the extremes. The adaptation implemented and planned so far are based mainly on physical infrastructures and nature-based solutions, and less on planning and social policy. With greening the city, the sponge city principle and the integrated flood management planned at the Wiese, the city of Basel takes already important steps towards adapting to multiple hazards. But these efforts could be strengthened by the inclusion of social policy measures, which can be suitable for combined risks as well.

While there is not yet clear, which of the given RCP scenarios is most likely to occur, there is a possibility that the planned adaptation measures, which will be further promoted in the future, will mitigate the effects of climate change in terms of impacts in the city of Basel. However, the effects of neither the measures nor the sum of the adaptation cannot be quantified with this thesis. In addition, further adaptation measures will be necessary to compensate an increasing exposure due to increasing urban population in Basel and a possible increasing vulnerability due to changes in the socio-economic profiles or the demographic distribution. It is important to mention that the inclusion of the current and possible future adaptation measures in the city of Basel in this thesis is mainly based on the statements of expert in relevant fields, and does not reflect a systematic analysis of the report “Adaptation to climate change in the canton of Basel-Stadt” (Departement für Wirtschaft Soziales und Umwelt (Publ.), 2021).

As the present thesis does not examine temperature data from Basel, no forecast can be made on the development of local heat waves. Furthermore, the extreme event analysis concerning discharges and precipitation concentrates on the development of prolonged events, statements of this thesis concerning on maxima of single events are less robust. For both, maximum daily discharge and the hazard of pluvial floods as well as for the compound risk of heat and drought in the city of Basel, more research will enhance an adaptation tailored to local needs. With regard to the latter, the compound risk of heat and drought, the overall project of Muccione et al. (in prep.) to which this thesis is attached will provide further insights. In order to be able to assess future water extremes on the entire Rhine, a study including the catchment area as well as the rainfall over the regions of Bern and Aargau would be important.

While events and damages of floods and heavy rainfalls are systematically recorded in the SFLDD of the WSL (WSL, 2021), it is noted that so far, no identical database exists for the damages of drought events. Following the 2018 focus event, the "WSL Drought Initiative 2018" (WSL, 2020) was launched, having a strong focus on impacts on forests. Using the case study of Basel as an example, this thesis shows that damage to forests caused by droughts is relevant for urban areas too. But the thesis also shows that - especially in urban areas - the impacts of drought are more diverse, interconnected and far-reaching and go far beyond the impacts previously known. A database that also systematically records and monetizes these damages could be helpful to justify adaptation measures in urban areas to drought on a political level.

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9. Appendix

9.1. Results Literature Review

The following two tables summarize the results of the literature review, whereby some of the sources listed in Table 16 also contain information on adaptation and are therefore also included in this chapter. These papers have not been listed a second time in Table 17, instead the second table serves as a supplement to the first.

Table 16 Summary of reviewed literature on evidence on climate change and water extremes in Europe.

Autor, Year	Title | Process | Place	Method	Main Findings
(Guerreiro et al., 2018)	Future heat-waves, droughts and floods in 571 European cities • Heat-waves • Drought • River flood • Compound events 571 European cities	Usage of all model runs from CMIP5 for RCP8.5 to calculate Low, Medium and High Impact scenarios (10th, 50th, and 90th percentiles) of each hazard for each city.	While an increase in heatwave days was found in all European cities, they increased most in southern Europe. The strongest temperature increase on heatwave days was found in Central Europe. The low impact scenario shows an intensification of drought in southern and an increase of river flood in northern Europe. The high impact scenario indicates an increase in both drought and river flood risks for most cities.
(Tapia et al., 2017)	Profiling urban vulnerabilities to climate change: An indicator-based vulnerability assessment for European cities • Heat-waves • Drought • Pluvial, fluvial, and coastal flood 571 European cities	Indicator-based vulnerability assessment regarding impact chains in socio-economic and urban areas.	The highest vulnerability to heatwaves shows cities in South and Central Europe and the Baltic countries, resulting of combination of socio-economic and physical features. Places that are already among the warmest areas in Europe show the lowest vulnerability to heatwaves, which could be due to the already increased awareness. A high vulnerability to drought correlates with less diversified economies, expanding populations and underperforming water management systems. Crucial for a high vulnerability to pluvial and fluvial flood are socio-economic factors, physical features, the city commitment to adapt, and the level of awareness of the citizens. A spatial pattern can only be weakly detected, with somewhat higher vulnerability in the south than in the Scandinavian countries and the British Isles.
(Forzieri et al., 2014)	Ensemble projections of future streamflow droughts in Europe • Streamflow drought 446 gauging stations across Europe	Streamflow simulations with extreme value analysis based on a coupling of a hydrological model, climate simulations, and a water use scenario.	Intensity and severity of droughts will increase due to climate change, especially in southern Europe, where the future water use will worsen the situation by 10-30%. A reduction in droughts in Western, Central and Eastern Europe could be reversed due to intensive water use. The increase of drought in the south and decrease in the north is highly significant, the transition zone in between shows no clear trend.
(Paton et al., 2021)	Extent, trend and extremes of droughts in urban areas • Drought 31 German cities	Evaluation of 31 urban climate stations in Germany, period 1950-2019, with standardized precipitation index in terms of drought lengths, drought extremes, heat waves, and concurrent heat and drought months.	2018 showed a long drought averaging 6 months in most cities, with only one-third of the cities having one of the three longest droughts since 1950. southern and central cities show a significant increase in the number of drought months since 1950. More northern cities show an increase or no trend. The combination of simultaneous heat and drought shows a strong increase within the last two decades. The heterogeneity between the cities studied is large.
(Fischer & Schär, 2010)	Consistent geographical patterns of changes in high-	Analysis of high-resolution regional climate simulations.	The most pronounced changes concerning frequency and persistence of heatwaves occurs in southern Europe. The heatwave amplitude changes the most places of low altitude in

	impact European heatwaves • Heat-waves European countries / regions		southern Europe and in countries further north. The health impacts of these droughts are projected to be most severe in southern Europe.
(Alfieri et al., 2015)	Global warming increases the frequency of river Floods in Europe • River flood 37 European countries	An ensemble of RCP8.5 scenarios of downscaled climate projections (EURO-CORDEX) are examined with regard to magnitude and frequency of extreme streamflow events (statistical distribution and peak over threshold analysis).	Precipitation and streamflow will be reduced in southern Europe and have a large increase over Scandinavia and Iceland. No clear trend is evident in the transition zone in between. By the middle and end of the century, HQ_{10} will increase especially in northern Europe. HQ_{100} shows an increase by the end of the century in all countries studied. In general, the change in frequency of discharge extremes is supposed to have a larger impact than the increase in their magnitude.
(Skougaard Kaspersen et al., 2015)	Influence of urban land cover changes and climate change for the exposure of European cities to flooding during high-intensity precipitation • Pluvial flooding Odense	Estimation of changes in impervious surfaces based on Landsat satellite imagery (1984-2014) combined with current and expected future rainfall extremes (RCP4.5 and RCP8.5) result in flow simulations and flood hazard assessments.	For the city of Odense, the urban development of the past 30 years resulted in an increase of the city's flood exposure to pluvial flooding by 6% (10-year rainfall) up to 26% (100-year rainfall). For the RCP4.5 and RCP8.5 scenarios an increase of the flood risk of 40% and 100% respectively is estimated, highlighting that land cover change plays a crucial role for the city's exposure and adaptation to pluvial flooding.
(Skougaard Kaspersen et al., 2017)	Comparison of the impacts of urban development and climate change on exposing European cities to pluvial flooding • Pluvial flooding Odense, Strasbourg, Vienna, Nice	The method of Skougaard Kaspersen et al. (2015) applied to four cities differing in climatic conditions, trends in urban development and topographical characteristics.	During the past 30 years all four cities studied faced an increase in flood exposure. Under both scenarios (RCP4.5 and RCP8.5) climate change will further aggravate the exposure. While for Odense, Vienna, and Strasbourg the factors urban land cover change and climate change are to be weighted approximately equally, for Nice climate change is the clearly stronger driver for the increased exposure to flooding.
(Nicklin et al., 2019)	Understanding the Costs of Inaction – An Assessment of Pluvial Flood Damages in Two European Cities • Pluvial flooding Rotterdam, Leicester	Usage of flood modelling and a flood damage estimation tool to assess pluvial flood damage due to extreme rainfall.	In both cities studied the damage potential due to pluvial flood is higher than EUR 10 million. The flood damage correlates more strongly with the type of land use than with the flood depths. The residential sector shows the highest damage potential.
(Sedlmeier et al., 2016)	Compound extremes in a changing climate – a Markov chain approach • Compound events 8 European regions	Application of Markov chains to analyse heavy precipitation and cold (winter) and hot and dry days (summer) based on measured (1951-2010) and simulated data (up to 2050).	The compound event of heavy precipitation and cold days in winter is likely to increase in future in the following three regions: southwestern France, northern Germany, and Russia around Moscow. A combination of heat and dryness in summer is expected to increase in Spain and Bulgaria.
(Manning et al., 2019)	Increased probability of compound long-duration dry and hot events in Europe during summer (1950-2013) • Compound events Europe	Quantification of the probability in terms of duration and magnitude of long-duration meteorological droughts co-occurring with extremely high temperatures with a copula-based approach. A reference period (1950-1979) is compared to a present period (1984-2013).	In general, in Europe long-duration events of drought coincidence with high temperatures. The probability of the 95th percentile of heat and drought being exceeded simultaneously has increased from the reference period to the current period across Europe, the presumed driver of this trend being the rise in temperature.

Table 17 Summary of reviewed literature on adaptation and water risk management strategies in Central European cities.

Autor, Year	Title | Process | Place	Method	Main Findings
(Carter, 2011)	Climate change adaptation in European cities • Flood • Drought • Heat-waves Stuttgart, Basel, Freiburg (among others)	Literature review.	In addition to spatial planning and building regulation, the behavioural dimension is also crucial for a holistic adaptation. Communication, awareness, personal responsibility, and interdisciplinarity are key factors. Political barriers and maladaptation can be hindering factors.
(Aguiar et al., 2018)	Adaptation to climate change at local level in Europe: An overview • Flood • Drought • Heat-waves 147 localities	Investigation of local adaptation strategies regarding triggers and barriers for different sectors and risks.	The triggers for taking adaptation measures were mainly research projects, implementation of Europe-wide policies, or increasingly extreme events. Barriers to implementation were the lack of resources and political commitment as well as uncertainties. Patterns in adaptation planning and capacity could be identified: smaller localities are more likely to use (inter)national funding than large municipalities.
(Rossano, 2015)	From absolute protection to controlled disaster: New perspectives on flood management in times of climate change. • Flood Projects in Switzerland, France, Germany, Netherlands	Historic review with regard to spatial planning and technical solutions.	Across Europe, most populated landscapes are affected by flood potential. Throughout history, the perception of this disaster has changed. Technical measures have made floods less frequent, so they have become more abstract and worse perceived by people. For the future, a new approach that reintegrates flooding into spatial perception and planning is proposed.
(Priest et al., 2016)	The European Union approach to flood risk management and improving societal resilience: lessons from the implementation of the Floods Directive in six European countries • Flood Belgium, England, France, Netherlands, Poland, Sweden	Analysis of the flood protection with regard to legal and political aspects. Evaluate aspects that enhance or constrain the social resilience to floods.	The impact of the flood protection directives varies from country to country. Despite the efforts of transboundary measures in river basins, existing strategies of harmonization partly prevent this. To improve the situation, cooperation must be promoted and the scope of action of the respective authorities must be increased.
(Kreibich et al., 2017)	Adaptation to flood risk: Results of international paired flood event studies • Flood Germany	Analysis of eight different empirical case studies with two consecutive flood events, the second causing lower damage.	In all case studies, the lowered damage costs in the second event was associated with a reduction in vulnerability, which was lowered with in risk awareness, preparedness, and emergency management. This shows on the one hand the important role of vulnerability with regard to adaptation, and on the other hand the difficulty of taking measures without a stimulating event.
(Mücke & Litvinovitch, 2020)	Heat extremes, public health impacts, and adaptation policy in Germany • Heat-waves German cities	Examining the trend toward heat extremes, their health impact, and the policy framework for creating a national adaptation strategy in the context of an essay.	The extremely hot summer of 2003 served as a stimulating event, so that in 2008 Germany developed a national adaptation strategy that included measures to improve human health under heat. Measures included are heat health warning systems, action plans, and projects specifically focused on elderly people, as they are among the most vulnerable.
(Ferenčuhová, 2021)	Inconspicuous adaptations to climate	Discussing perception of and coping with local	Several ‘inconspicuous adaptations’ were described, including adjusting activities, changing

	change in everyday life: Sustainable household responses to drought and heat in Czech cities - Heat - Drought 6 cities in the Czech Republic	climate change within the urban context in focus groups with a total of 60 participants in six cities in autumn 2018.	the rhythms of activities, and home-made solutions. These may be important short-term coping strategies for increasing heat and drought events occurring also in urban areas.
(Stratópoulos et al., 2019)	Tree species from two contrasting habitats for use in harsh urban environments respond differently to extreme drought - Drought Central Europe	Comparison of six commonly planted tree species in a drought experiment with regard to their drought tolerance and cooling potential.	Species from drier habitats showed a lower decrease in sap flux, but also a lower stem growth which is associated with a possible better development of roots in deeper soil layers. Better regulation of water balance was also noted, which is expected to have a higher cooling capacity. A test of species is recommended to diversify their selection.

9.2. Results Newspaper Analysis

The following Table 18 and Table 19 show the direct results of the newspaper analysis with regard to the two extreme events studied, 2018 and 2021. Table 20 shows the detailed references to the individual articles.

Table 18 Results of newspaper articles analysis 2018.

Date	**Reference**	**Mentioned Impact**	
		What	**Where**
13.07.2018	(Schmid, 2018)	Dried out soils	Soils
		Low water levels in streams and rivers	Water bodies
18.07.2018	(Schwald, 2018)	Heat island effect, tropical nights	City Basel
		Fish in danger of dying from the heat	Rhine
		Forest fire risk	Hardwald
		Increase in cardiovascular problems	Population
20.07.2018	(sda, 2018)	Navigation channel is deepened by dredging (for 4.2 million CHF), in the city area over 4km	Rhine in the city area
24.07.2018	(Ecklin, 2018b)	Damage to beech trees, death of branches, crown parts and whole trees	Adjacent forests
		Breaking branches are a risk for forest visitors, partial areas closed, enter the forest at own risk	Adjacent forests
24.07.2018	(Ecklin, 2018a)	No drinking water shortage in the lower Baselland (water intake mostly at groundwater), water purchase from Hardwasser AG possible	Lower Baselland
		Groundwater level lowered, more Rhine water must be infiltrated to maintain level	Hardwald
27.07.2018	(Sikora, 2018)	Endangerment of fish due to decreasing oxygen content	Wiese
		Danger to trees, breaking branches also pose a danger during fires, forest fire danger level 4, fire ban in and around the forest	Adjacent forest
		Water withdrawal from surface waters only with a permit	Water bodies
31.07.2018	(Gubler, 2018a)	Beech trees wither, caution during forest walks	Adjacent forest
31.07.2018	(Gubler, 2018b)	Function of the forest as a recreational area endangered	Population
03.08.2018	(SIS et al., 2018)	Tram track distortions	Streetcar rail network
03.08.2018	(Wehrli, 2018)	Birsfelden pier cannot be used by passenger ships	Pier Birsfelden
07.08.2018	(Hauswirth, 2018a)	Trees with premature leaf shedding, deadwood formation, branching, and cracks in the trunks	City Basel (Totentanz, Münsterhügel, Theaterplatz)

07.08.2018	(Schenker, 2018)	Green branches also affected by summer breakage, danger of falling branches, barriers	Forest and fitness trail in Riehen
08.08.2018	(Inglin & Fellmann, 2018)	Heat as a hazard to vulnerable persons, review heat plans.	City Basel, population
10.08.2018	(Tschopp & Schwald, 2018)	Dry soils, surface runoff during short term thunderstorm	Soils
		Swimming ban in Wiese and Birs	Local recreation
11.08.2018	(Griesser, 2018a)	High transportation costs during low water lead to increased gasoline prices by 4-6 Swiss centimes/litre	Population
		No danger to the security of supply, switch to train traffic	National supply
		Dredging the shipping channel	Rhine
11.08.2018	(Griesser, 2018b)	Cargo ships have to operate with less cargo, increases costs of transportation and goods	Port of Switzerland
		Increased gasoline prices	Population
30.08.2018	(Hauswirth, 2018b)	Frequent dry periods in recent years have consequences for tree health, questionable impact on urban tree population	City Basel
		Fire ban	Adjacent forests
		Swimming ban	Birs and Wiese
14.09.2018	(Fischer, 2018)	Findings of tiger mosquitoes, possible spreading	City Basel
18.09.2018	(Felber, 2018)	Low water (level < 6m) until end of August on 145 days, more ships needed to transport the same amount of goods, increased costs, cargo handling no longer economical	Port of Switzerland
26.10.2018	(Griesser, 2018c)	Short-time work in port companies	Port of Switzerland
		Federal agency approves release of diesel from compulsory stocks	National supply
26.10.2018	(Reichen et al., 2018)	Port companies apply for short-time work, container traffic reduced by a factor of 10	Port of Switzerland
30.10.2018	(Regenass, 2018)	Standstill of the three upper Rhine ferries	Port of Switzerland

Table 19 Results of newspaper articles analysis 2021.

Date	**Reference**	**Mentioned Impact**	
		What	**Where**
15.07.2021	(Coviello, 2021)	Suspended shipping traffic	Rhine
		Banks closed off to protect the population	Rhine, Birs
15.07.2021	(Regenass, 2021)	Danger of people going to the Rhine and drowning, barrier fences are provided	Rhine
		Grasses along the Wiese were cut for improved water drainage	Wiese
		Provision of inflatable barriers, rake of the stream channels is continuously cleaned of flotsam	Riehen (Aubach, Bettingerbach, Immenabch)
		IWB suspends pump for groundwater recharge in Lange Erlen, drinking water supply guaranteed as groundwater sufficient for days to weeks	Lange Erlen
		Declining electricity production, costly manual cleaning of rakes, shift work and rising personnel costs	Power plant Birsfelden
16.07.2021	(bz, 2021)	As a precautionary measure, a decentralized storage for mobile water barriers with sandbags is created	Bank below Mittlere Brücke in Kleinbasel
		Closure of the Rhine for navigation and ferries	Rhine
		Warning to stay out of the water, danger due to river speed, turbid water and flotsam	Rhine
16.07.2021	(Mathari, 2021)	Stuck cargo ships, also in the following weeks	Port of Switzerland
16.07.2021	(sda, 2021)	More than 20 cargo ships stuck	Port of Switzerland
17.07.2021	(Hofer, 2021)	Undercutting of the bank, landslide, two fishing piers swept away (estimated damage 150'000.- CHF each), erosion is stopped with rock blocks	Bank Rankhof
		Motorized traffic closed for several days	Grenzacherstrasse
20.07.2021	(Scheier, 2021)	Removal of the accumulated driftwood	Landings of the ferries

02.08.2021	(Tschan, 2021)	Landslide, two fishing piers crashed, securing the foot of the slope with granite blocks	Bank Rankhof
06.08.2021	(Dähler, 2021)	Three fishing piers caught by water and destroyed, fourth questionable, reinforcement bank with granite blocks	Bank Rankhof
28.10.2021	(Hoskyn, 2021)	Direct award of CHF 800,000 for the repair of the Rhine embankment	Bank Rankhof
		Reconstruction embankment	Nature reserve Rheinhalde

Table 20 Bibliography of newspaper articles analysis 2018 and 2021.

Overview of Media Articles of the Extreme Events 2018 and 2021
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Coviello, M. (2021, July 15). Ein Notstand wie 2005 wird nicht ausgeschlossen. *Neue Zürcher Zeitung*, 3.
Dähler, T. (2021, August 6). Die Behörden kannten die Gefahr, handelten aber nicht. *Basler Zeitung*, 17.
Ecklin, M. (2018a, July 24). Die Dürre ist eine tickende Zeitbombe. *Basellandschaftliche Zeitung*, 17.
Ecklin, M. (2018b, July 24). Vorsicht bei Waldspaziergängen. *Basellandschaftliche Zeitung / MLZ*, 17.
Felber, P. (2018, September 18). Zu wenig Wasser für Schifffahrt. *Basellandschaftliche Zeitung*, 23.
Fischer, M. (2018, September 14). Kein Fund in Fricktaler Fallen. *Aargauer Zeitung / MLZ / AZ Fricktal*, 27.
Griesser, P. (2018a, August 11). Eine Frage des Tiefgangs. *Basler Zeitung*, *11*, 7.
Griesser, P. (2018b, August 11). Niedrigwasser treibt Benzinpreis in die Höhe. *Basler Zeitung*, 1.
Griesser, P. (2018c, October 26). Niedrigwasser wird zur Geduldsprobe. *Basler Zeitung*, 9.
Gubler, T. (2018a, July 31). Situation wird immer prekärer. *Basler Zeitung*, 1.
Gubler, T. (2018b, July 31). Wie nach einem Sturm. *Basler Zeitung*, 25.
Hauswirth, M. (2018a, August 7). Der grosse Durst der Bäume. *Basler Zeitung*, *7*, 18.
Hauswirth, M. (2018b, August 30). Bäume können Trockenheit besser überstehen als gedacht. *Basler Zeitung*, 21.
Hofer, D. (2021, July 17). Der Rhein kannte kein Erbarmen. *Bz - Zeitung Für Die Region Basel / Schweiz Am Wochenende*, 21.
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9.3. Additional graphs: Analysis of measured hydrological and meteorological data

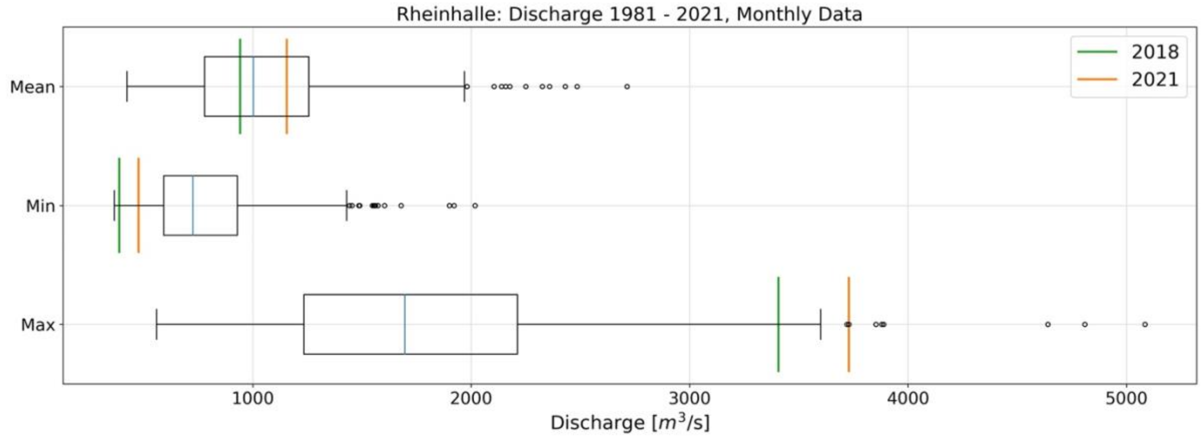

Figure 41 Boxplot of mean, minimum, and maximum discharge data with monthly resolution, 1981 - 2021, Rheinhalle.

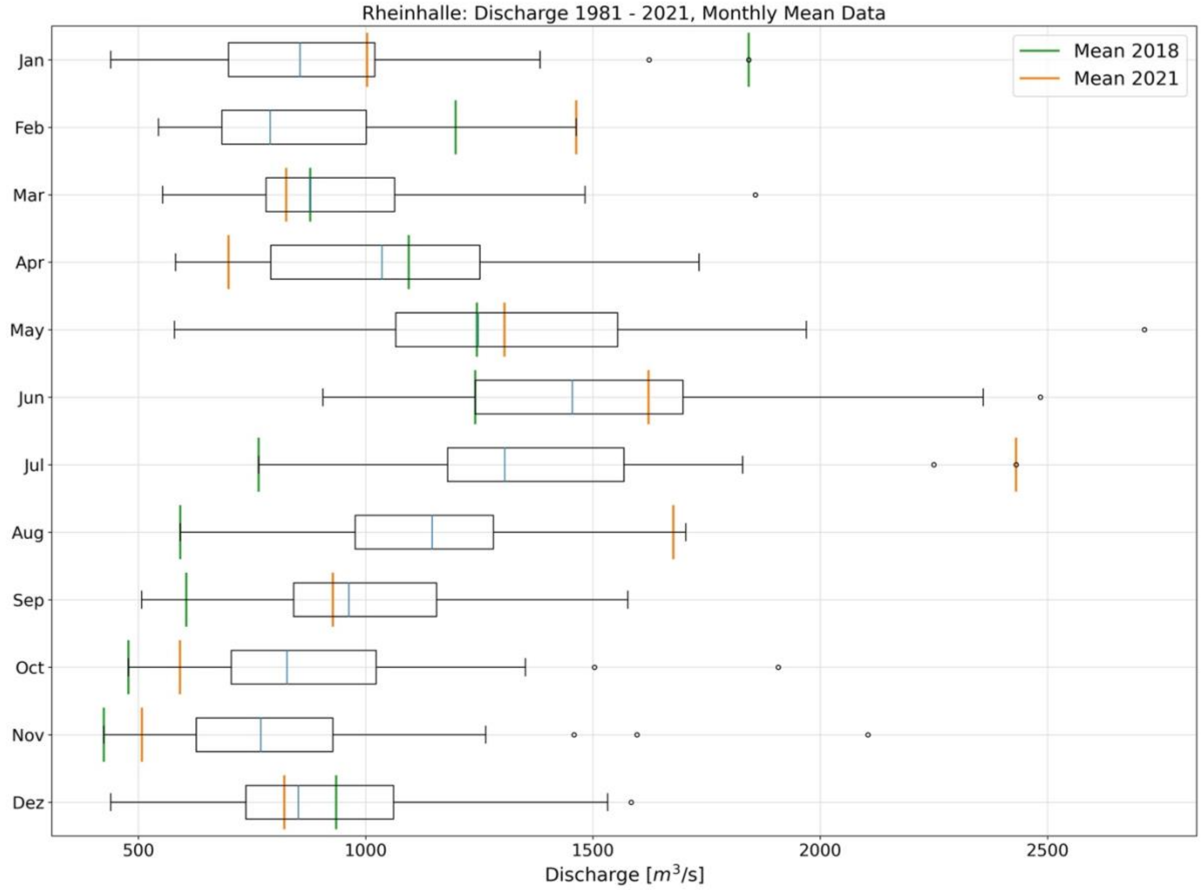

Figure 42 Boxplots per month of monthly mean discharge, 1981 - 2021, Rheinhalle.

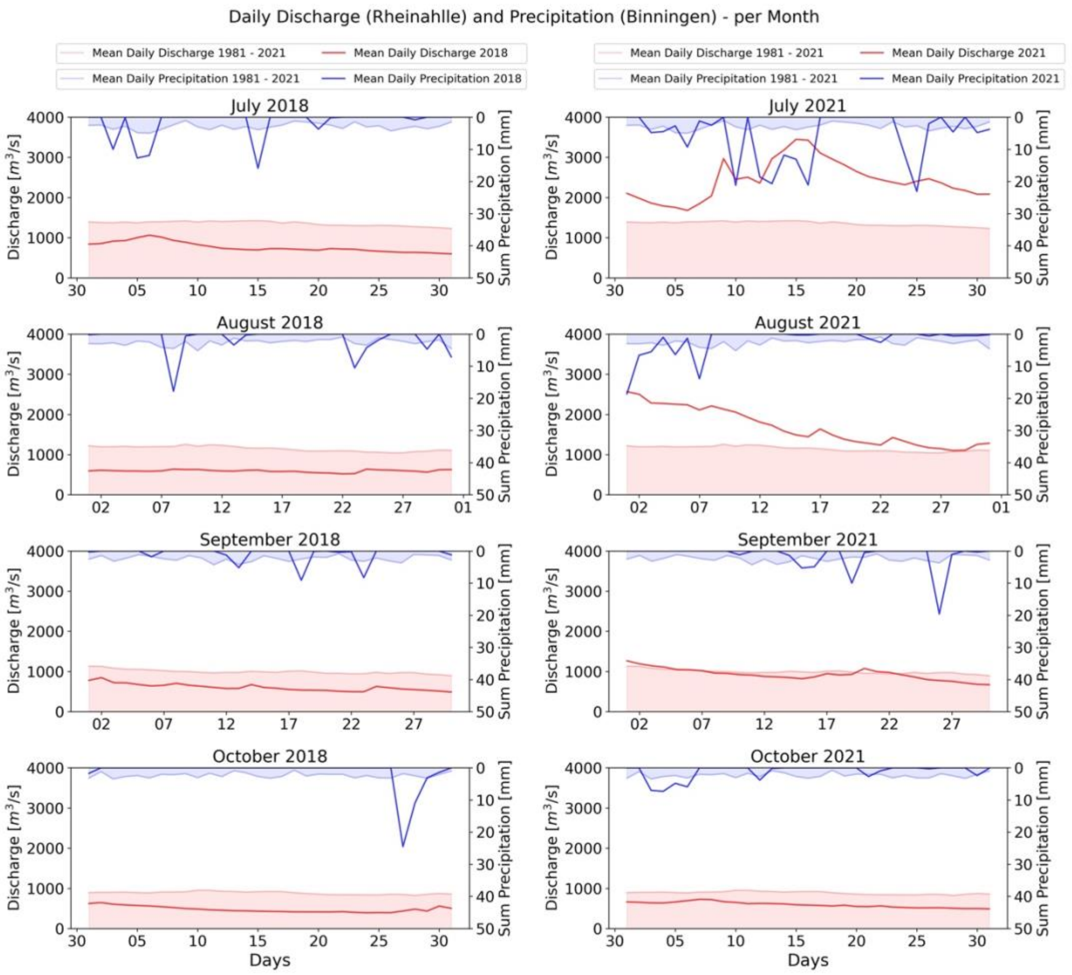

Figure 43 Hydrograph of daily mean discharge and sum precipitation data, 2018 and 2021 compared to 1981 - 2021, months July – October, Rheinhalle and Binningen.

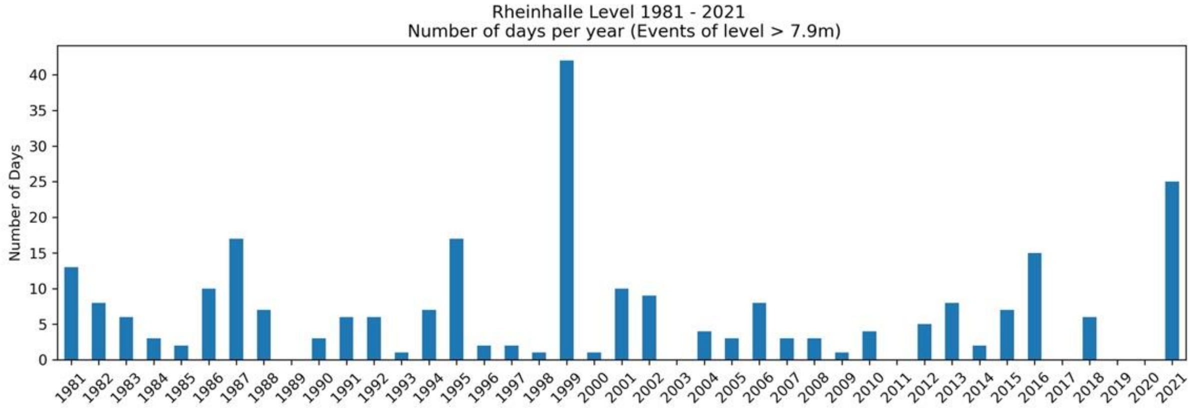

Figure 44 Level Rheinhalle, events of levels ≥ 7.9m, number of days per year.

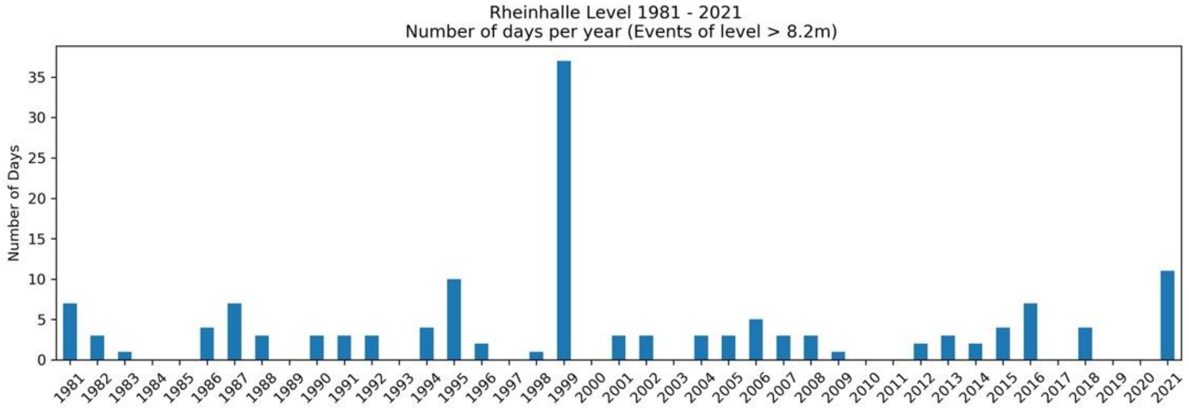

Figure 45 Level Rheinhalle, events of levels ≥ 8.2m, number of days per year.

9.4. Additional graphs: Identification of future trends with Hydro-CH2018

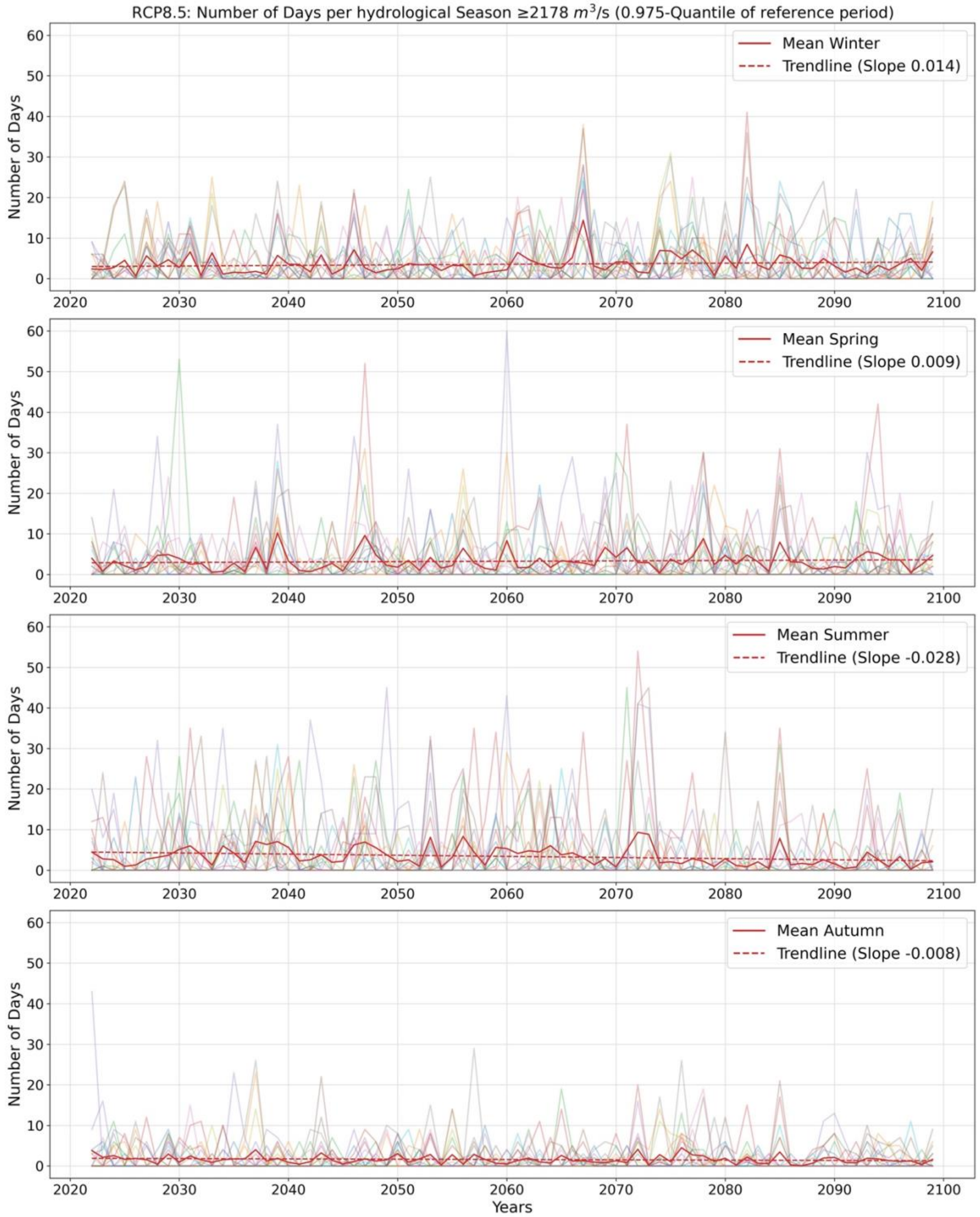

Figure 46 Expected future number of days per hydrological season above the 0.975-quantile of the reference period discharge (1981-2021) according to Hydro-CH2018, RCP8.5, Rheinhalle. For each season, the 18 models of the scenario are shown in pastel colours, their mean and trend line in red.

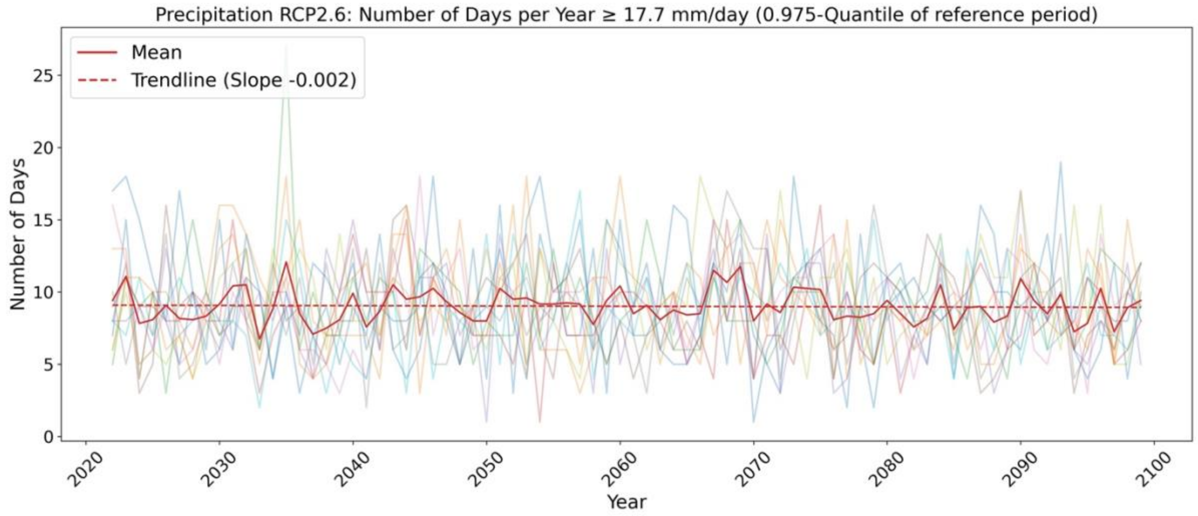

Figure 47 Future Precipitation extremes. The expected future number of days per year above the 0.975 quantile of the reference period (1981-2021) according to Hydro-CH2018, RCP2.6. The 12 models of the scenario are shown in pastel colours, their mean and trend line in red.

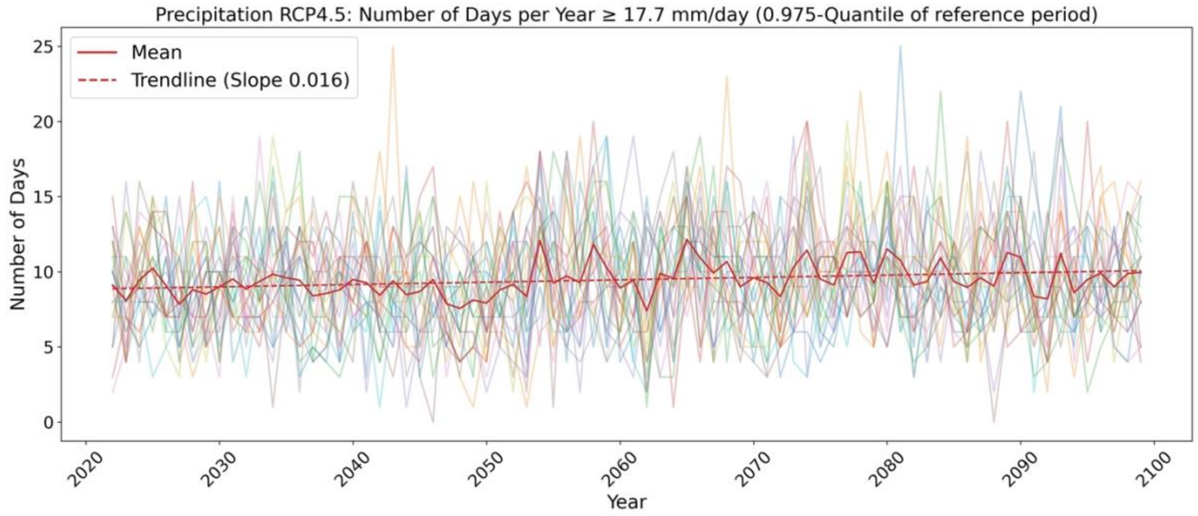

Figure 48 Future Precipitation extremes. The expected future number of days per year above the 0.975 quantile of the reference period (1981-2021) according to Hydro-CH2018, RCP4.5. The 25 models of the scenario are shown in pastel colours, their mean and trend line in red.

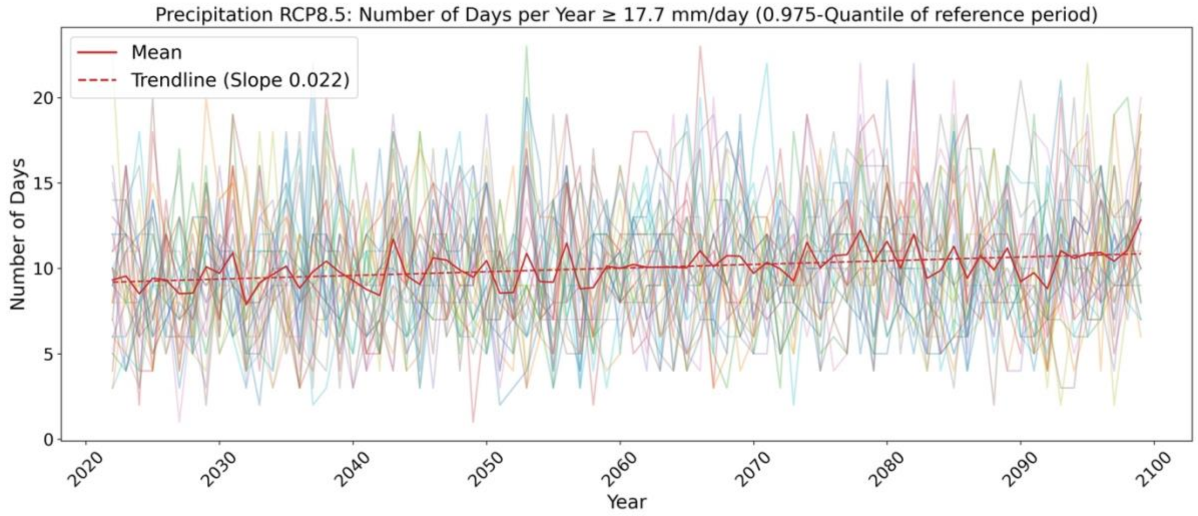

Figure 49 Future Precipitation extremes. The expected future number of days per year above the 0.975 quantile of the reference period (1981-2021) according to Hydro-CH2018, RCP8.5. The 31 models of the scenario are shown in pastel colours, their mean and trend line in red.

9.5. Summaries of interviews with key informants

The following interview summaries were first given to the interviewees in German for proofreading and then translated into English with appropriate corrections. Documents referred to by the interviewees during the interview are indicated as sources in the summaries.

9.5.1. Expert in environment and energy, canton of Basel-Stadt

Basel addressed the topic of adaptation to climate change at a very early stage (Klimafolgenbericht 2011, 2017). This was followed in 2019 by the Basel climate analysis and in 2021 by the documents "Stadtklimakonzept" (Bau- und Verkehrsdepartement des Kantons Basel-Stadt (Publ.), 2021) and "Anpassung an den Klimawandel im Kanton Basel-Stadt (Klimafolgenbericht 2021)" (Departement für Wirtschaft Soziales und Umwelt (Publ.), 2021), which were also very specifically oriented towards Basel. Experiences from other cities have been incorporated into the reports in some topics such as facade greening or wastewater. With regard to unexpected events and combined risks, Basel's local situation was not addressed, but reference was made to the federal perspective. This is justified by the fact that their effects tend to be large-scale, so that the whole of Switzerland (or possibly the whole of Europe) can be affected. Preventive measures for such cases are only possible to a limited extent. On the one hand, for economic reasons, preventive measures cannot be implemented if the costs are very high and the probability of occurrence is very low at the same time. On the other hand, unexpected events are practically impossible to predict.

For drinking water production, the Rhine has enough water even at low water. Contamination by industry could pose a problem, as pollutant concentrations are elevated when runoff is low. In such cases, the seepage of Rhine water into the groundwater is temporarily interrupted. As part of the general water supply planning for 2040, the drinking water production rate will be expanded to create redundancy at the Hardwald and Langen Erlen drinking water production sites. The limiting factor for drinking water supply in the event of very hot and dry summers could nevertheless remain the maximum drinking water delivery rate (pump capacity of drinking water extraction from enriched groundwater), although this could be mitigated with a call for water conservation or flexible water prices. Here, the question also arises whether the city wants to install even more pumps for a peak demand on a few days a year, which would lead to a higher water price, or whether the intensive irrigation of private gardens can be dispensed during heat periods. On heat days the city's parks and lawn also have an increased need for water. However, larger trees need groundwater, as their roots are in the aquifer, and if its level drops for a long period of time during long dry periods, this can lead to their death. This would be a great loss for the city, as the city climate concept intends a city as green as possible as a measure against the heat. Irrigation of such large urban trees is only possible to a limited extent, as their roots are very deep and are only insufficiently reached by irrigation. In extreme cases, there is a conflict of interest between the goal of a green city to improve the urban climate and the drinking water supply.

Floods originating from the Rhine are not problematic, not even for events with higher return periods. Surface water and urban flash floods have been a problem in Riehen so far, with measures already planned. Basel introduced a new wastewater process control system, which allows for better control. A detailed hazard map of surface runoff in Basel is in progress. For individual buildings, property protection measures are useful, but the building owners are responsible for these structural adjustments. The city climate concept intends increased rainwater infiltration as part of the sponge city principle. There are already requirements in this regard for construction projects. Drainage and green spaces are incorporated into the planning process at an early stage, particularly in the case of area developments. With regard to the drinking water supply, the pumping of Rhine water has already had to be stopped during floods due to the high turbidity. However, since drinking water treatment always includes settling processes and pre-filtering, no problem is suspected here.

In all measures, it must be taken into account that Basel is already a densely built city and thus the room for action is limited.

9.5.2. Expert in water supply, IWB and Hardwasser AG

The summer of 2018 was a relatively extreme situation for the Hardwald. Because the water supply of the trees there does not depend on groundwater (floor distance aquifer about 30m), but on precipitation, about one fifth of the trees died, especially beech trees. Although the trees are not absolutely necessary for water seepage in the Hardwald, they cannot be completely separated from it either. Shading of the seepage ditches by the forest reduces algae growth. Due to the unstable forest in the summer of 2018, among other things with branch breakages, safety precautions (perform maintenance work by two people, mandatory wearing of helmets) were necessary. Access for people looking for recreation was also restricted for months. The repair of the damage led to increased forest management costs, which were partly transferred to Hardwasser AG. In order to ensure a stable forest in the protection zone in the future, it is relevant for the drinking water treatment company which tree species will be planted in the Hardwald in the future.

In the Lange Erlen, the forest takes on a more important role, as this is not an artificially created seepage ditch, but an open, natural area. In addition to the shade provided by the trees, the biomass that lies on the surface of the seepage areas and feeds the microorganisms that clean the water in the soil, as well as the root system that keeps the soil open for infiltration, are important here. Because the floor distance to the aquifer is smaller in the Langen Erlen and the roots reach it, less damage occurred to the trees here in the summer of 2018.

At low water, the increased Rhine water temperature is not critical for drinking water withdrawal, the resulting rise in groundwater temperature occurs at Hardwasser AG with a delay of about four months and reaches its maximum in January, with the ground passage having a cooling effect. The higher water temperature has negative effects rather on ecology and industry. The latter uses cooling water, the quantities of which can account for up to 20% of daily drinking water requirements, and industry has already built its own groundwater wells. The water volumes in the Rhine are also less of a problem for drinking water treatment than for shipping or power plants.

Water contamination tends to occur less in the summer because treatment plants work better at higher temperatures. Overall, however, the concentration of pollutants doubles with a halved discharge volume. In the case of pollution by chemicals and trace substances, on the one hand their input is investigated in cooperation with the industrial companies, on the other hand it is possible for the waterworks in the Lange Erlen to draw water from the Wiese. So far, this has only occurred in winter; in extreme cases, an additional treatment step would be necessary. Overall, the Wiese tends to play a subordinate role in water withdrawal, as there is a risk of insufficient residual water; a corresponding framework agreement with the Office for the Environment and Energy is in progress. In recent years, the Wiese was mainly used when the Rhine water was polluted during floods or due to chemical pollution.

If more extreme and longer dry and hot periods would occur, the peak demand of water would also increase and persist. To reduce this, measures such as the introduction of a peak tariff would be necessary. If the water supply were extended to these peak days, there would be a lot of reserve, which would only be effectively used on a few days per year. Reservoir volume is secondary; pumping into the reservoir is much more important. The reservoir volume itself lasts for about 8 hours and therefore cannot bridge when the pumping stations from Hardwald and Lange Erlen cannot supply enough. Increased infiltration could not solve the shortage, because then the minimum retention time would be undercut, and the drinking water quality would suffer. In order for both plants, Langen Erlen and Hardwald, to be able to cover an average day alone, an expansion with new wells is planned in Langen Erlen. There is enough reserve in the system so that individual peak days are unproblematic. However, if such a situation lasted for weeks, the system would reach its limits. The idea to discharge water from the Birs into the Hardwald was rejected, while the costs are enormously high the benefit is questionable as also the Birs can also dry up. It is difficult to estimate what would happen if a year like 2018 occurs several times in a row.

At Hardwasser AG, the Rhine water pumps, which maintain the groundwater mountain in the Hardwald, should not be shut down if possible. In the Lange Erlen, on the other hand, pumping can be interrupted in the event of high water or contamination in the Rhine, since the Feldberg groundwater also flows in through the Wiese plain. Since there is no peak consumption at the same time during high water, interrupting pumping is unproblematic.

9.5.3. Expert in water supply, Hardwasser AG

As long as in the Rhine flow a few hundred m^3/s, this is sufficient for drinking water production. Also, in winter 2020/21, the Rhine discharge was low ($600m^3/s$), whereby no restrictions for water withdrawal have arisen. An increase in groundwater temperature is present, but this does not lead to adversely affected drinking water quality.

In the summer of 2018, the drought severely affected the forest, which was probably already weakened by the previous warm summers. Many trees, especially beeches, died. Spontaneously falling branches posed a danger, so maintenance work was reduced, and guidelines were drawn up for employees. For pedestrians, there was a temporary ban on visiting.

When the hardwood forest is thinned out and more light reaches the infiltration system, algae growth increases there. The algae must in turn be removed, although it is not known to what extent they get through the soil passage. When the drinking water was sterilized using UV light, algae were detected at times. It is not yet possible to say whether there is a connection with the algae in the infiltration systems. In principle, the infiltration system in the Hardwald can be operated independently of the stock of trees. Since there is a vertical distance (depth to groundwater) of about 20m between the forest floor and the groundwater mountain, the trees do not reach the aquifer and are dependent on rainwater. Only the trees growing directly next to it benefit from the water of the infiltration system.

The frequency of peak days in terms of water consumption is increasing. In an extreme case, the fourth basin in the activated carbon filter could be operated without activated carbon for a short time, and the resulting slightly lower water quality would still be within the norm. Such operation would certainly be run only in case of extreme events, where there would be no time for activated carbon supply. Heat periods and associated peak consumption should not last longer than 2-4 weeks according to current knowledge about global warming. However, the development of the climate could have an unfavourable effect on this assessment in the future.

If groundwater levels around the Hard drop due to drought, even more water must be pumped into the Hardwald to maintain the groundwater table there. Low groundwater levels around the Hard increase the gradient to the groundwater tabletop in the Hard, and the discharge of the water mountain to the periphery is increased in this situation. In such a situation, infiltration should not be shut off if possible. Shutting off infiltration usually occurs as a result of high turbidity in the Rhine during high water. Thus, it is unlikely that low water flows in the rivers and low groundwater levels, as they occur during drought and high turbidity of river water, as occurring during high water in the Rhine and other rivers, coincide.

In the summer of 2021, no problems arose due to turbidity during the flood, because the flocculant iron chloride can be added if turbidity is high. Problematic, but not very pronounced in summer 2021, is the rise of groundwater levels in the periphery of the Hardwald. If the gradient between Hardwald and Schweizerhalle is too low, the chemical industry there will have to increase its pumping to raise the gradient. In 1999, the discharge of the Rhine at the Rheinhalle gauging station was up to 4600m^3/s, and an additional 1000m^3/s would endanger the structure of the Rhine pumping station. However, studies show that this would not occur even with 500- or 1000-year floods. Furthermore, since 1999, increased attention has been paid to the flood situation in river systems throughout Switzerland. The coordinated operation of weirs and retention volumes ensure that peaks from the tributaries do not overlap at the same time, if possible. This effect is noticed in Basel, it does not protect against floods, but helps to break extreme peaks.

An increase in heat days is expected in the future, which may lead to additional tree mortality in the Hardwald.

9.5.4. Expert in waters and natural hazards, canton of Basel-Stadt

The flood in the summer of 2021 was not extreme in itself, but the high discharge rates lasted for an exceptionally long period. This was relevant for navigation, whose normal operations were restricted for about a month due to the high-water levels. It is difficult to take direct measures against this; the third port basin in Kleinhüningen will provide relief, as further transport by rail will be possible from there. Driftwood can be a problem for ships as long as the Rhine is still navigable. The temporary ban by the canton on swimming in the Rhine and on access to the water space led to a use conflict as the population had only limited understanding for this. The prolonged flood situation also led to saturated embankments, so that a flood peak triggered landslide at the section Rheinhalle. A superordinate concept for bank protection, which also takes into account prolonged flood situations and the climate scenarios 2060, was developed. Surface runoff occurred in the months of June and July 2021 in Riehen and Bettingen, streets and neighbourhoods were flooded without causing damage to objects. Measures in this regard have already been implemented in Bettingen and submitted to the politicians in Riehen. The Wiese has no great damage potential with the runoff that has occurred in 2021.

If Basel had been affected by precipitation like that which fell in Germany in the summer of 2021, greater damage would have been caused. Especially due to the Birsig, which would have already overflowed its banks in the canton of Baselland and would have brought water into the city centre. A combination of already full lakes and such heavy precipitation as in Germany but over the regions of Bern or Aargau could also cause the Rhine to overflow its banks in Basel. This has already occurred at the Kaserne, the lowest point. However, since there is a certain lead time on the Rhine due to the buffering of the lakes and critical weather situations can be detected, there would be enough time to prepare appropriate mobile measures. In contrast, the Wiese swells very quickly. Compared to Germany, Switzerland has a better warning system at the federal level, although it is questionable to what extent the population is sensitized to the warnings.

With regard to flood situations in Basel, the distinction between the Rhine and the smaller tributaries is important. The Rhine in Basel is under the influence of lake runoff management. Prolonged high-water levels can occur, while being well prepared for events with higher return periods. However, for events with return periods of 2-10 years, the Rhine is already on the upper range (referred to (BAFU, 2021)). There is less damage potential for private individuals or buildings than for embankments and bank walls. Redevelopment at the Rankhof and the Pfalzmauer are planned. At the Wiese and the Birs, however, short, high runoff peaks can occur. The “WieseVital” project combines revitalization and flood protection. By giving the watercourse more space, room is created for higher peak discharges. According to the Natural Hazards Map 2012, the Birsig has the largest flood damage potential for Basel with CHF 1.7 billion. Taking into account the climate scenarios, even higher potential damage amounts can be assumed. In order to prevent this in the future, a corresponding measure will be presented to the politicians in the summer of 2022, after the construction of which damage potential from the Birsig will only exist for events that are rarer than HQ_{300}. The flood hazard map will be renewed successively, a detailed surface runoff hazard map is being planned. A tendency towards larger single events and shorter return periods is already visible in the measured data. All planned flood protection projects not only take into account the 2060 climate scenarios of the federal government, but also include an additional safety factor.

In the summer of 2018, the combination of low water levels and high temperatures was particularly problematic for the Wiese, as its water temperature rose even in deeper zones. Possible solutions are planting of the watercourse and protection of the cooler zones due to groundwater inflow for the fish. In the summer of 2018, various measures were considered, but they would also have been in conflict with the drinking water supply. In recent years, it is noticeable that extreme low water situations of the Wiese are increasing. The question arises whether there is a more suitable substrate for urban trees for hot weather conditions that still allows infiltration. There is also a need to reconsider stormwater management or species selection for new plantings. The summer of 2018 has shown that green spaces use a large amount of water, and in the future the question may also arise as to whether a soccer field, for example, really needs to be green during such a summer. Awareness-raising among the public in this regard has hardly taken place yet, and restrictions on water use in hot weather also meet with little understanding, or only when the IWB announces a drinking water shortage, as in the summer of 2018. Although a first step has been taken with the city climate concept, an overarching communication strategy by the canton would be desirable. Precisely because high and low water alternate, the other topic is quickly forgotten again.

In the case of flood protection, a risk assessment including future development is already in progress and is also easier to implement politically. Throughout Switzerland, there is a trend towards an overall view, i.e. flood protection that also integrates measures that are necessary during low water. An overarching guideline and more coordination of projects by the federal government would be desirable.

9.5.5. Expert in energy supply, IWB

IWB has as a shareholder various participation in other power plants throughout Switzerland, most of which are water dependent. The Birsfelden power plant is a small part of this but has a strong regional presence. As a run-of-river hydroelectricity, Birsfelden is not very flexible, but it supplies important base load energy, although fluctuations can also occur. These are balanced out by purchasing rights to other power plants (pro rata procurement of electricity) or by trading transactions. In the event of frequency fluctuations in the power grid, Swissgrid activates positive or negative control power. IWB offers Swissgrid the Birsfelden power plant for negative control power so that output can be reduced in the event of over-frequency in the transmission grid or other grid security needs.

In the summer of 2021, the flood did not cause any major problems for the Birsfelden power plant. The damage to one turbine occurred before the flood and was not caused by it, but a lot of discharge remained unused as a result. The optimal capacity of the power plant is at discharges of about 1500m^3/s. At higher discharges, the power curve decreases due to the reduced difference between upstream and downstream water. As the unused water is let over the weir, the level below continues to rise, and the power output decreases all the more. Flooding is not critical to the power supply, and the loss of power is offset by trading. However, in the summer of 2021, there was so much water that not only the weir but also the bottom outlet had to be opened. This was partly responsible for the undercutting of the embankment at Rankhof. The driftwood that had to be removed from the upstream rake was about 90 tons and therefore more than during an average summer month (7-20 tons), but the resulting extra costs are negligible. Manual operation of the crane used to remove the driftwood required shift work for several days. If this condition were to continue for weeks, a problem would arise with regard to personnel scheduling, which could be solved with temporary employees.

Flood situations do not cause any safety problem for the Birsfelden power plant, not even for those with higher return periods, as the weir is designed for discharges of up to 5500m^3/s. At high discharges, a part of the water goes unused over the weir. The most extreme flood events imaginable would lead to flooded districts or defective power poles and, as a consequence, to an energy overload in the grid. Conversely, if one of the two power lines to Basel and the Birsfelden power plant were to fail at the same time, the power supply would already be tight. In principle, however, the system is redundant, and a local supply bottleneck is very unlikely. Problems in the power supply of Basel would be, if then rather nationally or internationally caused.

Even prolonged low water levels pose few problems for the power supply. In spring and summer, there is sufficient energy available in Switzerland due to the hydropower plants in the Alpine region. In winter, when the reservoirs have hardly any inflow due to the cold and are emptied because they also produce valuable peak energy for other countries, a lot of energy is imported from foreign power plants. If low water were to be present for weeks at the same time, importing energy would be a question of price. The fact that the output of the Birsfelden power plant was lower in the summer of 2018 has already been noted, but this was not a problem for IWB. For other power plants that need the river water for cooling, low levels in combination with high temperatures are rather critical, since as a consequence the output has to be reduced to protect aquatic life.

During both low and high water, the Birsfelden power plant experiences performance losses. In order to be able to compensate for these as effectively as possible with electricity trading, reliable forecasts of events are more important than the events themselves.

Personal declaration

I hereby declare that the submitted Thesis is the result of my own, independent work. All external sources are explicitly acknowledged in the Thesis.

Basel, 21. April 2022 Esther Gerber