Effects of climate change on Swiss water bodies

Hydrology, water ecology and water management

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Abstracts

The Hydro-CH2018 project analysed the effects of climate change on Swiss water bodies. Climate change is altering the entire water balance, especially the seasonal distribution of water resources in the water bodies and groundwater. Low flow is becoming more frequent and the water temperature is increasing. This has a serious effect on water ecology, flood protection and water use. The report "Effects of climate change on Swiss water bodies" gives a concise overview of the results and is a gateway to further technical information and data. The project was treated as a priority theme within the National Centre for Climate Services (NCCS).

Keywords:
Hydrology, Climate change, Watercourses, Lakes, Groundwater, Water temperature, Water quality, Water ecology

Das Projekt Hydro-CH2018 hat die Auswirkungen des Klimawandels auf die Gewässer in der Schweiz untersucht. Mit dem Klimawandel verändert sich der gesamte Wasserhaushalt, besonders aber die jahreszeitliche Verteilung der Wasserressourcen in Oberflächengewässern und im Grundwasser. Niedrigwasser wird häufiger und die Gewässer werden wärmer. Dies hat grosse Auswirkungen auf die Gewässerökologie, den Hochwasserschutz und die Wassernutzung. Der Bericht «Auswirkungen des Klimawandels auf die Schweizer Gewässer» bietet eine kompakte Übersicht über die Ergebnisse und ist ein Einstieg zu weiteren Fachinformationen und Daten. Das Projekt wurde als Themenschwerpunkt im National Centre for Climate Services (NCCS) durchgeführt.

Stichwörter:
Hydrologie, Klimawandel, Fliessgewässer, Seen, Grundwasser, Wassertemperatur, Wasserqualität, Gewässerökologie, Wasserwirtschaft

Le projet Hydro-CH2018 s'est penché sur les effets des changements climatiques sur les eaux suisses, lesquels modifient l'ensemble du régime des eaux, mais plus particulièrement la répartition saisonnière des ressources en eau dans les eaux superficielles et souterraines. Les étiages deviennent plus fréquents et les eaux se réchauffent, entraînant d'importantes répercussions sur l'écologie des eaux, la protection contre les crues et l'utilisation de l'eau. Le rapport « Effets des changements climatiques sur les eaux suisses » propose une vue d'ensemble synthétique des résultats du projet Hydro-CH2018, mené au National Centre for Climate Services en tant que thème prioritaire. Il sert également de base à d'autres données et informations spécialisées.

Mots-clés:
hydrologie, changements climatiques, cours d'eau, lac, eaux souterraines, température de l'eau, qualité de l'eau, écologie des eaux, gestion des eaux

Il progetto Hydro-CH2018 ha esaminato gli effetti dei cambiamenti climatici sulle acque della Svizzera. Con i cambiamenti climatici si modifica il regime idrico nel suo complesso, ma in particolare la distribuzione stagionale delle risorse idriche nelle acque superficiali e sotterranee. Le magre diventano più frequenti e le acque si riscaldano. Ciò ha conseguenze importanti sull'ecologia delle acque, sulla protezione contro le piene e sull'utilizzazione delle acque. Il rapporto «Effetti dei cambiamenti climatici sulle acque della Svizzera» offre un compendio dei risultati e costituisce il presupposto per l'accesso a ulteriori dati e informazioni specialistiche. Il progetto è stato condotto come tematica prioritaria nel National Centre for Climate Services (NCCS).

Parole chiave:
Idrologia, cambiamento climatico, corsi d'acqua, laghi, acque sotterranee, temperatura delle acque, qualità delle acque, ecologia delle acque, gestione delle acque

Foreword

Switzerland is a land of glaciers, snow, rivers and lakes. But large parts of the country are also intensively used, which includes use of water resources. They are affected in three ways: by water abstraction, by pollutant inputs and by the draining and engineering of what were once wetlands. In addition, the fundamental hydrological constants of the Swiss waters are shifting due to climate change: seasonal water availability is changing, and the environment in and on the water has to adapt to higher temperatures and changes in streamflow.

In order to limit global warming to below 2 °C, the international community adopted the Paris Agreement in 2015. By ratifying it, Switzerland made a commitment to reduce its greenhouse gas emissions to half their 1990 level by 2030. To achieve this target, concerted efforts by industry, politics and society are necessary. Renewable energies and energy efficiency are therefore being promoted and greenhouse gas emissions from transport, buildings, industry and agriculture must be reduced.

Switzerland is strongly affected: The CH2018 climate scenarios for Switzerland produced under the aegis of the National Centre for Climate Services (NCCS) show that without resolute action on climate protection, the average annual air temperature will rise by up to 4 °C from the present level by the end of the 21st century. Climate protection measures can limit this warming to 1.5 °C.

What is the effect of this on water balance, water ecology, flood protection, water use and water protection? To answer these questions, the Federal Office for the Environment (FOEN), in collaboration with the scientific community, established hydrological information and scenarios for the future (Hydro-CH2018), based on the CH2018 climate scenarios. Building on these, the FOEN, together with other government departments affected, analysed the impact on water management and ascertained the need for action for the future. The work was carried out within the framework of the NCCS across various sectors.

This report gives an overview of the latest information on water and climate change. The new hydrological scenarios, along with the long-term data series and the government's modern measuring infrastructure, are an important basis for the measures to adapt to climate change in Switzerland. They enable the right options for future water management and healthy water bodies to be pursued in good time. They also reveal where the limits of adaptation lie – including in an international context – and what can be achieved by resolute action on climate protection.

Karine Siegwart, Vice-Director
Federal Office for the Environment (FOEN)

Summary

Switzerland is one of the most water-abundant countries in Europe. It also has large water reservoirs in the form of lakes, glaciers, snow and groundwater. The great Rhine and Rhone rivers and main tributaries of the Po and Danube rise in the country. Changes in the water balance in Switzerland have direct effects on the countries downstream.

According to MeteoSwiss, since 1864 the annual average temperature in Switzerland has increased by 2 °C, which is twice the global average. The new CH2018 climate scenarios predict a further increase of around 4 °C by the end of the century without climate change mitigation measures. With resolute action on climate protection, this increase could be limited to just 1.5 °C. Without climate change mitigation measures, precipitation will also show even greater changes and its increase in winter and decrease in summer will be further exacerbated.

Without climate change mitigation the glaciers in the Alps will lose around 95% of their current volume by the end of the century. In future more rain than snow will fall. The melt water from snow and glaciers will then be lost from summer runoff – summer runoff will reduce and winter runoff will increase. In a scenario without climate change mitigation, the total discharge from Switzerland would fall slightly by the end of the century. The total groundwater volume would hardly change, but groundwater recharge would increase in winter and decrease in summer.

In future, Switzerland will therefore continue to have enough water over the year as a whole, but without adaptation measures more regional shortages could occur in summer. The generally lower runoff in summer and autumn will be intensified by longer and more frequent dry periods. That is exactly when the need for water will increase significantly due to the higher temperatures, particularly in agriculture. In future it will be increasingly important to maintain integrated water resource management for all the needs of a catchment, paying particular attention to water quality and reducing substance inputs. Hydropower production and tourism must also adjust to the climate-related changes. Because warmer air can hold more water, heavy rainfall in Switzerland has already increased significantly in frequency and intensity since records began, and the climate scenarios indicate a further rise. There will then be more surface runoff and local flooding.

The annual average temperatures of the rivers and lakes have risen sharply in recent decades. The hydrological scenarios show a further significant increase by the end of this century. The rise is particularly marked in summer and temperatures that are critical for aquatic organisms will be exceeded more often. The temperature increase in lakes changes their mixing characteristics and can have a serious impact on their ecosystems. Groundwater reacts more slowly to climate change, but here too temperatures will rise.

The water ecosystems are already under severe pressure due to various anthropogenic stress factors such as control structures, chemical pollution and changes in flow dynamics due to hydropower. The consequences of climate change add to this: fish and other cold-blooded species cannot simply adapt to higher water temperatures. Other climate-related changes such as the drying out of sections of watercourses and changes in stratification in lakes can disturb the balance of sensitive ecosystems. Near natural water bodies have greater resilience and adaptability to the effects of climate change. Against this background, it is becoming more urgent to implement water protection measures such as restoration, reducing substance pollution and securing sufficient water quantities as quickly as possible.

In addition to these measures, it is essential to have robust measurement infrastructure to monitor the water bodies and provide long-term data series, together with further development of the hydrological predictions to incorporate new technologies and methods. With these knowledge bases, Switzerland will also have a reliable basis in the future for decision making on the measures for adaptation to climate change.

1 Introduction

The priority theme 'Hydrological principles of climate change' of the National Centre for Climate Services (NCCS) – Hydro-CH2018 for short – analysed the effects of climate change on the water balance, water bodies and water management. Based on the new climate scenarios for Switzerland, the studies show that changes such as the extent of summer droughts will be even greater than previously thought. The results are openly accessible in various publications and on the NCCS website and the Hydrological Atlas of Switzerland (HADES).

Information on the effects of climate change on Swiss water bodies and the water balance are an important basis for targeted adaptation. In the light of this, the Federal Council commissioned the Federal Office for the Environment to prepare reliable hydrological bases for the adaptation measures (FOEN 2014, measure wg2). This includes producing regular hydrological scenarios, improving knowledge of the hydrological processes and monitoring and recording the changes that have already occurred due to climate change.

The assignment was implemented as part of the priority theme 'Hydrological principles of climate change' of the National Centre for Climate Services (NCCS) – 'Hydro-CH2018' for short. The priority theme takes the name of the CH2018 climate scenarios published by the NCCS at the end of 2018 (*www.klimaszenarien.ch*). Based on those scenarios, the effects of climate change on hydrology, water ecology and water management were studied in collaboration with numerous Swiss research institutions. The main results are summarised in this report.

Synthesis and gateway to other products

This report represents an overview and gateway to other products and in-depth materials from the Hydro-CH2018 project. Unless otherwise stated, they can be viewed on the NCCS website (*www.nccs.admin.ch*).

Additional products available from Hydro-CH2018

- NCCS brochure 'Swiss water bodies in a changing climate' *(www.nccs.admin.ch/hydro_brochure_en)*
- NCCS website with general information on this priority topic, the climate scenarios and other NCCS priority themes. Central access to all Hydro-CH2018 products and publications. *(www.nccs.admin.ch/hydro_en)*
- NCCS web atlas with many graphics from this report and other graphics from Hydro-CH2018 *(www.nccs.admin.ch/nccs/en/home/data-and-media-library/data.html)*
- Hydro-CH2018 technical reports on the various topics and research projects, and scientific publications *(www.nccs.admin.ch/nccs/en/home/the-nccs/priority-themes/hydro-ch2018.html)*
- Data access: graphics, maps and indicators in the Hydrological Atlas of Switzerland (*www.hydromapscc.ch*) and the federal government map portal (*www.map.geo.admin.ch*).

What's new in Hydro-CH2018?

CH2018 made new climate scenarios available for the Hydro-CH2018 project. They show a number of improvements over the CH2011 scenarios (*www.ch2011.ch*). Newer emission scenarios, a larger number of climate models with higher resolution and better statistical methods for downscaling of the climate model data to Switzerland were used. This resulted in continuous climate data from 1981 to 2099 and higher spatial resolution (for further information see the CH2018 Technical Report).

As a result, continuous hydrological time series from 1981 to 2099 could be produced and analysed for the first time in Hydro-CH2018. The results largely confirm earlier findings from the projects 'Climate Change and Hydrology in Switzerland' (FOEN 2012), Brennpunkt Klima Schweiz (Swiss Academy of Science 2016) and the National Research Programme NRP 61 'Sustainable water management' (*www.nfp61.ch*). But in some areas the changes are even more pronounced than expected from earlier studies, e.g. on the scale of summer droughts. Hydro-CH2018 placed more emphasis on topics which were less in focus in previous reports. For example, trends already measurable in flow records or water temperature were correlated with their future development. Focus topics such as groundwater, low flow (drought), water temperature and effects on water ecology and management were analysed in depth. The report provides a comprehensive yet concise overview of the future effects of climate change on the Swiss water balance, water bodies and water management and deduces strategic approaches for adaptation to climate change. The results from 11 research projects undertaken as part of Hydro-CH2018 by leading Swiss water research institutions are embedded (Table 1-1). The FOEN also commissioned various research institutions to produce background reports on the topics discussed in the report. Three workshops on the topics: 'Adaptation in the water sector', 'Need for further research' and 'Necessary information" helped to consolidate the project (Chapter 8).

Table 1-1: List of Hydro-CH2018 research projects

Project content	Research institution	Chapter in report
Hydrological scenarios, based on high-resolution stochastic climate data: What are the effects of natural variability in the climate data on the hydrological scenarios?	ETH Zurich	4.3
Water balance and drought: How does climate change affect drought, plant physiology regulation of transpiration and future irrigation requirements?	ETH Zurich	4.3
Forest dynamics, land use and water balance: How will future changes in forest dynamics affect evaporation and runoff?	WSL	4.3
Quantifying the proportion of discharge from snow and glacier melt: How does the melting of the glaciers and reduction in snowpack affect discharge?	University of Zurich	6.1
Updated hydrological scenarios based on the new climate scenarios: How does discharge change in different climate scenarios?	University of Bern	6.2
Multipurpose water reservoirs: Can lakes and artificial reservoirs help to overcome summer water shortages?	WSL and UAS Rapperswil	6.3
How do groundwater resources in alpine catchments change with climate change and what influence do they have on runoff formation?	University of Neuchâtel	6.4
Influence of climate change on the temperature of rivers and lakes: How will water temperatures in the Swiss rivers and lakes develop in future?	EPF Lausanne, Eawag and University of Lausanne	6.7.1
Temperature development in Swiss unconsolidated rock groundwater resources: What are the main factors influencing the temperature development of groundwater resources and how will groundwater temperature develop in the future?	University of Basel	6.7.3
AgriAdapt: How is the irrigation requirement changing as climate change advances and how does this affect the groundwater level?	Agroscope	7.1.2

2 Methodology

2.1 Models and their uncertainties

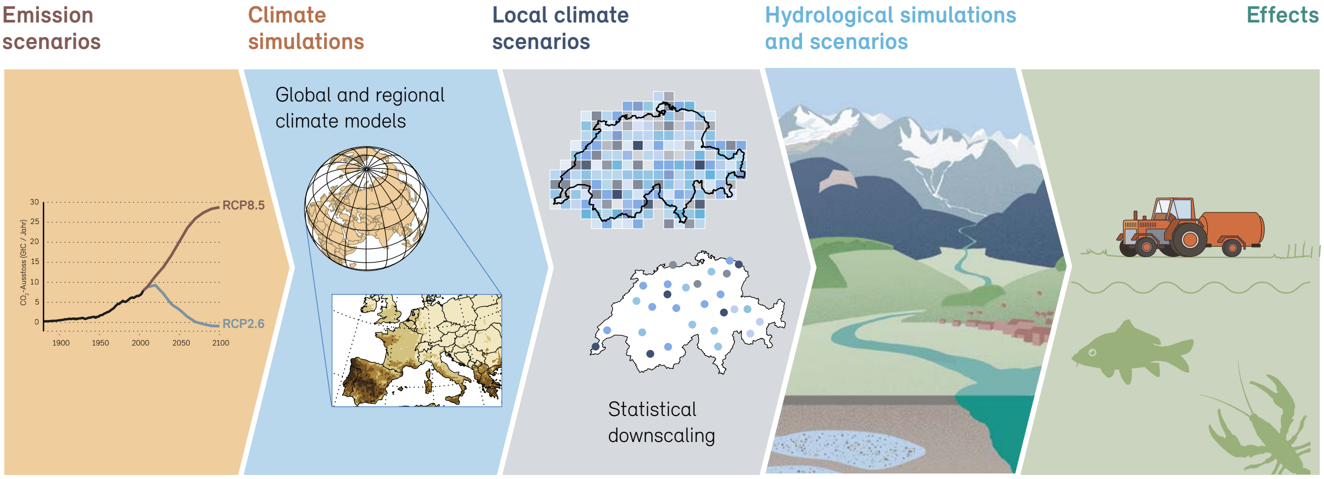
To draw conclusions about the changes in the future water balance requires an entire chain of climate and water balance models. With every step, better modelling of certain processes is achieved, but additional uncertainties emerge.

It's a long way to deduce the effects of climate change on Swiss hydrology and water management from future global greenhouse gas emission scenarios. Different models, process steps and assumptions are needed (Figure 2-1). Assumptions have to be made about future global greenhouse gas emissions, which in turn form the basis for global and regional climate models and finally the CH2018 climate scenarios. From these, with the help of hydrological models, the Hydro-CH2018 hydrological scenarios were generated to derive the effects of climate change on the Swiss water balance. Some of these scenarios were further used as input for other models (e. g. vegetation models) to analyse effects on plant growth or irrigation needs in agriculture, for instance.

Models can only simulate actual conditions in a simplified form and their results are inevitably subject to some uncertainty. With each step in the process chain, the number of possible combinations and the complexity of the computations increase. In order to limit computing time, the number of scenarios analysed and the variables in each modelling step must be limited.

Figure 2-1: Model chain to assess the effects of climate change on water management

Uncertainties emerge in every process step, starting with the selection of the emission scenarios to be input into the global climate models, then the regionalisation process (improving the resolution) as a pre-requisite for the hydrological modelling, and finally analysis of the effects on water ecology or water management.



Sources of uncertainty

- Development of future greenhouse gas emissions
- Model selection and structure
- Scaling and correction of model results
- Input data

- Initial conditions
- Model parameters
- Data for calibration and validation

- Natural variability
- Process understanding
- Unforeseeable events which tip the balance of a system

Source: own representation, according to CH2014-Impacts (SCNAT 2016)

Although the uncertainty increases with each modelling step, the accuracy of specific technical and regional predictions improves, because the models can be calibrated and validated using observed values. For example, it is only by a combination of climate and hydrological models that reliable conclusions can be drawn on the future discharge changes in a catchment.

The uncertainties in the climate models are addressed in the climate scenarios by specifying a range of possible future developments using different model chains. This range and the uncertainty in the climate models are thus also mirrored in the hydrological models. The actual magnitude of the range of uncertainty in the hydrological modelling can be assessed by comparing several models.

2.2 Climate scenarios

How will the climate of Switzerland develop if concerted climate change mitigation efforts are pursued or if no measures are taken? Emission and climate scenarios can be used to reveal the very different developments. Switzerland is a small country for which the results from global and regional climate models have to be refined by statistical methods.

The largest uncertainty for long-term projections concerns future global greenhouse gas emissions. To model the range of possible developments, the results of two possible emission pathways are shown for both the climate scenarios and the CH2018 hydrological scenarios (IPCC 2013) (Figure 2-2):

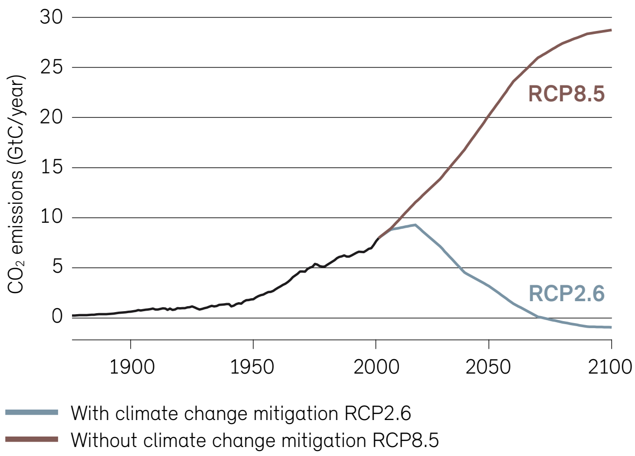
- “Concerted climate change mitigation efforts” (RCP[1]2.6): With an immediate, dramatic reduction in greenhouse gas emissions, global warming will be kept below 2 °C. This accords with the 2015 Paris Agreement, often called the Climate Agreement.
- “No climate change mitigation” (RCP8.5): Climate protection measures are not taken and emissions and warming keep increasing.

1 RCP is the abbreviation for Representative Concentration Pathway, which means that the scenarios are based on assumptions for the future concentrations of greenhouse gases and aerosols.

In the priority theme Hydro-CH2018, the two scenarios are always juxtaposed, the ‘without climate change mitigation’ scenario being important as a reference for adaptation measures. For ease of reading, some of the graphics in this report only show the ‘without climate change mitigation’ scenario. Results for both scenarios can be found in the other Hydro-CH2018 products.

Figure 2-2: Emission scenarios considered

Global net CO_2 emissions from fossil and industrial sources. Two possible scenarios are shown.



Source: Adapted from IPCC 2013/WGI/Box 1.1/Figure 3b

CH2018 climate modelling and scenarios

The effects of different greenhouse gas emission scenarios on the global climate are computed using global climate models. To improve their coarse spatial resolution, the results from the global climate models are used as boundary conditions for simulations of the regional climate models for Europe.

For emission scenario RCP8.5, the CH2018 climate scenarios use the results of 31 climate model simulations from the European project EURO-CORDEX (*www.euro-cordex.net*). Each one results from a combination of one of nine global and one of seven regional climate models. The regional climate models compute at a spatial resolution of 12 km and 50 km. For scenario RCP2.6, only 12 simulations – far fewer – are available. By comparing the different climate model simulations, the uncertainties associated with climate scenarios can be assessed.

The spatial resolution of the regional climate models is still too coarse for their use for hydrological models for a small, mountainous country like Switzerland. With the empirico-statistical method Quantile Mapping, the coarse resolution regional climate model data was refined using measured data and adjusted to local scales. The CH2018 climate data are available for seven climate parameters as time series at existing weather stations. Nationwide maps with a raster resolution of 2 km were also produced for temperature data and the daily precipitation total. All the time series and raster data are available throughout the 1981–2099 period on a daily basis (*www.nccs.admin.ch*).

2.3 Hydrological scenarios

The processed climate model results are the input data for the hydrological modelling. Various hydrological models tailored to the specific research question were used in the Hydro-CH2018 project. This resulted in the hydrological scenarios indicating the future developments in the Swiss water bodies.

The area analysed for the hydrological modelling comprised all of Switzerland, the Principality of Liechtenstein and other foreign regions draining into Swiss territory: also called ‘hydrological Switzerland’ as a whole. Table 2-1 lists the hydrological models used in Hydro-CH2018 and the variables analysed in each case. The water balance scenarios for hydrological Switzerland were computed using the PREVAH-WSL model. Hydrological scenarios for 93 catchments were produced with the PREVAH-UniBE model, and the HBV Light-UniZH model was used for 190 glaciated headwater catchment. Some specific research questions were only processed for selected catchments within Switzerland. Due to the long computing times, e.g. for modelling of water temperature and groundwater recharge, only a few regions and water bodies could be examined (see Table 2-1 and Annex Table A1).

Basic data used

Table 2-2 shows the main data used for the hydrological modelling and its origin. Other data used in the various Hydro-CH2018 research projects can be found in the specific project reports.

Table 2-2: Data used for the hydrological modelling

Data	Data origin
Discharge, water level, groundwater levels, water temperatures	Federal Office for the Environment FOEN, cantons, power companies and research institutions
Climate data such as temperature, precipitation, solar radiation, wind, humidity	Federal Office of Meteorology and Climatology (MeteoSwiss)
Climate scenarios CH2018 Climate model data from EURO-CORDEX and CMIP5	NCCS Earth System Grid Federation
Digital elevation model, information on geology and soil, topographical map bases	Federal Office of Topography (swisstopo) and the European Environment Agency (EEA) Copernicus Programme
Glacier levels and scenarios	Glacier monitoring service GLAMOS, Zekollari et al. 2019
Snow data MODIS snowpack product MOD10A1 and MYD10A1	WSL Institute for Snow and Avalanche Research SLF US National Snow and Ice data Center (NSIDC)
Land use	Federal Statistical Office FSO, Federal Office for Agriculture FOAG (AGIS), European Environment Agency (EEA) Copernicus Programme

Time periods considered

Unless otherwise stated, the period 1981–2010 is defined as the reference period in this report (reference period according to the World Meteorological Organization WMO). That period was the starting point for computation of the scenarios. References to current climate in this report mean the climate in the reference period.

The scenarios describe the expected average 30-year climate conditions, grouped around the years 2060 and 2085. References in the text to “mid-century” refer to 2060 (i.e. 2045–2074 period) and “end of century” or “distant future” to 2085 (i.e. 2070 – 2099 period). In order to enable robust conclusions on changes to be drawn despite the high variability between the individual years, the 30-year averages are always used. Any differences in the periods examined are mentioned in the report.

Table 2-1: Models used in the Hydro-CH2018 project

Variable analysed	Model	Specific results for	Number of model chains RCP2.6	Number of model chains RCP8.5
Water balance, particularly discharge	PREVAH-WSL	• General information on the water balance of hydrological Switzerland • 30 large catchmentss 700 – 35,900 km² in size, with discharge measurements	7	14
	PREVAH-UniBE	• Information for different discharge parameters of specific catchments • 93 catchments 10 – 1700 km² in size, with discharge measurements • a variety of catchment characteristics and elevations	8	20
	HBV Light-UniZH	• 190 glaciated headwater catchments • Focus on snow and glacier melt modelling	8	21
Soil moisture and evaporation	COSMO-CLM² coupled ETH Zurich regional climate model	Europe on a 0.44 × 0.44 ° (50 km) raster. Three separate RCP8.5 runs based on the GCM MPI-ESM-LR were performed	0	3
Water temperature	Simstrat (v. 2.1.2) Eawag	29 lakes	7	17
	Alpine3D EPFL	10 rivers	4	7
Groundwater recharge and levels	Hydrogeosphere and HBV Light Uni Neuchâtel	• 11 alpine catchments • Test region in Seeland (Broye) • 3 locations for computation of recharge from precipitation	0 1 0	3 1 6
	Feflow: ArcMap Basel Uni Alpine 3D EPFL	• 5 Swiss regions and 35 aquifers • Calculation of temperature change from changes in groundwater recharge processes	1	1
Process studies	PREVAH-WSL, combined with forest dynamic model	6 catchments	8	18
	Topkapi-ETH ETHZ, driven by weather generator AWE-GEN-2d	Thur, Kleine Emme and Maggia	0	9
	Plant growth model CropSyst	Test region in Seeland	4	6

Climate model simulations considered

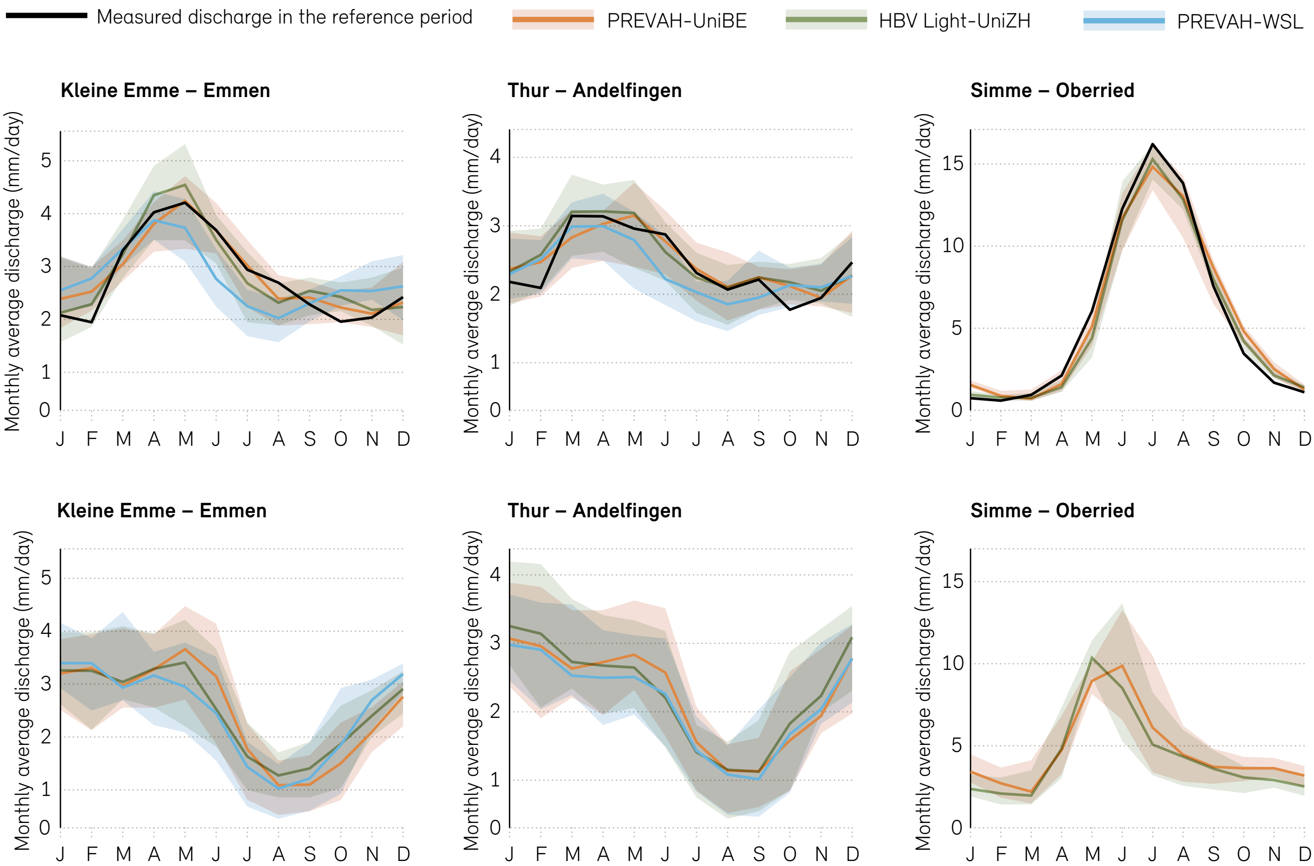
Only a selection of the possible climate model simulations from the CH2018 climate scenarios were used as inputs for the hydrological modelling, as not all the climate parameters required for the hydrological models exist for all the climate models. The model chains used by the three hydrological models PREVAH-UniBE, PREVAH-WSL and HBV Light-UniZH are not identical. The difference between the model chains used in PREVAH-UniBE and HBV Light-UniZH is very small, however far fewer chains were computed by the PREVAH-WSL models for RCP8.5. If results existed in two different spatial resolutions for the same climate model chain, only the 12 km resolution was considered. Due to the long computing times for specific hydrological models such as the groundwater and water temperature models, only a few climate model simulations could be processed in some projects (Table 2-1). These were preselected to model the full spectrum and uncertainty of the climate models wherever possible. The fewer the projections that can be examined, the less well the range of uncertainty is represented. The climate projections used in the studies are listed in the Annex (Table A2).

Uncertainties in the hydrological modelling

The CH2018 climate scenarios are the input data for the hydrological modelling and are already subject to uncertainty. In addition, they only supply daily data for various

Figure 2-3: Comparison of the annual discharge for the Kleine Emme, Thur and Simme catchments computed using three hydrological models

The graphs show the measured and the computed average monthly discharge for the reference period (1981–2010) (median and range of uncertainty; top row). The computed data for the end of the century without climate change mitigation (RCP8.5) is also shown (bottom row). In essence, the regime and its changes show good agreement between the different models and with the measured data.



Source: Mülchi et al. (2020)

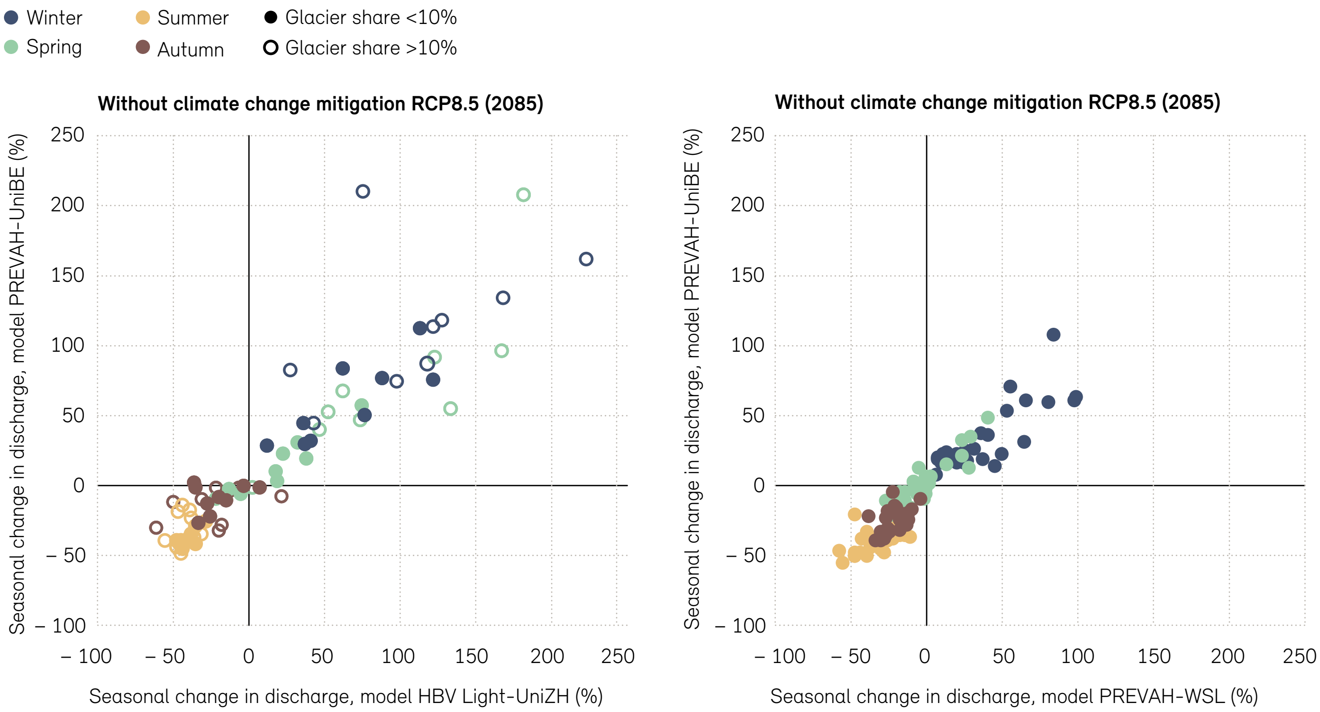
climate parameters, but many hydrological models need hourly data as input variable. Further processing is therefore applied, e.g. for precipitation or temperature, to refine the temporal resolution. Other models compute directly with daily data, the consequence being that the diurnal variation in processes such as snow melt or those occurring within hours such as flooding cannot be modelled at all or only poorly, in small regions. Other uncertainties arise in the selection of hydrological model and the approach for computing of processes such as runoff formation, evaporation and snow or glacier melt. A further source of uncertainty lies in determining the model parameters. If possible, they are obtained by calibration with measured data such as discharge or snowpack. In regions without monitoring, they have to be transposed from regions with hydrological measurements by using regional features, which further increases the uncertainty. To eliminate this source of uncertainty, only regions with discharge monitoring were modelled in PREVAH-UniBE. Also, all the models assume that the parameters calibrated for current conditions also apply in the future. This is a specific uncertainty factor in the modelling of hydrological extremes where the dominant processes could change (Matti et al. in prep.).

Comparison of the hydrological models

In order to estimate the effect of the uncertainty factors on the results, the computed seasonal discharge for the reference period and scenario RCP8.5 in the three models PREVAH-WSL, PREVAH-UniBE and HBV Light-UniZH were compared (Figure 2-3). Only climate model chains shared by all the models were considered. The three models simulate the annual discharge for the reference period accurately, and the medians of the monthly values and range of uncertainty show good agreement. For the future, all the models for the Thur and Kleine Emme show a similar

Figure 2-4: Comparison of seasonal discharge deviation

The relative changes in seasonal discharge towards the end of the century are shown for the scenario without climate change mitigation (RCP8.5) compared with the reference period (1981–2010) for the three water balance models PREVAH-UniBE, PREVAH-WSL and HBV Light-UniZH used in Hydro-CH2018. The changes predicted by the various models are essentially very similar. The greatest differences are in glaciated regions in winter and spring, when discharge is very low and small differences result in large percentage changes.



change in discharge. In the case of the Simme, which rises in glaciated regions, the annual maximum discharge indicated by the PREVAH-UniBE and HBV Light-UniZH models shows a minor temporal shift. In general, the uncertainty in the hydrological modelling is slightly larger in glacial regions than in those without glaciers. The PREVAH models tend to have a simpler approach to computing the glacier melt. The HBV Light-UniZH model was further developed and calibrated to calculate snow melt and glacier melt in particular. In this report, therefore, the HBV Light-UniZH model results are shown for catchments with a glacier area of more than 10%. More detailed information on the models is given in Table A1 in the annex.

For a statistical comparison of the results, the deviation between the reference period and the 2070–2099 period was determined for each hydrological model and catchment for the scenario without climate change mitigation RCP8.5, for both annual and seasonal discharge (Figure 2-4 and Table 2-3).

Table 2-3: Comparison of model results

The difference in predicted climate change discharge between the reference period (1981–2010) and the 2070–2099 period was examined for the scenario without climate change mitigation (RCP8.5) for annual and seasonal flow given in the PREVAH-UniBE, PREVAH-WSL and HBV Light-UniZH models.

		PREVAH-WSL	HBV Light-UniZH
PREVAH-UniBE	Number of shared regions	29	18
	Percentage of regions with a difference in predicted climate change-induced annual discharge of <10%	95%	83%
	Percentage of regions with a difference in predicted climate change-induced seasonal discharge of <10%	60%	55%

Table 2-3 shows the percentage of regions where the deviation between two models varies by less than 10%. The HBV Light-UniZH and PREVAH-WSL models have only three shared regions and are therefore hard to compare. Overall, the results of the three models show good agreement, and even in the regions with larger percentage variations between the models, the trend (increase or decrease) is consistent for all the seasons.

The largest percentage variations between the models occur in winter and spring, particularly in highly glaciated or high-elevation regions. This can be explained by the fact that discharge is generally very low in winter and spring and small variations can result in a large percentage variation. The greatest absolute differences in discharge between the models occur in summer, again in glaciated regions.

Because the three models only have a small overlap of shared regions, the hydrological range of uncertainty cannot be systematically assessed, as can be done for the climate models. Therefore, the uncertainty from the climate scenarios is also adopted as the range of uncertainty for the hydrological modelling. In general, for all the results, the deviation compared with the reference period should be considered rather than the absolute values. The report always shows only the results of one model per catchment, in the following order of selection:

- PREVAH-UniBE: 93 small or medium-sized regions, without glaciers or with less than 10% glacier area
- PREVAH-WSL: for the water balance of Switzerland and 30 large catchments
- HBV Light-UniZH: glaciated headwater catchments

Further information and references on 'Methods and uncertainties'

- Matti et al. (in prep.): Uncertainty and further methodological topics. Hydro-CH2018 report.

3 Water balance in response to climate change

Climate change affects the entire water balance: precipitation and runoff alter, temperatures and evaporation increase, the glaciers melt ever faster, less snow falls in winter, causing a lack of water from snow melt in the summertime.

With annual precipitation of over 1400 mm, Switzerland is one of the most water-abundant countries in Europe. It also has large water storage reservoirs in the form of natural lakes, artificial reservoirs, glaciers, snowpack, soil and groundwater. The great Rhine and Rhone rivers and the main tributaries of the Po and Danube have their sources in the Swiss Alps. Changes in the various elements of the Swiss water balance have a direct impact on the downstream riparians.

The water balance equation describes the relationship between runoff (Q), precipitation (P), evapotranspiration (E) and change in storage (dS) per unit time (dt), and therefore forms the basis of all hydrological modelling and scenarios.

$$Q = P - E + dS/dt$$

All the variables in the water balance equation are affected more or less seriously by climate change (Figure 3-1). Changes in precipitation and the rise in temperature are mainly responsible. Evapotranspiration increases and discharge from glacier melt decreases on the long term due to warming. More precipitation falls as rain rather than snow in winter, which reduces the amount of snow melt in the summertime. The result is reduced runoff in summer and autumn in many regions of Switzerland. But runoff tends to increase in winter and spring. Over the year as a whole, runoff hardly changes in many catchments, with at most a slight reduction (Section 6.1).

Water reservoirs react at different rates to climate change

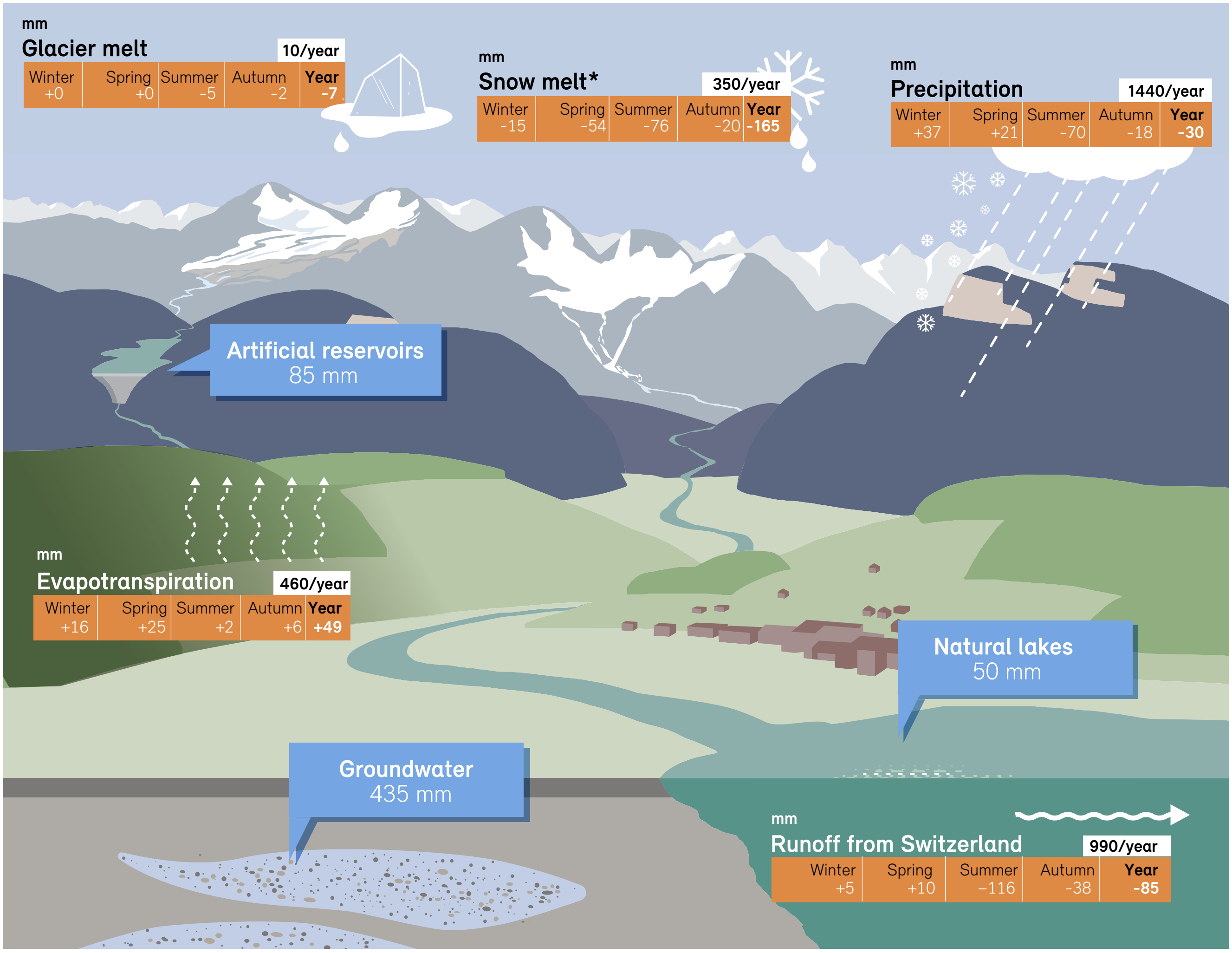
Climate change is altering the filling rate of the water reservoirs over the year, and the contribution from snow and glacier melt is generally decreasing. The climate-related storage changes are overlaid in the short term by the prevailing weather conditions and human abstraction.

The water reservoirs react on different time scales: The quickest to react is soil, which releases water absorbed during a precipitation event to the water bodies or by evapotranspiration to the atmosphere within anything from minutes to months, depending on its characteristics. At the other end of the scale are glaciers and deeper groundwater resources, which can store water for years, decades or even centuries. The more long term the operation of a water reservoirs, the slower it reacts to climate change.

Water reservoirs are central factors in the hydrological system: If they change, runoff formation, water temperature, substance transport and ultimately the aquatic ecosystems can be impacted. Table 3-1 gives the temporal effect plus an overview of the capacity of the various water reservoirs.

Figure 3-1: Impacts of climate change on the water balance

Climate change affects all the water balance variables. The water balance variables modelled – runoff, precipitation, evapotranspiration and ice and snow melt – are given for the reference period (1981–2010) (white background) and the distant future (2070–2099) (orange background) without climate change mitigation (RCP8.5), computed for hydrological Switzerland by the PREVAH-WSL model (data from Brunner et al. 2019c). The sustainably usable annual water storage volume (blue background) can only be specified for the reference period. For natural lakes and artificial reservoirs it was calculated from the average annual water level fluctuations or from the weir regulations for the lakes (Brunner et al. 2019a). The sustainably usable water storage volume for groundwater comes from Sinreich et al. (2012). The data on lakes and groundwater covers the territory of Switzerland, whereas transboundary lakes are considered in their entirety.



350 Annual totals in mm for reference period (1981–2010)

+21 Increase and decrease in mm per season and year for 2070–2099 period without climate change mitigation (RCP 8.5) compared with the reference period

85 Annual available water from water storage in mm

* Snow melt is part of precipitation

Table 3-1: Important water reservoirs in Switzerland

Capacity of important water reservoirs in Switzerland and the period during which they can store water, also called water retention time. The soil capacity cannot be assessed. The concept of sustainable usable supply is only applied to lakes and groundwater, since only from these sources water actively abstracted for human use.

	Total capacity	Sustainable usable supply	Water retention time in water reservoirs						Further information in Section	Reference for capacity data
	km³	km³ per year	Minutes	Hours	Days	Weeks	Months	Years		
Soil	–	–	■	■	■	■	■		4.3	
Snow	22[1]	–		■	■	■	■		5.1	Brunner et al. 2019c
Glaciers	53[2]	–					■	■	5.2	Langhammer et al. 2019
Natural lakes	130[3]	2		■	■	■	■		6.3	FOEN lake data Brunner et al. 2019a
Artificial lakes (reservoirs)	3.5[2]	3.5		■	■	■	■		6.3	Federal Office of Energy
Groundwater	150	18			■	■	■	■	6.4	Sinreich et al. 2012

[1] 1981–2010 average
[2] 2019 status
[3] Total capacity of transboundary lakes

4 Climate variables

Air temperature, precipitation and evaporation strongly influence the water balance and water bodies. As a result of climate change, temperature and evaporation increase and precipitation amounts change, with more in winter and less in summer.

4.1 Air temperature

Over the past 150 years the average annual air temperature in Switzerland has risen by around 2 °C, which is twice the global average. This warming trend is set to continue apace in the future. Heatwaves will become more frequent, longer and more intense.

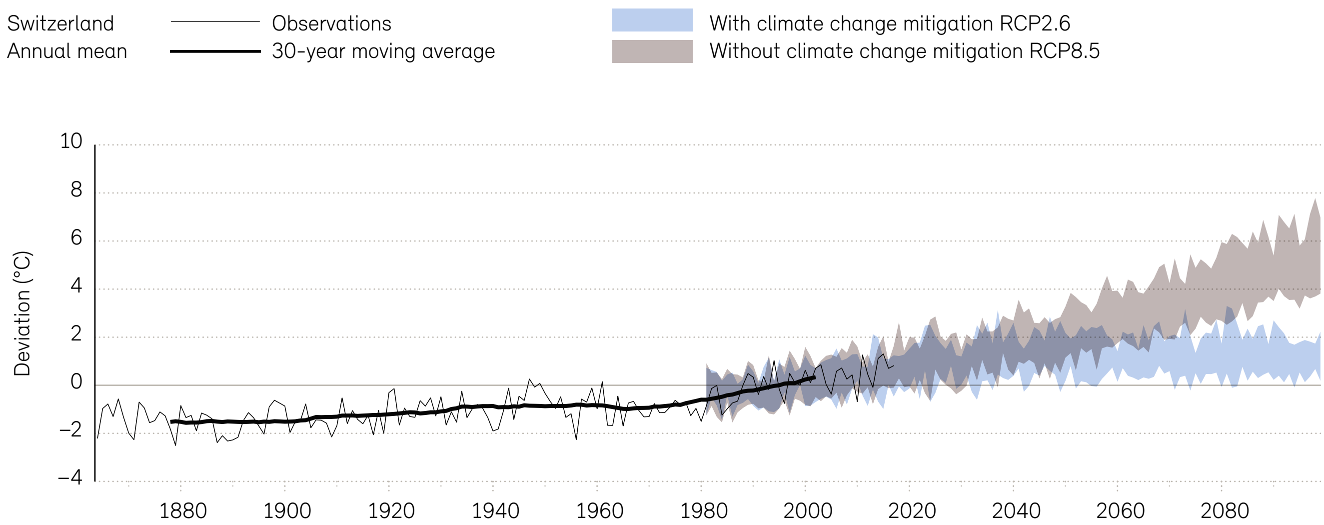
The average air temperature in Switzerland has risen by nearly 2 °C since records began in 1864 (Figure 4-1), an increase which is twice the global average (Begert et al. 2018). This warming has been observed to accelerate since the 1980s: Nine of the ten hottest years have occurred since 2000. This is leading to more frequent and intense heatwaves: The number of hot days (daily maximum temperature above 30 °C) has increased significantly at lower elevations, while the number of frost days (daily maximum temperature below 0 °C) has decreased. The average zero-degree isotherm in winter has risen by 300 to 400 m since 1961 (Technical Report CH2018). The dynamic of the zero-degree isotherm over the year is of great hydrological importance, because it determines whether precipitation falls as snow and is stored or as rain which immediately contributes to runoff. It also defines the elevation below which snow and glacier melt can occur.

Continued rise in temperature

The CH2018 climate scenarios show a further significant rise in temperature during all seasons of the year. In the scenario with climate change mitigation (RCP2.6), a further increase in the annual average temperature of some 0.6 to 1.9 °C can be expected in Switzerland by the end of the century (Figure 4-1). In the scenario without climate change mitigation (RCP8.5), the annual average temperature will rise by 3.3 to 5.4 °C by the end of the century. Maximum temperatures in summer will rise very sharply. Heatwaves and hot days and nights will be both more extreme and much more frequent. In winter, without climate change mitigation the zero-degree isotherm will rise from the current approximately 850 MASL (Metres above sea level) to around 1700 MASL.

Figure 4-1: Evolution of mean annual air temperature near ground in the past and future

The expected deviation of average temperatures from the reference period (1981–2010) with climate change mitigation (RCP2.6) and without climate change mitigation (RCP8.5) are shown.



Source: NCCS (2018)

4.2 Precipitation

The average annual precipitation in Switzerland has hardly changed since records began, and significant changes are not expected in the future. However, the seasonal distribution of the precipitation will change significantly, with a reduction in summer and an increase in winter. The rise in heavy rainfall events already observed is likely to continue.

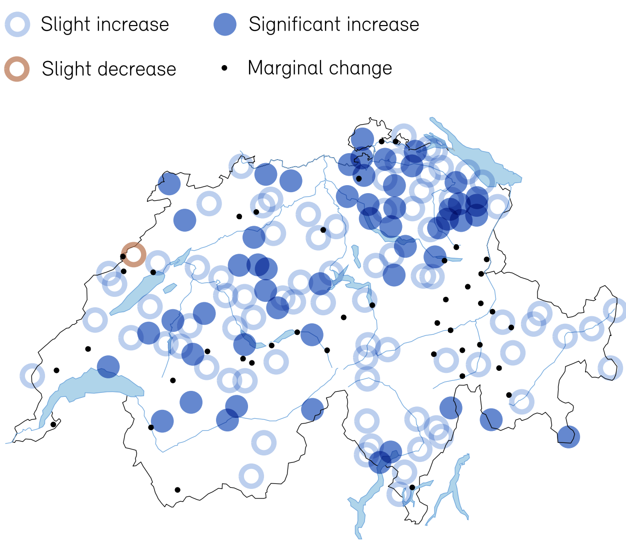
Swiss daily precipitation totals have been recorded since 1864, and at 10-minute intervals since 1978. Annual precipitation amounts vary considerably from area to area, from less than 600 mm in dry valleys in Valais to over 3000 mm at high elevations in the Alps.

Changes to date

The annual and seasonal precipitation levels have not changed significantly since records began. An exception to this is winter precipitation on the northern side of the Alps, which has increased by 20% over the last 100 years. What has changed is the frequency and intensity of heavy rainfall events. The intensity of the maximum daily precipitation in a year on average for all the weather stations has increased by some 10.4% in 100 years, which represents 7.7% per degree Celsius of warming. This approximately corresponds to the figure predicted by physicists at rising temperature (Clausius-Clapeyron equation). For the 1961–1990 period, the 100-year daily precipitation was computed for each station. The frequency of these intense events has risen by 26.5% in 100 years (Scherrer et al. 2016). In Switzerland, local heavy precipitation lasting for minutes and hours is predominantly caused by thunderstorms in summer. Heavy precipitation over a large area which lasts for a day or longer can be caused by different weather conditions. Depending on the region, they vary in intensity and occur at other times of the year.

Figure 4-2: Trends observed in the heaviest one-day precipitation events in the year

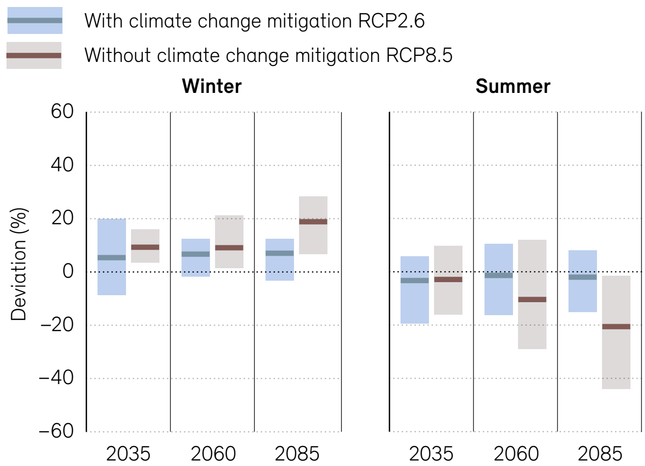
The blue dots show a significant increase, the light blue circles a slight increase and the brown circle a decrease in measured precipitation amounts in the 1901–2014 period. Black dots represent a marginal change in the precipitation amount.



Source: NCCS (2018) and Scherrer et al. (2016)

Figure 4-3: Future average summer and winter precipitation for three time steps in Switzerland

The expected deviations (median and range of uncertainty) from the reference period (1981–2010) in winter (left) and in summer (right) are shown for two emission scenarios and three future periods until the end of the century (2035, 2060 and 2085).



Source: NCCS (2018)

Seasonal shifts in the future

Future annual precipitation will hardly change according to the CH2018 climate scenarios. A slight decrease is expected in the distant future only in the scenario without climate change mitigation. The seasonal distribution of the precipitation will shift, however (Figure 4-3). In a scenario without climate change mitigation, winter precipitation will increase by around 20% by the end of the century and summer precipitation decreases at the same rate. However, the uncertainty of the trend is greater for summer precipitation. A further factor is that more precipitation will fall in the form of rain rather than snow in winter due to the rise in the zero-degree isotherm.

Longer dry periods and increasing heavy precipitation in the future

Longer and more frequent dry periods in summer are expected in almost all of Switzerland by the end of the 21st century without climate change mitigation. The periods of successive days without rain in summer will be extended in the distant future by one to nine days in the scenario without climate change mitigation (Technical Report CH2018).

The CH2018 climate scenarios also predict an increase in the intensity and frequency of heavy rainfall events for all periods in the future. The increased intensity is similar for all seasons and will be around 20% by the end of the century without climate change mitigation. The differences between the climate models and the uncertainty are greatest for heavy precipitation in summer. Generally speaking, climate models do not yet offer a sufficiently refined simulation of the complex, small-scale meteorological processes during heavy convective precipitation generation in mountainous Switzerland.

Uncertainties in weather types

The intensity and frequency of heavy precipitation and sustained droughts are influenced by the temperature increase (thermodynamics), by changes in atmospheric circulation, and the stratification of the atmosphere (Technical Report CH2018). In the past, there have been repeated decadal variations in the frequency of atmospheric circulation patterns and the resultant weather types (Weusthoff 2011), leading in some decades to clusters of large-scale high or low flow events.

Hydrological scenarios, based on high-resolution climate data: What is the effect of the natural variability in the climate data on the hydrological scenarios?

Method

The natural variability of the atmosphere was simulated for nine CH2018 climate projections using a weather generator. Meteorological parameters with high temporal and spatial resolution (e.g. hourly precipitation data) were then calculated for the three catchments of Thur, Kleine Emme and Maggia, as can be expected under future climate conditions. On the basis of these climate data, hydrological scenarios were then computed using the hydrological model Topkapi-ETH. The results were compared with the current natural variability.

Main results

- The models show changes in annual precipitation as early as the 2020–2049 period, but the changes are only greater than the current natural variability in a scenario without climate change mitigation and at the end of the century
- The change in heavy precipitation can vary widely over a small area and even within catchments. For the Kleine Emme and Thur, heavy precipitation increases in the lower lying areas by the end of the century, but decreases at higher elevations.
- Hourly heavy precipitation levels increase without climate change mitigation by the end of the century (median by 5% for the Thur and Kleine Emme and 20% for the Maggia). This increase, which is calculated for heavy precipitation events with both a 2-year and a 30-year return period, is not statistically significant and is within the range of natural variability.
- The changes in annual high flows are not statistically significant and are also within the current natural variability.

Hydro-CH2018 project of the Swiss Federal Institute of Technology Zurich (ETHZ), Institute of Environmental Engineering

The CH2018 climate scenarios also show decadal variations in the future frequency of weather types, but for frequently occurring types they hardly differ from those observed in the past. Reliable conclusions are not yet possible for the rare, persistent weather types responsible for hydrological extremes, such as extensive flooding and extreme drought: different climate models supply different results for both frequency and persistence. Statistical analysis is also impossible due to the rarity of these hydrological extremes (Huguenin et al. 2020). Therefore, some uncertainty remains about the future development of these extremes.

4.3 Evaporation and soil moisture

The land surface forms the link between the atmosphere and water bodies and has fundamental importance in the hydrological system. As air temperatures rise, evaporation increases and the soil moisture reduces, which in turn impacts on the climate as feedback.

The soil is the most important water reservoir for vegetation, because it retains the moisture necessary for growth, even in long periods without precipitation. The soil is also crucial for hydrology. Depending on the composition, structure and actual moisture content, the precipitation either drains quickly as surface runoff, is stored in the soil or percolates through it and reaches water bodies or groundwater with a temporal shift. The soil and the moisture stored in it thus influence the total discharge and storage resources (e. g. groundwater recharge, flooding).

Water stored in the soil is released into the atmosphere by evaporation and soil moisture is reduced. Evaporation can take place directly from the surface of water and soil or by plant transpiration. Evaporation, or evapotranspiration, in turn influences precipitation formation, air temperature and atmospheric circulation (e. g. persistence of weather conditions).

No increase in evaporation yet

The longest evaporation measurement series in Switzerland began in 1976 and stems from the ETH Zurich Rietholzbach lysimeter in the Toggenburg region. Over the last 40 years, no significant trend in evaporation from its grassland has been observed (Hirschi et al. 2017). Evaporation is usually calculated as a meteorological parameter and is not measured directly.

Switzerland does not have a national monitoring network for soil moisture. Although measurements are taken by many cantons and by research institutions, their objectives are often different. On the research side, SwissSMEX for example supplies soil moisture data from 19 stations. The measurement series are however too short for conclusions to be drawn regarding longer-term trends at this stage. Switzerland also lacks nationwide soil maps with sufficiently high resolution for hydrological issues.

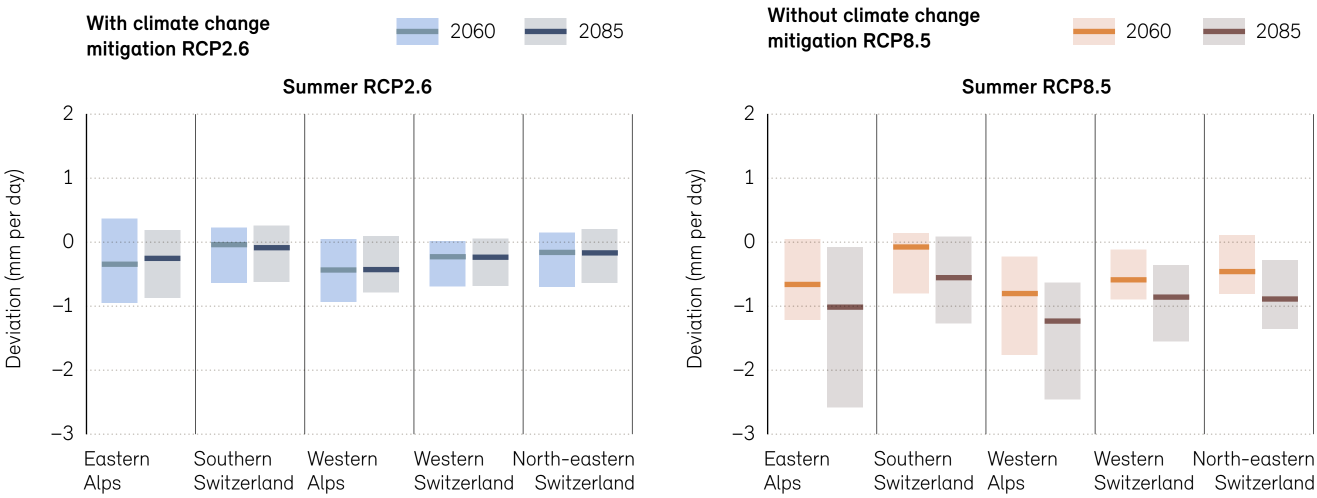
Increasing evaporation in the future

As temperatures rise due to climate change, the potential evaporation increases, i. e. the maximum evaporation possible with unlimited water available, which is the case over a lake, for example. How the (effective) evaporation at a specific location develops as the temperature rises depends on the local water availability. Evaporation can even decrease despite rising temperatures if the water reserves in the soil are exhausted. The hydrological scenarios show an increase in average evaporation in Switzerland by the end of the century of 5% with climate change mitigation and 10% without climate change mitigation (Brunner et al. 2019c). Future land use changes which can cause evaporation to either increase or decrease are not covered by the climate scenarios to date – or only in part.

Climate change can affect evaporation in different ways. Earlier snow melt in the Alps and a tree line which is retreating up the mountain to higher elevations lead to an increase. This is because soil and vegetation reflect less radiation than snow and warm up much more, so that more water evaporates. A decrease can occur, for example, in a long period of drought when plants wither and shed their leaves leading to reduced transpiration. Many plants are also known to use water more efficiently when CO_2 levels in the atmosphere are higher, causing transpiration to be reduced (Bernacchi and Van Loocke 2015).

Figure 4-4: Seasonal change in the indicator 'Precipitation minus evaporation' (d[P–E]) for Switzerland

Shown are future deviations (median and range of uncertainty) for the summer months of June, July and August from the reference period (1981–2010) for the two emission scenarios with and without climate change mitigations for different regions in Switzerland. This indicator provides information on changes in the water stored in the soil. Without climate change mitigation, this variation will decrease by around 1 mm per day by the end of the century.



Source: NCCS Web Atlas CH2018 *(www.nccs.admin.ch/nccs/de/home/materialien-und-data/data/ch2018-webatlas.html)*

Water balance and drought: How does climate change affect drought, plant physiology regulation of transpiration and future irrigation needs?

Method

Using the coupled regional climate model COSMO-CLM[2], the effects of climate change on the water balance and drought periods in Europe were computed on a 50-km raster (RCP8.5). Particular attention was paid to future irrigation needs and plant physiology adaptations to the higher CO_2 levels. The model chains from CH2018 were also analysed in more detail in terms of future drought.

Main results

- Without climate change mitigation, longer periods of drought, loss of soil moisture and a reduction in runoff are expected in Switzerland in future. The precise degree of dehydration in summer is still uncertain.
- Assuming an unchanging agricultural land use area, the irrigation needs for the crops currently cultivated will double due to climate change by the end of the century.
- Some plants react to higher CO_2 levels by closing the pores on their surface (stomata), which reduces water loss. This leads to a general reduction in evapotranspiration, which could further exacerbate the rise in air temperature and extreme temperatures in many parts of Central and Northern Europe.
- Although the global climate models address this plant physiology effect, it is lacking in the regional climate projections used for the CH2018 climate scenarios. If the process is included, the projected maximum temperature in summer increases even further compared with CH2018 (Schwingshackl et al. 2019).

Hydro-CH2018 project of the Swiss Federal Institute of Technology Zurich (ETHZ), Institute for Atmospheric and Climate Science

Forest dynamics, land use and water balance: How do future changes in forest dynamics affect evaporation and runoff?

Method
The water balance model PREVAH-WSL was coupled with a forest development model. The effects on forest development and water balance were computed for six catchment on the basis of the CH2018 climate scenarios.

Main results
- On the Swiss Plateau and in the Prealps, no major changes in discharge due to changes in forest dynamics are anticipated.
- Climate change fosters an increase in forestation in the Alps. The increase in forested areas also depends on the further development of alpine farming, as woodland cannot grow on grazed pastures.
- Increasing forestation in the Alps would have a significant influence on evaporation and discharge. In the distant future this could lead to more evaporation in alpine catchments and therefore to a reduction in annual runoff of up to 10%. Due to the increasing root depth, this effect is most marked in autumn, which would further exacerbate the climate-related minimum discharge level at that time of year (Speich et al. 2020).

Hydro-CH2018 project of the Federal Institute for Forest, Snow and Landscape Research (WSL), Mountain Research Unit

Soil dehydration in summer
In the summer months the combination of lower precipitation and more evaporation makes the soil drier. Figure 4-4 shows how the balance of precipitation and evaporation alters as climate change advances in different regions of Switzerland. In a scenario without climate change mitigation, an average of one millimetre less water per day in soil and runoff during the summer months can be expected in most regions by the end of the century. This equates to around 20% of the current average summer precipitation in Switzerland. During extreme droughts with a prolonged precipitation deficit, the reduction in water availability may be much greater.

Feedback with the land surface also plays an important part in the occurrence of droughts and heatwaves. The water vapour content of the atmosphere increases due to evaporation: plants, soil and air cool down. Transpiration protects plants against overheating, while moist soil slows down the rise in temperature during heatwaves through evaporation (Vogel et al. 2017). However, if the soil has already dried out, it can prolong droughts and heatwaves (Lorenz et al. 2010) and even reinforce stationary anticyclones (Merrifield et al. 2019). As climate change advances, this feedback effect could make periods of drought more intensive.

Further information and references on 'Evaporation and soil moisture'

- Hirschi M. et al. 2020: Soil moisture and evapotranspiration. Hydro-CH2018 report.
- Speich M. et al. (in prep.): Einfluss der Walddynamik auf den zukünftigen Wasserhaushalt von Schweizer Einzugsgebieten. Hydro-CH2018 report.

5 Cryosphere

In Switzerland, melting of the glaciers, a shift of the zero-degree isotherm to higher elevations and thawing of the permafrost due to the higher air temperature have been observed for some time. These developments will be exacerbated in future due to climate change. Natural hazards will increase in the high mountains and water management will have to adapt to the changes in water supply.

5.1 Snow

Snow melt currently makes a vital contribution to discharge in Switzerland. In future, the zero-degree isotherm will be higher in winter due to climate change. This means that less precipitation will be stored in the snowpack and the snow will melt earlier in the year.

Snowpack is a natural water reservoir which is crucially important for the seasonal water balance in Switzerland. According to model calculations, in the 1981 – 2010 reference period some 40% (22 km^3) of the total annual runoff came from the snowpack. It builds up in the alpine region over the winter (when flows are low, particularly in the alpine catchments) and normally reaches its peak in March. The ensuing snow melt dominates discharge in many catchments in spring and early summer.

Reduction in snowpack already detectable

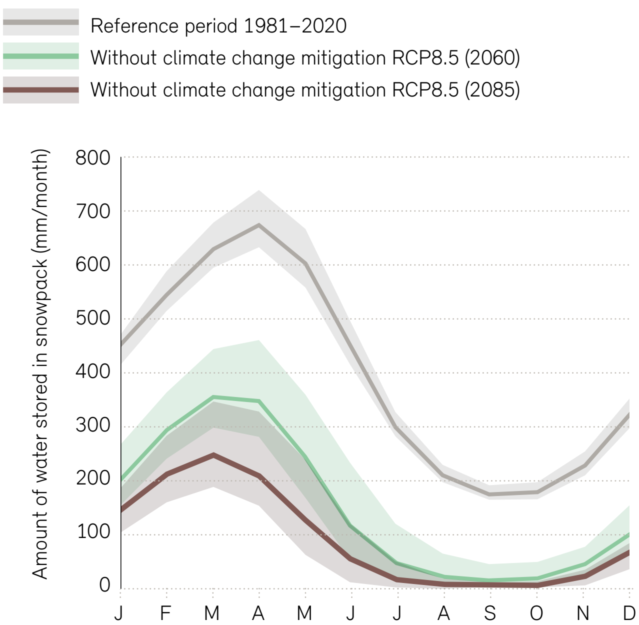
The proportion of precipitation which falls as snow is controlled by the air temperature and has already decreased considerably due to warming. To date, it is mainly lower and medium elevations that are affected. The percentage of days with snowfall below 500 MASL has fallen since 1961 by some 40% and the water quantity stored in the snow in spring (snow water equivalent) below 1000 MASL by as much as 75% (Marty et al. 2017).

Snow volume to decrease further in future

As winter temperatures rise, so too does the zero-degree isotherm: by around 150 metres per degree Celsius of temperature increase (CH2018), which causes the proportion of snow in the total precipitation to be further reduced. The addition of new snow to the permanent snowpack starts later in the year and is limited to higher elevations. The snow melt starts earlier in the spring. The hydrological scenarios indicate a decrease in the average annual water quantity stored in the snowpack by the end of the century of 42% with climate change mitigation and 78% without climate change mitigation (Figure 5-1). At the same time, the maximum snow volume will shift from March to February. While temperature rises, the expected increase in winter precipitation will only have a positive impact on the snowpack at very high elevations. It will not compensate for the general decrease in snow volumes. These changes in snowpack have significant effects on seasonal runoff (Section 6.2).

Figure 5-1: Mean change in the amount of water stored in the snowpack without climate change mitigation by the mid and end of the century for elevations above 1500 MASL

The proportion of water stored as snow (median and range of uncertainty) decreases in every season of the year by the end of the 21st century. The changes in a scenario without climate change mitigation (RCP8.5) compared with the reference period (1981 – 2010) show that very little water is stored in the form of snow by the end of the summer, even at higher elevations. Lack of snow means lower discharge from snow melt. Less snow is also available for the glaciers.



Source: Own graphic with data from Brunner et al. (2019c)

Further information and references on "Snow"

- Marty C. et al. 2020: Snow. Hydro-CH2018 report.

5.2 Glaciers and permafrost

The Swiss glaciers have already lost 60% of their volume since 1850. By the end of the 21st century, remnants of the great glaciers will only remain at very high elevations. Summer discharge from glaciers will be strongly reduced. The permafrost is thawing, increasing the potential for natural hazards.

Glacier ice forms in regions at high elevation (glacier accumulation zone), when some of the snow that has fallen over the year does not melt and turns into ice. The ice moves slowly down the valley due to gravity and melts in the summer half of the year in lower lying areas (ablation zone). Due to the temperature increase, on the one hand glacier melt increases and on the other hand the accumulation zones shrink and growth is reduced. This results in a loss of glacier volume. The smaller the glacier, the quicker it reacts to climate change.

Massive glacier retreat since 1850

By the end of the Little Ice Age around 1850, the ice volume in the Swiss Alps is estimated to have been around 130 km^3. In 2010 it was around 60 km^3 (Fischer et al. 2015) and in 2019 just 53 km^3 (Langhammer et al. 2019). In total, therefore, the glaciers have lost around 60% of their volume since 1850. The glacier volume has decreased by 10% in the last five years alone (2015-2019) (*www.glamos.ch*).

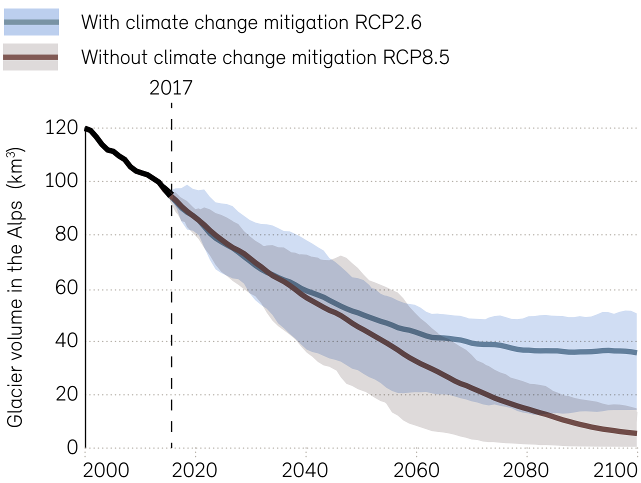
The glaciers have great importance for the water balance, because they store precipitation over seasons, years, decades or even centuries. Glaciers make a vital contribution to the discharges from many alpine water bodies, including the great Rhine and Rhone rivers, particularly in hot and dry periods in summer.

Only a few glaciers left by the end of the century

The glacier scenarios show that a large percentage of the ice fields in the Alps will have disappeared by the end of the century (Figure 5-2). With climate change mitigation, some 37% of the 2017 glacier volume will remain, but only around 5% without climate change mitigation. Since glaciers often take decades to adapt to a new climate, some of the glacier retreat cannot now be prevented, even by resolute climate protection, because the glacier volume is still "too high" to be in equilibrium, even for the current climate (Zekollari et al. 2019).

Figure 5-2: Changes in the ice volume of all the alpine glaciers by the end of the century

The remaining ice volume of the glaciers in the Alps (mean value and range of uncertainty) under the different climate scenarios is shown. Before 2017 the calculations used climate observation data. Without climate change mitigation, 95% of the current glacier volume will have melted by 2100.



Source: adapted from Zekollari et al. (2019)

Permafrost is warming – greater risk of natural hazards

Permafrost means subsoil with a temperature below 0 °C throughout the year. It is widespread in the Alps above around 2500 MASL and lies hidden in icy talus slopes and moraines, rock glaciers and steep rock faces with ice-filled pores and clefts. The observations in the Swiss Alps over the past two decades show a general rise in permafrost temperatures, a decrease in the ice content and an increase in rock glacier flow rates (PERMOS 2019). Due to the comparatively small ice volume (roughly around a quarter of the glacier volume) melt water from permafrost in the Alps contributes less to total discharge. However, warming of the permafrost can have far-reaching consequences for natural hazards and habitats. Changes in permafrost affect the stability of steep mountain flanks and infrastructure in the high mountain ranges. The number and severity of debris flows and rockfalls may increase.

Further information and references on "Glaciers and Permafrost"

- Ayala A. et al. 2020: Glaciers. Hydro-CH2018 report.
- Nötzli J., Phillips M. 2019: Mountain permafrost hydrology. Hydro-CH2018 report.

6 Water bodies

The hydrological scenarios show how climate change will affect runoff, groundwater recharge and water temperatures. Water quality and ecology will suffer and high and low flow situations will intensify.

6.1 Annual runoff

The average annual runoff only changes slightly due to climate change. Only in the scenario without climate change mitigation does it decrease slightly by the end of the century. The greatest reduction occurs in regions which are currently still glaciated. But seasonal runoff will change significantly, with drastic consequences for water use (Section 6.2).

Although annual runoff in the Swiss watercourses vary widely from year to year, their long-term average has hardly changed since measurements began early in the 20th century. On the Rhine in Basel, for example, no upward or downward trend in annual discharge can be detected in the measurement series from 1871 (Weingartner 2018). The reason is that the long-term annual precipitation has changed very little. Catchments with runoff from glacier melt are the only ones to have higher annual levels because the glaciers are melting.

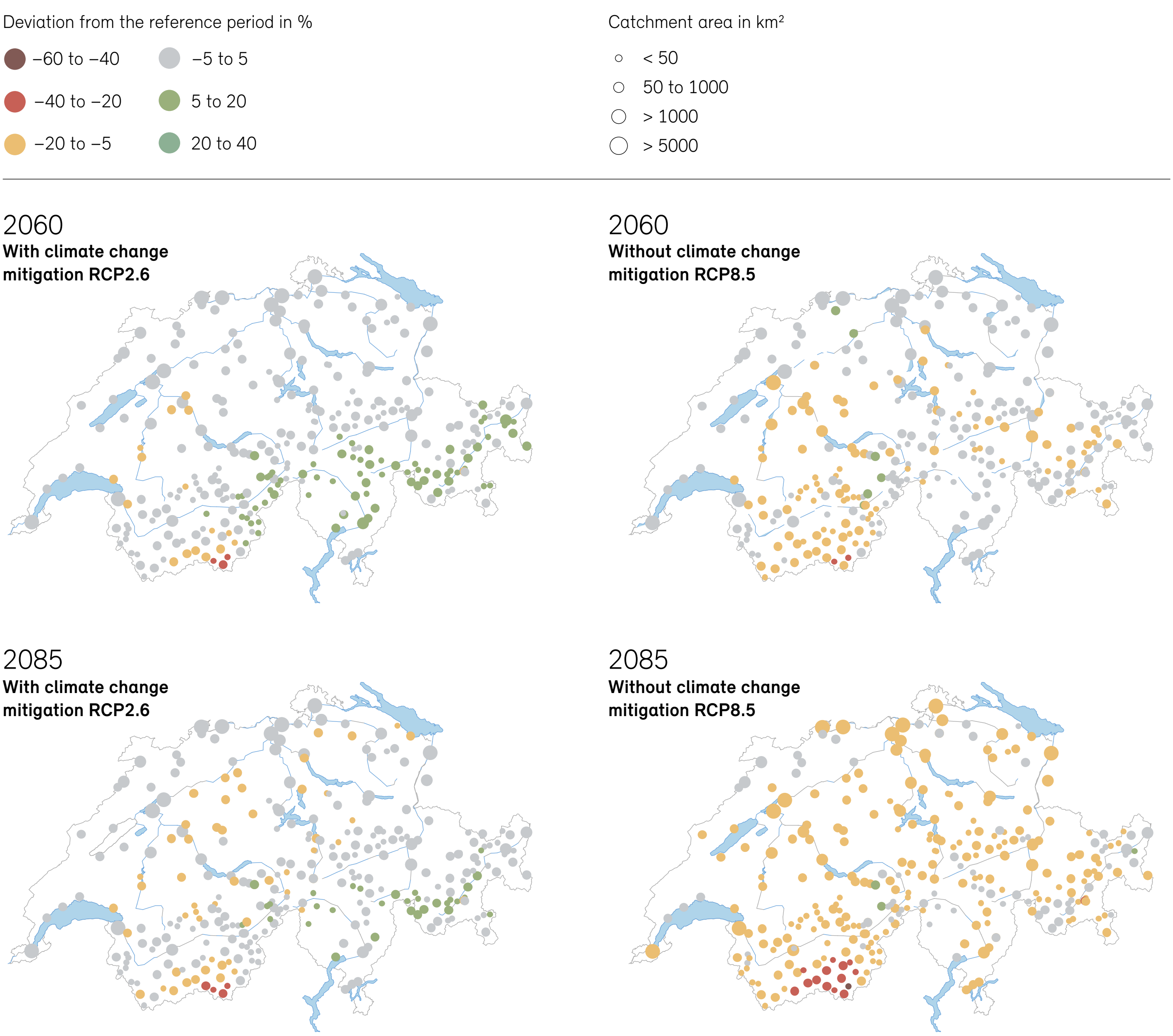
Some decrease in annual runoff without climate change mitigation
Average annual runoff will continue to change little in most catchments in the next few decades (Figure 6-1). In a scenario with climate change mitigation, the hydrological scenarios show no clear deviation by the end of the century for most catchments. Just in a scenario without climate change mitigation, a slight decrease in average annual runoff will occur towards the end of the century of around 9% on average in Switzerland. In around 25% of regions, annual runoff hardly changes even without climate change mitigation (deviation of ±5% by the end of the century) and for a further 65% the deviation is between –5 and –20%. The reasons for decreasing annual runoff are a slight reduction in annual precipitation and the rise in air temperature, with associated follow-up processes such as extended vegetation periods and greater evaporation. A further factor in the Alps is that the glaciers will have disappeared or shrunk considerably by the end of the century and the melt water content will be much lower than at present (Freudiger et al. 2020). In these regions the reduction in annual runoff may be significant. Nevertheless, in an average year the amount of water that Switzerland will have in future will be similar to today's level over the year as a whole.

Contribution from melt water will decrease significantly
In heavily glaciated catchments, the annual runoff due to glacier melt may still increase further up to 2050 (±15 years) according to the scenario without climate change mitigation. However, the maximum glacier melt water contribution to annual runoff ('peak water') has already been reached in more than 90% of glaciated catchments and will decrease further in most headwater catchments in future. By the end of the century the contribution of melt water to annual runoff will be reduced, e.g. in the Rhone at Gletsch from the current 27% to 10% (with climate change mitigation) or even to 4% (without climate change mitigation) (Figure 6-2).

Snow is even more important for runoff in the headwater catchments: It accounts for around 40% in the Rhone at Gletsch and the Weisse Lütschine at Zweilütschinen. In all the scenarios the contribution of melt water to annual runoff decreases in the majority of headwater catchments in future. In just a few very high elevation catchments, the contribution from snowpack melt increases, so that in some cases the rising snow melt contribution may partly compensate for the decrease in glacier melt contribution – if only for the scenario with climate change mitigation (Freudiger et al. 2020).

Figure 6-1: Change in annual runoff by catchment and scenario

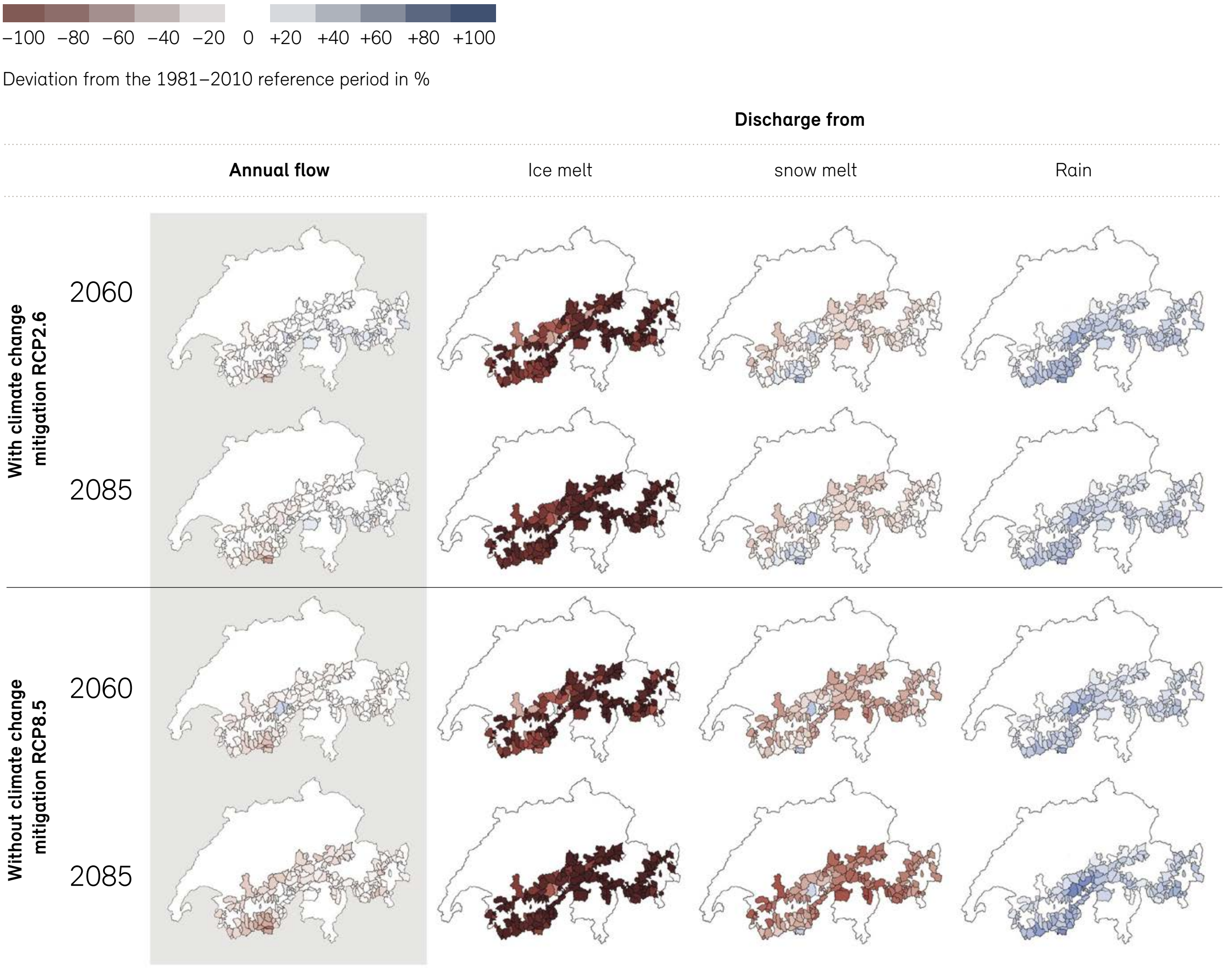
Shown are the median percentage changes in annual runoff obtained by the hydrological scenarios compared with the reference period (1981–2010) for scenarios with and without climate change mitigation (RCP2.6 and RCP8.5 respectively) for the near and distant future. The annual changes are small and without climate change mitigation annual runoff is slightly reduced by the end of the century.



Source: Data from Mülchi et al. (2020), Freudiger et al. (2020), Brunner et al. (2019c)

Figure 6-2: Change in runoff contribution from rain and snow and ice melt, and total runoff

Shown are the changes in 190 glaciated headwater catchments of Switzerland compared with the reference period (1981–2010) with and without climate change mitigation (RCP2.6 and RCP8.5 respectively). 0% means no change from the reference period, at –100% the contribution has completely disappeared and at +100% it has doubled. Ice melt is significantly reduced in all the scenarios; in the one without climate change mitigation, it will no longer contribute to runoff by the end of the century in many regions, and the contribution from snow melt will also have decreased considerably.



Source: Freudiger et al. (2020)

Quantification of runoff contribution from snow and glacier melt: What are the effects of the melting of the glaciers and the reduction in snowpack on discharge?

Method

The runoff contribution from rain, snow and glacier melt were determined for 190 glaciated headwater catchments in the Swiss Alps using the hydrological model HBV Light-UniZH. The snow and glacier modules of the model were specifically adapted to optimise the representation of snowpack and glaciers. The model was calibrated using discharge data, snowpack and glacier data. This enabled the runoff contributions to be calculated for regions without such data, as data on snowpack and glacier coverage is available nationwide.

Main results

The findings on snow and glacier melt in Section 6.1 and parts of Sections 6.2 and 6.4 of the report are based on the results of this project. The total glacier melt contribution of the 190 headwater catchments currently makes up 8% of annual runoff and reduces to less than 2% without climate change mitigation towards the end of the century. The contribution from snow reduces from the present 34% of annual discharge to 25% without climate change mitigation by the end of the century.

Hydro-CH2018 project of the University of Zurich, Department of Geography

6.2 Seasonal runoff

The seasonal runoff distribution has already changed in recent decades. Runoff has decreased in summer and increased in winter. This development will continue with climate change and may result in water use restrictions.

The Swiss watercourses have different seasonal runoff regimes which are determined by seasonal precipitation distribution, evaporation and the contribution from snow and glacier melt. In pluvial regimes, runoff is determined principally by precipitation distribution and evaporation. Lower lying regions on the northern side of the Alps have this type of regime. Here, runoff remains relatively balanced over the year (Figure 6-1). In nival regimes, the precipitation distribution is complemented by snowfall and snow melt. Runoff is therefore low in winter (December to February) when the snow is lying and high in spring (March to May) when the snow melt sets in. Alpine regions without glaciers have nival regimes. In glacial regimes, glacier melt is added in summer (June to August) and increases runoff significantly. It is on the southern side of the Alps that most regimes reach their maximum runoff in spring and autumn (September to November), because most of the precipitation falls then. They are referred to as southern alpine regimes in the following. In addition to these main regimes, there are transient regimes and regional subtypes (Weingartner and Aschwanden 1992).

Change in runoff regimes

The runoff regimes changed over the 1961–2015 observation period (Weingartner 2018). Runoff increased in the winter months in most catchments (see Figure 6-3), because the air temperature rose and more precipitation fell as rain rather than snow in winter. In contrast, a decrease in average runoff was generally observed in summer – except in highly glaciated catchments. In spring, runoff tended to rise in the alpine region due to the earlier onset of snow melt, but to fall on the Swiss Plateau and in the Jura. The changes are most pronounced in the Alpine region. In general, there is an obvious shift in runoff regime from glacial towards nival and from nival towards pluvial.

In the heavily glaciated catchments such as the Massa (Figure 6-3b) with a glacial regime, seasonal runoff has increased in winter, spring and summer, the rise in summer runoff being caused by glacier melt. Nival regimes have their highest average runoff in spring due to snow melt. As this is starting earlier and earlier, runoff has risen in March and April in the majority of catchments. This also means that the snowpack has melted earlier, the result being that a decrease in average runoff in summer can be seen in many places – in the Plessur for example.

Runoff is tending to fall in spring and summer in the pluvial catchments on the Swiss Plateau and in the Jura, but the changes observed are small overall, as the example of the Aach shows. Annual runoff is decreasing in southern alpine regions, with summer levels falling very sharply. It is worth noting, however, that this finding relates to long-term seasonal averages. The average seasonal runoff in individual years can vary widely from this.

Further increase in runoff in winter

The hydrological scenarios indicate a further increase in winter runoff throughout Switzerland. This is due to the predicted increase in winter precipitation and the shift from snow to rain. Figure 6-4 shows how the seasonal runoff over the year will change in typical catchments and runoff regimes by the middle and end of the century. Figure 6-5 gives an overview of the changes at all the stations modelled.

An increase in winter runoff of around 10% with and 30% without climate change mitigation can be expected on average in hydrological Switzerland by the end of the century (Brunner et al. 2019c). The increase in winter runoff is particularly significant in regimes that are now nival. The smallest changes in winter runoff occur in catchments

Figure 6-3: Changes observed in runoff and runoff regimes in Switzerland

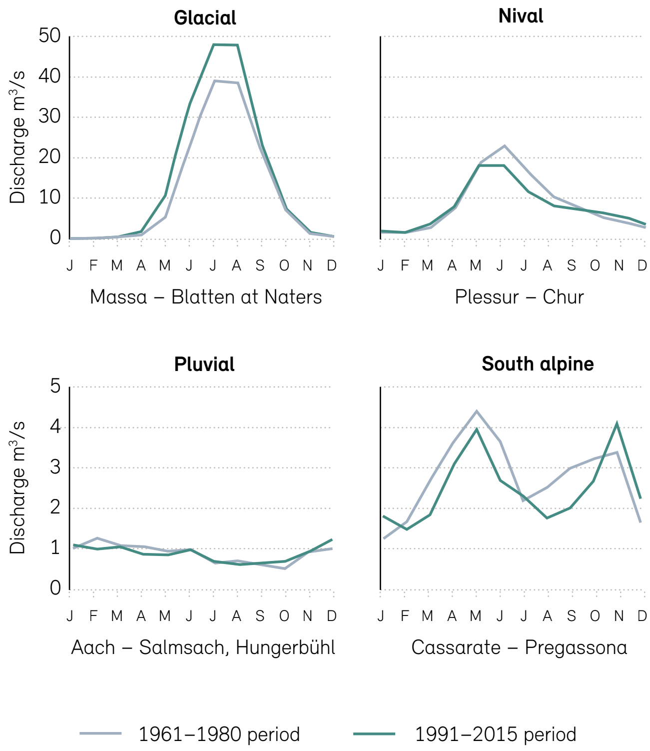
The changes in runoff in different regions (a) and in four selected catchments (b) with different runoff regimes are shown. An increase in runoff in winter and a decrease in summer can already be observed.

a Change in seasonal and annual runoff for various regions in Switzerland from 1961 to 2015

Region	Year	Winter (DJF)	Spring (MAM)	Summer (JJA)	Autumn (SON)
	Regions < 1000 km²				
Alpine region Catchments with glaciers	↑↑↑	↑↑	↑↑↑	↑↑↑	→
Alpine region Catchments without glaciers	→	↑↑	↑	↓↓	↑
Swiss Plateau/Jura	→	↑	↓	↓	↑
Southern Switzerland	↓	↑	→	↓	↑
	Regions > 1000 km²				
	→	↑	↓	↓	↑

Trend towards increasing runoff		Trends towards decreasing runoff	
↑	Low	↓	Low
↑↑	Medium	↓↓	Medium
↑↑↑	High	→	No change

b Average monthly runoff for the 1961–1980 and 1991–2015 periods for four catchment areas with glacial, nival, pluvial and south alpine runoff regimes



Source: Weingartner (2018), data: FOEN

both on the Swiss Plateau, where the snowpack already contributes little to it, and at very high elevations, where most of the precipitation will continue to fall as snow in future due to the low winter temperatures (Mülchi et al. 2021a).

Elevation-dependent increase or decrease in spring runoff

In spring, changes on the Swiss Plateau and in the Jura differ from those in the higher regions. Spring runoff decreases at lower and medium elevations, as the examples of the Plessur and Thur show (Figure 6-4). The causes are the reduced snowpack and higher evaporation due to the earlier start of the vegetation period and the higher temperatures. In contrast, spring runoff increases in the alpine region because the snow melt starts earlier. Discharge of large catchments like the Rhone and Rhine is more balanced due to these changes in opposite directions, with more in March and less in May. Total runoff from Switzerland to the downstream riparian's hardly changes.

Runoff decreasing in summer and autumn

The scenarios show an average decrease in summer runoff for hydrological Switzerland of around 10% with and 40% without climate change mitigation by the end of the century. The factors responsible for this decline are lower summer precipitation, higher evaporation and the decrease in glacier and snow melt water (Figure 6-2). Areas at all elevations and in all regions are affected by decreasing summer runoff. A significant drop can be expected on the Swiss Plateau and in the Jura and the Prealps, especially in late summer (e. g. Birs, Thur and Ilfis). A significant decrease in summer runoff is also expected in Ticino (e. g. Verzasca). Similarly, it will be strongly reduced in regions which are currently still glaciated (e. g. Rosegbach).

In autumn, runoff will also decrease by the end of the century, with all elevations and regions being affected. In hydrological Switzerland, the overall decrease will be around 5% with and 20% without climate change mitigation. The reduction in runoff in summer and autumn is also clearly apparent in the large river basins such as the Rhine and Rhone, representing total inflow from the smaller ones (Figure 6-4). In general, this overview gives a clear indication that a seasonal and sometimes significant redistribution in runoff will occur in future. The main challenge for water management and ecology will be the reduction in summer, when the low discharge will be combined with high water temperatures and greater demand for water.

Updating of the hydrological scenarios on the basis of new climate scenarios: How does runoff change in different climate scenarios?

Method

In total, 93 catchments (FOEN stations) were calibrated and validated using the PREVAH-UniBE model. They cover various runoff regimes (pluvial, nival, glacial, southern alpine) and catchment sizes (10–1700 km^2). Runoff time series were then computed for each catchment for different emission scenarios (RCP2.6, 4.5, 8.5) at daily intervals. The daily discharge results were analysed for different indicators on medium, high and low discharge. As the new climate scenarios are available continuously over 120 years, the timing of significant changes in runoff can also be determined for the first time.

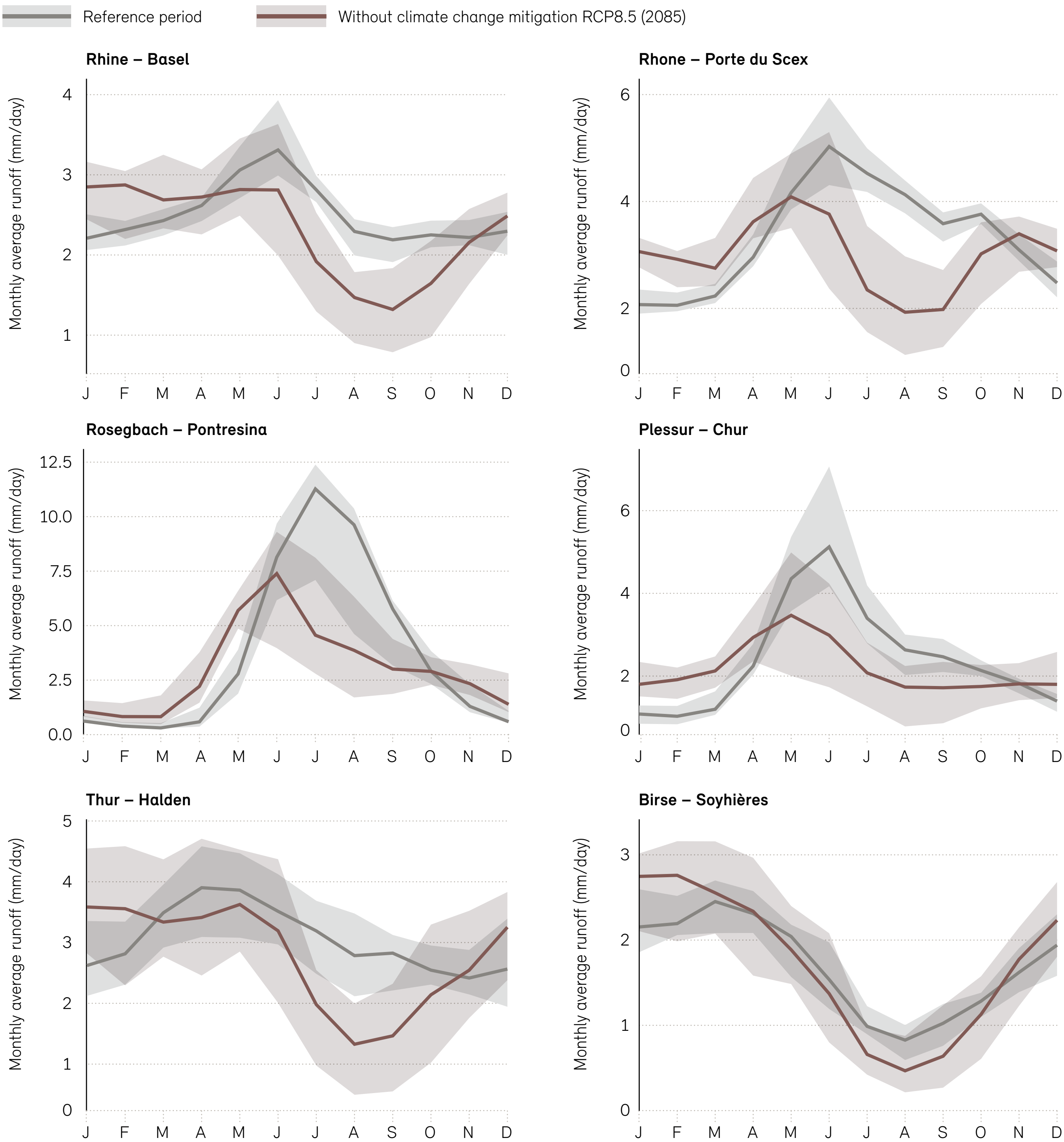
Main results

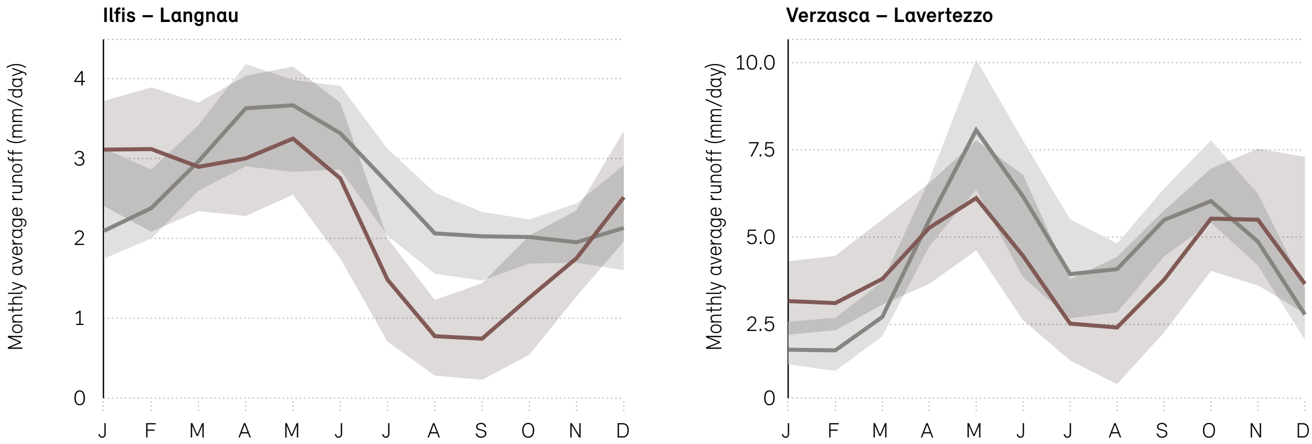
- The timing of significant changes in runoff tends to be earlier in the higher catchments than in the Swiss Plateau regions.
- Sections 6.1, 6.2 and 6.4 of the report are based largely on the results of this project. Further results are available on the NCCS web atlas and the Hydrological Atlas of Switzerland HADES (*www.hydromapscc.ch*).

Hydro-CH2018 project of the University of Bern, Department of Geography

Figure 6-4: Change in average monthly runoff in eight typical catchments

Using the model PREVAH-UniBE and PREVAH-WSL (Rhine and Rhone), the hydrological scenarios (median and range of uncertainty) were calculated for the reference period (1981–2010) (grey) and the scenario without climate change mitigation (RCP8.5) for end of the century (red). A considerable decrease in runoff in summer and an increase in winter can be expected in every region.





Source: Mülchi et al. (2020)

Figure 6-5: Runoff changes in winter, spring, summer and autumn

Shown are the median percentage changes in seasonal runoff compared with the reference period (1981–2010) computed in the hydrological scenarios with (RCP2.6) and without (RCP8.5) climate change mitigation in the near and distant future. Runoff increases in winter throughout Switzerland and decreases in summer and autumn. In spring there is a difference in reaction between low and high elevations.

Deviation from the reference period in %

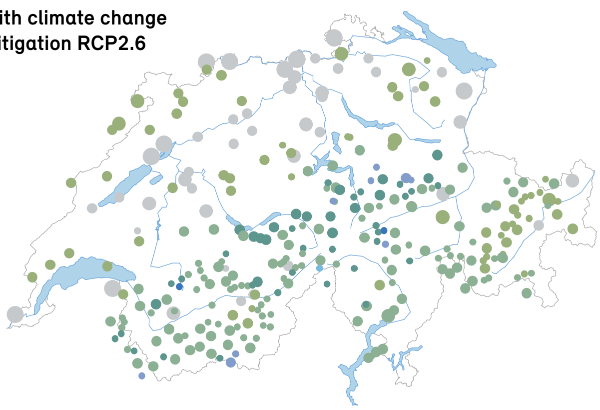
- −60 to −40
- −40 to −20
- −20 to −5
- −5 to 5
- 5 to 20
- 20 to 40
- 40 to 60
- 60 to 80
- 80 to 100
- 100 to 150
- > 150

Catchment area in km²

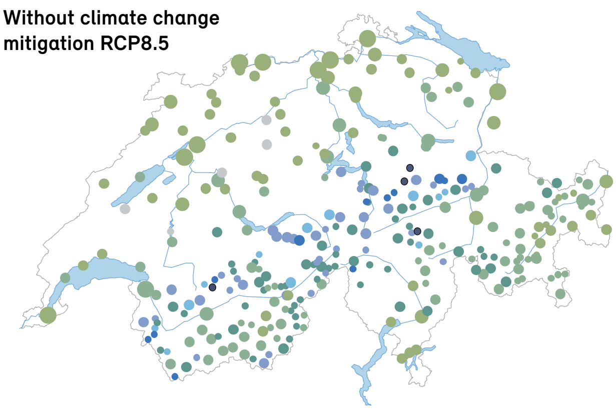
- < 50
- 50 to 1000
- > 1000
- > 5000

Winter

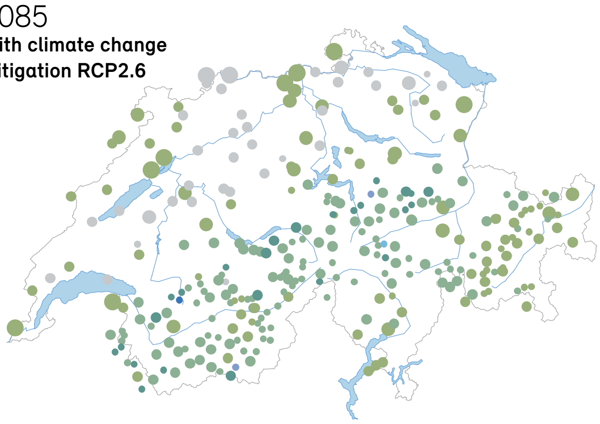
2060
With climate change mitigation RCP2.6



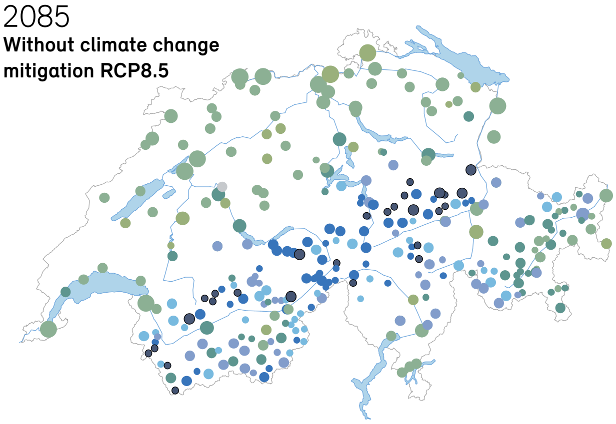
2060
Without climate change mitigation RCP8.5



2085
With climate change mitigation RCP2.6

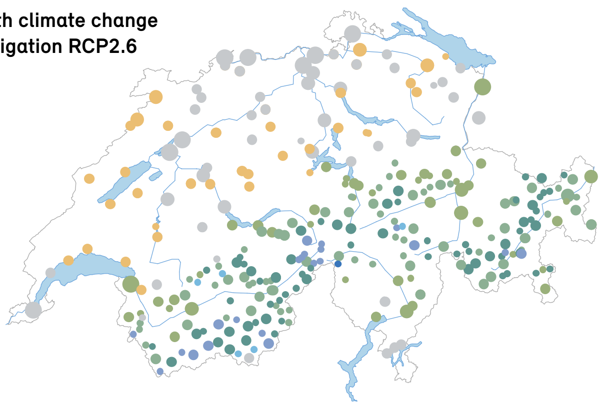


2085
Without climate change mitigation RCP8.5

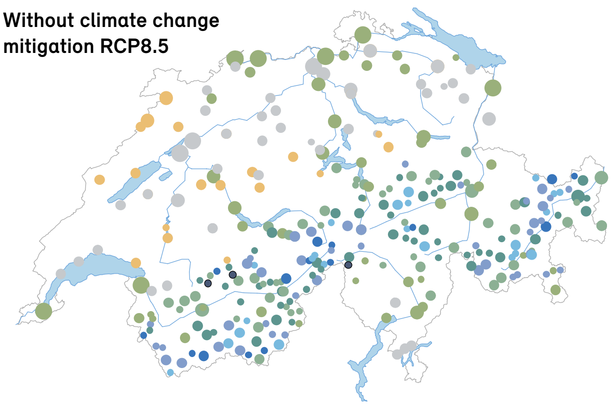


Spring

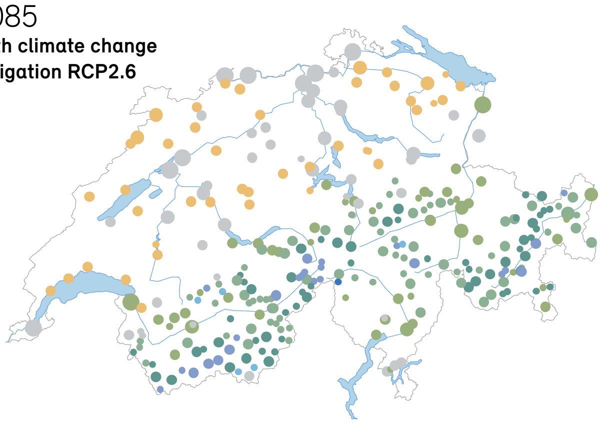
2060
With climate change mitigation RCP2.6



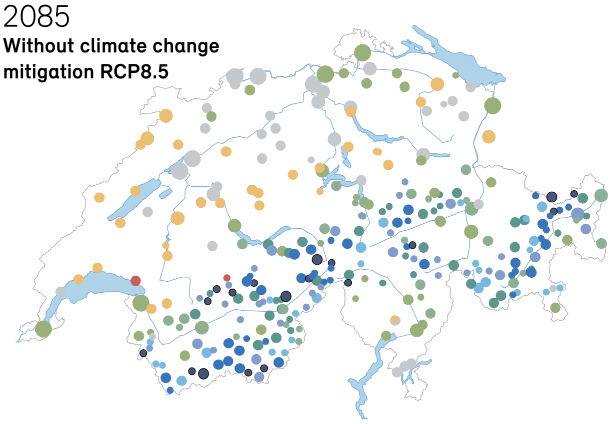
2060
Without climate change mitigation RCP8.5



2085
With climate change mitigation RCP2.6



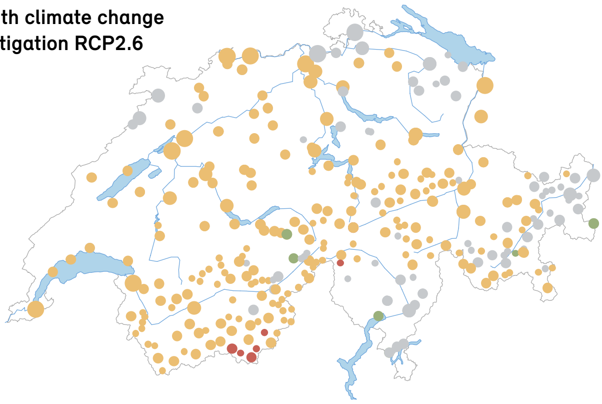
2085
Without climate change mitigation RCP8.5



Summer

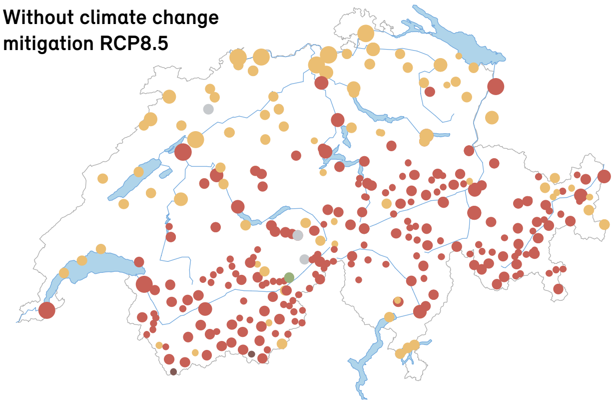
2060

With climate change mitigation RCP2.6



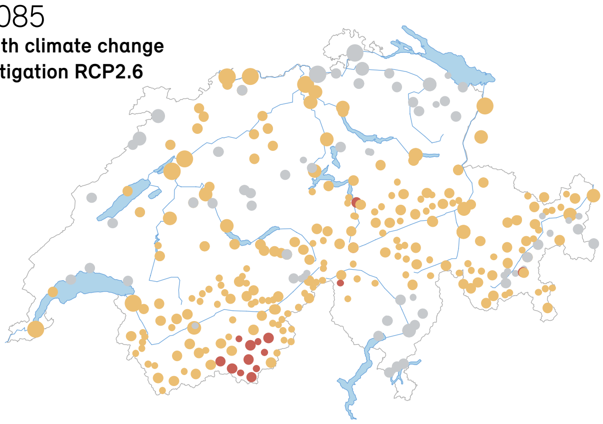
2060

Without climate change mitigation RCP8.5



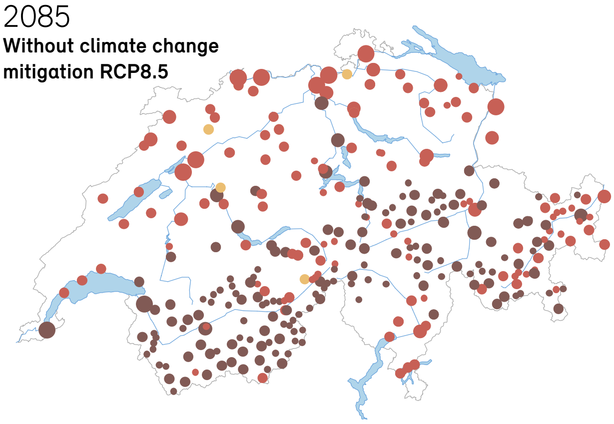
2085

With climate change mitigation RCP2.6



2085

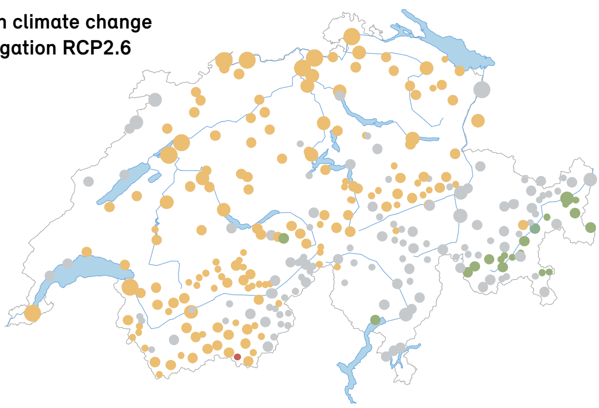
Without climate change mitigation RCP8.5



Autumn

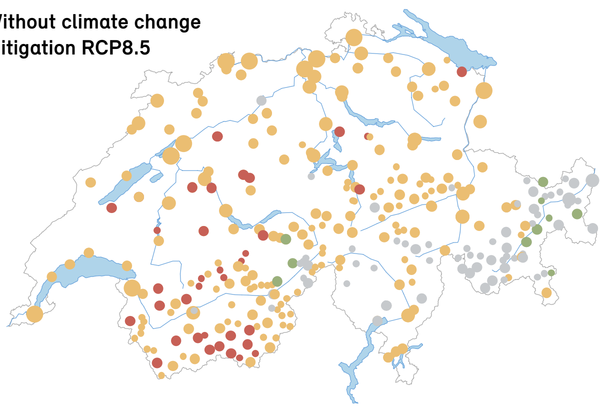
2060

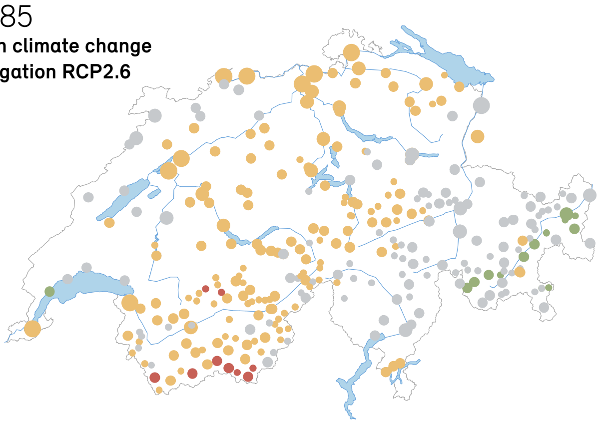
With climate change mitigation RCP2.6

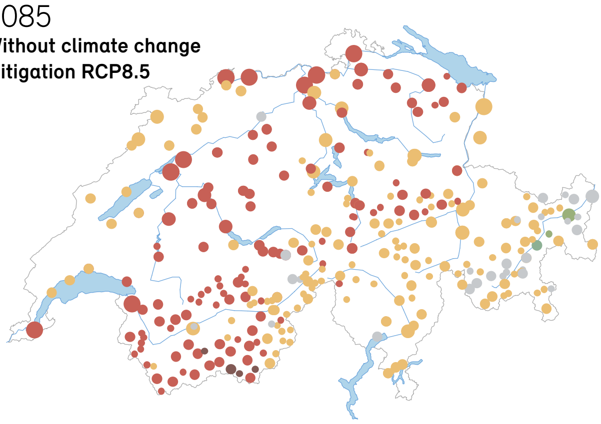


2060

Without climate change mitigation RCP8.5







Source: data from Mülchi et al. (2020), Freudiger et al. (2020), Brunner et al. (2019c)

Further information and references on 'Changes in runoff'

- Freudiger D. et al. 2020: Quantifying the contributions to discharge of snow and glacier melt. Hydro-CH2018 report.
- Mülchi R. et al. 2020: Neue hydrologische Szenarien für die Schweiz. Hydro-CH2018 report.
- Weingartner R. 2018: Veränderung der Abflussregimes der Schweiz in den letzten 150 Jahren. Hydro-CH2018 report.

6.3 Lakes and reservoirs

Natural lakes and artificial reservoirs are important storages for water resource management. Water inflow is altering due to climate change. The way in which this affects water levels and flow depends on whether a lake is regulated and how a reservoir is controlled. In alpine regions, new water bodies are being formed in glacier forefields due to glacier retreat.

Natural lakes are the second largest water storage resource in Switzerland (after groundwater) with a volume of around 130 km^3. Many lakes are regulated, meaning that the lake outflow is over a weir and the water level is controlled under the Weir Regulations. Many lake regulation systems were designed for better protection against floods, but now also address ecology, hydropower production, tourism (leisure navigation, bank accessibility) etc. Very few of the large lakes are unregulated, just Lakes Constance, Walen, Greifen and Baldegg. Here the water level follows the inflows with a temporal shift. Naturally, the fluctuations in water level are generally greater in the unregulated than in the regulated lakes. The potentially usable amount of water can be roughly estimated from the difference between the maximum and minimum water levels under the Weir Regulations. This is estimated for unregulated lakes from the average difference between the minimum and maximum annual water levels. The volume actually usable on a given date depends on the water level on that date and can approach zero if the water level in the lake is low, e. g. during droughts. Some lakes, e. g.

Lakes Zurich and Lucerne, have even been lowered in the past below the minimum lake water levels in the Weir Regulations to maintain sufficient flow in the downstream watercourses (e.g. 2018). In this way it was possible to reduce the negative effects of the drought on the water ecology of the rivers Limmat and Reuss.

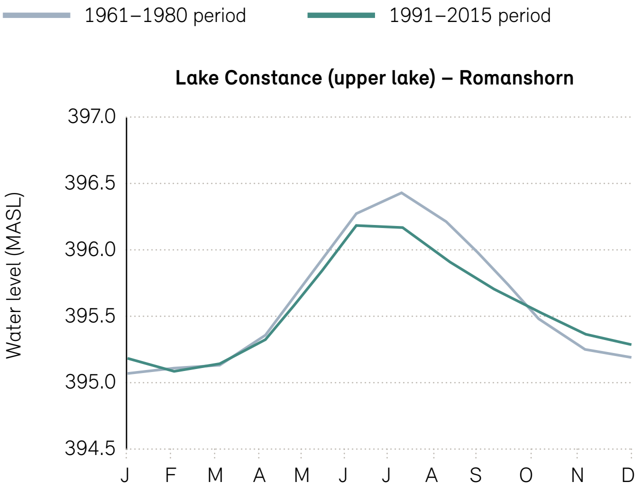
In contrast, almost the entire volume can be used in the artificial reservoirs (Brunner et al. 2019a). They are mainly alpine reservoirs created by construction of a dam. According to the Federal Office of Energy, their usable storage capacity is around 3.5 km^3. The main function of most reservoirs is to generate power, but some are also used for flood protection, snowmaking or drinking water supplies.

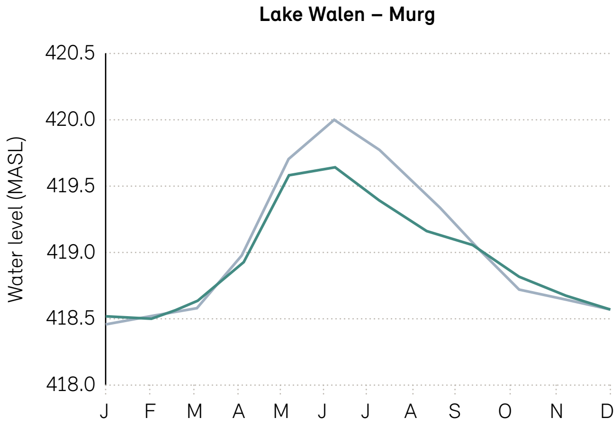
Changes observed in lake water levels

Changes in water levels have been observed in recent decades on Lakes Constance and Walen, the two largest unregulated lakes in Switzerland. Average water levels

Figure 6-6: Average water levels on the unregulated lakes Constance and Walen

Water levels in summer decreased significantly in the 1991–2015 period compared with 1961-1980, while winter levels increased slightly.





Source: FOEN measured data

Figure 6-7: Retreat of the Trift glacier from 1984 to 2019

A striking example of the progressive glacier retreat over recent decades is the Trift glacier, where a new lake has formed in the forefield. The glacier levels in 1984, 2011 and 2019 are shown.

1984

2011

2019

Photos: Oberhasli power plant (KWO) (left and centre: Gadmen Cultural Centre, right: Françoise Funk-Salamí) have fallen significantly in summer and increased slightly in winter (Figure 6-6). This shows that lake water levels are following the same pattern as the inflow regimes due to climate change (Section 6.2).

Future lake water levels

Climate change will greatly affect the inflows into the lakes and reservoirs (Section 6.1). On the unregulated lakes, this will have a direct impact on water levels and will result in low levels in summer and autumn in particular. In the regulated lakes, the effects can be partly alleviated, but the Weir Regulations were not created with this objective. Studies are therefore being carried out on what impact the inflow changes will have on the lake levels and whether action needs to be taken in respect of the regulations (Swiss Confederation 2014), e.g. by keeping water levels higher than previously in spring so that more water is available in summer. It is conceivable that the demand for abstraction of water from the lakes will increase, particularly in summer, and this may conflict with reduced water availability. For the artificial reservoirs, the question arises of using them for alleviating periods of water scarcity. The Hydro-CH2018 project on reservoirs (see box) examined whether natural lakes and artificial reservoirs can help to overcome future summer water shortages and if so how.

New water bodies forming in glacier forefields

New lakes, streams and wetlands are forming in the Alps due to melting of the glaciers. Researchers at the University of Zurich estimate that up to 500 new lakes with an area of 50 km^2 and a volume of 2 km^3 could form (Haeberli et al. 2012). But the smaller lakes will silt up quite quickly. Some of the new lakes and former glacial valleys could be used as reservoirs – by building dams if necessary (Farinotti et al. 2016). Fundamental issues of protection and use of these newly forming, high alpine lakes and landscapes have yet to be resolved at society level.

Further information and references on 'Lakes and reservoirs'

- Brunner M. et al. 2019a: Wasserspeicher. Welchen Beitrag leisten Mehrzweckspeicher zur Verminderung zukünftiger Wasserknappheit? Hydro-CH2018 report.
- Brunner M. et al. 2019c: Present and Future Water Scarcity in Switzerland: Potential for Alleviation through Reservoirs and Lakes.

Water storage: Can natural lakes and artificial reservoirs help to alleviate summer water scarcity?

Method

Using the hydrological model PREVAH-WSL, hydrological scenarios for the whole of Switzerland were computed using eight climate model chains with climate change mitigation (RCP2.6) and 18 without (RCP8.5). Based on the results, the changes in the total water availability in Switzerland were determined. The future water needs were also estimated on the basis of the hydrological scenarios.

Main results

- In the case of artificial reservoirs, virtually the entire storage capacity is actually usable, but in most cases is currently reserved for hydropower production. In the case of the natural lakes, only a small part is sustainably usable, because the water level must not fall below a minimum. Minimum outflows to the downstream waters must be met in all the lakes.
- Summer water shortages can be expected, mainly on the Swiss Plateau and to some extent in alpine regions. The artificial reservoirs are mainly located in the Alps, far away from the regions with potential water scarcity. This makes the possible contribution of alpine reservoirs to reducing summer water scarcity on the Plateau quite small. Local reservoirs would have greater potential, but space for these is generally lacking in that region.

Hydro-CH2018 project of the Mountain Hydrology, and Economics and Social Sciences Research Units of the Federal Institute for Forest, Snow and Landscape (WSL) and the Institute for Construction and Environment of Rapperswil University of Applied Sciences (HSR)

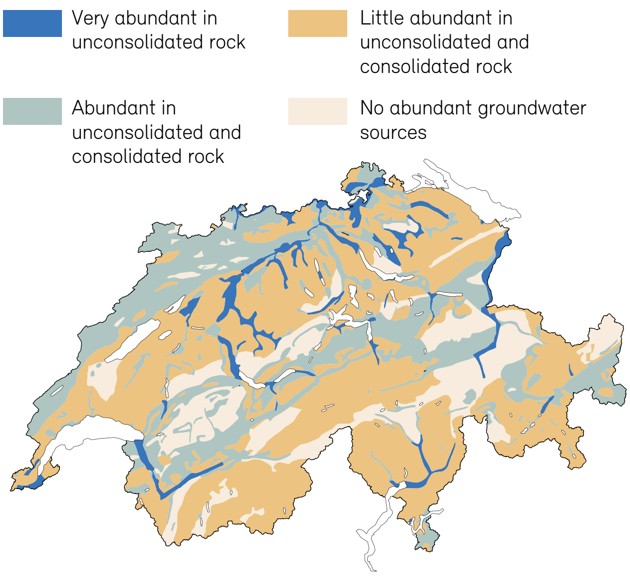
6.4 Groundwater

Switzerland has very large groundwater resources but with a heterogeneous spatial distribution. This is why more local, temporary deficits in groundwater availability are already occurring during drought. This trend will increase due to climate change. Groundwater recharge will increase in winter and spring and decrease in summer and autumn.

Groundwater is the largest and most important water storage resource in Switzerland. A distinction is made between groundwater in unconsolidated rock, fractured rock and karstic limestone. Its total volume is estimated at 150 km³, but the sources vary in abundance (Figure 6-8). Karst has the largest share at around 120 km³, followed by fractured rock at 20 km³ and unconsolidated rock at 10 km³. The sustainably usable resources are approximately 18 km³ per year nationwide, a large part of which comes from the abundant unconsolidated rock aquifers in the river valleys (Sinreich et al. 2012).

Figure 6-8: Outline map of the abundance of groundwater resources in Switzerland

The very abundant groundwater resources are found mainly in the unconsolidated rock aquifers in the river valleys.



Source: Sinreich et al. (2012)

The term "sustainably usable" means the amount of groundwater that can be abstracted on average in a normal year without causing a permanent reduction in its level or having other negative impacts on the environment. In periods of low water levels in particular, most of the small and medium-sized watercourse streamflow stems from groundwater. Delicate humid ecosystems also need sufficiently high groundwater levels (Section 7.3.4). Much less groundwater can thus be sustainably usable in dry years. In practice, the amount actually usable is often even lower, due both to conflicts of use and water quality impairment and because the groundwater resources are very unevenly distributed spatially and are not always available where water is needed.

Change in groundwater volume observed

As a rule, changes in groundwater levels represent only a small proportion of the total groundwater volume of Switzerland. The natural variations observed for the unconsolidated rock groundwater resources are in the centimetre to metre range, compared with a total aquifer depth which is often a few tens of metres. The situation is different in karst aquifers, where wide discharge variations at springs or total drying out are an indication of significant changes in recharge rate over the year. Depending upon how long water is retained in the groundwater, i. e. how quickly a groundwater resource reacts to drought or periods of heavy precipitation, aquifer levels and spring discharges can be affected months later or even into the following year. Small aquifers near the surface react very quickly and are prone to frequent local water scarcity problems in periods of drought.

The National Groundwater Monitoring NAQUA shows that the groundwater resources are fully recharged on a regular basis throughout Switzerland. Although repeated periods of several years with somewhat higher or lower groundwater levels do occur, a general trend has not been seen over the full measuring period, which is now around 20 years. In terms of quantity, therefore, the Swiss groundwater resources can be assumed to be largely stable, in a multi-year balance at least (FOEN 2019b).

Groundwater recharge a key process

Groundwater recharge is a key process in understanding the effects of climate change on groundwater quantity and temperature. It is important to distinguish between groundwater resources with diffuse recharge from percolation of precipitation and those with highly localised infiltration from surface water. The amount of recharged groundwater is not normally measured directly but is estimated on the basis of precipitation, evaporation and discharge. It varies widely in space and time and is around one third of annual precipitation on average across Switzerland.

More groundwater recharge from precipitation in winter and spring

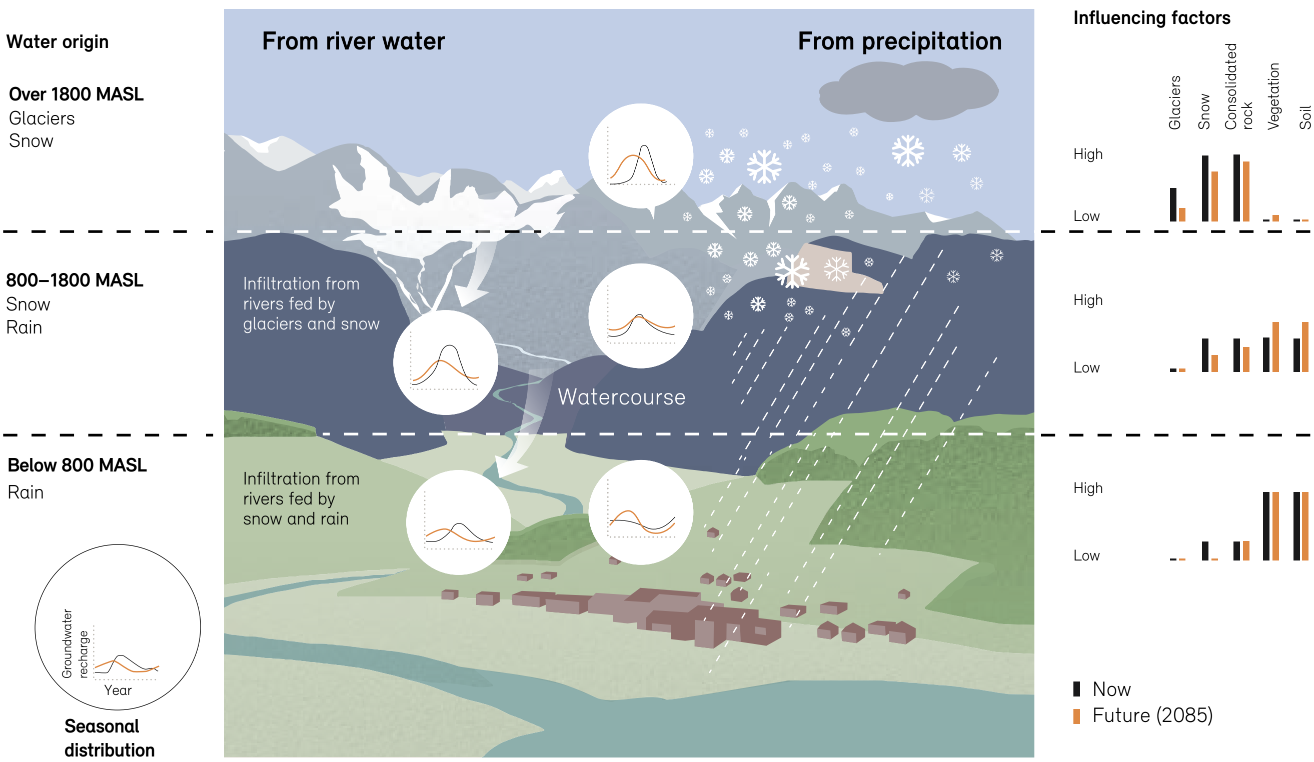
In regions with recharge from precipitation, groundwater is mainly formed by percolation of rain and melt water. As a general rule, more water can percolate through permeable soil and geology. Not all percolated water enters the groundwater, however, since it also supplies the water needs of the vegetation, evaporates or enters a surface water body. Groundwater recharge therefore varies according to the season and elevation (Figure 6-9).

As a result of the expected increase in winter precipitation, the higher rain contribution and the earlier snow melt, groundwater recharge will increase in winter and early spring at all elevations. In higher regions this factor will be reinforced because the ground will be frozen or covered with snow for a shorter period in the wintertime.

The changes in recharge from precipitation were calculated for three locations on the Swiss Plateau (Figure 6-10). For a scenario without climate change mitigation, it increases slightly in winter and spring by the end of the century.

Figure 6-9: Groundwater recharge and influencing factors due to climate change

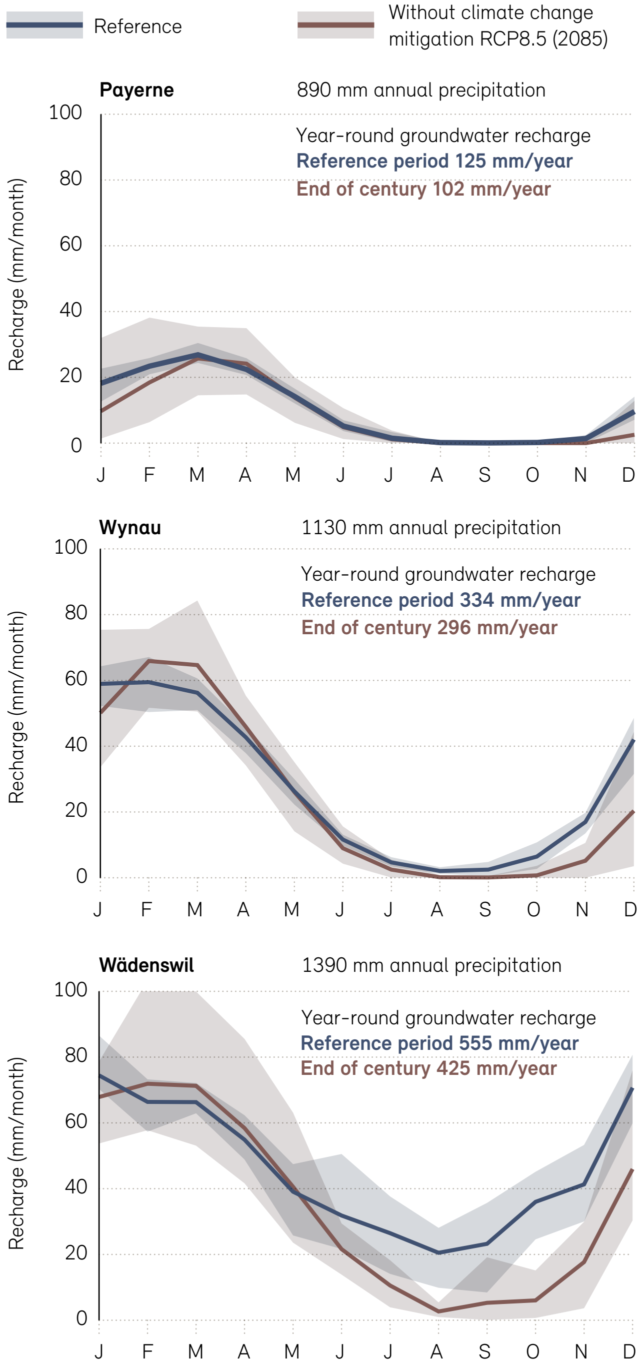
How much groundwater is recharged from river water or precipitation depends on the nature of the catchment. The amount varies according to the season and the elevation of the regions concerned. As climate change progresses, groundwater recharge will increase in winter and early spring at all elevations and decrease in summer and autumn.



Source: Hunkeler et al. (2020)

Figure 6-10: Changes in groundwater recharge from precipitation

Changes in groundwater recharge from precipitation in % (median and range of uncertainty) at three locations on the Swiss Plateau with soil of average permeability. The scenario without climate change mitigation (RCP8.5) is shown for the distant future compared with the reference period (1981–2010). Groundwater recharge will increase in winter and decrease in summer, however the annual balance is negative.



Source: Hunkeler et al. (2020)

Reduced groundwater recharge in summer and autumn

In areas of low precipitation (e. g. Payerne), groundwater recharge barely occurs in summer. In wetter regions (e. g. Wynau and Wädenswil), groundwater recharge will decrease in summer due to lower precipitation and higher temperatures, which will lead to more evaporation (Figure 6-10). On parts of the Swiss Plateau, the aquifers will not start to recharge until later in the year, as the summer soil moisture deficit first has to be compensated before water can start to percolate to the groundwater again. Evaporation also increases due to the longer vegetation period and higher temperatures. In contrast, longer groundwater recharge can occur in alpine regions in autumn, because the snowpack appears later in the year.

Groundwater recharge due to infiltration from surface waters will also decline considerably in the summertime. In Switzerland this occurs typically along river valleys with thick layers of valley gravel (e. g. large valleys on the Swiss Plateau, Rhone valley, Upper Rhine valley). Groundwater recharge then depends not only on the local climate conditions but also on the streamflow of the surface water body. The groundwater recharge for a river from the Alps occurs during the maximum discharge in spring or summer. Recharge by infiltration therefore changes in time according to the climate-related changes in the regime of the surface water supplying it.

Negative annual balance without climate change mitigation

Over the year as a whole, the amount of recharged groundwater is lower at all three locations studied (Figure 6-10), because the loss in autumn (and summer at wetter locations) cannot be fully compensated in winter. The reduction is greater at locations which still have high precipitation now, because recharge is also decreasing here in summer. The reduction is also greater at locations with low soil permeability, as this cannot absorb the extra water in winter and spring as effectively, and more precipitation runs off along the surface. But as long as the total groundwater recharge is sufficient to fill the aquifers over several years, little will change in relation to the total resource volume, even with climate change. The change in recharge does however affect the seasonal distribution of groundwater levels and thus its sustainably usable volume.

How do the groundwater resources in alpine catchments alter with climate change and how does this influence runoff formation?

Method

The relationship between the groundwater and runoff dynamics was analysed for 11 alpine catchments. Measured data and geological information were integrated in physically based models. These simulations can quantify the influence of climate change on the groundwater resource and the reaction of the catchments.

Main results

- Alpine groundwater resources in unconsolidated and consolidated rock react differently to climate change. The main change in unconsolidated rock is the seasonal dynamics, but over the year as a whole the amount remains the same. Unlike locations on the Swiss Plateau, the seasonal groundwater dynamics are reduced in the alpine unconsolidated rock.
- Long-term decreasing trends in stored groundwater can also be seen in the alpine consolidated rock.
- Despite the earlier snow melt and higher evapotranspiration in summer, the groundwater reserves and recharge rate in alpine regions remains much higher in summer than in winter. Extensive deposits of unconsolidated rock have a balancing effect on discharge, because they can store and then release large amounts of groundwater according to the season.

Hydro-CH2018 project of the University of Neuchâtel, Centre for Hydrogeology and Geothermics

Further information and references on ‘Groundwater’

- Epting J. et al. 2020: Ist-Zustand und Temperatur-Entwicklung Schweizer Lockergesteins-Grundwasservorkommen Hydro-CH2018 report.
- Hunkeler D. et al. 2020: Effect of Climate Change on Groundwater Quantity and Quality in Switzerland. Hydro-CH2018 report.
- Arnoux M. et al. 2020a: Dynamiques du stockage en eau souterraine et du régime hydrologique des bassins versants alpins face aux changements climatiques. Hydro-CH2018 report.

6.5 Flooding

The hydrological scenarios do not yet provide robust quantitative conclusions on how the frequency of flooding and flood discharge will change. Nevertheless, various climate-related processes indicate that floods and surface runoff will increase as climate change progresses.

During a flood the water level of a water body is well above the long-term average. Flood discharge is classified as HQx according to the probability that it will occur or be exceeded once in x years. The flood parameters HQ30, HQ100 and HQ300 are used for the design of flood protection measures and the creation of hazard basics.

Long periods of extensive heavy precipitation over several hours or days, sometimes combined with snow melt, can result in extensive flooding. These events affect large catchments or entire regions and also result in high water levels in lakes and groundwater. Short, localised heavy precipitation events, especially in summer, which last for a few minutes or hours cause local flooding in small watercourses and torrents or surface runoff outside the channel.

Frequency of flood events is changing

Reconstructions can be made about extensive flooding in the past from sediment analyses and historical records. These show that alternate phases with many or few floods have occurred repeatedly in Switzerland over the last 10,000 years (Ruiz-Villanueva and Molnar 2020). In the past 500 years these fluctuations were typically at intervals of around 30 to 100 years (Schmocker-Fackel and Naef 2010) and were caused by large-scale changes in the atmospheric circulation across Central Europe (Stucki et al. 2012). This means that the flood parameters are not constant over time and change with climate. This is a challenge for flood protection.

There was a period with many extensive floods throughout Switzerland towards the end of the Little Ice Age in the second half of the 19th century. This was the catalyst for many flood protection projects and watercourse corrections. In contrast, unusually few extensive floods were experienced in Switzerland between 1940 and 1970 (called 'disaster gap'). Over recent decades, a large number of extensive floods has occurred and has led to flood protection adaptations and the introduction of integrated risk management (Section 7.2).

The increased number of floods in recent times has also been observed in many other parts of Europe. The last 30 years have seen the most floods in Europe for 500 years. This is the more remarkable because flood phases in Europe in the past have tended to occur during cool climate periods, whereas the last 30 years have been warmer than average. The current high flood phase is unique in climate terms (Blöschl et al. 2020).

Figure 6-11: Flooding and surface runoff

The photos show on the left the Lütschine flood of 25 August 2005 in the Lütschental, and on the right a localised surface runoff event in the canton of Schaffhausen in May 2013.

Photos: left: FOEN, right: Canton of Schaffhausen Civil Engineering Department

Change in factors influencing floods

Whether a flood event occurs and what peak discharge it causes depends on a combination of many influencing factors. Certainly, heavy precipitation triggers the flood, but the same precipitation event can result in one case in a serious flood, while in another the discharge is much lower, due to a lower zero-degree isotherm or lower soil moisture before the event, for example. With climate change, it is not only the heavy precipitation but also other factors affecting flooding that change (Figure 6-12):

More energy and humidity in the atmosphere

As climate change progresses, the precipitation potential increases, because the air can hold 6 to 7% more water for each degree Celsius of warming. Global climate models also show that without climate change mitigation, more atmospheric humidity will be transported towards the Alps in future and the potential for more intensive precipitation and floods will increase (Brönnimann et al. 2018). Wernli et al. (2016) studied the effects of this climate impact on flood events in a theoretical experiment. Using a weather and a hydrological model, they simulated various past events with different initial conditions. They assumed humidity up to 10% higher and temperatures up to 3 °C higher over the Atlantic. The experiments show that flood discharge may increase at a similar rate to humidity.

Climate change thus increases the potential amount of precipitation and this may affect both shorter heavy precipitation events and long-lasting precipitation. In physical terms, more frequent and intensive events should be assumed, for local floods and surface runoff at the very least. An increase in runoff would also have to be expected during extensive floods. The hydrological scenarios can only model these changes to a certain degree: Although they point to a slight increase in flood frequency and intensity by the end of the century without climate change mitigation, the rise is not significant (Mülchi et al. 2020). It is particularly uncertain whether the rare severe floods will occur more often.

Uncertainties in the atmospheric circulation

The unclear signal in the hydrological scenarios may also be due to methodology: Firstly, the extreme precipitation causing the widespread flooding or its natural variability may be underestimated in the CH2018 climate scenarios. The circulation changes in the atmosphere and resultant extensive extreme precipitation observed in the past could also be only partly simulated by climate models (Brönnimann et al. 2019).

Secondly, statistical methods have to be used for the hydrological modelling, in order to improve the spatial and temporal resolution of the precipitation data. The regional climate models supply their data at a spatial resolution of 12 × 12 km or 50 × 50 km, and the model output is generally only available at daily intervals. These levels of resolution are insufficient for good simulation of flood events in the topographically complex and quite small Swiss catchments using hydrological models. The results from the climate models are thus further refined by statistical methods (Chapter 2). It cannot be excluded that extreme precipitation is underestimated by these methods.

Changes in snow and soil moisture

As a result of the rise in the snow line and zero-degree isotherm, precipitation is falling more frequently as rain rather than snow up to high elevations in the Alps. This prolongs the flood season in spring and autumn. In the Jura, floods now occur mainly in winter due to events in which heavy precipitation and snow melt coincide throughout the catchment (rain-on-snow events). The frequency of such events will be reduced due to climate change, since the duration and depth of the snowpack in the Jura will be greatly reduced. These events will also become less frequent in the alpine foothills. In the Kandertal and Lötschental valleys in October 2011, there was a severe rain-on-snow flood never previously observed in that form (Badoux et al. 2013). It is still unclear whether these rain-on-snow events will increase in the Alps due to climate change. The expected changes in snowpack may – depending on the region and season considered – either stimulate or inhibit floods. The same applies to soil moisture: Soil with low moisture can absorb and store more precipitation and hence reduce flood discharge. On the other hand, very dry soil can also develop water-repellent properties, so that precipitation cannot percolate and forms surface runoff. This occurs mainly in soil used for agriculture which has little vegetation cover and is heavily compacted, and can lead to soil erosion.

Figure 6-12: Factors influencing floods and how they develop with climate change

Spatial impact on floods — Increase expected — Decrease expected — Increase or decrease possible — No change

Climate impact: More energy and humidity in the atmosphere

- General increase in precipitation potential but variable catchment reaction depending on catchment properties.
- Increase in the frequency and intensity of heavy precipitation events and therefore local floods.

Climate impact: Changes in atmospheric circulation

- High atmospheric variability also in future.
- Climate models can currently only estimate the impacts on extreme precipitation events to a limited extent.
- The atmospheric circulation has a particular impact on extensive, long-lasting heavy precipitation and therefore on extensive floods.

Climate impact: Higher zero-degree isotherm

- More precipitation in the form of rain which feeds discharge directly.
- Mainly in alpine catchments a larger area is subjected to rain.
- Flood season is extended, therefore potentially more precipitation events that can cause flooding.

Climate impact: Reduced snowpack and snow melt

- The influence of snow melt in the Jura and alpine foothills decreases.
- On the Swiss Plateau the influence of snowpack on floods is already minimal.
- Possible greater influence of snow on floods in alpine regions (rain-on-snow events).

Climate impact: Change in soil moisture

- Reduction in average soil moisture on the Swiss Plateau may increase the water retention capacity during precipitation in the short term, but the effect is small during more sustained precipitation.
- Water-repelling effects can occur in dehydrated soil, especially if it is compacted, so that in some cases less water can infiltrate during heavy precipitation events during droughts. → Reduced water retention capacity and increased risk of surface runoff.

Climate impact: Greater sediment availability

- Increase in damage potential due to more debris for mobilisation in the Alps.
- Changes in sediment transport due to changes in runoff.

Higher availability of sediment
Due to thawing of the permafrost and retreat of the glaciers, more sediment is available in the mountains for being mobilised during heavy precipitation events. It is mainly in the steep torrents that sediment is transported during flood events, and other material can be eroded out of the channel. For example, a flash flood in a torrent can trigger a debris flow due to additional sediment erosion. The streamflow then slows down in the less steep river and stream stretches downstream of the torrents where the sediment is redeposited. This deposition reduces the flow capacity of the channel, which can lead to flooding and bursting of banks, resulting in major damage (Speerli et al. 2020).

Different regional reactions to heavy precipitation
The anticipated increase in heavy precipitation due to climate change will affect discharge with different regional levels of severity. The soil, rock, vegetation, topography and built-up area all affect what proportion of the precipitation can be retained in a catchment and what proportion contributes to flood discharge. If the absorption capacity of the catchment is high, increase in discharge is lower compared to precipitation, but if its capacity is exhausted, all the precipitation can run off and the increase in discharge is disproportionately high. The complex interaction of many, sometimes opposing, factors makes robust quantitative conclusions about the future incidence of severe floods more difficult.

Further information and references on 'Flooding'

- Burlando et al. (2020): Evaluation of future hydrological scenarios using stochastic high-resolution climate data. Hydro-CH2018 report.
- Mülchi R. et al. 2020: Neue hydrologische Szenarien für die Schweiz. Hydro-CH2018 report.
- Ruiz-Villanueva V., Molnar P. 2020: Past, current and future changes in floods in Switzerland. Hydro-CH2018 report.
- Speerli J. et al. 2020: Auswirkungen des Klimawandels auf den Sedimenttransport. Hydro-CH2018 report.

6.6 Low flow

On the Swiss Plateau, in the Jura and Southern Switzerland, future low flow situations in water bodies will be more severe and frequent in summer and autumn, with negative consequences for water ecology and water use. In the Alps, however, runoff will increase in winter during what has been the low flow season to date.

Low flow is defined as an unusually low discharge in surface waters. Low flow situations are generally characterised by the parameters Q_{347} and NM7Q. Q_{347} is the discharge of a watercourse which is at least reached or exceeded for 95% of the time, that is on 347 days in an average year (averaged over 10 years). The discharge Q_{347} is defined in the Waters Protection Act (Article 31 Section 1 WPA) as the minimum residual flow and plays a key role as low flow indicator. The second indicator is NM7Q, defined as the lowest arithmetic mean of seven consecutive daily values of the discharge in a period considered. NM7Q is a robust indicator with low susceptibilty to measurement error or short-term effects.

Low flows increase in the Alps
In high-elevation alpine catchments, low flow is caused by cold periods when all the precipitation falls as snow and cannot feed runoff directly. In these areas the lowest annual flow normally occurs between January and March. Low flows (and thus the parameter NM7Q) increased significantly in the majority of glacial and nival catchments between 1961 and 2018. The Q_{347} minimum flows also increased (Figure 6-13). In general, therefore, runoff has increased in the Alps during the typical low flow season in winter, mainly because more precipitation is falling as rain and less as snow in winter due to climate change.

On the Rhine, extreme low flow in winter has also become rarer since the 19th century (Pfister et al. 2006), but this is not just a consequence of climate change. Hydropower plant reservoirs and regulation of the natural lakes also play a significant role. Some of the summer discharge is stored in alpine reservoirs and used for power generation in winter. This leads to a considerable increase in winter discharge.

Low flows already more pronounced in summer

In the non-alpine regions, low flow occurs due to lack of precipitation, often combined with high evaporation. The typical low flow period is between late summer and late autumn, although there is considerable year-to-year variability. Days with flows below Q_{347} can occur in every month apart from March to May. In the 1961–2018 period, no significant changes in Q_{347} and the annual NM7Q data can be seen for the majority of the non-alpine catchments.

Figure 6-13: Observed development of low flows since 1961

Trends were calculated for different runoff regimes for the low flow discharge parameters NM7Q (seasonal and year) and Q_{347} (year only) for the period 1961 – 2018. An increase in these indicators means that the low flows increase, whereas a decrease means that they fall. In nearly all the catchments, low flows decrease significantly in summer. High-elevation regions show an increase in winter and spring. In regions with low flow in winter, the annual values for Q_{347} and NM7Q have already increased.

	NM7Q					Q_{347}
Regime	**Winter (DJF)**	**Spring (MAM)**	**Summer (JJA)**	**Autumn (SON)**	**Year**	**Year**
Glacial and glacio-nival	↑	↑	↑	→	↑	↑
Nivo-glacial	↑	→	↓	↑	↑	↑
Nival	→	↑	↓	→	→	↑
Prealpine-nival	→	↑	↓	↑	→	→
Pluvial	→	→	↓	→	→	→
Jurassic	→	↓	↓	→	→	→
South alpine	↑	→	↓	→	→	↑

↑ Marked or significant increase

↓ Marked or significant decrease

→ No change

Average occurrence of NM7Q and standard deviation of average occurrence

Source: Weingartner and Schwanbeck (2020)

The situation is different when the lowest summer flow discharges (NM7Q) are examined. They decreased significantly in the majority of the northern alpine catchments studied – including the catchments in the Alps with little or no glaciation (Figure 6-13). The increasingly early snow melt, increased evaporation and lack of precipitation are the critical processes involved.

Trend analyses cannot be carried out for the very rare and extreme low flow events that occur statistically every 50 or 100 years, as the measurement series are too short. Historical analyses do show that in the past there were repeated unusually dry and warm phases in summer in Switzerland and Central Europe, e.g. in the 1940s and 1960s (Kohn et al. 2019). In the last 20 years there have been many unusually hot and dry summers breaking records for low flow and temperature (e.g. 2003, 2015, 2018). The trend towards hot summers is clearly verified (Technical Report CH2018), which means that the number of extreme low flow events cannot in all likelihood be explained just by natural variability.

A long-term tendency is not yet apparent in relation to groundwater levels and spring discharges. However, the years 2003, 2011 and 2018 had very low groundwater levels and many small springs ran dry, such as in the Jura, the hills and the Prealps (FOEN indicator 'High and Low Groundwater Levels'[2]).

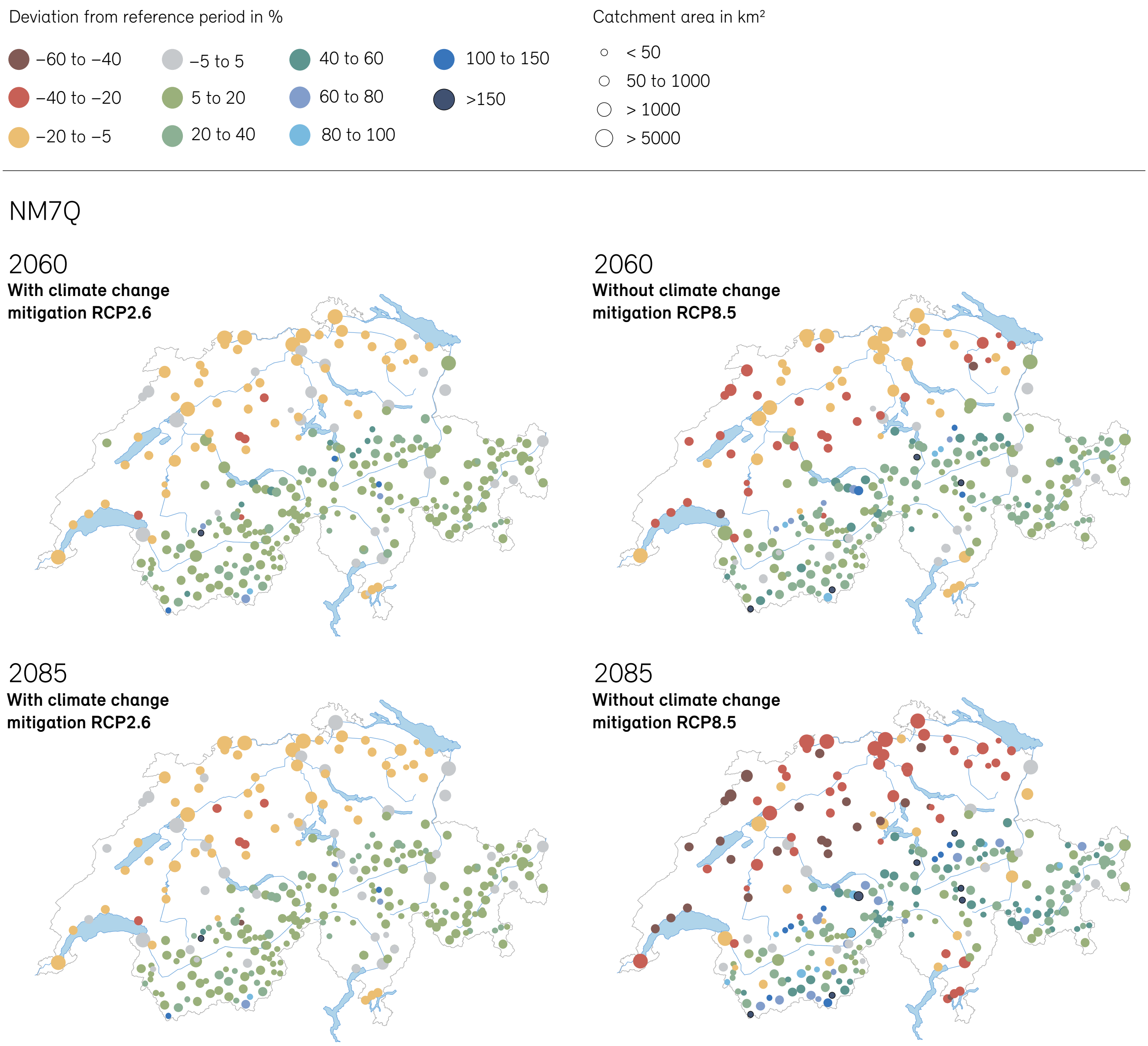
Trend towards more extreme low flows in summer continues

The CH2018 climate scenarios indicate that average summer precipitation amounts are decreasing and droughts are tending to last longer (Section 4.2). A consequence of the higher temperatures is that evaporation also increases as long as there is enough water available in soil and vegetation. The hydrological low flow scenarios indicate a decrease in low flow discharge in summer and autumn on the Swiss Plateau and in the Jura and Southern Switzerland. Since the lowest flows of the year generally occur during that period, these changes are also apparent in the annual NM7Q and Q_{347} (Figure 6-14 and Figure 6-15, example of the Thur).

2 *www.bafu.admin.ch* > Topic Water > Data, maps and indicators > Indicators > Water indicators

Figure 6-14: Low flow scenarios

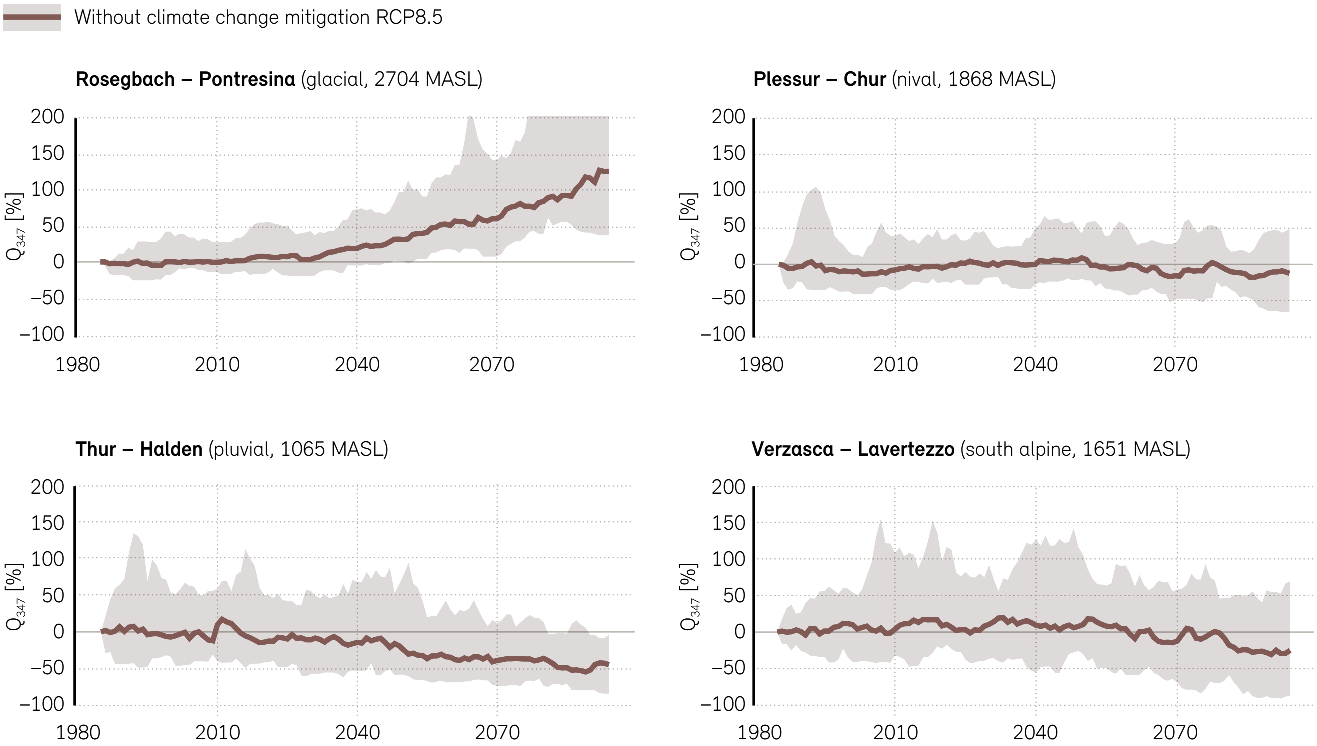
The changes compared with the reference period (1981–2010) for the low flow discharge parameter NM7Q with climate change mitigation RCP2.6 (left) and without climate change mitigation RCP8.5 (right) for the middle and end of the century are shown. A decrease in the annual values means that the discharge during low flow is reduced. At low elevations, low flow occurs in summer and the low flow discharges decrease as climate change advances. In the Alps, low flow occurs in winter and the discharges increase.



Sources: Data Mülchi et al. (2020 and 2021b), Freudiger et al. (2020), Brunner et al. (2019c)

Figure 6-15: Development of Q_{347} over time

The percentage change in the low flow indicator Q_{347} (median and range of uncertainty) compared with the reference period (1981–2010) was analysed for moving ten-year periods from 2010 to 2099 for the scenario without climate change mitigation (RCP8.5). In the glacial Rosegbach region, the flow indicator Q_{347} increases markedly by the end of the century, but decreases in the Thur (pluvial) and Verzasca (southern alpine). The Q_{347} hardly changes in the Plessur.



Source: Mülchi et al. (2021b)

Shift in the low flow season in the Alps and Prealps

The hydrological scenarios paint a a somewhat more differentiated picture in the Alps and Prealps. The winter discharge during low flow increases in the near future at elevations of between 1500 and 2000 MASL due to the milder and wetter weather. However, without climate change mitigation the discharge during the summer decreases so much due to the reduction in melt water that in some regions the low flow season is shifting from winter to autumn or summer. In these regions low flow will then be caused by lack of precipitation rather than low temperatures. Although all regions below 1500 MASL show a significant decrease in Q_{347} by the end of the century without climate change mitigation, the changes in regions between 1500 and 2000 MASL are small (Figure 6-15, examples of Plessur and Verzasca), with the Q_{347} being both slightly increased or decreased. All the scenarios for the very high elevations above 2000 MASL indicate an increase in low flows Q_{347}, even for the distant future, and therefore less significant low flow situations in winter (Figure 6-15, example of Rosegbach).

Future development of extreme low flow events is uncertain

Specific large-scale circulation patterns in the atmosphere have a decisive impact on the occurrence of extreme meteorological drought and low flow, i. e. very rare events. For example, persistent high pressure systems extending to a great altitude cause atmospheric blocking of the west wind zone and hence greatly reduced precipitation. Uncertainties still exist in the climate models about how these specific atmospheric patterns will develope as climate change advances. It also remains unclear to what extent the frequency and intensity of extreme drought and low flow events will increase (Woollings et al. 2018).

Susceptibility of water bodies falling dry varies
In low flow periods, many watercourses are fed mainly from groundwater. In addition to the weather conditions, vegetation and type of soil, the runoff during low flow is critically dependent on the hydrogeological conditions in the specific catchment (Carlier et al. 2018). Extensive groundwater resources in consolidated rock and/or in unconsolidated deposits reduce susceptibility to drought. These hydrogeological processes continue to exist with climate change.

Specific hydrogeological conditions can cause a watercourse to run completely dry locally through infiltration into the groundwater. For the entire discharge to infiltrate the subsoil, the unconsolidated deposits within it must be vast enough to be able to absorb all the water and transport it underground. The river bed must also be sufficiently permeable. Complete drying due to infiltration is only observed in medium-sized and small watercourses. The discharge during low flow in larger watercourses is too high to allow all water to percolate completely and run underground. Watercourses are often observed to dry up in karst regions. Low flow situations can be more pronounced if water is abstracted directly from the surface waters or adjacent groundwater. On the other hand, the discharge is increased if water is introduced, e.g. from wastewater treatment plants. Very low flows in summer, particularly if combined with high water temperatures or drying of the watercourse, are very problematic for the aquatic ecology (Section 6.9) and can lead to restrictions in water use (Section 7.1).

Further information and references on 'Low flow'

- Kohn I. et al. 2019: Low Flow Events – a Review in the Context of Climate Change in Switzerland. Hydro-CH2018 report.
- Mülchi R. et al. 2020: Neue hydrologische Szenarien für die Schweiz. Hydro-CH2018 report.
- Weingartner R. and Schwanbeck J. 2020: Veränderung der Niedrigwasserabflüsse und der kleinsten saisonalen Abflüsse in der Schweiz im Zeitraum 1961–2018 Hydro-CH2018 report.

6.7 Water temperature

Climate change increases the water temperatures in watercourses, lakes and groundwater. This warming is already clearly measurable in surface waters, though the rise in groundwater temperatures is less distinctive. Higher water temperatures, especially in summer, have negative impacts on water quality and ecology.

6.7.1 Watercourses

The average water temperature of the watercourses has already increased considerably in recent decades. The hydrological scenarios show that this rise is set to continue, especially in summer and in the alpine regions.

At the source of a watercourse, the temperature of the water emerging from the subsurface is close to the annual average air temperature. Exceptions are glacial streams, which are fed by melt water at a temperature of around 0 °C. As water moves downstream, its temperature is mainly influenced by radiation and the air temperature. The water is cooled in summer by shade from vegetation, melt water inflows and inflow of groundwater. Watercourses with large discharge or which are deep also warm more slowly. The temperature of lake outflows corresponds to that of the lake surface over the year and can be accordingly high in summer. In winter groundwater inflow and high discharge rates counteract the cooling.

Thermal use of water for cooling in power plants and industrial plants increases its temperature, whereas heat extraction for heating reduces the temperature. Hydropower use also has an influence on the temperature. In pumped-storage hydropower plants, cold water from high-elevation reservoirs enters lower level water and cools it in summer. As the flow rate downstream of hydropower plants is irregular, this results not only in wide fluctuations in flow rate (hydropeaking), but also in greater unnatural temperature variations (thermopeaking). The diurnal and even the annual water temperature can therefore be changed below artificial reservoirs. The temperature in residual flow sections of a watercourse is also influenced by the reduced flow. A watercourse may be warmer or cooler compared to a natural flow, depending on the season and local conditions (Schmid 2019).

Strongly increased water temperature, particularly in summer

The water temperatures of 52 Swiss watercourses recorded over recent decades were systematically analysed. Records are available from 1970 for 31 stations. The average warming of the watercourses during the 1979–2018 period has been 0.33 °C per decade (Figure 6-16) and in the past 20 years as much as 0.37 °C per decade. This represents around 90% of the rise in average air temperature in the same period (Michel et al. 2019). The increase in water temperatures has been moderated by the cooling effect of melt water from the Alps.

Watercourses have warmed very substantially in summer (0.58 °C per decade), with much less pronounced warming in winter (0.22 °C per decade). The greater increase in summer can be explained by the greater warming of the atmosphere at that time of year. At the same time, however, summer discharge has also decreased on the Swiss Plateau (Section 6.2), and heatwaves have become more frequent.

Critical temperature thresholds exceeded more often

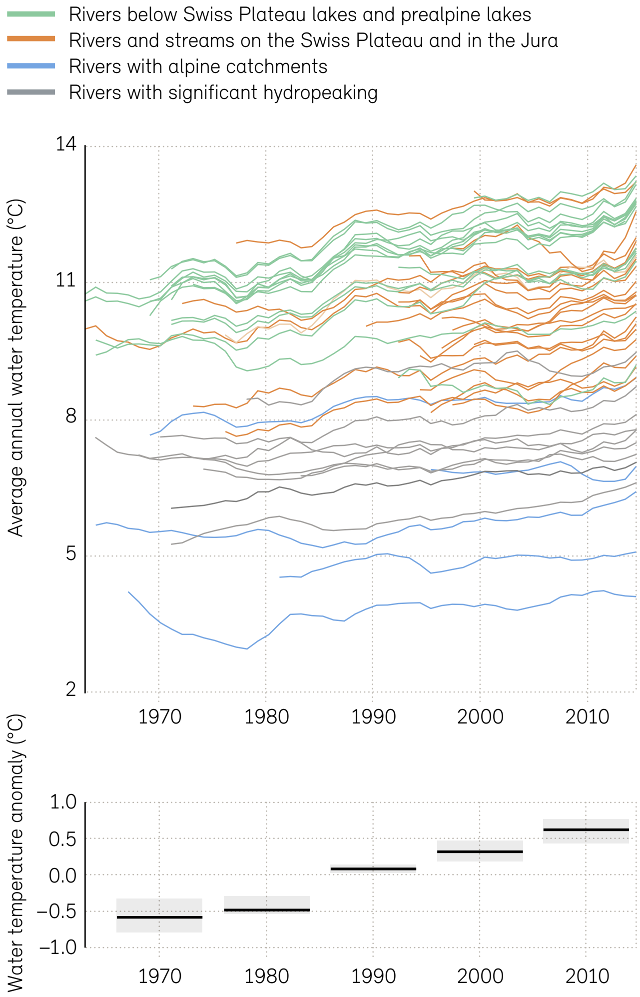
The hot summers of 2003, 2015 and 2018 saw record-breaking temperatures at many stations and in summer 2018 there were new records at 25 out of 83 monitoring stations (FOEN 2019a). Temperatures well over 25 °C were recorded in the Upper Rhine, Limmat, Thur and the Rhone below Lake Geneva, among others.

High water temperatures can cause stress in many aquatic organisms and in extreme cases can be fatal. Outbreaks of certain diseases are also linked to higher water temperatures (Section 6.9.2). As Figure 6-17 shows, since the 1980s more and more water bodies have experienced temperatures that are critical for outbreaks such as Proliferative Kidney Disease (PKD) in trout. In addition, these warm periods are lasting longer and longer. The total number of days per year on which temperatures over 15 °C occur has increased by an average of 20 days over four decades, with even greater warming observed in some regions (Michel et al. 2019).

High water temperatures also make cooling water use more problematic: Firstly, rising water temperatures make the usable temperature difference smaller, which must be offset by abstracting more cooling water. Secondly, there is a ban on returning warmed process water to watercourses at a temperature of over 25 °C.[3]

Figure 6-16: Temperature development observed in watercourses

The lines show the 5-year moving average in mean annual water temperature recorded at 52 stations. The colours represent different types of watercourses: see legend. Also shown are the water temperature anomalies per decade compared with the average for the 1970–2018 period (bottom). The temperatures of most watercourses have increased significantly since the 1970s.

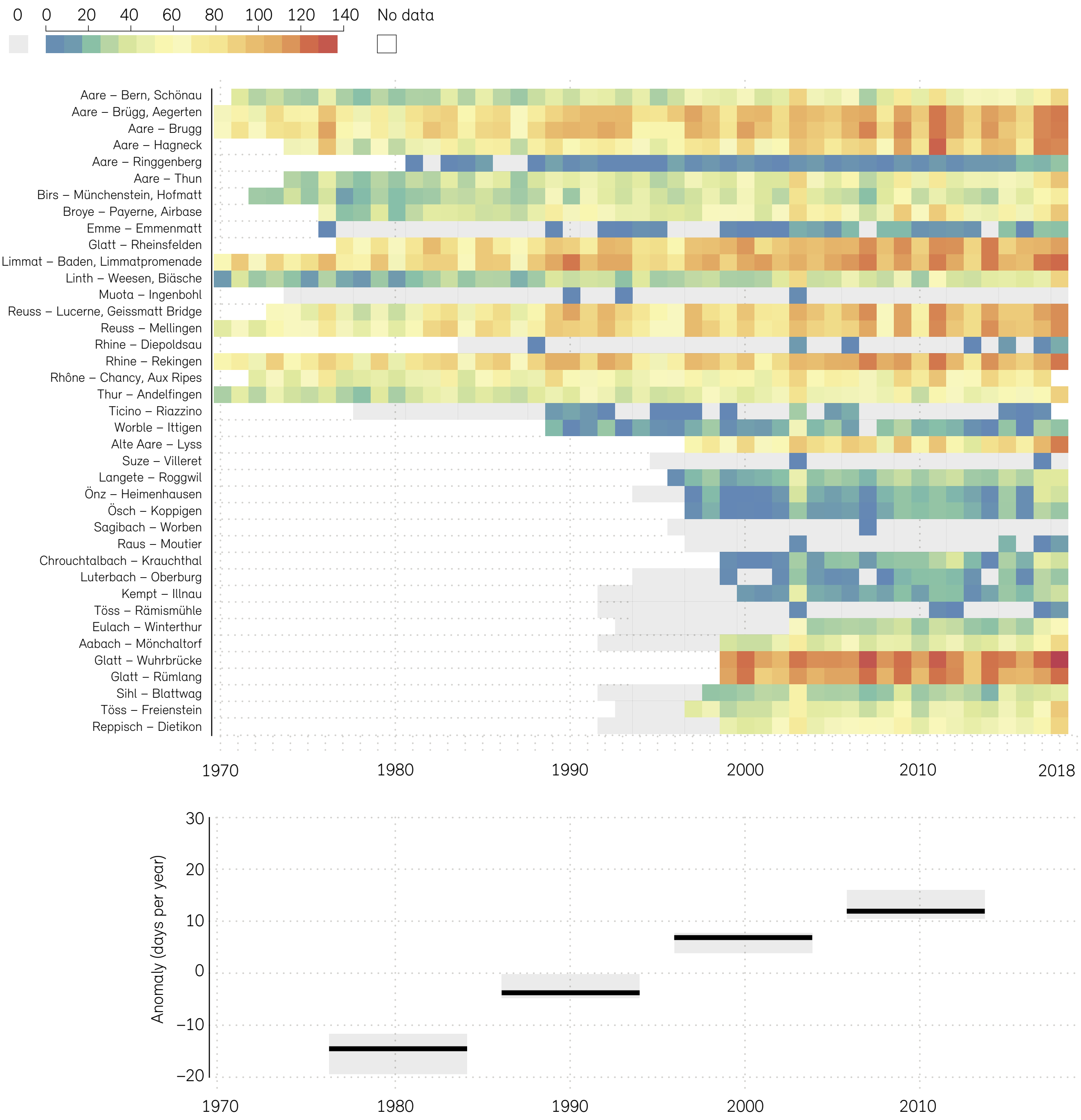


Source: Michel et al. (2019)

3 Exemptions are possible under certain conditions, see. Annex 3.3, section. 21 para. 4 b GSchV.

Figure 6-17: Water temperature of 15 °C exceeded more often

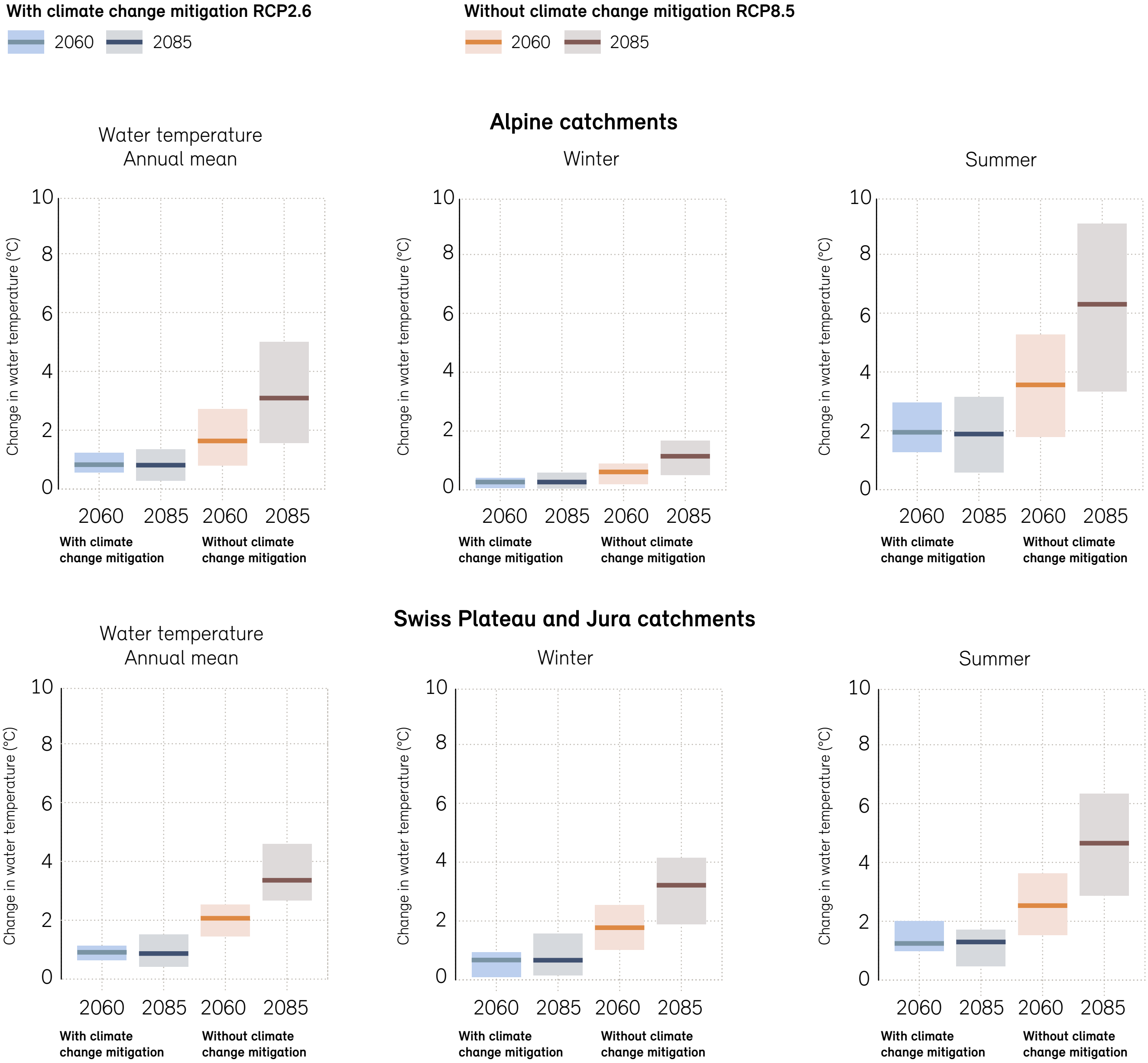
The number of days on which 15 °C is exceeded in a watercourse is an indicator for the occurrence of Proliferative Kidney Disease (PKD) in trout.



Sources: Michel et al. (2019), database: FOEN, Canton of Bern and Canton of Zurich

Figure 6-18: Change in the water temperature in watercourses on the Swiss Plateau and in the Jura and Alps

Average changes in water temperature (mean and range of uncertainty) for the full year and for winter and summer with (RCP2.6) and without climate change mitigation (RCP8.5) for mid-century (2055–2065) and for the end of the century (2080–2090) compared with the reference period (1990–2000). The alpine rivers Inn, Kander, Landwasser and Lonza and the Plateau and Jura rivers Birs, Broye, Eulach, Ergolz, Rietholzbach and Suze were studied. The water temperature will increase further in all the rivers.



Source: Michel et al. (in prep.)

Further significant increase in water temperature expected in future

On the Swiss Plateau and in the Alps, the average annual temperature of the watercourses will rise further in future. For a scenario with climate change mitigation, the models calculate further warming of 0.85 °C by mid-century. In this scenario, a further significant temperature increase is not to be expected in the second half of the century (Michel et al. in prep.). In a scenario without climate change mitigation the situation is different: by mid-century the models predict warming by 2.1 °C on the Swiss Plateau and 1.6 °C in alpine watercourses; by the end of the century these numbers rise to 3.2 °C in all the watercourses (Figure 6-18). This warming represents a continuation of the trends observed over past decades (Michel et al. in prep.).

The difference between the Alps and the Swiss Plateau/Jura is greater for seasonal water temperatures than for average annual temperatures. In winter, the watercourses on the Plateau will warm considerably, without climate change mitigation by over 3 °C towards the end of the century. In the Alps water temperatures only increase by around 1 °C in winter, although the air temperature increases by 4 °C without climate change mitigation. Here, discharge in winter mainly stems from groundwater or the increasing snow melt, which have a cooling effect.

In summer, the watercourses will warm even more: without climate change mitigation already by mid-century by around 2.5 °C on the Plateau and 3.6 °C in the Alps, and by the end of the century even by 3.1 to 6.1 °C on the Plateau and 4.1 to 8.1 °C in the Alps. In addition to the higher air temperature, a critical factor is that summer precipitation and runoff will be reduced, and the cooling melt water contribution will decrease, particularly in the alpine regions. The soil will also warm more in the Alps because the snowpack is melting earlier. Hence, alpine water temperatures will rise even faster than the air temperature.

The size of the catchment area of the water bodies studied has no effect on the computed temperature increase. However, temperature records and scenarios for the future do not exist for very small watercourses. There is thus a possibility that the temperature increase in those watercourses may turn out differently and perhaps be even greater. Large Swiss Plateau rivers directly below the large lakes have not been considered either; here the temperature is mainly influenced by the lake water outflow. The surface water in the lakes will be 3 to 4 °C warmer in summer without climate change mitigation by the end of the century (Section 6.7.2), and the warming in the outflows is expected to be similar.

6.7.2 Lakes

Surface and deep water in the lakes has warmed in recent decades. Winter ice cover on lakes has decreased and the stable water stratification in summer persists for longer. This development will continue with climate change. As a result, the ecologically important mixing regimes in the lakes will also change in part.

The water temperature in lakes depends on the solar irradiation, local air temperature, water temperature of the inflows and frequency of extremes such as heatwaves, storms and floods and is also influenced by the morphology and turbidity of the lake. The temperature distribution within a lake is not homogeneous. In the summertime lakes have stable thermal stratification, with warmer water in the surface layer a few metres in depth and colder deep water (summer stratification).

The two layers of water can only mix when the temperature – and therefore the density – of surface and deep water is equal. This circulation affects the heat and substance distribution within a lake. The frequency and intensity of mixing of the water bodies is vital for the lake ecology, as it is the only means of establishing a balance of substance concentrations (nutrients, oxygen and pollutants) between deep and surface water (Section 6.9.1).

The density anomaly of water also causes heat-related stratification in winter. Winter stratification occurs if the temperature of the surface water falls below 4 °C, the density decreases and the cold surface water can no longer sink. The deep layer then consists of water at maximum 4 °C. This inverse temperature distribution is a pre-condition for ice formation.

Surface water layer already warmed

The average warming of the surface water layers of Swiss lakes in recent decades is approximately 0.4 °C per decade and around 2 °C from 1960 – 2010 (Råman Vinnå et al. 2021), and changes in mixing have been observed. For example, heatwaves like the one in summer 2003 caused increased and extended summer stratification. Mild winters such as those in 2006 and 2007 prevented the seasonal mixing down to the deep water in some lakes. The total freezing of Swiss lakes has become much rarer since the 1960s, particularly on the Swiss Plateau (Hendricks Franssen and Scherrer 2008).

Further significant warming

The future development of the temperature and stratification regime was modelled for 29 lakes (Figure 6-19). A further increase in the temperature of the surface water layer (down to 1 m deep) is expected in all the lakes: for a scenario without climate change mitigation of between 3 and 4 °C in most lakes towards the end of the century, and with climate change mitigation of only 1 °C. The difference in surface temperature between the lakes studied is small. This development is very similar to that of the watercourses.

Greater differences between the lakes can be expected in terms of deep water warming. While small or high-elevation lakes continue to cool to 4 °C down to their depths in winter, the increase in deep water temperature is expected to be small. In larger lakes, the models show warming of the deep water by 1.5 to 2.5 °C by the end of the century without climate change mitigation. This variation in deep water warming can be explained by the different effects of climate change on the mixing regime (see below).

Mixing regimes of the lakes are changing

As a result of the altered water temperatures, the mixing regimes of the lakes are changing in various ways: The stable stratification conditions in summer are lasting longer, but winter stratification is occurring less often and the formation and duration of the lake ice is decreased (Figure 6-20).

Effect of climate change on the temperatures of watercourses and lakes: How will the water temperatures of the Swiss watercourses and lakes develop in future?

Method

Using the models Snowpack/Alpine3*D* (Lehning et al. 2006) and StreamFlow (Gallice et al. 2016), temperature scenarios were modelled for six watercourses on the Swiss Swiss Plateau (Birs, Broye, Eulach Ergolz, Rietholzbach and Suze) and four in the Alps (Inn, Kander, Landwasser, Lonza), as examples. The results are summarised in Figure 6-18. Due to the long computing times, only seven RCP8.5 and four RCP2.6 climate projections could be considered for a shorter reference period (1990–2000) and two ten-year periods in the future (2055–2065 and 2080–2090).

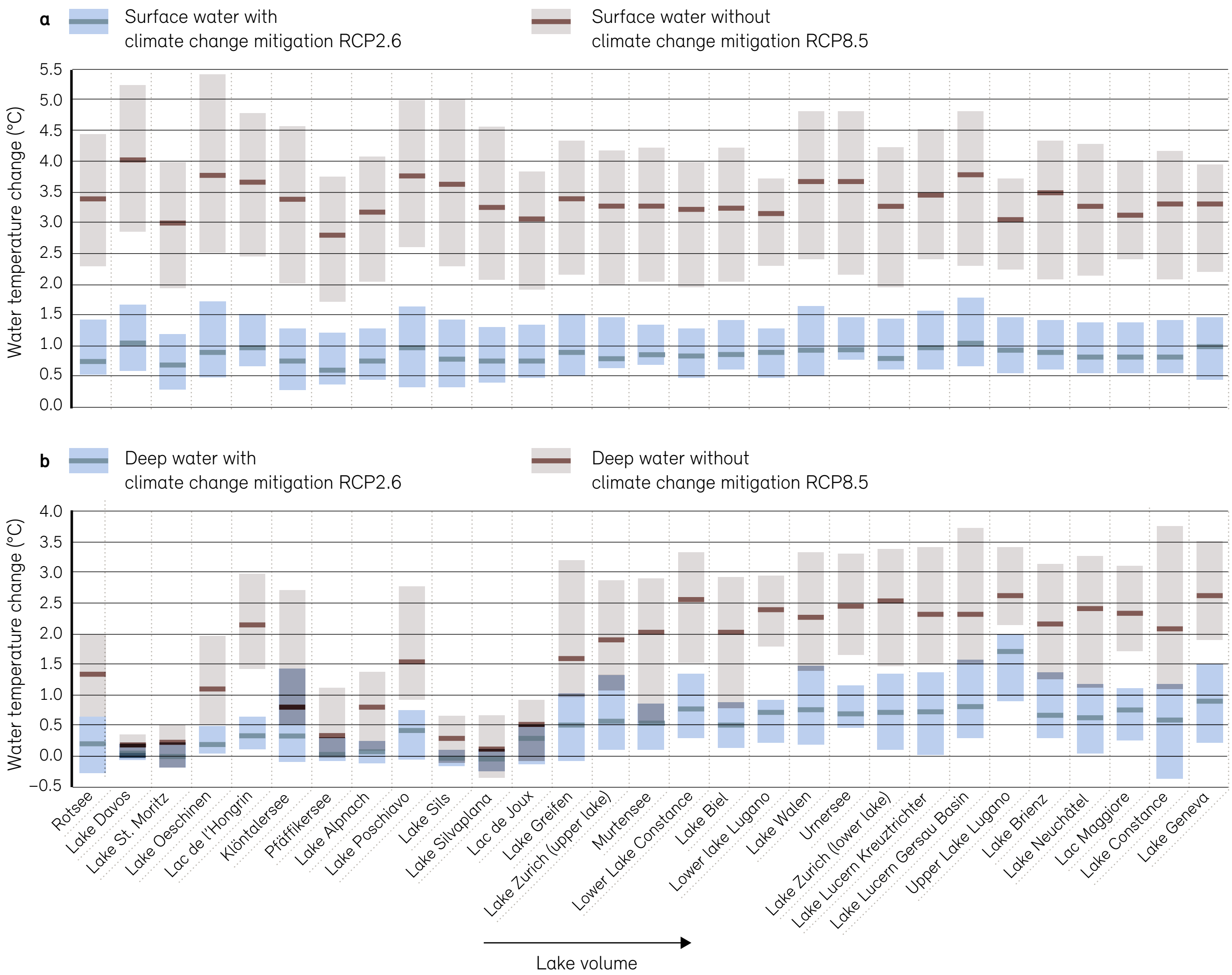
The temperatures and mixing processes in 29 lakes were computed using the one-dimensional physical lake model Simstrat continuously for the years 1981 to 2099 for the three scenarios with climate change mitigation (RCP2.6), with medium climate change mitigation (RCP4.5) and without climate change mitigation (RCP8.5). The selected lakes cover the elevation range from 200 to 1800 MASL and volumes from 0.004 to 89 km^3.

Sections 6.7.1 and 6.7.2 are based mainly on the results of the project.

Hydro-CH2018 project of the Lausanne Federal Technical University (EPFL), Laboratory of Cryogenic Sciences, the Institute of Aquatic Science Eawag, Applied Systems Analysis Research Group and the University of Lausanne, Institute of Earth Surface Dynamics

Figure 6-19: Water temperature scenarios for 29 Swiss lakes

Shown are the modelled changes in water temperature (median and range of uncertainty) at the end of the century (2071–2099) (a) on the surface (down to 1 m depth) and (b) on the lake bottom (1 m above bed) compared with the reference period (1981–2010). The scenarios with (RCP2.6) and without climate change mitigation (RCP8.5) were considered. The lakes are shown in order of volume. The surface water temperature will increase in all the lakes. Warming of the deep water is dependent on the mixing regime of the lake.



Source: Own graphic based on Råman Vinnå et al. (2021)

Lakes which mix twice a year internally (in autumn and spring) and develop winter and summer stratification in between are classified as having a dimictic regime. A layer of ice currently forms on these lakes in winter, but the initial reaction to the continuing warming of the climate is that ice is no longer formed. Then the winter stratification disappears, and the lake only mixes once, becoming monomictic. If the lake warms further, then – depending on its characteristics such as depth and wind exposure – full annual mixing may continue to occur annually, or only every few years (oligomictic) or in extreme cases may cease altogether, if additional stabilisation of the water column occurs due to dissolved substances (meromictic).

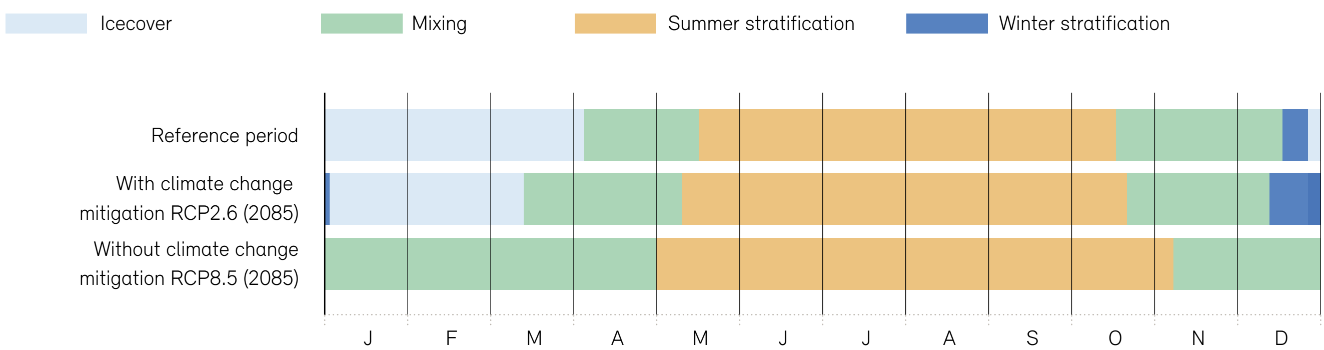
The way in which the mixing regimes of lakes change depends on both their elevation and their other characteristics such as lake morphology and wind exposure. Lakes at higher levels (e. g. Lake Silvaplana) and small lakes at low levels (e. g. Lake Alpnach) remain dimictic in all the climate scenarios, but with much shorter winter stratification and reduced or total absence of icecover. The unchanged mixing regime means that these lakes only have slight increases in deep water temperature. However, the loss of ice can result in the summer stratification being prolonged and the warming of the surface stratum being greater in these lakes than would be expected merely due to the higher air temperature.

Medium-sized lakes at medium elevations which are currently covered regularly with ice, such as Lac de Joux (Figure 6-20) and the Klöntalersee, will become fully or partly monomictic, depending on the climate scenario, and will largely lose their ice cover, at least in the scenario without climate change mitigation. The same applies to medium-sized lakes at low levels, such as the Pfäffikersee, on which even today icecover rarely or never forms. In the scenario without climate change mitigation (RCP8.5), the models indicate a shift to a monomictic regime for seven out of eight dimictic lakes in the distant future. In the scenario with climate change mitigation (RCP2.6), only three of the eight are affected.

Larger lakes at low levels are already monomictic or oligomictic and will generally remain in that state, but their deep water temperature will increase more than in the dimictic lakes. Interestingly, the simulations for most of these lakes do not show a clear change in mixing frequency. However, there is quite considerable uncertainty in the prediction for depth and frequency of mixing in the case of lakes on the threshold between monomictic and oligomictic. A decrease in mixing has already been observed in recent decades in some lakes (e.g. Lake Zurich; North et al. 2014), but not in others (e.g. Lake Geneva, Schwefel et al. 2016). On Lake Constance, reduced mixing has been observed in very warm winters (Straile et al. 2010), but no clear trend over 30 years (Rhodes et al. 2017). Less frequent mixing reduces the oxygen supply to the deep water, with significant ecological consequences (Section 6.9.1). It is therefore important to keep the development of mixing depth and frequency in these lakes under close observation (Gaudard et al. 2019).

Figure 6-20: Change in seasonal stratification and icecover on Lac de Joux

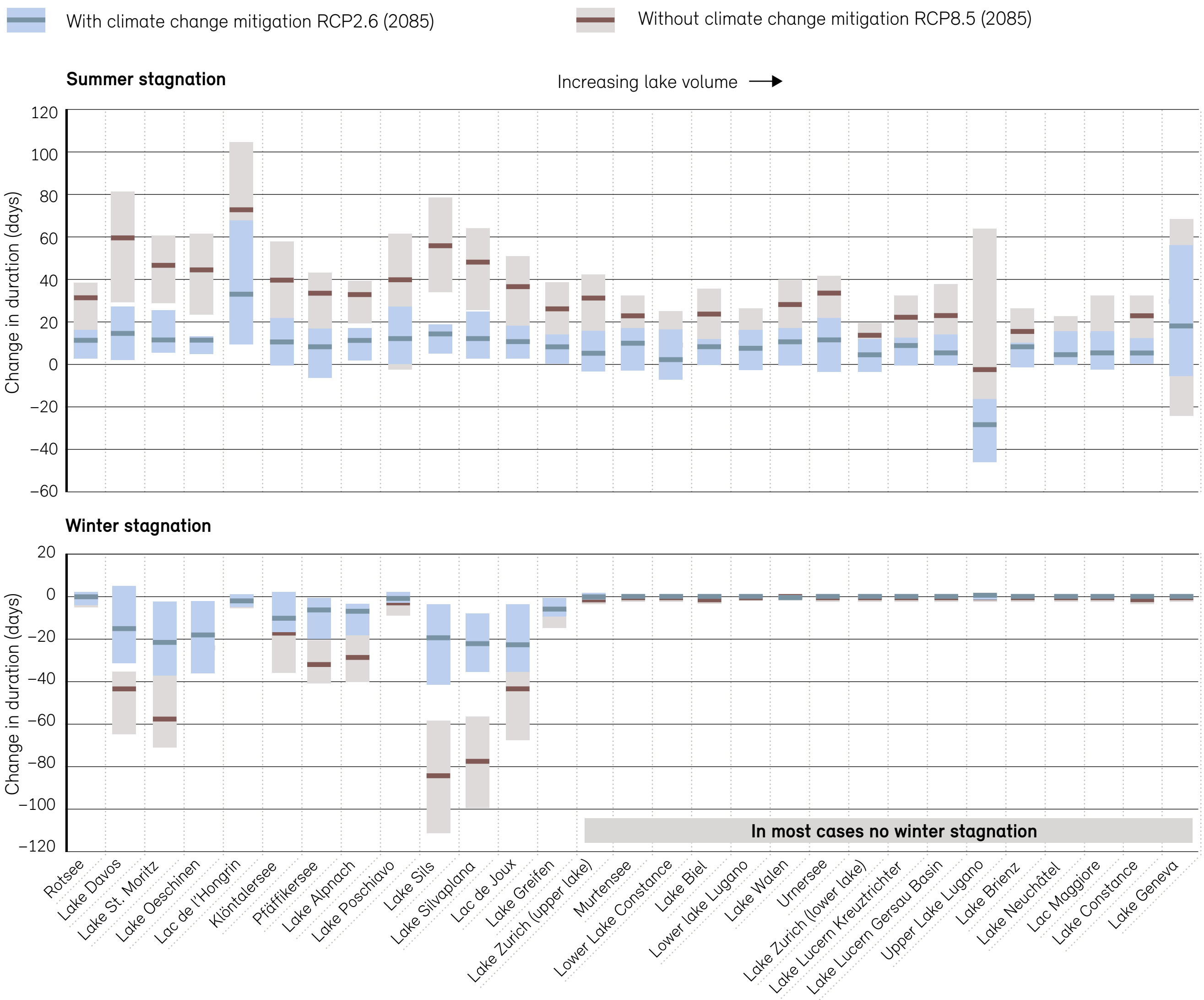
Shown is the modelled median occurrence of icecover, mixing and summer and winter stratification over the course of the year for the reference period (1981–2010) and scenarios with (RCP2.6) and without climate change mitigation (RCP8.5) by the end of the century (2071–2099). With climate change mitigation, the duration of the icecover is shortened and without climate change mitigation ice no longer forms on the lake in winter. The period of summer stratification is extended, particularly in the scenario without climate change mitigation, by around 40 days. Without climate change mitigation the lake changes from a dimictic mixing regime with mixing in spring and autumn to a monomictic one with mixing in wintertime only.



Source: Own graphic based on Råman Vinnå et al. (2021)

Figure 6-21: Change in the summer and winter stratification period in 29 Swiss lakes

Shown are median and range of uncertainty for the change in the duration of stratification in summer (top) and winter (bottom) for the 29 lakes studied (in order of volume). The scenarios with (RCP2.6) and without climate change mitigation (RCP8.5) were calculated for the end of the century (2071–2099) compared with the reference period (1981–2010). In general, the stratification period increases in summer but reduces in winter. The simulated changes are greater in smaller lakes. No change is expected in future for lakes for which the model predicts – in most cases – that winter stratification has already ceased during the reference period.



Source: Own graphic based on Michel et al. (in prep.).

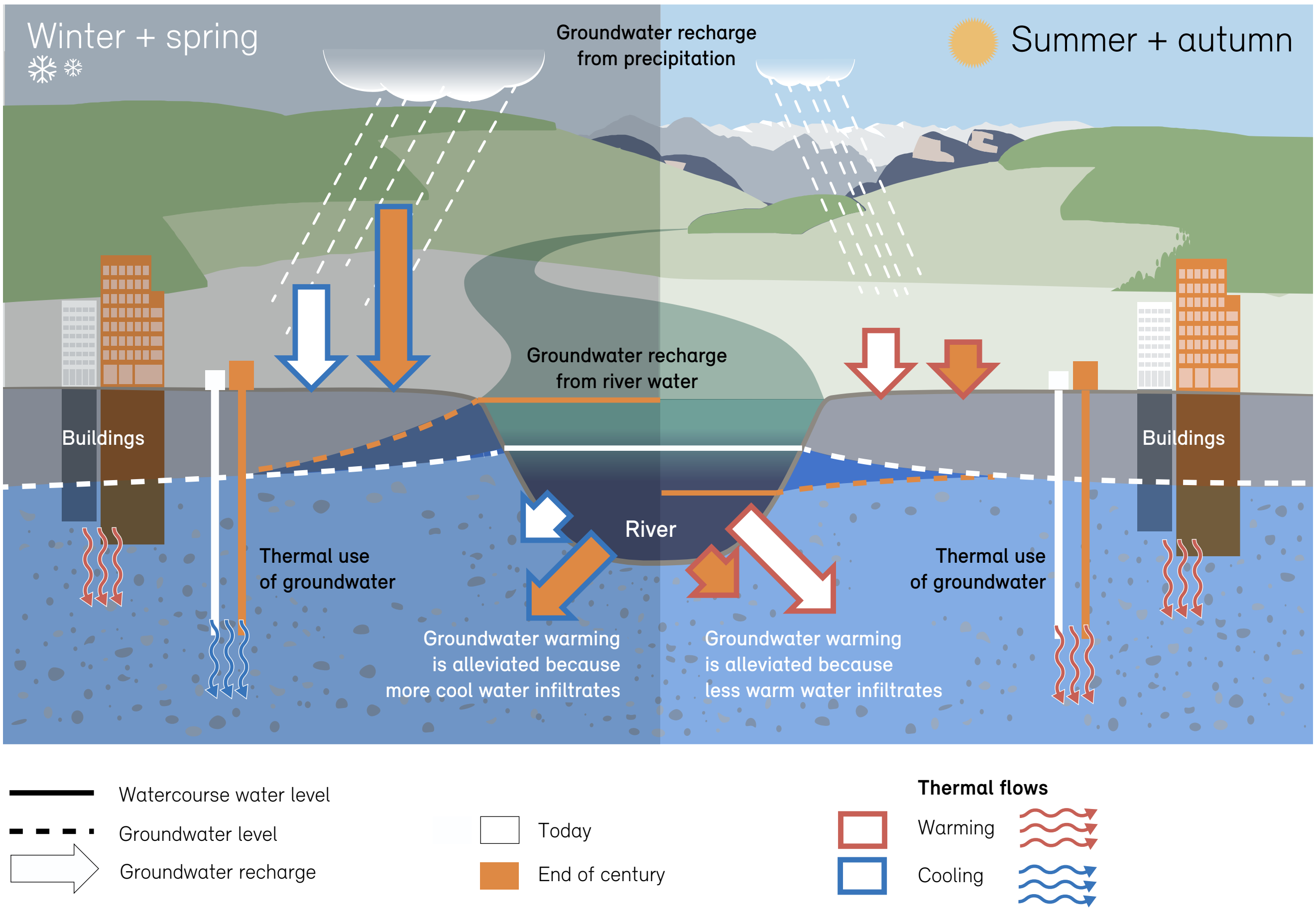
6.7.3 Groundwater

Throughout Switzerland, no clear indications of warming have yet been detected in groundwater – in contrast to the surface waters. However, groundwater temperature has already increased significantly in urban areas due to human activity. Wide local variations in groundwater temperature will continue in the future.

The temperature of groundwater reacts much more slowly to climate change than that of surface water. It varies in place and time and is dependent on the annual average temperature of the air, hydrogeological conditions, groundwater recharge processes and anthropogenic influences. If groundwater near the surface is recharged by precipitation, its temperature is determined by the temperature of the air, precipitation and soil. If the recharge is from river water infiltration, the groundwater temperature is largely determined by the river water temperature. The groundwater temperature is also subject to significant anthropogenic effects from thermal use (abstraction for heating or cooling) and infrared radiation from buildings near groundwater in urbanised regions (Epting et al. 2017).

Figure 6-22: Warm and cold inflows to groundwater

Shown are warm and cold inflows in the course of groundwater recharge for medium-sized and small aquifers in the valleys at lower levels in Switzerland, e. g. along the Birs, Suze and Eulach. Groundwater recharge from cool water will increase in winter, whereas recharge from warm water in summer will decrease. These negative feedback effects delay the increase in groundwater temperature due to climate change. The anthropogenic heat input will increase, however.



Source: Own graphic after Epting et al. (2020)

Temperature development of Swiss unconsolidated rock groundwater bodies: What are the main factors driving the temperature development of groundwater resources and how will the groundwater temperature develop in future?

Method

For 35 aquifers in five regions of Switzerland (Basel-Stadt, Basel-Landschaft, Biel, Winterthur and Davos), the impact of climate change on groundwater recharge and temperature was studied in detail and key representative parameters were obtained (e. g. aquifer geometry, storage characteristics and groundwater recharge rates and retention times). Firstly, groundwater resources in urban areas were simulated in 3*D* heat transport models with high temporal and spatial resolution. Secondly, and in collaboration with the EPFL using the Alpine3*D* model, precipitation and flow development and the change in temperature were evaluated for the three emission scenarios – with climate change mitigation (RCP2.6), with medium climate change mitigation (RCP4.5) and without climate change mitigation (RCP8.5) – for the 35 aquifers. The analyses enabled to define the sensitivity of groundwater temperatures in connection with the basic groundwater recharge processes for different future emission scenarios.

Main results

- The impact on groundwater temperatures is associated mainly with seasonal shifts in its recharge. For instance, a shift in precipitation and flood events from the summer to the winter months results in an increase in groundwater recharge at comparatively 'cool' times of the year.
- In urban and shallow groundwater resources with a shallow water table such as in Davos, groundwater temperatures are expected to suffer a greater impact. In contrast, changes in the temperature of groundwater resources which are deep, such as in Biel, or where the water table is very deep, such as Winterthur, are expected to be less pronounced and to occur over long observation periods.

The conclusions about the future in sections 6.4 and 6.7.3 are based on the results of the project.

Hydro-CH2018 project of the University of Basel, Applied and Environmental Geology Research Group

Delayed increase compared with air temperature

In the 2000–2016 period, half the 65 monitoring stations in the National Groundwater Monitoring Programme NAQUA saw an increase in groundwater temperature. A cooler temperature was only recorded at a few stations (Schürch et al. 2018). However, the 15-year analysis period is comparatively short. The increase in average annual air temperature predicted by the climate scenarios has an impact on groundwater temperature, but with a temporal shift. The deeper and larger an aquifer is, the more slowly it reacts. However, the warming trend is alleviated by the fact that groundwater recharge will occur increasingly at cooler times of the year. This also applies to recharge from watercourses, because the majority of the infiltration will take place in winter due to the expected reduction in summer flow. Added to this there will be a higher proportion of melt water initially (Epting et al. 2020). The extent to which these negative feedback effects can counteract or reduce the warming depends predominantly on local conditions such as elevation, type of groundwater recharge etc. (Figure 6-22).

Substantial increase in groundwater temperatures in urban areas

The direct anthropogenic influences will also dominate the groundwater temperature in urban areas in future (Epting and Huggenberger 2013). Data from different monitoring stations in Basel show that the groundwater temperature increased by 3.0 ± 0.7 °C in the 1993 to 2016 period alone. In highly urbanised regions the groundwater reached temperatures of up to 18 °C (Epting et al. 2020 and 2021). Due to climate change, the cooling requirements of households, industry and commerce are growing, particularly in the cities, which means that greater thermal use of the subsurface can be expected, mainly for cooling. This is compounded by the waste heat from underground structures which will also increase due to the expansion of built-up areas, leading to a further rise in groundwater temperatures in the cities.

Further information and references on 'Water temperature'

- Epting J. et al. 2020. Ist-Zustand und Temperatur-Entwicklung Schweizer Lockergesteins-Grundwasservorkommen. Hydro-CH2018 report.
- Michel A. et al. (in prep.): Water temperature in lakes and rivers. Hydro-CH2018 report.
- Michel A. et al. 2019: Stream temperature evolution in Switzerland over the last 50 years.
- Råman Vinnå L et al. 2021: The vulnerability of lakes along an altitudinal gradient to climate change.

6.8 Substances in water

Climate change is altering the transport of pollutants and nutrients and their concentration in the water. The availability and transport of sediment is increasing, especially in the mountains.

6.8.1 Pollutants and nutrients

Biochemical reactions are accelerated by the warming of the climate, causing pollutants to decompose more quickly. Increases in heavy precipitation and droughts can also result in higher pollutant and nutrient inputs into the water as well as in higher concentrations.

Surface water and groundwater contain dissolved or suspended substances. The pollutants and nutrients which are currently problematic in terms of water quality consist mainly of localised inputs from the urban drainage system and diffuse inputs from agriculture, residential developments and traffic. Climate change affects both the anthropogenic sources and the biological, chemical and physical transport and transformation processes taking place in the environment and the water bodies.

Change in nutrient and pollutant sources

The influence of climate change on the nutrient and pollutant sources is expected to be mainly indirect through adaptation measures in agriculture. The vegetation period is lengthening, different crops and varieties are being cultivated, irrigation will increase and harmful organisms and plant diseases will be different. Effects on the plant protection products and fertilisation practices used are also involved. Furthermore, regulatory measures such as substance authorisation, the economic framework and agricultural policy have a significant influence on the nutrient and pollutant sources.

Acceleration of biochemical reactions

Pollutants and nutrients are degraded and transformed on the plant, in the soil and in the groundwater. These processes are taking place biologically through microorganisms or by means of chemical reactions. Biochemical reactions are affected by the temperature and availability of water and oxygen. A temperature increase of 2 to 4 °C typically accelerates the reactions by 10 to 40% (Davidson and Janssens 2006), as long as the optimum temperature of the microorganisms involved is not exceeded. An increase in the soil moisture also promotes faster reactions in the soil, as long as it is not too wet and still contains sufficient oxygen (Schlesinger et al. 2015). The temperature increase and the higher CO_2 levels in the atmosphere also accelerate growth in some plants, increase nutrient absorption and encourage soil bacteria activity (Hagedorn et al. 2018).

Climate change will therefore tend to accelerate the decomposition and transformation of pollutants and nutrients in the soil and groundwater. Generally speaking, faster pollutant decomposition has a positive effect on water ecology, unless problematic, highly mobile degradation products are formed and enter the water at an accelerated rate. While the acceleration of the decomposition processes is unambiguous in the cold months of the year, these are decelerated in summer by the expected reduction in soil moisture and the more frequent droughts and heatwaves (Schlesinger et al. 2015). This slowdown varies considerably by region, soil and land use (Benateau et al. 2019).

Climate change will intensify substance transport into water bodies

The increase in heavy precipitation expected due to climate change will lead to more surface runoff, preferential water flow in the soil and soil erosion. Due to these hydrological processes, more plant protection products and phosphorus from agriculture and also eroded soil particles, microplastics from tyre wear and other pollutants from roads and impermeable surfaces will be discharged into the water. Climate change thus intensifies the transport of both natural particles and pollutants and nutrients.

Another problematic substance, particularly for drinking water, is nitrate. Surplus nitrate which plants cannot absorb during the vegetation period is transported from soil to groundwater as it recharges, mainly in winter. As groundwater recharge in winter increases, the potential for nitrate transport will also rise. In a scenario without climate change mitigation in the Broye region for example, a 44% increase in winter nitrate leaching into groundwater is expected, whereas according to that study, summer nitrate leaching would fall by 25% (Zarrineh et al. 2020). The increased winter nitrate leaching is undisputed, but the situation in summer is less clear. If the crops can absorb all the nitrate, it will not leach out. Depending on management methods, nitrate leaching could also increase in summer, for instance if the increase in droughts shortens the growing period or reduces productivity, so that the plants absorb less nitrate. There would then also be surplus nitrate in the soil in summer which could be washed out either during heavy summer rainfall or later in the following autumn and winter (Hunkeler et al. 2020).

Less dilution at low flow

Because runoff decreases significantly in late summer and autumn, the treated waste water discharges from industry and settlements are less diluted in those seasons. This results in higher pollutant concentrations in the watercourses, due for example to micropollutants from medicines and cosmetics, which can be problematic for many aquatic species. The smaller the watercourse, the more critical is the discharge of municipal wastewater for the chemical water quality. The upgrades initiated at around 140 wastewater treatment plants to add an additional treatment stage will counteract this impact from micropollutants. Treated waste water discharge also increase the channel flow, which can have a positive effect on the water ecology during droughts.

6.8.2 Sediment

With the thawing of the permafrost and the increase in heavy precipitation, more sediment will be mobilised in the Alps. How sediment transport will then change in the major rivers is not yet fully understood, as it depends mainly on the development of flood discharges.

Sediment refers to pebbles, gravel, sand, silt and clay transported in a water body during high discharges. As a result of the thawing of the permafrost and melting of the glaciers, more sediment is available in the mountains and can be mobilised during heavy precipitation events. The increase in heavy precipitation is leading to more mass movements and higher discharge in the torrents and therefore to greater erosion. Climate change is causing greater sediment discharge from torrents into the valley rivers and more sediment deposition into the flatter valley rivers, deltas and lakes (Figure 6-23). As sediment is retained by lakes, climate change has little effect on the amounts in rivers below lakes, but its discharge can lead to increased silting problems in lakes, which causes a particular difficulty in reservoirs.

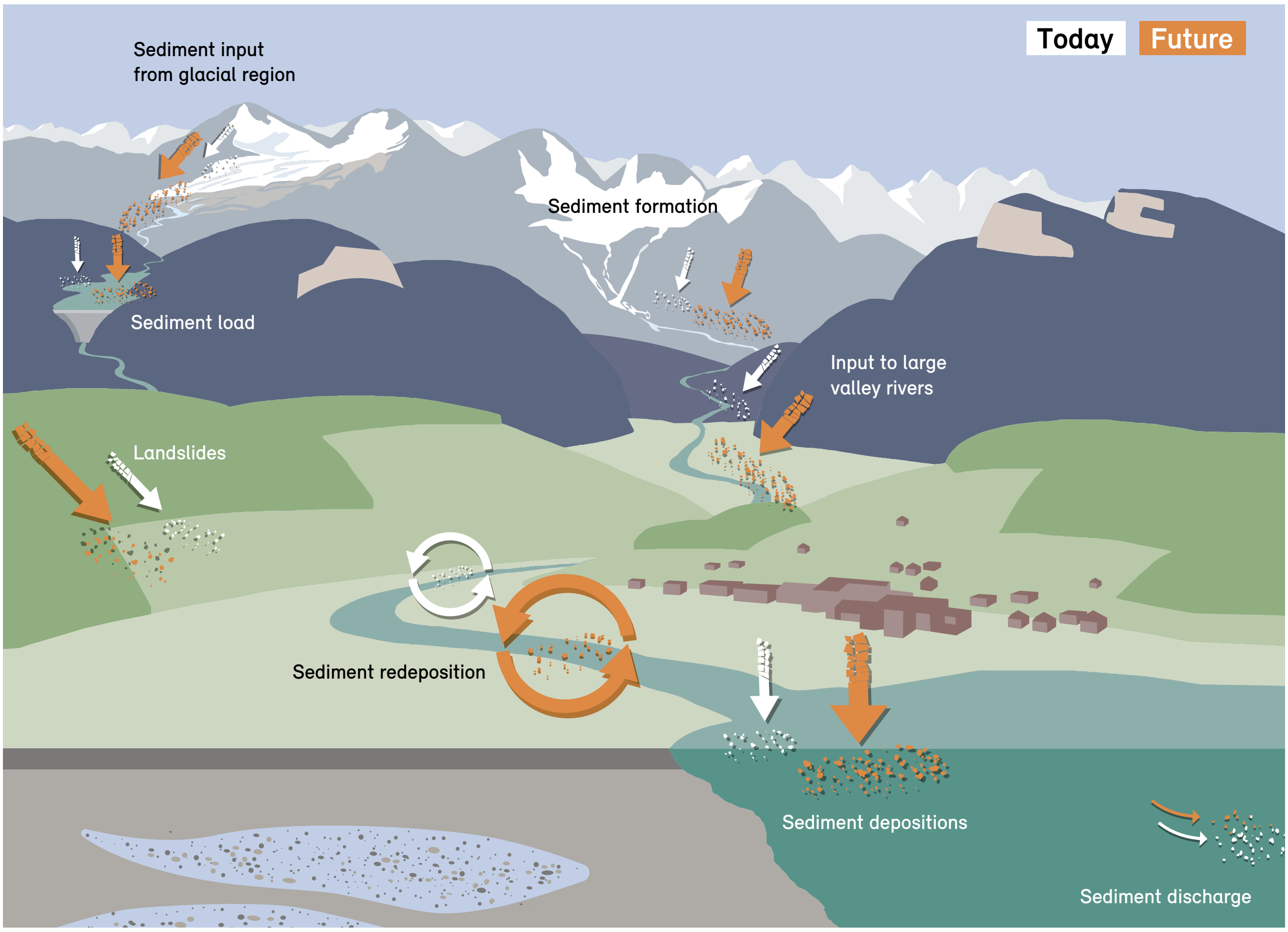
A minimum flow is necessary for sediment to be transported in the channel. The larger and heavier the sediment, the higher the minimum flow must be. Since the seasonal flow distribution will change, the times of the year with sediment transport will also change and it will tend to increase in winter. This can have negative impacts on fish populations (Section 6.9.2). Sediment redistribution in the watercourses will also increase (Speerli et al. 2020). The largest volumes of sediment will be transported during flood events, and there is some uncertainty about their future development. However, there are indications that flooding will increase (Section 6.5).

The amount of suspended matter (e.g. silt and clay) in the water will increase and its transport will occur more frequently. Pollutants such as heavy metals and organic compounds can attach themselves to suspended particles and be carried along with them. Even without pollutants, excessive levels of suspended matter can have negative effects on aquatic organisms. The changes in suspended particle transport therefore have a direct impact on water quality and ecology (Binderheim and Göggel 2007).

Sediment transport controls the creation of habitats in and along water bodies. For example, fine sediment on the foreshore is an ideal nutrient base for deciduous riverside forests. Redistribution of gravel banks increases their permeability to water and air and generates

Figure 6-23: Schematic representation of the changes in sediment transport in an example of a water system in the mountains

The formation and the transport of sediment will increase due to climate change.



Source: Speerli et al. (2020)

new habitats in the water (FOEN 2017b). The exchange between groundwater and river water is also affected by sediment transport. Accretions or deposition of fine sediment resulting in channel bed sealing can reduce water exchange, whereas it is increased by channel erosion or redistribution of the bed during floods. Climate change and the resultant sediment transport changes have both positive and negative effects for water quality and ecology (FOEN 2017b).

Further information and references on 'Sediment' and substances in water

- Benateau S. et al. 2019: Climate change and freshwater ecosystems: Impacts on water quality and ecological status. Hydro-CH2018 report.
- Speerli J. et al. 2020: Auswirkungen des Klimawandels auf den Sedimenttransport. Hydro-CH2018 report.

6.9 Water ecology

Climate change magnifies the stress already experienced by aquatic ecosystems. Many species cannot adapt to higher water temperatures – or only to a limited extent. Other changes such as drying of watercourse sections and changes in stratification in lakes can disturb the equilibrium of ecosystems. They also encourage the spread of invasive species.

6.9.1 Effects on habitats and the ecosystem

Short-term extreme weather events and longer-term climate developments both affect the aquatic habitats and ecosystems. For instance, connectivity between the water bodies deteriorates and habitat diversity tends to decrease.

Springs, watercourses, lakes, riverside forests and wetlands accommodate a multitude of habitats and species (FOEN 2017a). Globally, huge numbers of fresh water species are being lost (IPBES 2019). Some reasons for this are the destruction of water bodies, water correction and control structures, water pollution, over-abstraction, fishing and hunting of endangered species, the spread of invasive species and the effects of climate change. The situation in Switzerland mirrors these developments.

Aquatic organisms are adapted to specific habitat conditions including water temperature, flow rate, depth, structure, chemistry etc. Specialist species can only tolerate small variations in the habitat conditions and live in ecological niches. Generalists are less discriminating and can survive in a broad spectrum of habitats. The aquatic organisms studied here are fish, macroinvertebrates larger than around 1 mm, such as crabs, insects, molluscs and phytoplankton (e.g. diatoms, algae and cyanobacteria) and zooplankton (small animal organisms floating freely in the water).

Change in local habitat conditions

Climate change affects the habitats and ecosystems in the Swiss water bodies in various ways. It primarily changes the local habitat conditions directly, mainly through the rise in water temperature, the seasonal shift in runoff and the altered mixing regimes of the lakes. By these effects, it removes the ability of the organisms to survive locally if, for example, the new local conditions do not provide them with an ecological niche (Benateau et al. 2019).

Increasing disturbance

Climate change can also upset the balance of the aquatic ecosystem through the increase in temporary disturbances such as heatwaves and drought. If specific tolerance levels are exceeded, drastic changes can occur in some cases in a short time. During heatwaves in recent years, for instance, numerous water sections dried out or the water temperatures rose above the tolerance threshold for coldwater fish species (see also Figure 6-26). In summer 2003 the 25 °C mark was exceeded in the Rhine for a prolonged period for the first time, as a result of which most of the grayling stocks died. And in summer 2018 many cantons reported fish and crab fatalities. The drying of water sections can be fatal for macroinvertebrates as well as fish.

Reduced connectivity

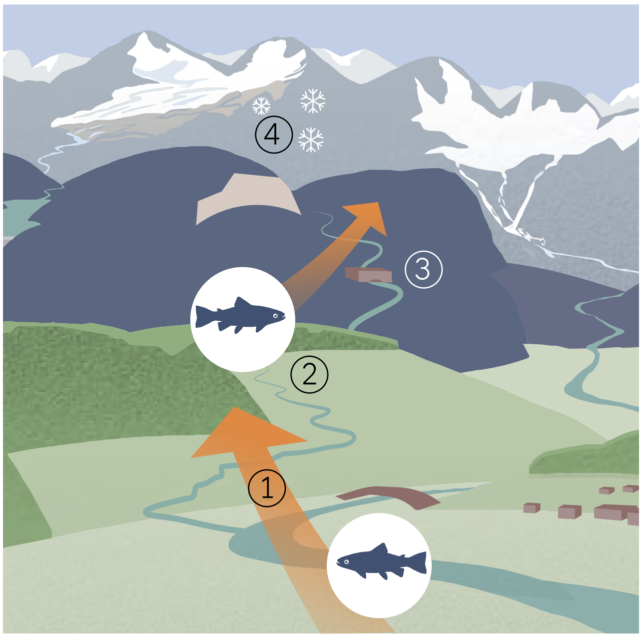
Climate change reduces the ecological connectivity along the watercourse, particularly if it runs dry for the first time or more often or becomes too warm. Good connectivity is important for the survival of many species in response to climate change (Altermatt et al. 2013). For example, when water warms, some species move their habitat to cooler stretches of water, which tend to be at higher elevations, if the two are connected. But they can only relocate if those habitats do not just meet their thermal requirements, they must also supply all the other habitat requirements (Figure 6-24). For instance, cold-water graylings cannot just move their habitat up to higher regions, because they are not adapted to the flow conditions in fast-flowing torrents. Similarly, fish in lakes may not be able to escape to the cooler deep water, for instance because little food is available. Even if a suitable alternative habitat is available for a species, it cannot always be reached. The route may either be too long or arduous, or natural or man-made obstacles to migration may make it impassable (Section 7.3.3).

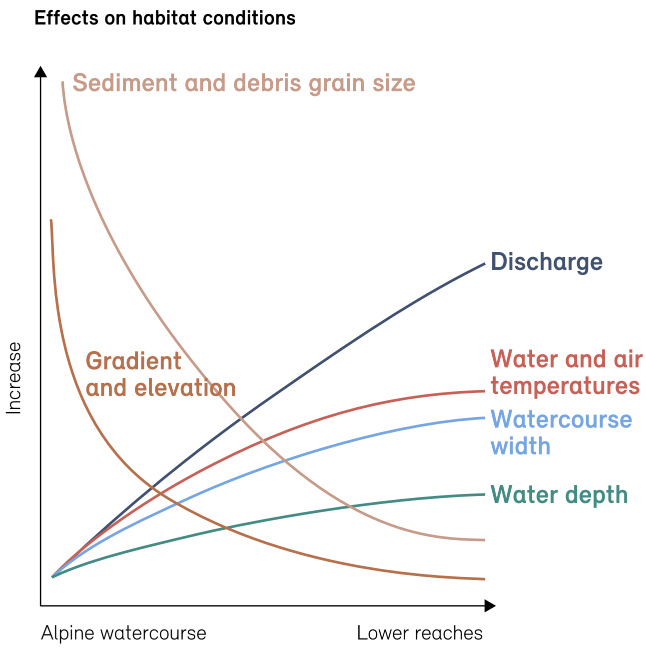
Change in phenology

Climate change also significantly alters the phenology, which is the time when specific development processes

Figure 6-24: Connectivity in the context of changed habitat conditions

For species and habitats to relocate, they must be able to manage the route (1) to the higher level habitat (2) and it must be free from obstacles to migration (3). Relocation is limited, because habitat conditions change considerably with elevation (4 and right).





Source: after Benateau et al. (2019)

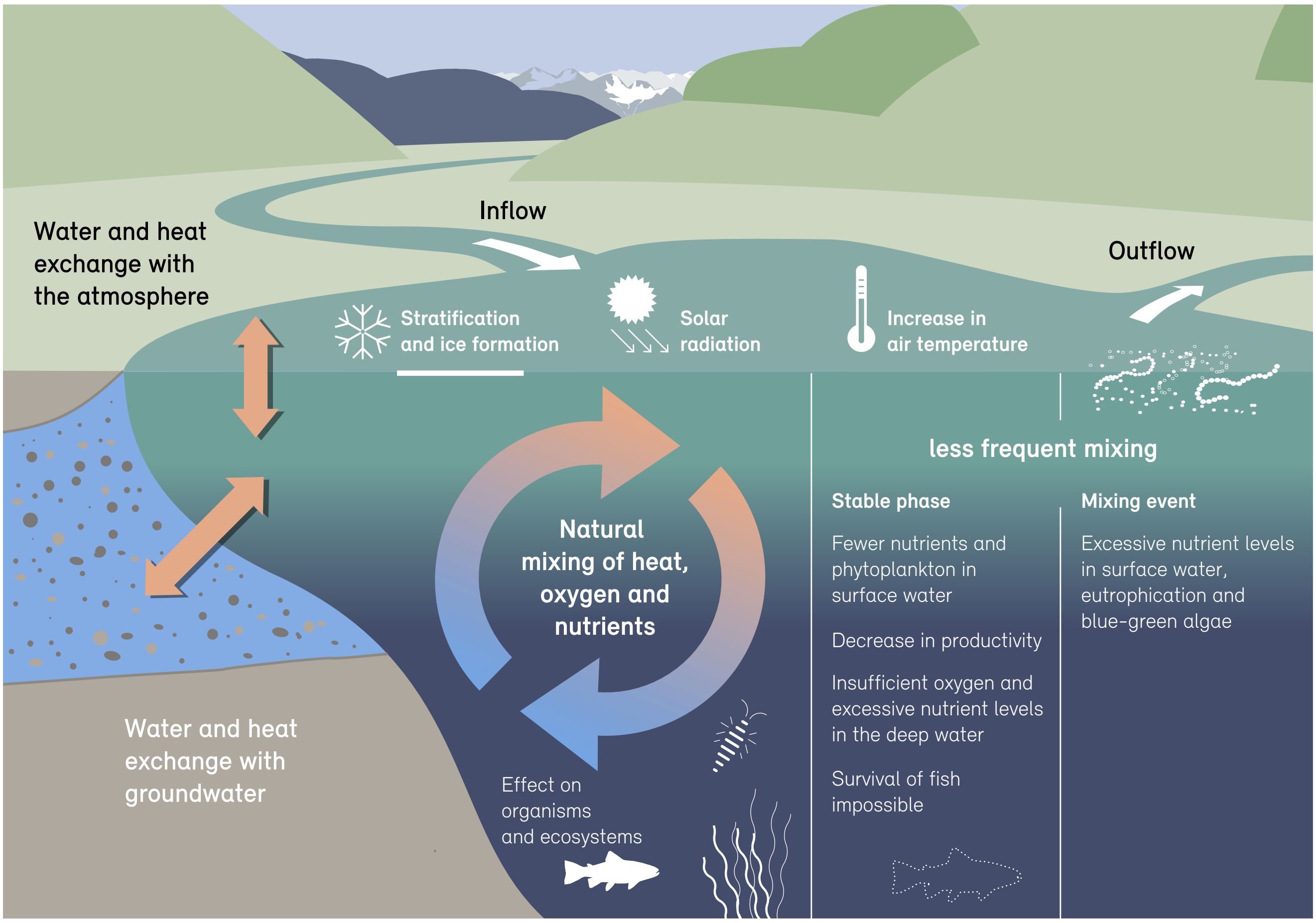
occur over the year (Altermatt 2010). Due to the rise in temperature, earlier hatching of aquatic insects and an earlier onset of spring blooms in phytoplankton and zooplankton have already been observed (e. g. Everall et al. 2015). The interactions between different species within an ecosystem can also be perturbed. If it is not possible for organisms higher up in the food chain – such as fish, birds or mammals – to adapt the timing of their development processes to the new nutrition resources, they will lack the food supplies necessary to rear their young and see them develop. These effects of climate change across several levels of the food chain are complex and operate on long-term time scales (e. g. Van Asch et al. 2013).

Consequences for the watercourse ecosystems

The diversity of habitat conditions is generally declining in the alpine watercourses due to the rise in water temperature and the reduction in melt water. Diversity can also increase locally, e. g. where previously there were glaciers (Benateau et al. 2019). Habitat homogenisation may enable generalists from lower elevations to colonise these waters, but the specialists previously living there will be displaced. There may be a species increase locally, but regionally a reduction in biodiversity and homogenisation of habitats is expected due to the disappearance of many ecological niches and specialists (Brown et al. 2007). If the glaciers melt due to the continued advance of climate change and alpine watercourses then dry out more frequently, the generalists will also suffer (Rolls et al. 2017).

Figure 6-25: Important processes in lake ecosystems which can be altered by climate change

A very serious impact on the lake ecosystems is caused by changes in the mixing regime, i. e. if a lake mixes less frequently, less deeply or not at all.



Source: Own graphic after Gaudard et al. (2017)

At lower elevations, a distinction must be made between small and large watercourses. Small watercourses can be expected to dry out more often in summer, leading overall to a reduction in biodiversity (Soria et al. 2017). It is still unclear how biodiversity will change in the larger watercourses, as the effects on the different species are very variable.

Consequences for lake ecosystems
The ecosystem of a lake is strongly characterised by the temperature-dependent seasonal stratification of the water. In some lakes, climate change stabilises this stratification and leads to less seasonal mixing (Section 6.7.2). This reduces the exchange of nutrients and oxygen between deep and surface water. The consequence can be a lower oxygen concentration in the deep water, as has already been observed in large lakes (Lakes Geneva, Constance, Zurich, Lugano, Maggiore). In extreme cases, species such as fish can no longer live at the depths affected. The absence of mixing leads to the deep water being enriched with nutrients which are no longer transported to the surface water. This can reduce the growth of phytoplankton and zooplankton in the surface water in nutrient-deficient lakes.

If mixing is restored after a long period of stratification, nutrient-rich deep water will be brought to the surface in a short time, which will greatly promote the growth of phytoplankton and zooplankton. The climate-related changes in the nutrient balance, oxygen content and plankton have an impact on the entire food chain and lake ecology. Cyanobacteria, commonly known as blue-green algae, are part of the phytoplankton and benefit from high temperature, nutrient-rich water. If nutrient levels are very high (eutrophic), cyanobacteria can multiply and can in some cases form toxic cyanotoxins in late summer – as has happened in 2020 in Lake Neuchâtel (harmful algae bloom HAB). This can then have an impact on the food chain in the ecosystem.

6.9.2 Effects on individual species and biodiversity

It is becoming harder and harder for specialist and cold-adapted (cryophilic) species to cope with the pace of climate change. Generalists and warmwater species are among the winners. In general, biodiversity is coming under increasing pressure.

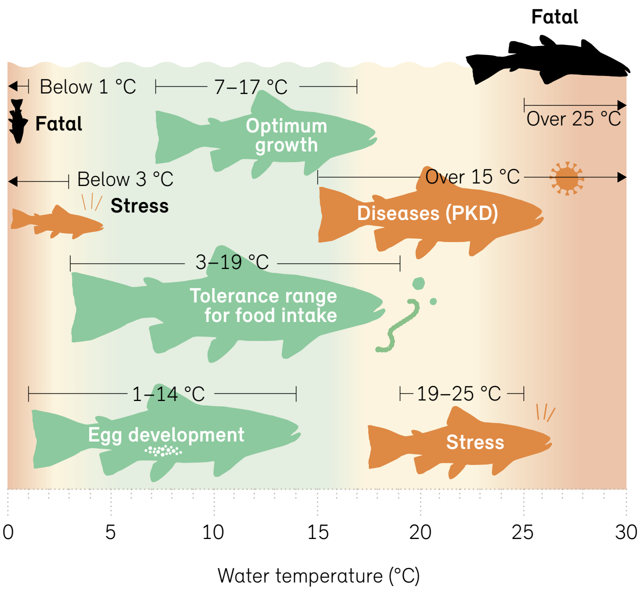
Climate change leads to more homogeneous habitats in watercourses and lakes (Benateau et al. 2019), species extinction and a loss of genetic diversity within species (Bálint et al. 2011). The effects on the species are explained below using various examples as impacts on biodiversity.

Example of brown trout
The example of the brown trout shows the impact of climate change on fish which are reliant on cool, oxygenated water (Hari et al. 2006). Their population has declined significantly in Switzerland in recent years (Borsuk et al. 2006). The water temperature controls not only the metabolism but also the migration, feeding and mating behaviour of coldwater aquatic organisms like the brown trout. The ideal water temperature range for the full life cycle of the trout is between 8 and 19 °C and it cannot survive above 25 °C (Burkhardt-Holm et al. 2002). Figure 6-26 shows the optimum temperatures and tolerance ranges of the brown trout for typical activities and stages of life. If a population already lives in water at a temperature close to its tolerance limit, then even a small further increase in temperature can result in local extinction. New competitive conditions are also created by the appearance of more warmwater species such as the chub. As the water temperature rises, parasitic diseases such as Proliferative Kidney Disease (PKD) become more common. PKD can cause high mortality rates in trout if the water temperature is over 15 °C for a prolonged period. As indicated in Section 6.7, these critical temperature conditions have occurred more frequently and in more and more watercourse sections in recent decades.

More frequent and severe flooding in winter and spring make the conditions worse for brown trout reproduction. From late October to early January it lays its eggs in spawning pits (redds) in the gravel beds of rivers and lakes, where the eggs and the newly spawned fish spend up to six months. Higher flow rates during flood events, particularly in watercourses with control structures, can damage the spawning pits and wash away the eggs or the young fry. The higher particulate loads faced by young fish and fry due to floods can also have negative consequences for the fish population (Burkhardt-Holm 2009). It is therefore important to keep the watercourses as natural as possible to ensure there are areas with lower flow rates. Connectivity with branch arms must also be maintained so that the trout can move into them to lay their eggs (Junker et al. 2015). Climate change also means that the egg development time of the trout is less and less compatible with the flow characteristics of the watercourse.

Figure 6-26: Thermal requirements of the brown trout

Shown are the temperature ranges in which the brown trout can best develop (green), is under stress (orange) or its survival is under threat (black). The trout is coming under increasing pressure due to the rising water temperature. Higher water temperatures cause stress and restricted activity and foster disease.



Source: Own graphic after Elliot (1994)

The example of the brown trout makes it clear how seriously fish are affected by climate change. Apart from causing warming, it also alters flow conditions, food supplies, sediment transport, water body structure and hatcheries and intensifies hazards such as competing species and new diseases. The combination of these effects places enormous stress on aquatic organisms, which future water protection can best counteract by reducing further stresses and maintaining or restoring natural watercourses.

Example of macroinvertebrates

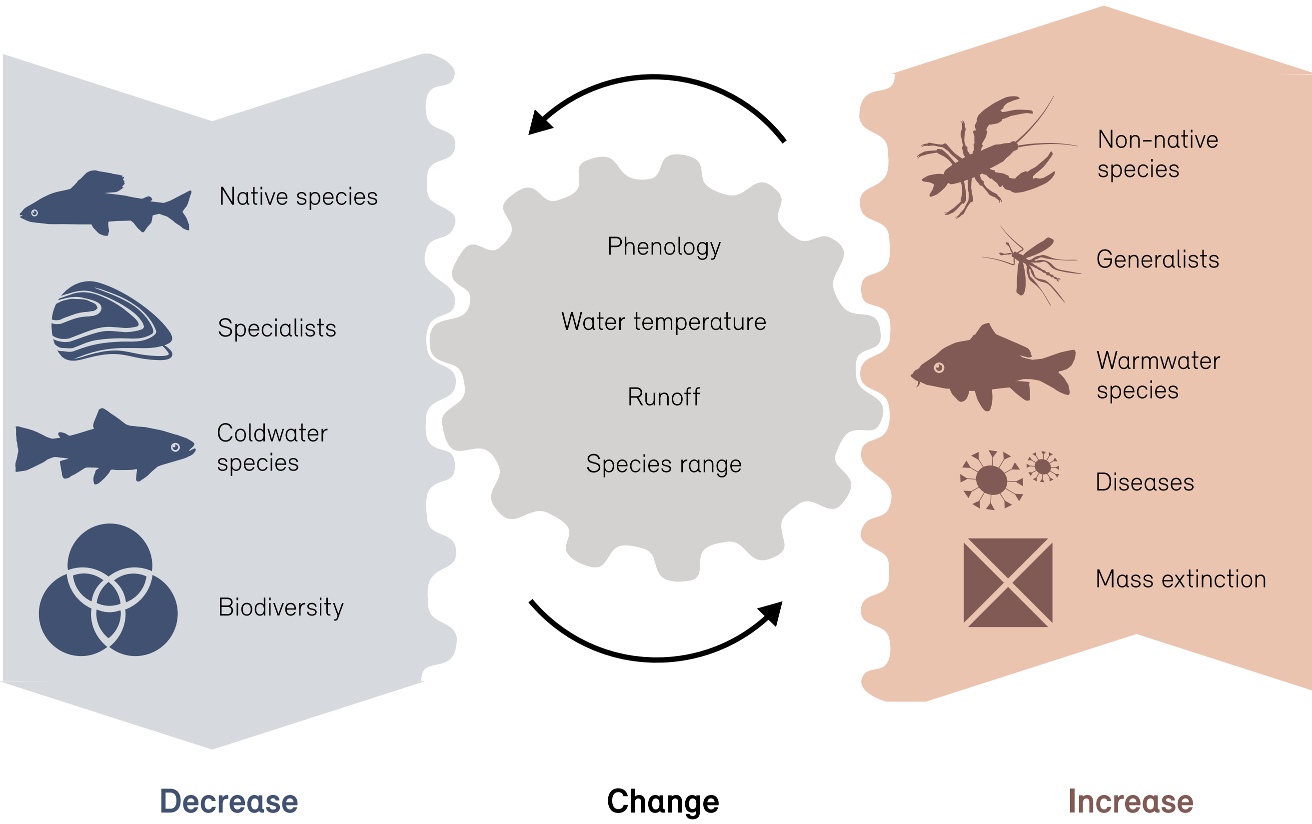
Macroinvertebrats react very quickly to changes in climate. The water temperature affects them very significantly (Rüegg and Robinson 2004) and it is in this group that considerable changes in species diversity and composition are expected (Jacobsen et al. 2014). Due to the temperature increase in Swiss standing water bodies, 11% of water beetle species and 33% of dragonfly species are threatened with extinction, although 63% of dragonflies can benefit from the elevated temperatures (Rosset and Oertli 2011). But even if a species does survive climate change, it will have far less genetic diversity. According to a study by Bálint et al. (2011), 67% of the macroinvertebrate species examined will survive, but with only 16-35% of the genetic variations within the species. The successful species live mainly at lower elevations and can extend their habitat to higher elevations, but the alpine species do not have this option and are therefore particularly badly affected. Other coldwater species such as many stoneflies are also at risk due to the warming of the climate. Increased sensitivity to pesticides has been observed in the common freshwater shrimp, which is widespread in Switzerland, when water temperatures are higher (Russo et al. 2018).

Reduced biodiversity

Although new and valuable habitats will be created locally, such as in glacier forefields due to the retreat of the glacies, habitats in general will become more similar because ecological niches disappear. The main sufferers will be highly specialised and cold-water species, whereas generalists and warmwater species will benefit (Figure 6-27). When climate change shifts the habitats of species, some can colonise higher elevation Swiss regions but others cannot. New non-native or even invasive species immigrate. These invasive species can compete with indigenous species and put them under even more pressure. The genetic diversity within the species will decrease. This is critical because the ability to adapt to new conditions can also decrease (Bálint et al. 2011). The long-term change in habitats combined with more frequent disturbance due to extreme events will bring about an increase in disease and mass fatalities. Until now, populations have generally been able to recover from extreme events, but this will become increasingly difficult as climate change progresses, until at some time a limit beyond which irreversible changes will occur is reached, culminating in extinction of a species (Harris et al. 2018). The functioning of an ecosystem is based on complex dependencies

Figure 6-27: Climate change winners and losers

Climate change alters the aquatic ecosystems and organisms in a variety of ways and results in a new species composition.



Source: Own graphic after Benateau et al. (2019)

between the species. Changes in one species can therefore weaken the stability and resilience of an entire ecosystem (Benateau et al. 2019). All these factors will lead to a further loss of species diversity (Urban et al. 2016).

Further information and references on 'Water ecology'

- Benateau S. et al. 2019: Climate change and freshwater ecosystems: Impacts on water quality and ecological status. Hydro-CH2018 report.

7 Water management

The results of the Hydro-CH2018 project show that climate change will intensify the pressure on management of the Swiss water resources. All three divisions of water management – water use, flood protection and water protection – are significantly affected by climate change. Measures already introduced are helping to prepare water management for the future climate. Further adaptations to climate change must follow.

7.1 Water use

Water is among the most vital resources for life and the economy. We need it as drinking water, for irrigation, for energy production and in industry. Water availability and the water demand for various uses will change.

7.1.1 Drinking water supply

The majority of drinking water supplies are obtained from groundwater resources, but these are already under pressure due to settlement development and diffuse substance inputs, particularly on the Swiss Plateau and in the main alpine valleys. More frequent and longer droughts pose further challenges for the water supplies.

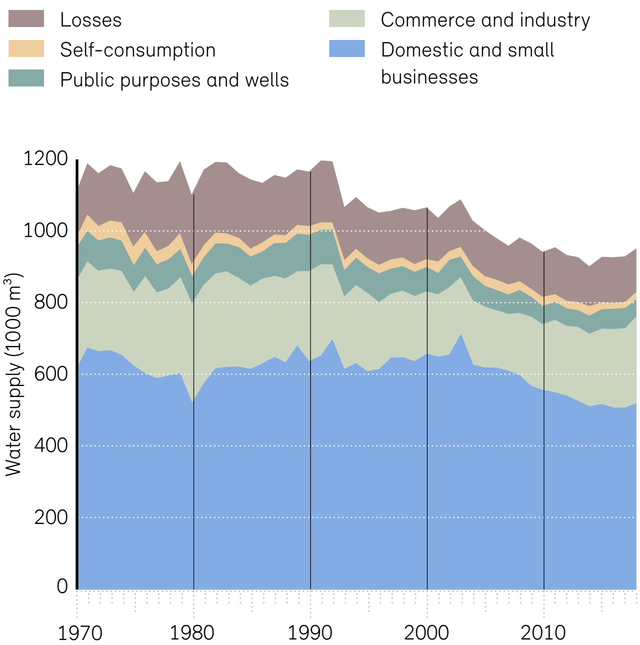
The drinking water supply of around 953 million m³ (2018) provides most of the water for domestic use and some for commerce and industry. Consumption has decreased slightly since the 1990s, but has begun to increase again in recent years (Figure 7-1). Some 80% of drinking water is obtained from groundwater (including spring water). It is extracted from some 18,000 groundwater wells in the public interest, i. e. they are used by the public water suppliers or the food industry. Most of the water can be fed into the drinking water system without treatment or after simple treatment methods. The other 20% of drinking water is obtained from treated lake water (SVGW 2020).

Effects of drought

As climate change progresses, summer and autumn discharge will be severely reduced, especially in Swiss Plateau and Jura rivers (Section 6.2, Figure 6-3) and droughts will increase. This will also affect the groundwater resources in an exchange process with the rivers and may reduce the groundwater volumes available (Section 6.4). During the droughts in 2015 and 2018, the water tables at around 60% of the NAQUA National Groundwater Monitoring stations were below average levels for months. Groundwater levels only recovered slowly after the 2003 drought, e. g. in the Upper Emmen and Lower Wigger valleys, because precipitation continued to be low in 2004 (Hunkeler et al. 2014). This shows that the drinking water supply must also adapt to temporary reduced availability. In some cases, the water supplies available for drinking water were reduced in the regions affected by drought in the past. Since Switzerland has adequate groundwater resources, even with climate change, the main challenges faced are protection of the groundwater necessary for drinking water and the distribution of the drinking water.

Figure 7-1: Development of water supply in Switzerland 1970–2018

Water supply is shown by use over time. Consumption has decreased slightly since the 1990s, but has begun to increase again in recent years.



Source: Swiss Gas and Water Association SVGW

Increased conflicts of use

In response to climate change, the demands on water, such as service water for agricultural irrigation, may intensify. If service water is obtained from groundwater, there is a danger that the resources locally available may be overused. To prevent these conflicts, it is essential to identify the groundwater resources and wells which are vital for the supply of drinking water. Their long-term operation must be guaranteed, i. e. including during periods of drought.

In connection with the energy transition, other applications are increasing, such as cooling water use and the use of groundwater for low-carbon, climate-neutral heating systems (heat pumps). The boreholes required for ground source heating systems can pose a risk of contamination of the groundwater. These boreholes should preferably be restricted to a few locations with large, professionally operated and maintained infrastructure.

Groundwater impairment due to diffuse pollutant inputs

A major challenge for the water suppliers is to supply water of sufficient quality. Nitrate levels exceed the limit in the water protection regulations for groundwater of 25 milligrams per litre at around 15% of the NAQUA National Groundwater Monitoring stations and at as many as 40% of stations in catchments dominated by arable farming (FOEN 2019a). At more than half of the monitoring stations, residues of plant protection products (PPP) or their decomposition products (metabolites) occur in the groundwater. The limit in the water protection regulations of 0.1 micrograms per litre is exceeded by PPP active ingredients at 2% of groundwater monitoring stations and by metabolites, to which the limit only partly applies, at as many as 20% of sites. In relation to the metabolites of the fungicide chlorothalonil, it is assumed according to the FOEN that more than half of the NAQUA monitoring stations on the Swiss Plateau are above the limit.[4] Harmful substances in groundwater pose problems for many water suppliers, if they do not have enough unpolluted replacement or mixing water to supply drinking water in the quality required under the food regulations. This situation becomes even worse during droughts, which will increase with climate change.

4 *www.bafu.admin.ch/chlorothalonil*

Climate change exacerbates quality problems in groundwater

In intensively farmed regions, good quality drinking water must be obtained increasingly from wells near large watercourses. Here, potentially polluted groundwater is diluted by river water infiltration. If streamflow is reduced during periods of drought, infiltration into the groundwater and consequently the dilution rate are reduced as well. The wells may then temporarily not be usable due to quality reasons, precisely at a time when water demand is highest.

During periods of low flow, the proportion of wastewater in watercourses from wastewater treatment plants (WTP) is higher. If this surface water infiltrates, higher concentrations of micropollutants and pathogens can enter the groundwater. Progressive climate change will result in more frequent droughts and will therefore have an indirect negative effect on the quality of groundwater resources near rivers and of drinking water wells on watercourses with a high proportion of treated wastewater.

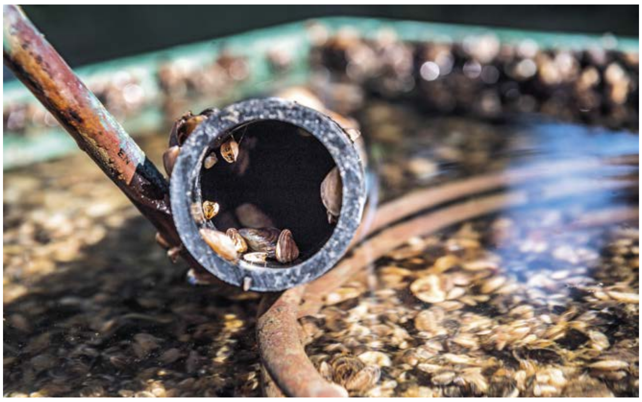
Possible consequences for drinking water abstraction from water bodies

For many large urban areas, lakes are important sources of untreated water, often in good quality and sufficient quantity – such as Lake Constance and Lake Zurich. A consequence of climate change can be the increased appearance in the lakes of previously non-native or rarely occurring organisms and other effects such as lack of oxygen at depth. Examples are toxic cyanobacteria and their constituents (Section 6.9.1) or the recent migrant to Lake Constance, the quagga mussel, which attaches itself to filter systems and the insides of water pipes (Figure 7-2). The existing drinking water treatment processes normally ensure that these organisms are trapped and harmful substances are removed, but this development must be carefully monitored and the treatment systems must be adapted if necessary.

As a result of the increase in extreme precipitation, untreated wastewater can enter watercourses from combined sewer overflows more often, unless counter – measures are taken. The levels of suspended particles in the water due to erosion, surface runoff and redistribution processes can also increase. For rivers, the costs for indirect use (e. g. groundwater enrichment with river water or

Figure 7-2: Problem organisms for drinking water supply

Toxic blue-green algae and the invasive quagga mussel in lakes can be a problem for drinking water supplies from lake water and can lead to higher costs for water treatment and maintenance of the infrastructure. Quagga mussels are up to 40 mm in size and cling fast everywhere.



Source: left: Andrea Stalder, Thurgauer Zeitung, right: © pegasosart, stock.adobe.com

the use of bank filtrates) for drinking water abstraction could rise in future if the water treatment plants have to operate more frequently under difficult conditions or be upgraded to accommodate new and more extreme conditions. Disinfection methods can only work safely and efficiently up to a certain particle level. Strategies to combat these impacts are already being studied and observed in the Greater Basel area, which is heavily dependent on water from the Rhine.

Water distribution

Other effects can occur in water distribution: Drinking water can warm significantly during heatwaves while being fed from the water works to the domestic user, particularly in exposed pipelines. This tends to encourage microbiological problems, and the cost of preventive maintenance to the pipes or of treatment and disinfection may rise. This impact will be compounded by the gradual increase in the temperature of the groundwater and surface water used, due to climate change.

Adaptation options

The water utilities have been well prepared for the droughts of recent years. Major supply problems have been prevented to date by taking supplies from adjacent utilities and from hydrologically independent drinking water resources (secondary pillar). But low water tables in dry years such as 2018 led widely to some precautionary appeals to save water. A few water suppliers also experienced shortages, some of them having to adopt emergency supply measures in six cantons (FOEN 2019b).

Strategies for adaptation to climate change

- Increase drinking water supply resilience in the face of shortages due to drought by: regional water supply plans, inventory of water wells, identification of wells that are vital for the water supplies, water supply networking, water abstraction from two independent hydrological sources, increased reservoir capacity, long-term security of groundwater wells (planned groundwater protection).
- Segregate service water use (e. g. water for agricultural irrigation) from the drinking water supply. Identification of service water needs and water saving measures for service water.
- Improve the hydrogeological basics: computer and predictive modelling for the important aquifers, vulnerability of groundwater resources to drought and pollutant inputs, monitoring of the discharge dynamics of springs.

Supply problems can best be avoided in future by regional water supply planning and additional networking of adjacent water suppliers. In principle, every water utility should draw its water from at least two independent hydrological sources (FOEN 2014). It is also essential to protect groundwater wells systematically to ensure their long-term security of supply as drinking water resources (Section 7.3.4). This will prevent usable supplies becoming even scarcer due to pollutant inputs, resulting in higher water treatment costs.

Further information and references on 'Drinking water supply'

- Lanz K. 2020: Trinkwasserversorgung. In: Lanz K. (Ed.): Auswirkungen des Klimawandels auf die Wasserwirtschaft der Schweiz. Hydro-CH2018 report.

7.1.2 Agricultural irrigation and process water for industry and commerce

Climate change severely affects irrigation in agriculture. Until now, relatively few areas of Switzerland have been irrigated. This is set to change as a result of rising temperatures and more frequent droughts in summer and the increase in cultivation of vegetables and other special crops. Climate change has little effect on water needs in industry and commerce.

In addition to the drinking water suppliers, Swiss water bodies are used by self-supply licensees, mainly in agriculture, and by industry and commerce. Data is sparse on the volumes used, the latest estimate being from the industry report by the Swiss Gas and Water Association (SVGW 2015). In 2009, some 1200 million cubic metres were obtained under self-supply licenses, about half coming from surface waters (Freiburghaus 2009). Process water is mainly used in industry and commerce for cooling, cleaning and other processes which do not require potable water. In agriculture, a large proportion of service water involves the use of spring water for the water fountains and grazing water troughs. Process water needs in industry and commerce do not generally increase during periods of drought, but pumping may be restricted due to the reduced water availability.

Climate change has a severe impact on agricultural irrigation. In a normal year over 95% of agricultural land in Switzerland manages without artificial irrigation According to the Swiss farming data for 2010, 2013 and 2016, only around 34,000 hectares are regularly irrigated, which is 2% of the agricultural area of the country (Federal Statistical Office BFS 2016).

Figure 7-3: Irrigation systems

Different methods of irrigation: sprinkler irrigation (top), water-efficient drip irrigation (middle) and traditional irrigation (bottom).

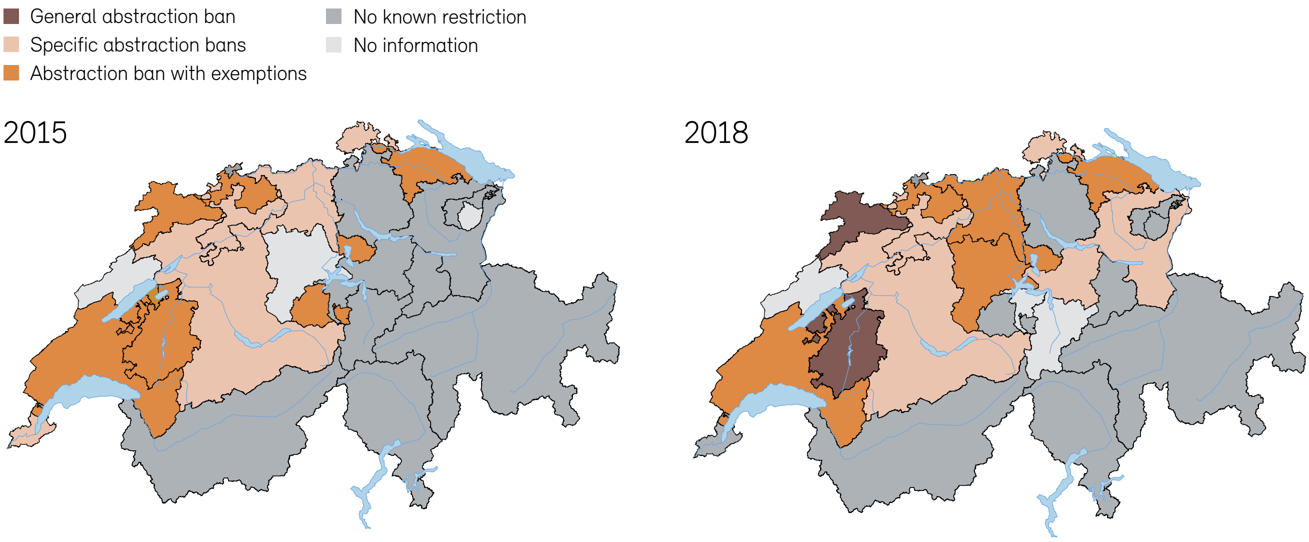
Source: © lysala, stock.adobe.com

Source: © lavizzara, stock.adobe.com

Source: © Rotscher, stock.adobe.com

Figure 7-4: Restrictions on water withdrawal

Bans and restrictions on extraction from surface waters for agricultural irrigation in the second half of both 2015 and 2018.



Source: FOEN (2016) and FOEN (2019b)

The great majority of farms have no – or no permanent – infrastructure for widespread irrigation. It is mainly only special crops such as vegetables, fruit and berries that are irrigated regularly. Arable crops like potatoes, sugar beet and maize are also irrigated. A third of the irrigation area is artificial pasture and permanent grassland. The largest percentage consists of the traditionally irrigated meadows in the dry valleys of the Alps (BFS 2016). Bio-climatic conditions and, above all, socioeconomic conditions determine whether and how land is irrigated. All the crops needing irrigation are far from being worth watering.[5] Whether irrigation is economically viable depends partly on the availability of the water resources. Irrigation as a means of stabilising yields is a more attractive proposition where water can be obtained reliably and cheaply than in regions with limited availability. It is also important for the costs actually incurred to be passed on to those causing them (polluter pays principle), i.e. that true-cost pricing is guaranteed.

More frequent restrictions on water abstraction for irrigation

Water use in agriculture is highly weather dependent (Hofer et al. 2017). As temperatures rise, the potential evaporation from soil and transpiration from plants and therefore the irrigation needs of the crops also increase. At the same time, less water will be available in the summer months in the important arable land on the Swiss Plateau due to climate change. Summer precipitation and discharge will decrease and droughts will become more frequent and severe. In the dry years of 2015 and 2018, water abstraction had to be restricted in many places to ensure the minimum residual flow to protect the aquatic organisms (Figure 7-4). The main impact was on small and medium-sized watercourses, which make up approximately 80% of the total watercourse network (FOEN 2009). Even today, therefore, a large part of the network is no longer a reliable resource for irrigation in extreme situations.

If the cultivation systems are not adapted, the scenarios for the end of the century show an increase in the demand for irrigation of 10–20% with climate change mitigation (RCP2.6) and as much as 40–50% without (RCP8.5) (Hirschi et al. 2020, Holzkämper 2020). If large areas are planted with water-intensive crops in future, the increase in demand will be even greater.

5 Crops are considered as needing irrigation if the natural rainfall amounts and the water storage capacity of the soil are insufficient for good plant growth. A crop is worth watering if the yield or quality gain is greater than the cost of irrigation.

Complementary adaptations

To guarantee sustainable use of the water resources, regional water resource planning and management must be implemented. The crucial factors are to record the uses and to avoid overuse of the water resources. To prevent serious conflicts, the different uses must be prioritised, so that the necessary restrictions can be put in place in the event of persistent shortage.

Precautionary measures will be necessary in the growing regions particularly affected by drought to minimise conflicts between irrigation, water ecology and other water uses, particularly the drinking water supply, in extreme years. It is important to guarantee the true-cost pricing principle when the measures are implemented. The possible measures include adaptations in management (e.g. choice of crops, varieties and locations, soil cultivation practices etc.) or in infrastructure (e.g. supply pipes) for additional irrigation with water from large reservoirs (lakes, large rivers). Regional irrigation systems which supply extra water from lakes, large rivers or reservoirs are currently under consideration in many places. Aside from large water bodies, irrigation with groundwater or from the public supplies is also under discussion. This must never lead to overuse of the drinking water resources and shortages of supply. Small local reservoirs on farms are another approach. Because transporting water from lakes and rivers further away involves costly infrastructure and high investment costs, irrigation cooperatives are being set up. Under certain conditions, projects of this kind will be supported by infrastructure improvement grants from federal government and the cantons, e.g. the Furttal irrigation project (Müller 2019).

Extra water cannot solve all the problems. Firstly, irrigation is uneconomic for the great majority of crops, and secondly other climate-related risks must be taken into account when considering agricultural adaptations, such as heat stress, more pest problems and damage due to heavy rainfall and hail. Agricultural development is determined primarily by political and social requirements and market forces. In recent years, for example, the land area

AgriAdapt: How is the irrigation requirement changing as climate change advances and what impact does this have on the water table?

Method

The impact of climate change on crops, irrigation requirements and water tables was analysed for an aquifer in the Bernese lake region using an integrated modelling system consisting of plant, hydrological and groundwater models.

Main results

- Without climate change mitigation (RCP8.5), the irrigation requirement would increase by around 40% by the end of the century, and with climate change mitigation (RCP2.6) an average increase of around 13% could be expected.
- Without climate change mitigation and with more intensive farming (+20% of crops requiring intensive irrigation), the water requirement would rise on average by a further 35%. A potential means of saving water is to increase cultivation of early ripening varieties and winter crops.
- Without climate change mitigation (RCP8.5), the estimated water requirement for irrigation would exceed the current drinking water requirement in the future.
- Without climate change mitigation (RCP8.5), a lower water table is expected in summer and autumn. This effect would be compounded by additional water abstraction for irrigation. Nevertheless, the effect of climate change on the water table is more dominant than the effects of the land use scenarios considered (+/-20% of crops requiring intensive irrigation).

Hydro-CH2018 project of the Agroscope, Climate and Agriculture Research Group used for vegetable growing, which relies on continuous watering, has increased by 24% (BFS 2018). The choice of crops and cultivation like soil treatment methods and the further development of the agricultural market system towards more sustainability are therefore crucial in the longer term.

Strategies for adaptation to climate change

- Adapt the cultivation systems to reduce the water requirement, selection of crops and soil cultivation practices suitable for the location.
- Crop failure insurance against excessive drought as a safeguard.
- Optimised professional irrigation, supported by digital soil moisture monitoring systems, efficient irrigation technologies, better training on irrigation.
- Plan and manage the water resources to ensure sustainable use and prevent overuse. The water uses should be prioritised to avoid conflicts in the event of severe drought. Adaptation of the licensing system.
- Plan service water use for agricultural irrigation and implement usage-related financing. Adopt precautionary measures against water use conflicts. Introduce the polluter pays principle – true-cost pricing – for service water.

Further information and references on 'Agricultural irrigation'

- Holzkämper A. et al. 2020: AgriAdapt – Modellgestützte Untersuchung der Einflüsse von Klima- und Landnutzungsänderungen auf Grundwasserressourcen im Berner Seeland. Hydro-CH2018 report.
- Lanz K. 2020: Landwirtschaftliche Bewässerung. In: Lanz K. (Ed.): Auswirkungen des Klimawandels auf die Wasserwirtschaft der Schweiz. Hydro-CH2018 report.

7.1.3 Hydropower

In Switzerland, more than half the electricity is generated by hydropower. Hydropower is currently still benefiting from the melting glaciers throughout the year. In the longer term the melt water flows will decrease. But the role of hydropower as storage for solar and wind power and to stabilise future power grids will increase.

In Switzerland, water has been used to generate electricity since the end of the 19th century. Many of the hydropower plants were built between 1945 and 1970 and have 80 year concessions. The large storage power plants are in the Alps and the large run-of-river plants are found on the Swiss Plateau.

Impact on storage and run-of-river plants differs

While power production in storage power plants can be adjusted to a certain extent to reflect demand and price, in run-of-river plants it is dependent on the current water availability. The watercourses will have higher runoff in winter in future, which means that more electricity can generally be produced by hydropower at this time. The expected reduction in summer runoff will result in less water being available for power production at that time. Storage power plants can partly compensate for these seasonal changes by retaining water.

Positive and negative effects for run-of-river plants

The Swiss Competence Center for Energy Research SCCER studied how climate change will affect electricity production at eleven run-of-river plants in Switzerland (Figure 7-5). Winter production rises at nearly all the stations in future compared with the 1981–2010 reference period, by an average of around 5% by mid-century, for both the scenarios with climate change mitigation (RCP2.6) and without (RCP8.5) (SCCER-SoE 2019). The figure increases to 10% by the end of the century without climate change mitigation, but remains stable with climate change mitigation. With climate change mitigation, annual production will be unchanged or only fall slightly. Without climate change mitigation, falls of 3% by mid-century and 7% by the end of the century are expected. Exceptions to this are high-elevation alpine power plants which show an increase in production even then. This can be largely explained by the melting of the glaciers. Swiss hydropower as a whole is currently still benefitting from glacier melt. In the 1980 to 2010 period, 3 to 4% of Swiss hydropower production came from glacier melt, which equates to some 1.0 to 1.4 TWh per year. However, the glacier melt contribution will fall by 0.56 TWh per year by mid-century and by 1 TWh per year by the end of the century (Schaefli et al. 2019).

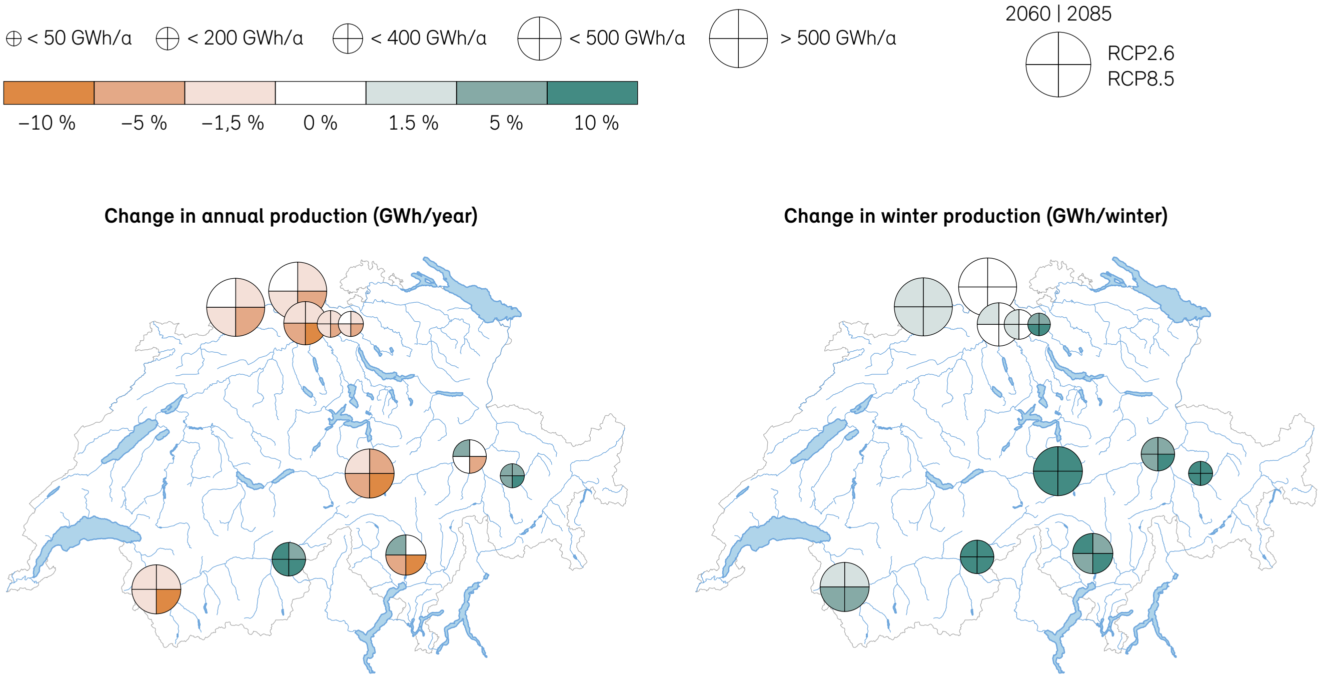
How electricity production will actually change depends also on the upgrade status of the plants. Low flows cannot be exploited due to the minimum residual flow and when flows are higher, the plant capacity (design water volume) is a limiting factor (SCEER-SoE 2019). In those power plants without maximum upgrade levels to date, more power could be produced than is now the case, for instance by increasing the design water volume or by more efficient power generation and the losses due to climate change could then be made up, whereby the ecological significance of the overflows at the intakes must be taken into account (dynamic residual flow).

Challenges and opportunities for storage power plants
Storage power plants have high exposure to natural hazards due to their alpine location. The melting of the glaciers, warming of the permafrost and more frequent heavy precipitation all intensify the natural hazard situation for the hydropower plants in the Alps. Depending on how full the reservoirs are, they can also retain large quantities of water during periods of high flow and contribute to flood protection. The demands for multi-purpose use of reservoirs, e. g. for flood retention or as a water resource in periods of scarcity could increase in the future. Alpine reservoirs can also be expected to silt up more quickly, due to additional sediment input. Attempts are being made to overcome the silting problem by technology and maintenance.

Hydropower is not just affected by climate change, it is also part of the solution
To implement the Paris Agreement, it is necessary to move energy supplies away from fossil fuels. Energy

Figure 7-5: Expected changes in run-of-river power plant production

The expected changes in the annual and winter production of typical Swiss run-of-the-river power plants in the 2060 (2045–2074) and 2085 (2070–2099) periods compared with the reference period (1981–2010) for a scenario with (RCP2.6) and without climate change mitigation (RCP8.5). The projections assume consistent power plant performance and unchanged residual flow.



Source: SCCER-SoE (2019)

Strategy 2050 provides for the hydropower contribution by 2035 to reach an average annual production of at least 37,400 GWh, 2.6% more than in 2018 (Article 2 Energy Act). To achieve this, efficiency gains will be needed and additional reservoir capacity or new plants will have to be built. The melting of the glaciers will open up new areas, some of which could be used for hydropower (Farinotti et al. 2019), as in the case of the planned storage power plant on the Trift glacier in the Bernese Oberland.

In addition to actual power generation, pumped storage power plants are important for electricity storage applications in order to stabilise the grids. This feature is becoming more important with the increase in electricity generation from solar and wind power plants which are weather dependent and therefore do not produce regularly.

Strategies for adaptation to climate change

- Realign plant configuration due to the change in water availability.
- Review the natural hazard risk for reservoir installations as a result of permafrost warming and glacier melt.
- Examine reservoir multifunctionality to provide a new service.
- Improve long-term flow predictions to optimise electricity production.
- Take account of climate change in pending relicensing procedures.

Further information and references on 'Hydropower'

- Lanz K., Wechsler T. 2020: Wasserkraft. In: Lanz K. (Ed.): Auswirkungen des Klimawandels auf die Wasserwirtschaft der Schweiz. Hydro-CH2018 report.
- SCCER-SoE (Ed.) 2019: Climate change impact on Swiss hydropower production.

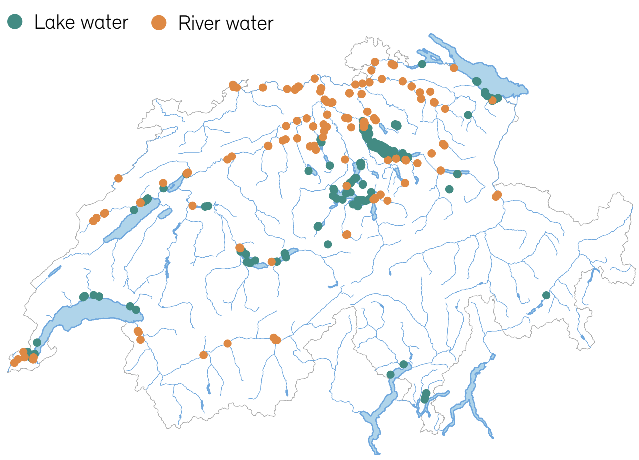
7.1.4 Thermal use of water

Water is used in Switzerland for heating and cooling. Climate change has a positive impact on heat use: The water bodies are warming up; therefore, more energy can be extracted from them. The opposite is true of cooling: Higher cooling requirements in summer are coming up against higher water temperatures and lower flows.

Watercourses have played an important role in cooling large industrial plants for decades. Since the shutdown of the Mühleberg nuclear power plant in December 2019, the Beznau nuclear plant is now the highest discharger of heat into a Swiss river, followed by waste incineration plants and industrial facilities. Although lakes and watercourses offer great potential for thermal use for heating, this is limited regionally by the effort and cost for the necessary district heating systems. Heating systems using lake or river water are most likely to be profitable when combined with large cooling applications, e.g. for industrial plants or computer centres (Rust 2017). Using the heat from the water bodies is a possible way of reducing Swiss greenhouse gas emissions and should be applied more widely. An overview of the thermal use of lakes and watercourses is shown in Figure 7-6.

Figure 7-6: Thermal use of river and lake water in Switzerland

The dots show where river water (orange) and lake water (turquoise) are currently used for heating.



Source: Data from Eawag, 2018 (*thermdis.eawag.ch*)

Little further potential for cooling systems on watercourses

The climate-related warming of the water in watercourses is reducing their cooling capacity. Primarily in summer, when the demand for cooling is greatest, watercourses are already reaching critical temperatures for aquatic organisms more and more often (Section 6.9.1). In the hot summers of 2003, 2006, 2015, 2018 and 2019, some major industrial facilities had to restrict their cooling operations for a time. To avoid additional heat stress on the water ecosystems in addition to the climate-related stress, new cooling uses on most watercourses must be examined critically. Possible potential exists on larger watercourses in the Prealps, which will still have high runoff in summer in the future.

Potential of lakes for thermal use

The large lakes have considerable potential for thermal use for both heat extraction and cooling, even as climate change progresses, due mainly to their large volumes and the deep water which stays cool in summer. To prevent negative effects on the lake ecosystem, the impact of water extraction and the return of warmed or cooled water on the stratification conditions affected by climate change must be considered. Thus, summer stratification is expected to be more pronounced and last longer in some lakes in future (Section 6.7.2). To prevent this impact being further increased by the use of cool water, the warmed water must be fed back into the deep water. This causes it to warm up, which also has a negative impact and must be minimised. This leaves little potential for cooling from small lakes with small deep-water volume. It should be possible to exploit the cooling potential of the cold deep water in large lakes, even in hot summers, without negative ecological consequences (Gaudard et al. 2019). For uses in lake outflow areas, there is also the possibility of discharging the water taken from the deep level back into the outflow after it is used and warmed. Depending on the temperature gradient, this might even cool the lake outflow if the returned water is still cooler than the surface water in the lake. But the thermocline between cold deep water and warm surface water is then lower in the lake due to water abstraction.

Groundwater heat use

Ground source heat and therefore also groundwater heat is used widely in Switzerland. The focus concerning thermal use of groundwater has not been on the effect on the groundwater temperatures up to now. It is more a matter of preventing conflicts with groundwater protection: Because the protective top layer of groundwater has to be penetrated for each use, thermal use is not permitted in groundwater protection zones or in groundwater resources which can be used for drinking water supplies.

Strategies for adaptation to climate change

- Prevent and reduce cooling and heating requirements by incorporating better building technologies and process optimisation.
- No new cooling systems on watercourses and upgrading of existing systems which are, or are now, non-compliant with water regulation requirements.
- Utilise the potential from lake water, taking account of the consequences for the ecosystems.
- Promote thermal use from water bodies.

Further information and references on 'Thermal use'

- Lanz K. 2020: Thermische Nutzung. In: Lanz K. (Ed.): Auswirkungen des Klimawandels auf die Wasserwirtschaft der Schweiz. Hydro-CH2018 report.

7.1.5 Leisure, recreation and tourism

The attraction of Switzerland for tourism and recreation lies mainly in its landscape and the water, snow and ice. Climate change will alter the tourism offering, predominantly due to the retreat of glaciers and the rise in the zero-degree isotherm, but it will also increase peoples need for cooling in the mountain regions and in rivers and lakes.

With 53.3 million overnight stays per year, tourism is important for the Swiss economy. It generates an annual turnover of CHF 18.7 billion or 2.4% of gross domestic product, and is a major employer with 175,489 full time equivalents in 2018 (Swiss Tourism Federation STV 2019, BFS 2019). The role of the lakes and rivers for recreation and tourism is set to become even more important in a time of climate change, as a base for tourist activities and a resource for the daily needs of tourists (Figure 7-7).

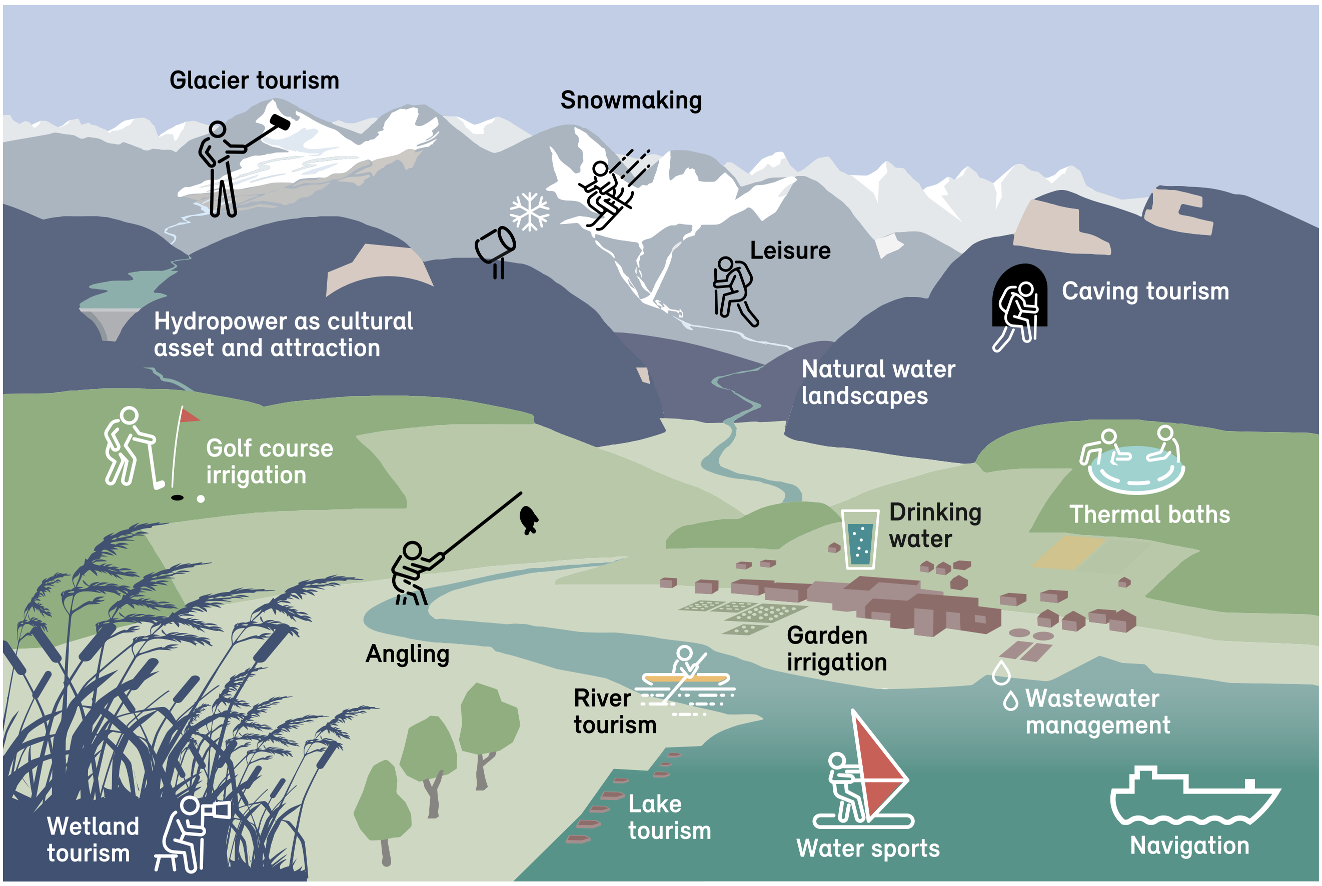
Challenges for winter tourism

Higher winter temperatures are causing the number of with new snow days in the Alps to decrease significantly (NCCS 2018). The winter sports resorts at lower levels have already felt the effects of the higher zero-degree isotherm in recent years and some have had to close down. To compensate for the decline in snowfall, most resorts have acquired snowmaking machines. In 2016, some 49% of the 22,500 kilometres of piste in Switzerland were created with artificial snow (Seilbahnen Schweiz 2017).

The water needed for snowmaking must be available at high elevations in the autumn and winter months when flows are low, and residual flow regulations must also be met even for watercourses high in the Alps. For this reason, many resorts collect melt water and rainfall in summer and store it in self-built reservoirs in the skiing areas.

Figure 7-7: Water dependence of tourism and recreation in Switzerland

Water is a central resource for the supply of tourism infrastructure and the basis of many winter and summer tourist activities.



Source: Internal graphic after Reynard et al. (2020a)

If this is not enough, water has to be pumped from lower levels. Sometimes water from the local drinking water supply is used for snowmaking, which can cause conflicts (Lanz 2016). In some resorts, water can be obtained from hydropower reservoirs, e.g. in Saas-Fee, Nendaz-Veysonnaz and Crans-Montana (Reynard et al. 2014).

Water use in alpine holiday destinations

The extreme seasonal variations in the number of overnight stays and the decentralised position of holiday destinations in the mountains make their adaptation to climate change very challenging. Drinking water consumption from the public supply increases dramatically on peak days. At the same time more wastewater is generated, which places great stress on the infrastructure and incurs higher costs. In places where peak days coincide more often with lower water availability in future, the probability of supply shortages will increase.

In summer, the scenery is changing due to the melting of the glaciers. Destinations visited nowadays for their glaciers or glacier attractions will lose some of their appeal.

Opportunities for summer tourism

Climate change also opens up opportunities for the tourist areas in the mountains. It can be assumed that holidaymakers will increasingly seek the cooler mountain climate on hot summer days. A few years ago, a correlation between the number of overnight stays by Swiss tourists in mountain regions and high temperatures at lower elevations was demonstrated (Serquet and Rebetez 2011). Because snowfall now starts later in the autumn, the hiking season is extending. It is still unclear whether the new mountain lakes and landscapes left behind by glacier retreat can become attractive destinations for holidaymakers. Also, attractive, versatile water bodies become more important for recreation in a time of climate change. Local swimming facilities and attractive lake and river banks are amenities for the population to cool down and relax.

Restrictions on leisure navigation

The summer of 2018 showed that drought and heat can also affect navigation on lakes and rivers. Worst affected were the unregulated Lake Constance and smaller lakes such as Zug, Hallwil and Greifen, where water levels could not be maintained despite regulation due to lack of inflows.

Table 7-1: Navigation restrictions on Swiss lakes and rivers in summer and autumn 2018

Lake	Effects, restrictions
Constance	Piers out of use at Bad Schachen from 23 July and Langenargen from 24 September, no wheelchair access at several stations from July
Constance (lower lake)	No scheduled boats between Diessenhofen and Stein am Rhein from 23 July to October
Constance (Altenrhein)	From 30 July no scheduled boats between Rorschach and Rheineck until end September
Walen	Relocation of Quinten jetty, steeper ramps at all jetties
Zug, Ägeri	Despite record low summer water levels, all stations accessible, but very steep ramps
Greifen	Mönchaltorf pier out of use from 16 July, lake level one metre lower than normal
Hallwil	Lake level over 60 cm lower than normal, serious boarding problems (ramp required), but all stations accessible
Maggiore	Isola Madre pier (Italy) inaccessible from August due to low water level
Zurich	No restrictions despite record low summer water level
Limmat (river)	Navigation temporarily suspended due to excessively high temperatures on board (glazed vessels)
Lucerne	No restrictions despite record low summer water level

Source: Reynard et al. (2020b)

Strategies for adaptation to climate change
- Innovate and diversify, especially by promoting summer and year-round tourism.
- Reduce water requirements to prevent overuse of resources. Databases with better resolution on water consumption for different uses at tourist destinations: overnight stays, snowmaking, golf courses, swimming pools, wastewater treatment. Implement regional water resource planning.
- Network the water supply and wastewater infrastructure with adjacent municipalities and expand storage capacity as the secondary independent hydrological source.

Further information and references on 'Tourism'

- Reynard E. et al. 2020a: Eau et tourisme. Hydro-CH2018 report.
- Reynard E. et al. 2020b: Wasser und Tourismus. In: Lanz K. (Ed.): Auswirkungen des Klimawandels auf die Wasserwirtschaft der Schweiz. Hydro-CH2018 report.

7.2 Protection against water

More frequent and intensive heavy precipitation, the climate-related increase in sediment transport and the continuing urban development in hazardous areas all intensify the risks from flood and surface runoff. Allowance is already being made for this in flood protection and urban drainage.

7.2.1 Flood protection

It is essential for future flood protection that the climate-related changes be considered. The basis has already been created in recent decades by integrated risk management.

Periods with many widespread flood events have occurred repeatedly in the past (Schmocker-Fackel and Naef 2010). Extensive and catastrophic floods can occur in the current climate, as the major events of 1987, 1999 and 2005 show, and such floods will also occur in future. The probability of certain high flows is not constant over time and is altering due to climate change. This probability of occurrence is an important parameter for the planning and design of flood protection measures, and there are indications that it is increasing (Section 6.5). Uncertainty about extreme events already exists today; it will increase further in future due to climate change. Flood protection must always account for this uncertainty. Due to climate change, more sediment is also likely to be mobilised, transported and deposited during flood events, which can cause serious damage.

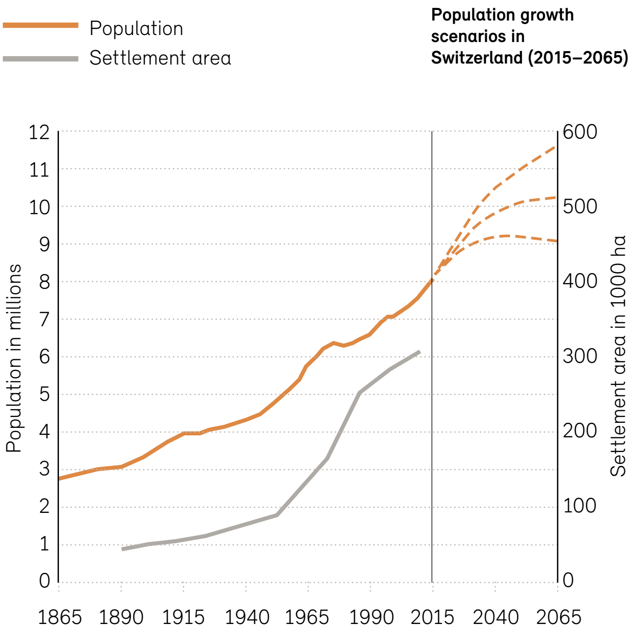
Continuous advances in flood protection

Protection against water grew in importance in the 19th century, when many more new areas near water were occupied as industrialisation and population grew. River courses were then corrected and dammed to increase their flow capacity in floods and to protect areas near rivers. The narrowing of the watercourses and retention of bedload from the lateral tributaries led to more erosion of river beds and banks. Attempts were made to counter this using further control structures. In the long term, this strategy proved unsuitable to provide sustainable protection for urban areas and properties against floods. After some devastating flood events with significant damage, a paradigm shift in relation to flood protection began in

Switzerland some 25 years ago: away from hazard prevention purely by structural measures and towards integrated risk management. Nowadays, natural hazard event prevention, mitigation, response and recovery are considered holistically and as cyclic processes. All the main stakeholders participate in the planning and implementation of measures, with technical, (spatial) planning and biological and organisational measures being combined as far as possible. Climate-related effects and influencing factors have also been included for some years. The report 'Living with natural hazards in Switzerland' (FOEN 2016) recognised the need for action; it is already partly implemented in flood protection.

Figure 7-8: Population and settlement area growth in Switzerland

The Swiss population rose by some 5.5 million people between 1865 and 2015 (orange line) and will increase further by 2065 but in different ways depending on the scenario (orange dashed lines). The built-up area of Switzerland is expanding faster than the population growth (grey). Around 1890 there were just 3 million inhabitants and less than 50,000 ha were developed, but the settlement area rose to over 300,000 ha in 2009 with a population of 7.5 million.



Sources: partially corrected data from the federal land use statistics and estimates. Permanent resident population according to ESPOP, STATPOP and the population scenarios by the Federal Statistical Office BFS.

Socio-economic development as potential damage driver

How flood risks develop in the coming decades depends not only on the change in peak water flow but also on whether the potential for damage continues to increase. Switzerland's settlement area more than tripled between the Second World War and 2009 (Figure 7-8). Due to expansion in built-up areas, the higher property values of buildings and more intensive use of space, even in danger zones, the potential for damage from flood events keeps increasing, but there is less and less space available for possible protective measures. To prevent a further increase in the risks, it is critical to include risk thinking when drawing up structure and land use plans or building regulations. National hazard maps have been produced for this purpose and show where in Switzerland settlements and traffic routes are under threat from floods and other natural hazards (ARE and FOEN 2005).

Strategies for adaptation to climate change

- Raise awareness and consideration of new or increased risks due to climate change such as processes concatenation or process thresholds being exceeded.
- Increase acceptance of drastic and unpopular measures such as retreat from regions at risk.
- Avoid new, unacceptable risks by risk-based land use planning.
- Manage sediment deposition in torrents and the delta areas of lakes.

7.2.2 Protection against surface runoff

The increase in heavy precipitation will lead to more frequent and intensive surface runoff and thus to more damage, even in regions which are not at risk from river and lake floods. Protective measures for property, risk-based land use planning and adaptation of urban drainage to climate change are important.

The CH2018 climate scenarios predict an increase in heavy precipitation of up to 20% by the end of the century without climate change mitigation. In torrential rain the soil cannot absorb all the water and it runs along the surface (called surface runoff). This can result in extensive flooding far from bodies of water. Surface runoff can cause damage costing millions to buildings, infrastructure and the landscape. For example, a persistent thunderstorm in Zofingen in July 2017 caused damage to many buildings outside the known hazard zones (Figure 7-9). The federal government took an important first step in recent years, in collaboration with the Cantonal Building Insurance Companies Association and the Swiss Insurance Association, by producing a national hazard map of Switzerland: It shows where surface water runs off, which areas are affected and how high the water could rise. In the context of climate change, it is important to raise awareness of the risks from surface runoff. Simple and inexpensive property protection measures or barrages and low barriers are often enough to prevent water flooding into basements and underground garages.

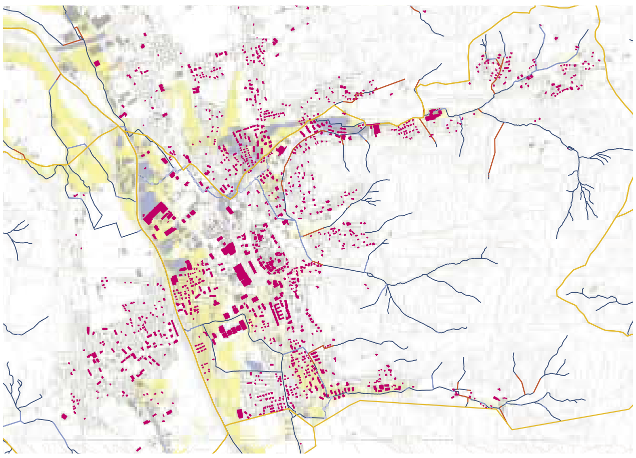
Urban drainage adaptation

Heavy precipitation is a particular problem in urban areas, where most of the surfaces are impermeable and water cannot infiltrate. The urban drainage system has to face this challenge as climate change advances. One possibility is to increase the discharge capacity from the settlement area by enlarging the sewers and by creating emergency runoff corridors. Heavy rain can also overload the sewers and allow untreated sewage to be discharged (combined sewer overflow CSO) (Section 7.3.2).

The more rapid draining of heavy rain from urban areas can increase flow further downstream. Consequently, new concepts and greater cooperation between urban drainage, urban planning and flood protection professionals are required. A holistic approach of this kind is the concept called 'sponge city', in which rainwater is stored in cisterns, storm water ponds or green roofs instead of being discharged directly through the sewers. This not only relieves the pressure on the drainage system but can also reduce the effects of summer heatwaves in cities and conurbations. Climate analysis maps show that the temperature on hot days can be 6 or 7 °C higher in areas such as parts of the city of Zurich than in rural areas (heat

Figure 7-9: New hazards outside zones at risk from floods according to the hazard map

Many of the buildings (coloured red) in Zofingen (Aargau) which suffered water damage as a result of a persistent thunderstorm in July 2017 lie outside previously known hazard zones. The reasons are surface runoff and backwater due to overloaded sewers.



Buildings with damage claims to insurance company (Aargauer Gebäudeversicherung)

Buildings affected

Hazard map, current status

Significant hazard

Average hazard

Low hazard

Residual hazard

No hazard as far as currently known

Register of streams

All watercourses

Underground passages

Flood spillway

Location specified

Location not specified

Municipality

Source: Canton of Aargau Environment and Water Department (ALG) (2017) island effect). Hence climate-compatible urban development now features more open spaces, green zones, shady places and open water.

Strategies for adaptation to climate change

- Create emergency runoff corridors for rainfall events in urban areas where the sewers and stormwater overflow tanks have insufficient capacity, so that the excess precipitation can reach the watercourses without causing damage.
- Climate-compatible urban development: creation of permeable surfaces, green space, green roofs and façades, construction of local reservoirs and basins for interim storage of rainwater and larger stormwater overflow tanks in the drainage system. These measures also help to counteract the heat island effect in the cities.

Further information and references on 'Flood protection'

- Lanz K. 2020: Hochwasserschutz. In: Lanz K. (Ed.): Auswirkungen des Klimawandels auf die Wasserwirtschaft der Schweiz Hydro-CH2018 report.

7.3 Water protection

The function of water protection is to protect the water bodies from negative impacts. This in order to safeguard long-term use by the population and preserve the aquatic ecosystems. In recent years various remediation programmes have been introduced to reduce substance pollution in the water bodies, to rehabilitate them and to protect them against overuse. These water protection measures will become even more important in the context of climate change.

7.3.1 Climate change and protection of changing water bodies

The Swiss water bodies and their banks are heavily used through human activity. Large sections are impaired in terms of water flow and quality and the structure of the water body. With climate change as an additional stress factor, rapid implementation of the water protection regulations and even more careful use are becoming more urgent. Unforeseen climate consequences can be expected to necessitate periodical reviews of water protection concepts and measures.

Rivers and lakes have a key function for society, the economy and nature. They shape landscapes and are our water resource. Water protection ensures that they can fulfil their functions as sustainably as possible as habitats for plants and animals, drinking water resources and recreation areas for people. They also need to be available as a basis for economic activity (e. g. thermal use, electricity production, tourism).

Many water bodies and their banks (watercourse corridor) are now impaired due to anthropogenic stressors such as control structures, chemical pollution and changes in flow dynamics. The consequences of climate change add to the negative effects of these man-made water changes or even reinforce them. Systematic implementation of the water protection regulations is therefore critical in strengthening the resilience and adaptability of the watercourses to climate change as quickly as possible. This requires a reduction in substance pollution, rapid implementation of revitalisation and hydropower remediation, legally compliant specification, design and management of the aquatic environment and safeguarding of sufficient volumes of water in the rivers and lakes.

Since climate change will also increase the stress on the water bodies from society (e. g. additional abstraction for irrigation and snowmaking, less pollutant dilution during low flow) various areas of responsibility for water protection have greater importance. Coordination with other sectors is generally becoming more important (e. g. flood protection, water use). Whether the current water protection strategies and practices can or must be improved in the light of climate change also needs to be regularly reviewed. In this context, the water protection measures are currently under examination at federal level in the project 'Überprüfung des Gewässerschutzes hinsichtlich Klimawandel [Review of water protection in the light of climate change]' by experts on behalf of the FOEN (Ecoplan in prep.). Exchanges of experience can contribute to strengthening enforcement by the cantons.

Federal and cantonal authorities monitor and record the state of the Swiss water bodies and their changes through several monitoring networks:

- For water quality, by the National Surface Water Quality Monitoring Programme NAWA, the National Groundwater Monitoring NAQUA and the networks monitoring temperature and suspended solids;
- For water quantity, by the networks monitoring water level and flow and NAQUA;
- For water ecology, by NAWA and biodiversity monitoring.

The state of the water bodies is determined from the observational data by the methods in the modular stepwise procedure (MSP). For water monitoring and assessment to operate as central control instruments of water policy, they must identify the effects of climate change and also and above all the effects of other anthropogenic influences on the water bodies. Regular checks should therefore be carried out as to whether the monitoring programmes and assessment methods need to be refined due to climate change.

Strategies for adaptation to climate change

- Continue water monitoring in order to identify and record changes. Regularly review whether there is a need for refinement of the monitoring programmes as a result of climate change.
- Federal and cantonal authorities should regularly review their existing water protection strategies and practices so that the rivers and lakes can fulfil their functions as climate change progresses.

7.3.2 Reducing substance pollution

The water quality is severely impaired by inputs of nutrients, plant protection products and other micropollutants. The aim is to use different measures to reduce existing pollution and minimise the risk of new contamination. This will reduce the stress on aquatic ecosystems, increase resilience and improve the water quality. It will also be of benefit for human uses.

Over 97% of Swiss municipal wastewater is collected centrally and processed at wastewater treatment plants (WTP). Around 1,300,000 km of sewers and 800 WTPs exist for this. Every day around 650 litres of wastewater per head is fed to the WTPs, with around 22% coming from households and the same amount from industry and commerce. 55% of the volume carried by the sewers is rainwater from roofs and streets or infiltration[6] (Maurer et al. 2012). After treatment at WTPs, 88.3% of the treated wastewater is discharged into watercourses and 11.7% into lakes (FOEN WTP database 2018). As these water bodies are habitats for animals and plants and are also used directly or indirectly as drinking water resources, the WTPs must provide a very high quality treatment service.

Improving the treatment service of wastewater treatment plants

Climate change reduces flows from watercourses from time to time, which causes discharges from the WTP to be less well diluted and substance pollution to be increased. However, the WTPs operate more efficiently at a higher water temperature and low precipitation, which tends to compensate for the poorer dilution (FOEN 2019b). The

6 Infiltration from spring outlets, streams, drains and invasive groundwater

upgrading of the treatment plants to include a fourth treatment stage under the 2014 revised water protection regulations are intended to reduce both the discharge into the water of micropollutants such as active pharmaceutical ingredients and biocides and also the critical spread of antibiotic-resistant bacteria through the water. Some 140 WTPs have been selected for this upgrade, based on goal-oriented criteria enshrined in law. They will be upgraded to integrate additional treatment stages by 2040.

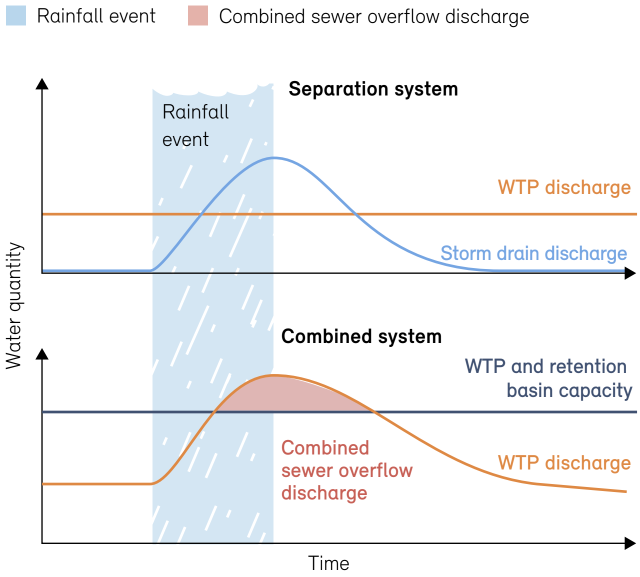
Adapting urban drainage to climate change

Two systems became established historically in Switzerland for the management of urban precipitation. In 70% of the settlement area, the rain from roofs and streets is fed jointly with the foul water by the so-called combined system to the WTP where it is treated. If the combined sewers and stormwater retention basins cannot absorb all the water during heavy rain, a mixture of foul water and rainwater reaches the water bodies without being treated. This is known as combined sewer overflow (Figure 7-10). The remaining 30% of the settlement area uses the separation system, in which a second drainage system collects the precipitation and feeds it directly to surface waters. In places where rainwater is heavily polluted, such as on roads with heavy traffic, this water has to be treated before being discharged into a water body.

The increase in heavy precipitation will result in more frequent discharge of untreated wastewater directly into the water bodies via combined sewer overflow in future unless the urban drainage is adapted. To relieve pressure on the sewers, more surface water should be allowed to percolate in built-up areas. Where this is not adequate, intermediate reservoirs must be established (stormwater overflow tanks, installations to treat combined overflows) or the combined sewers should be converted to a separate system (with separate stormwater drainage). Since urban drainage systems have a service life of several decades, the impact of climate change has to be included in current construction projects. Accordingly, legal frameworks such as the general and regional drainage plans and the relevant standards and databases must be regularly reviewed and updated.

Figure 7-10: Reaction of separation and combined systems to heavy rainfall

With combined systems which drain 70% of the built-up area, a mixture of foul water and stormwater can reach the water body during heavy rain without being treated.



Source: Braun et al. (2015)

Measures to reduce substance pollution

Many of the micropollutants such as insecticides, herbicides and fungicides are diffuse inputs from agriculture which will be unaffected by upgrading of water treatment plants. Phosphorus and nitrogen from fertilisers and manure are also discharged into the water. All these substances have a negative impact on the water ecology and the objective of water protection is to reduce their inputs. Climate change will lead to differences in agriculture, e. g. a geographical shift in intensive crop cultivation areas, cultivation of different crops and varieties and the emergence of new harmful organisms and diseases. These will change the use of plant protection products. These indirect effects are probably more significant in terms of water pollution by plant protection products than the actual direct effects of climate change. The increase in surface runoff and changes in groundwater recharge expected due to climate change may further increase transport of these substances into the water. Inputs of critical substances must be further reduced, which is being implemented among other things under the action plan on plant protection products (Federal Council 2017).

The main thrust is on reducing the use of these products by mechanical weed control, organic farming, bans on some plant production products, promotion of beneficial species etc. Other approaches are: prevention of surface runoff from the fields, extensive managed buffer strips along the water's edge or environmentally friendly cleaning of sprayer tanks. The measures and targets to reduce water pollution from plant protection products and nutrients must be implemented independently of climate change.

Strategies for adaptation to climate change

- Regularly review the drainage system of a region and adapt it if necessary. Limit the volume and frequency of combined sewer overflows.
- Continue to upgrade the wastewater treatment plants to improve treatment performance.
- Specify the spatial planning and extensively design and manage the watercourse corridors.
- Systematically implement the action plan on plant protection products.

Further information and references on 'Reducing substance pollution'

- Federal Council (Ed.) 2017: Aktionsplan zur Risikoreduktion und nachhaltigen Anwendung von Pflanzenschutzmitteln [Action plan for risk reduction and sustainable use of plant protection products].
- Lanz K. 2020: Siedlungsentwässerung. In: Lanz K. (Ed.): Auswirkungen des Klimawandels auf die Wasserwirtschaft der Schweiz. Hydro-CH2018 report.

7.3.3 Restoration of the watercourses

Surface waters which are close to their natural state are diverse habitats for native plants and animals. The aquatic ecosystems will also suffer climate-related changes. Natural watercourses can cope with these changes better than those subject to chemical pollution, control structures or hydrological effects from hydropower.

Many of the natural watercourses of Switzerland have been lost since the 19th century. Large channel corrections and control structures on small rivers and streams had far-reaching consequences. The reasons for these were improvements in flood protection, energy production, industrial use and the development of transport corridors, agricultural land and urban areas. Watercourses on the intensively used Swiss Plateau suffer most from a lack of structural diversity and are far removed from their natural state. In all, around a quarter of all watercourse sections in Switzerland are artificial, seriously impaired or culverted.

The waters protection legislation was revised in 2011 with the aim of restoration of the watercourses and removing the main impairments. The restoration of the watercourses was initiated independently of climate change, but contributes directly to their resilience and adaptability. The cantons have systematically analysed the watercourses in which the plants and animals living there are seriously affected and have planned where hydropower plant remediation and watercourse revitalisation are required.

Preserve and create diverse habitats

Climate change will lead to higher water temperatures and changes in flow and sediment transport. Many species cannot simply adapt to the different conditions. They must rely on colonising alternative habitats or retreating to other less affected areas in the water system in extreme situations such as heatwaves or low flow. An intact water body network with diverse habitats is necessary for this. Water bodies which are as natural as possible are central to preserving species diversity.

Migration options for the organisms in and on the water are critical for connectivity (Figure 7-12). But in Switzerland it is impossible for fish and other migratory species (e.g.

crabs) to move upstream and downstream due to around 1000 obstacles related to hydropower plants. Plants subject to mandatory remediation will therefore have fish passes installed by 2030. The connectivity is also compromised by around 100,000 groundsills and barrages over half a metre high. They will be routinely removed in connection with hydraulic projects and water maintenance.

The watercourses can only offer diverse habitats if they also provide a varied, well-structured bed, areas with different flow rates, areas to retreat to in extreme situations (e.g. low flow channels) and refuge areas for aquatic organisms. It is more important than ever for hydraulic projects to be designed to preserve and create diverse habitats. Because revitalisation projects have to last for decades, they should anticipate the future climate and already be considering the expected changes in water flow, temperature and ecology. The temperature increase can be alleviated by planting along banks to create shade, particularly on small watercourses. Species habitats will also shift within certain limits and new species will migrate into the watercourses while existing ones disappear. These new species may have different requirements from the present ones, e.g. on structure or flow rates. By the year 2090 around 4000 km of water section are due to be rehabilitated to restore their natural functions (Göggel 2012).

More space for watercourses

Water bodies and their banks fulfil many natural functions. Those which are near-natural need enough space; without it they cannot develop. Very diverse habitats develop in a confined space through the water-land interface,

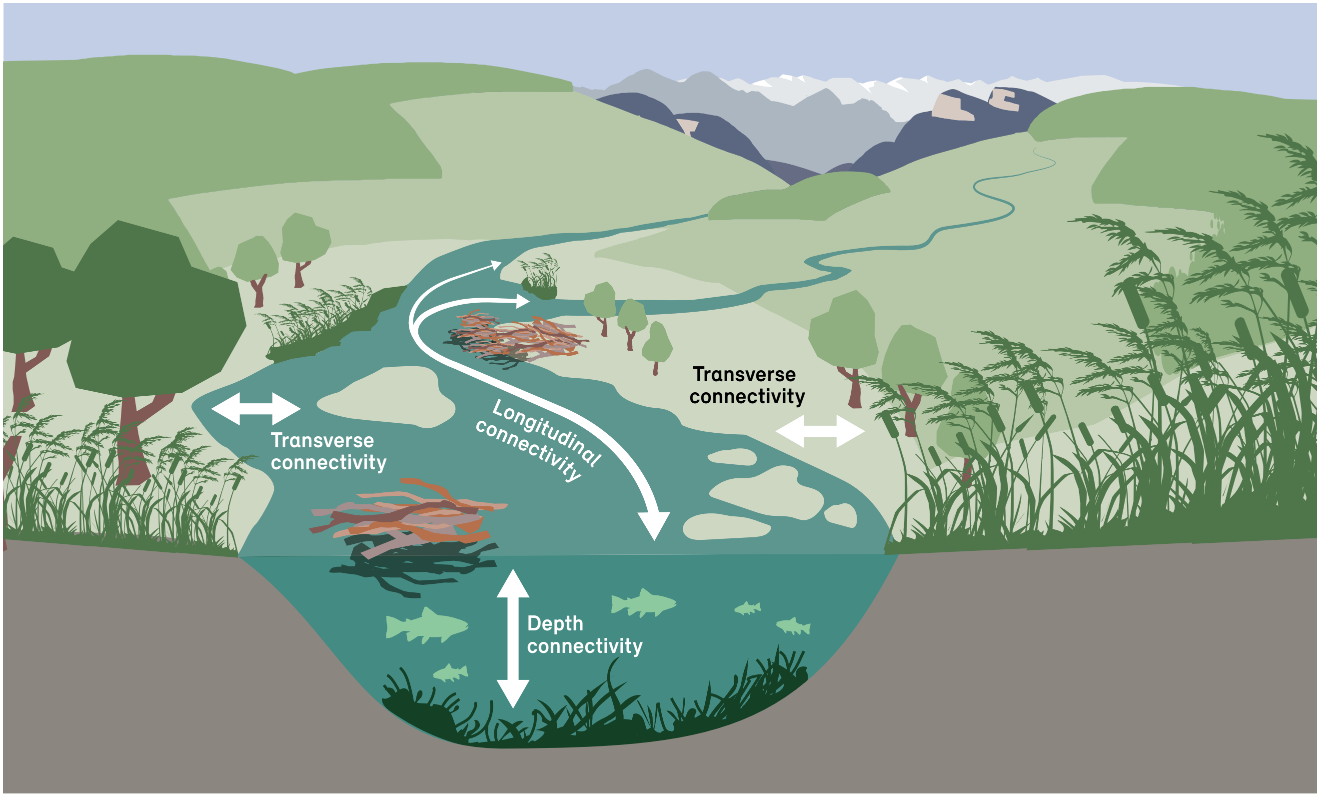
Figure 7-11: Valuable habitats after restoration

The Chli Rhi, an infilled tributary of the Rhine at Rietheim in the canton of Aargau, has been rehabilitated and allowed to burst its banks in a flood. A dynamic riparian forest landscape has become established. The photo shows the situation on 22 August 2016.

Photo: FOEN

Figure 7-12: Design of the connectivity in an intact watercourse system

To enable aquatic organisms to spread along the watercourse, good longitudinal connectivity is necessary. Many species migrate over long stretches to breed, but also cover short distances to search for food or to retreat during heatwaves or low or high flows. Good transverse connectivity (periodic flooding of water meadows) and depth connectivity in the form of exchange between surface water and groundwater are equally important.



Source: According to the FOEN (2011)

which is why the watercourse corridor is so important for biodiversity. The banks also act as a buffer for the input of pollutants and nutrients. In flood situations, water and bed-load can be retained throughout the watercourse corridor, reducing peak flows and damage. Many watercourses also feed groundwater.

The natural functions of a water body can only be restored if enough space is available. By planting location-compatible trees and shrubs near the water, the maximum water temperatures can be reduced and refuge areas from high water temperatures can be created, particularly along small rivers and streams. But cold-water zones can only be used as refuge areas if the aquatic organisms can reach them (able to migrate). Planting of appropriate trees and shrubs has a cooling effect and also enhances the structural diversity of the watercourse corridor and improves the habitat.

More focus on ecological requirements for residual flow

Water for electricity generation is abstracted from Swiss water bodies at around 1500 locations. A adequate amount water in the form of residual flow must be left after the water is taken. The Waters Protection Act of 1992 stipulated how adequate amounts of residual flow are determined, but this only applies to abstraction approved after 1992. The residual flow regulations only apply to older abstraction licences when the time comes for relicensing. The existing residual flow sections must then undergo remediation if economically viable (Articles 80 and 81 WPA). Residual flow is defined by the hydrological parameter Q_{347} and specific ecological requirements in the section affected. The requirement for habitats dependent on the water, for fish migration or for groundwater recharge must be considered. As far as this specification is concerned, the expected climate-related increase in water temperature, reduction in summer flow, low water flows and more frequent droughts will increase the importance of specific ecological requirements.

Consistently pursue hydropower remediation
Nearly all fish undertake longer or shorter migrations during their lifetime. As a result of hydropower use, many river and stream systems are partly or fully impassable to fish. Climate change makes remediation of the 1000 or so obstacles to their migration at hydropower plants in Switzerland more important, so that fish can escape during periods of drought and heat to stretches of water where they are exposed to less stress.

In storage power plants, water is collected in reservoirs and then released for electricity production. The power is generated intermittently according to demand and prices, which results in rapid flow and water level fluctuations in the stretches below the plants (hydropeaking). Some 100 Swiss hydropower plants cause these artificial flow fluctuations. This is problematic for the water ecology, because aquatic organisms can be swept away by the current or become stranded in areas which dry out when the flow rate falls suddenly. Power plants can also change bed load transport, especially in places where reservoir sections act as sediment traps and cause a bed load deficit in the lower reaches. Therefore, hydropower plants which cause artificial flow fluctuations and 150 installations which cause bed load deficits will also undergo remediation (FOEN 2015).

With the restoration and remediation work described, the aquatic ecosystems will be improved and made more resistant to climate-related stressors. As events occur, these longer-term measures must frequently be supplemented by measures effective in the short term such as emergency plans in fisheries. In the summer of 2018, for instance, the mouths of many streams along the Upper Rhine in the cantons of Schaffhausen, Thurgau and Zurich were dredged to provide cooler sanctuaries for the fish (FOEN 2019b).

Strategies for adaptation to climate change
- Systematically implement the cantonal restoration plans: remediation of fish passes, hydropeaking and bed load and revitalisation, including climate change factors.
- Regularly evaluate concepts for water protection and measures for their effectiveness in maintaining and creating climate-compatible aquatic habitats, and review the water protection measures in terms of climate change.

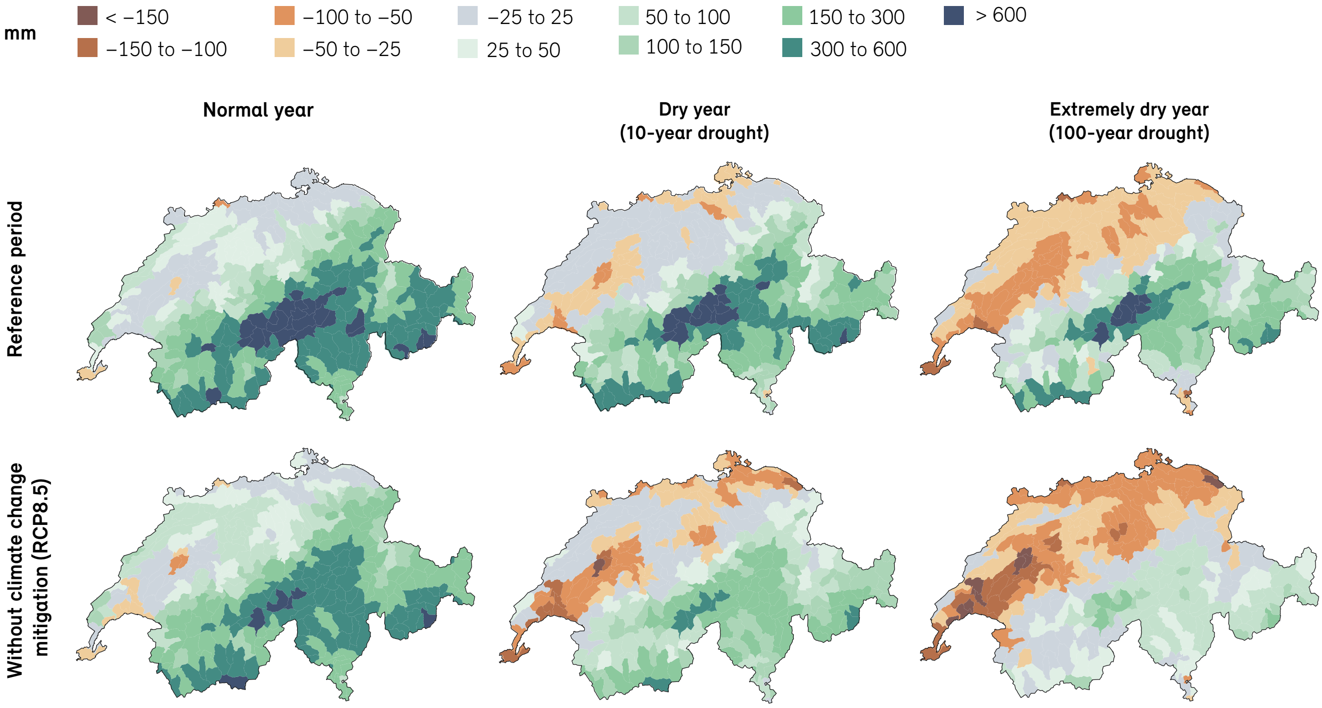
Further information and references on 'Restoration'
- FOEN 2015 (Ed.): Restoration of the Swiss waters. The cantonal remediation plans from 2015.

7.3.4 Protection of water resources and groundwater
Drinking water supply shortages due to drought can be avoided by good planning and forethought. However, there is a high demand for service water for irrigation during droughts. Protection of the water supply against increased demand and protection of groundwater and surface waters against overuse requires regional water resource planning and management.

Climate change is causing more droughts in summer and autumn almost everywhere in Switzerland. At the same time, the service water requirement in summer is rising, particularly for agricultural irrigation. Figure 7-13 shows how water scarcity (the ratio of water demand to water availability in surface waters) will change at catchment level in summer due to climate change. Even in the reference period, some catchments have a deficit from water bodies in summer (Brunner et al. 2019a). In normal years, the service water demand can be met by abstraction from groundwater, but in a 10 to 100-year drought event, large parts of the Swiss Plateau and Jura are even now suffering summer water shortages. This was confirmed in the dry years of 2003, 2015 and 2018, when bans on abstraction from surface waters and even from groundwater had to be imposed (FOEN 2019b). Further abstraction was not possible, particularly from smaller groundwater resources. Since groundwater availability is also reduced in a drought, it can be assumed that stricter regional restrictions will also have to be placed on abstraction from that source in the future.

Figure 7-13: Water shortage risk in the summer months (June, July, August)

The water balance is illustrated for normal, dry and extremely dry years, calculated from the availability in surface waters for each catchment minus the water requirement in that region under current and future conditions without climate change mitigation (RCP8.5). Brown shading indicates water shortage and blue-green indicates surplus water.



Source: Brunner et al. (2019a)

Drinking water supply security

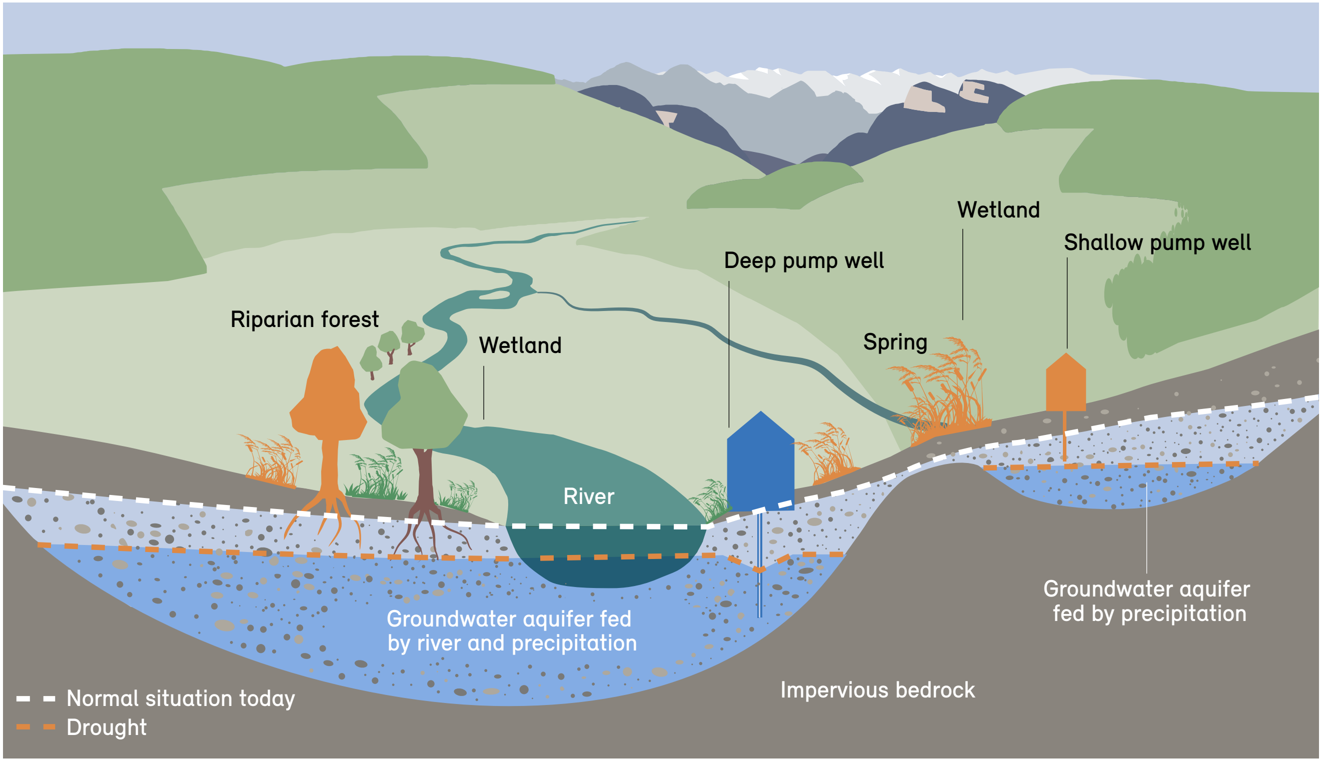
The drinking water supply can be ensured by networking the supplies and by better distribution. The basis for these measures is regional water supply planning in which the specific measures to secure drinking water supplies are defined and then implemented as part of the natural renewal and adaptation of the water supply infrastructure. It is important that the groundwater resources taken for drinking water supplies are not overused for other needs, particularly in agriculture. The water supplies must also be protected against demands from other users for the cheapest possible water in large quantities. The service water supplies must be developed or expanded if necessary. True-cost pricing must be incorporated in this process. By suitable measures in agriculture, such as innovative irrigation techniques, suitable drainage and cultivation of drought-resistant crops, overuse of the water bodies and/or deficits in the availability of service water can be prevented. In general, management of the water resources by the cantons is becoming more important in preventing conflicts between the water uses.

Ensuring groundwater functions during drought

Groundwater must be used in a way which preserves its important natural functions. Groundwater makes a significant contribution to feeding of many watercourses when flows are low and prevents aquatic habitats from drying out partly or completely. Forests also rely on groundwater during drought (Seibert et al. 2018b). The sensitivity of habitats and the susceptibility of groundwater wells to low flow and falling water tables varies considerably from place to place (Figure 7-14). A holistic regional consideration of groundwater resources and their use is required in order to conserve their functions for man and nature as far as possible, even in drought.

Figure 7-14: Water tables and groundwater functions

Effect of dry conditions on different groundwater functions: During prolonged droughts with low levels of groundwater, wetlands and water meadows dry out from time to time. Smaller pump wells cannot then reach deeper water resources and springs can dry up.



Source: Own graphic after Hunkeler et al. (2020)

Systematically protect groundwater wells for drinking water supply

Less groundwater is available locally and regionally during dry periods. The water supply is then mainly reliant on a few groundwater wells not affected by drought. These wells are essential for the supply of drinking water and their protection must be increased and accelerated as a precaution. All groundwater wells of public interest (supply of drinking water) must have designated inflow areas to protect the water quality, and remedial action must be taken on polluted wells. This mainly concerns adaptation of farm management to eliminate widespread pollution by nitrate and plant protection products. Appropriate action must also be taken to prevent drinking water sources being exposed to pollution which may be a risk to them due to their use in the inflow area.

The extreme pressures on the use of water on the Swiss Plateau and in the alpine valleys (see Figure 7-15) often lead to conflict between groundwater protection and land use needs for new development, transport networks and agriculture. Hence, many wells are no longer fully protected under the federal legal requirements. There is a clear need for action here under the provisions of water protection legislation. Existing and new conservation zones must be systematically protected to prevent them being at risk from short-term contamination due to events in the vicinity of the well (e. g. tank leaks, defective wastewater pipes).

Many wells have even had to be abandoned because suitable water quality could no longer be guaranteed or the risk of contamination was too great. For security of supply to continue, these land use conflicts must be resolved and widespread groundwater pollution must be combatted.

Figure 7-15: Impairment of the groundwater well environment by the expansion of built-up areas and traffic routes

The groundwater pumping stations in Niedergösgen (brown) and Schönenwerd (blue) were originally built on greenfield sites in 1962, but are now in built-up areas.

1962

2020

Sources: Lanz K. (ed.) (2020), based on Hug et al. (2017); base map: Federal Office of Topography

Strategies for adaptation to climate change

- Implement regional water resource management by the cantons.
- Exploit the potential for more efficient water use.
- Systematically enforce the planned groundwater protection and the domestic use of groundwater plan (Article 43 WPA and Article 46 para. 2 WPO), definition and protection of inflow areas.

Further information and references on 'Water protection'

- FOEN residual flow website: *www.bafu.admin.ch/restwasser*
- Brunner M. et al. 2019a: Wasserspeicher. Welchen Beitrag leisten Mehrzweckspeicher zur Verminderung zukünftiger Wasserknappheit? Hydro-CH2018 report.
- Practical bases for regional water resource management in three modules: *www.bafu.admin.ch/wasserressourcenmanagement*
- Seibert J. et al. 2018b: BAFU-Projekt Niedrigwasser und Grundwasser.

7.4 International importance of Swiss water bodies

The Rhine, Rhone, Ticino, Inn and Doubs rivers carry large volumes of water from Switzerland into surrounding countries and further on to the sea. Since the countries downstream rely on that water, Switzerland bears great responsibility for careful handling of the resource.

The neighbouring countries and downstream riparians use the water resources in many different ways, such as for drinking water, irrigation, cooling and electricity production. The basis for intact water ecology and flood protection must also be guaranteed downriver. The different interests are governed by international agreements, treaties or specific bodies (see case study of the Ticino, box below). Unobstructed shipping along the Rhine to the sea is also contractually guaranteed (revised Rhine Navigation Convention or Mannheim Convention of 1868). An overview of the internationally coordinated interests is shown in Figure 7-16.

Consequences for the Rhine riparians and Rhine navigation

In some ways, the impact of climate change on the boundary waters has a greater effect on the countries downstream than on Switzerland itself. For example, high flow in the Rhine below Basel occurs mainly in winter, which is when the river flow above Basel is low. With the rise in winter flows and precipitation, the high flow contribution

Ticino case study, Lake Maggiore

The Lake Maggiore catchment is divided almost equally between Switzerland and Italy, although the lake itself is mainly in Italy. The water management interface between Switzerland and Italy is the Sesto Calende weir, where the outflow from Lake Maggiore into the River Ticino has been regulated since 1943. Switzerland has no influence on the outflow control, but a regulation range for the lake level was agreed between Italy and Switzerland in 1938. The Italian Consorzio del Ticino is free to decide the lake outflow within the agreed limits.

In the summer months, irrigation is the priority in the downriver provinces of Lombardy and Piedmont: The Villoresi and Naviglio Grande canals fed by the Ticino supply up to 120 m^3/s to the arable lands of Lombardy (Gandolfi 2003). Abstraction from other areas benefits the Piedmont provinces of Vercelli and Novara, where around half the rice cultivation of Italy is concentrated. On one hand, the irrigation consortia take the view that the lake should be managed as a retention reservoir with a high water level so that irrigation is not restricted in July and August. On the other hand, the water requirement for agriculture could be hugely reduced by more efficient application techniques, given that micro irrigation systems in Lombardy only account for 1.4% in 2010 (Lombardy Region 2015).

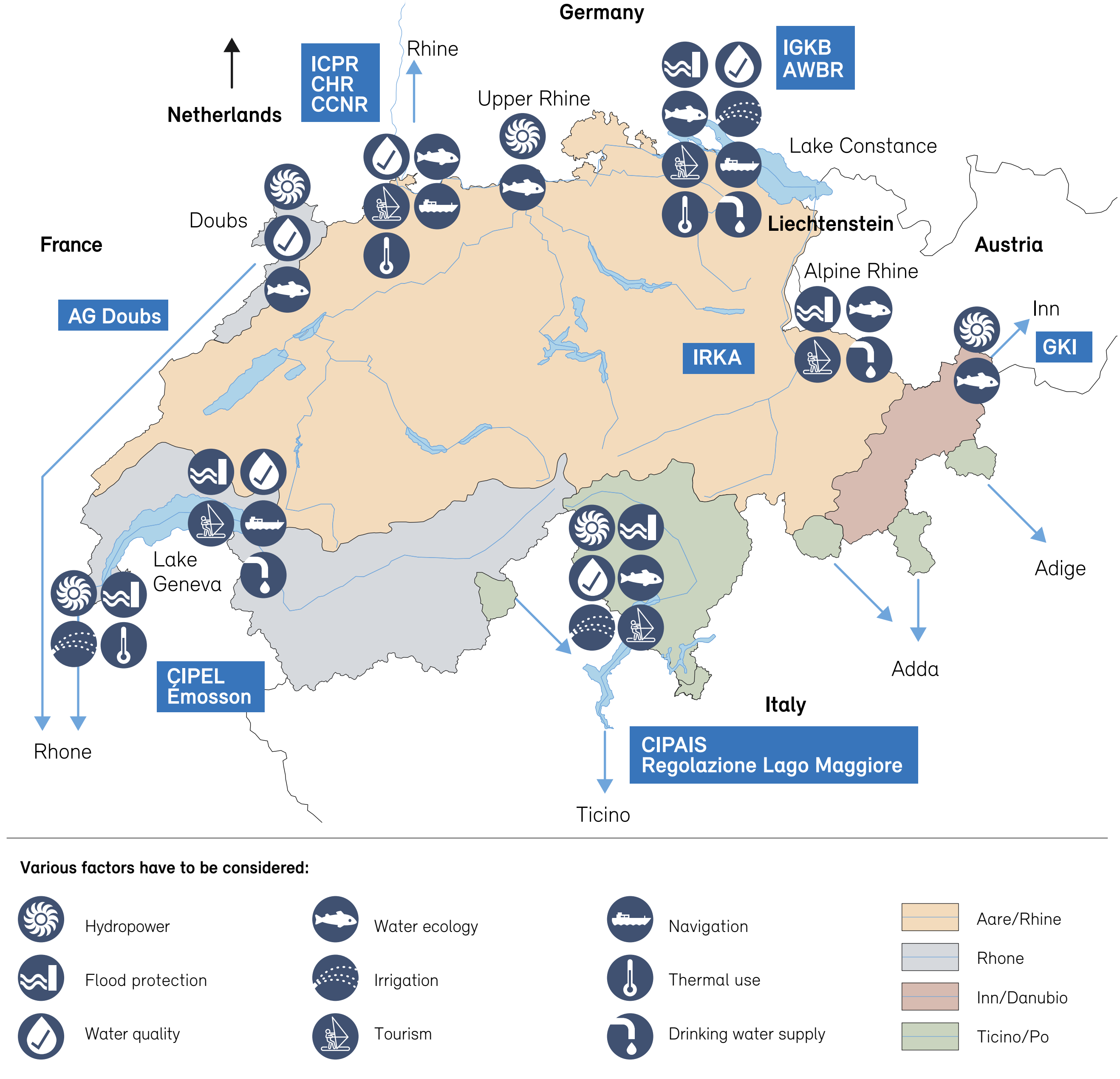
The lower reaches of the Ticino with the Parco del Ticino nature reserve suffer from reduced flow all year round, because up to 90% of the river water is diverted into canals. The local nature conservation associations are lobbying, like the farmers, for the highest possible water level in Lake Maggiore to guarantee sufficient residual flow in a sustained drought.

A rise in the maximum water level in summer is rejected by the lakeside communities on Lake Maggiore on both sides of the border. A high water level reduces the buffer capacity to absorb the torrential rains which are a frequent occurrence in the catchment of the lake. The risk of flooding is increasing along its banks and downriver at the confluence of the Ticino and the Po near Pavia. A higher lake level also has a negative impact on the accessibility of the beaches and on the Bolle di Magadino nature reserve, especially in spring.

When considered closely, regulation of the outflow and water level of Lake Maggiore causes conflict not between Italy and Switzerland but between the stakeholders further downstream and the interests of the lakeside communities.

Figure 7-16: Internationally coordinated management factors

The management of cross-border waters requires coordinated planning on many fronts and international commissions and working groups have been set up for this.



International bodies

AG Doubs Doubs binational working groups
AWBR Arbeitsgemeinschaft Wasserwerke Bodensee-Rhein
Regolazione Lago Maggiore – Italo-Swiss Bilateral Consultative Organisation on Lake Maggiore Regulation
CIPAIS International Commission for the Protection of Italo-Swiss waters
CIPEL International Commission for the Protection of Lake Geneva
Emosson Franco-Swiss working group on Emosson water agreements
GKI Inn Joint Venture Power Generating Plant
IGKB International Water Protection Commission for Lake Constance
ICPR International Commission for the Protection of the Rhine
IRKA Intergovernmental Commission on the Alpine Rhine
CHR Commission for the Hydrology of the Rhine basin
CCNR Central Commission for the Navigation of the Rhine

Source: After Lanz (ed.) (2020)

from Switzerland will increase in the cold season in future. However, the high flow contribution from snow and ice is decreasing, which could further increase future low flow events in summer and autumn in the lower reaches of the Rhine. During the low water event in September 2003, for instance, over 75% of the Rhine outflow at Lobith on the Dutch border came from the catchment above Basel. 16% of that was from glacier melt (Stahl et al. 2016). Commercial shipping had to be greatly reduced or halted completely for a time during that sustained and significant low flow period. As a result, imports coming by water such as crude oil and animal feed fell by 20% from the previous year (Swiss Rhine Ports 2019). The economic and strategic importance of Rhine shipping is huge: In terms of quantity, over 10% of Switzerland's export trade passes along the Rhine – around 7 million tonnes of goods and 100,000 containers annually. Because Switzerland is so dependent on imports along the Rhine, it has a great interest in internationally coordinated management of the river. If more frequent and severe low water events were to occur on the Rhine in future, as predicted by the hydrological scenarios, the economic risks would be considerable.

Water use conflicts

The effects of international water management and its adaptations vary widely from region to region. The reactions of the different water users can magnify conflicts between upper and lower reaches and between different sectors, as the Ticino case study shows.

Strategies for adaptation to climate change

- Manage the international river catchments with their vital lifelines for man and nature sustainably, to make them more resilient to the effects of climate change. Safeguard or improve their water quality, because they are used as drinking water resources by the communities downstream.
- Optimise water use (demand management): create incentives to utilise existing water saving potential, e.g. for irrigation and cooling. This reduces the pressure on the water resources and makes cross-border cooperation easier.
- Guarantee the reliability and safety of Rhine navigation, e.g. by dredging the navigation channel (started in the Basel city region).

Further information and references on 'Management of boundary waters'

- Lanz K. 2020: Bewirtschaftung der Grenzgewässer. In: Lanz K. (Ed.): Auswirkungen des Klimawandels auf die Wasserwirtschaft der Schweiz. Hydro-CH2018 report.

8 Improving the knowledge bases

Adaptation to climate change in water management is already under way. To react more effectively to the consequences of climate change and to refine and optimise the adaptation strategies, even more high-quality knowledge bases and databases are required. The research gaps indicated must be closed and monitoring improved. Dialogue must also be maintained with the users of that information.

To adapt to climate change, wide-ranging knowledge bases are required about the natural processes that are changing due to the climate and on the effects already observed and yet to come on the environment, society and the economy. These knowledge and decision-making bases will generally be created by research and environmental monitoring specialists, in close collaboration with experts and users in the field. Building on this, the actual adaptation measures will then be developed by professionals from the different sectors of water management. To ensure that the knowledge bases can be used to develop adaptation measures, they must be collated, interpreted and in some cases refined and then be processed so as to be user-friendly.

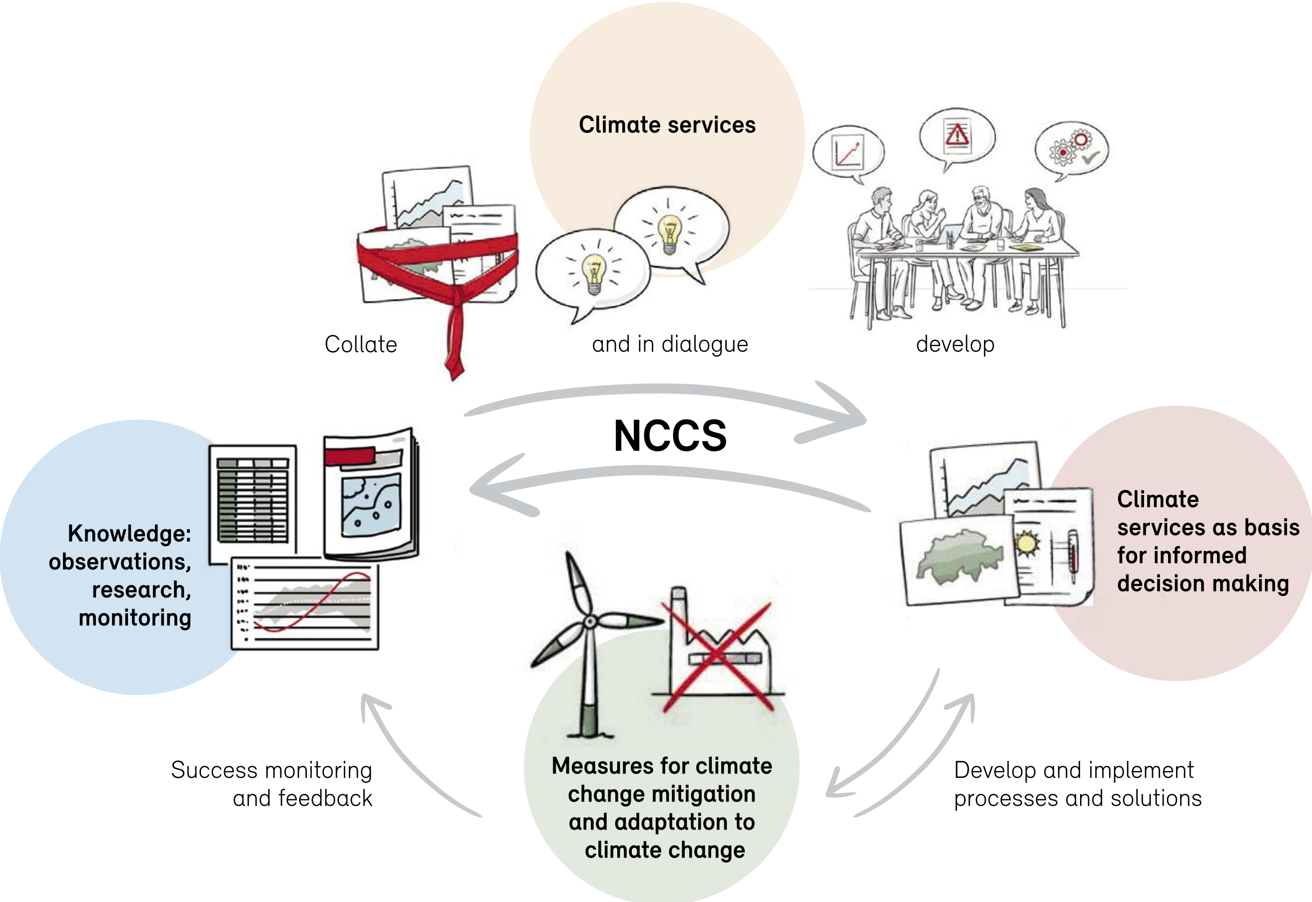
Hydro-CH2018 is a priority theme of the National Centre for Climate Services (NCCS). The purpose of that organisation is to make the necessary processed knowledge bases – also called climate services – available for Switzerland (see box). Another function of the NCCS is to pass on information requests from professionals to research and environmental monitoring groups. Conversely, climate protection and adaptation measures which are successfully implemented provide useful suggestions for optimising the knowledge bases and particularly the future scenarios. This interrelationship between knowledge, climate services and measures and the role of the NCCS within it is shown in Figure 8-1. The work is being performed under priority themes.

Climate services and NCCS

Climate services are scientifically based information and data about the past, present and future climate and its consequences for the environment, the economy and society. They form the basis for climate-compatible decisions. In 2009, the World Meteorological Organization (WMO) founded the Global Framework for Climate Services GFCS (*gfcs.wmo.int/*) which is calling for national coordinating mechanisms to be established for the development and delivery of climate services. These functions are coordinated for Switzerland by the National Centre for Climate Services NCCS, a federal network established in 2015. The NCCS is organised as a virtual centre and combines central and decentralised administrative units[7] of the confederation. The purpose of the NCCS is to combine climate services across different sectors and make them available for use, to promote dialogue with the stakeholders and thus to produce and communicate coordinated and customised climate services. The users can then develop processes and solutions for climate protection and adaptation to climate change.

7 NCCS members: Federal Office of Meteorology and Climatology MeteoSwiss, Federal Office for the Environment FOEN, Federal Office for Agriculture FOAG, Federal Office of Public Health FOPH, Federal Office for Civil Protection FOCP, Federal Office for Food Safety and Veterinary Affairs FSVO, Swiss Federal Office of Energy SFOE, ETH Zurich, Federal Institute for Forest, Snow and Landscape Research WSL. NCCS partners: Agroscope, Oeschger Centre for Climate Change Research, Research Institute of Organic Agriculture FiBL, ProClim, Prevention Foundation of Cantonal Building Insurers KGV, Swiss Hail Insurance Company, Swiss Insurance Association SIA

Figure 8-1: Interrelationship between knowledge, climate services as the basis for decisions and measures on climate protection and adaptation, and the role of the NCCS in that system



Source: after NCCS

Many climate services are already available
The priority themes of the NCCS provide climate services such as the CH2018 climate scenarios as the basis for all other priority themes and the Hydro-CH2018 hydrological scenarios. Climate services are also created by other federal projects such as the pilot programme 'Adaptation to Climate Change'. Climate services come in many different forms:

- Synthesis products give quick and easy access to current knowledge in the form of final and background reports, NCCS brochures, information on the NCCS website (*www.nccs.admin.ch*), videos etc.
- Events such as stakeholder workshops and the final symposium of the Hydro-CH2018 project, the annual NCCS Forum and the symposium 'Adaptation to Climate Change' provide a platform for knowledge transfer and dialogue between scientists and professionals and also for the formulation of needs by the stakeholders.
- Data portals such as the NCCS web atlas, HADES data and the map portal *www.map.geo.admin.ch* supply climate and hydrological scenarios, data and graphics.
- Provision of advice, communication and media relations on climate change and climate services.

Need for further climate services exists
The following requirements for climate services covering climate scenarios, hydrology and water management were identified at a stakeholder workshop in 2018:

- Information on and during droughts: Firstly, the latest information and forecasts are required when an event occurs and secondly there is a need for high-resolution,

long-term projections of low flow and drought parameters (e. g. Q_{347} and NM7Q).
- Nationwide, comprehensive information on current and future water temperatures in the rivers and lakes for water protection and thermal use.
- Nationwide, comprehensive information on local and large-scale heavy precipitation now and in the future for urban and road drainage and flood protection.
- Hydrological bases for agriculture to raise awareness and form the basis of decisions for agricultural policy and farming advice, and for insurers, cantonal departments and agribusinesses.
- Information on groundwater for heat transfer, particularly for urban regions with high usage through geothermal probes; on storage processes in aquifers and on the significance of karst regions during low flow periods
- Activities and materials for education, communication, awareness raising and consulting.

Driving research forward consistently
Further research is needed to cover the demand for climate services described above. In addition to continuing with basic research for purposes of improving process knowledge and models derived from it, the following areas have been identified as very important:

- Further development of climate modelling and statistical downscaling, particularly in terms of small-scale processes and structures such as convective precipitation modelling (e. g. thunderstorms). The objective is to improve the spatial and temporal resolution and the consistency between the various climate variables. On the basis of that more precise conclusions on future flood developments are expected.
- Conclusions on the development/changes in large-scale flooding in terms of probability, discharge and geographical extent.
- Systematic consideration of the hydrological cycle as a whole: atmosphere, land surface, hydro(geo)logy, ecosystems and effects of different uses. The individual subsystems are interdependent and influence each other significantly. But most environmental models are limited to one subsystem, while the others are greatly simplified or are only considered as a constant boundary condition. This makes it hard to identify and quantify feedback effects between the subsystems.
- In-depth analysis of the impact of climate change on water quality and the aquatic ecosystems. For instance, little is yet known about the consequences of increased irrigation on water pollution from pesticides and nitrates or the effects of climate change on erosion and sediment transport. Knowledge is also lacking about the combined impact of substance pollution and climate-related stress (multi stressors) on aquatic ecosystems.
- How to handle the uncertainties inherent in predictions. Of particular relevance are uncertainties about developments which transform a system rapidly and irreversibly and to a different state (tipping points). Up to now, knowledge of these tipping points has been inadequate for modelling purposes. But a suitable early warning system is essential to prevent irreversible changes. More research on the tipping points is therefore required.
- Socio-economic and policy research: Socio-economic scenarios are desirable, as inputs for environmental modelling, cost/benefit analyses for climate protection and adaptation measures, to derive acceptance and values (legitimation of decisions to act) and objectives for the intended future development of the water bodies.

Along with provision of these scientific bases, networking between research and practice should be intensified, such as by the creation of systematic interfaces (e. g. the VSA water quality platform).

Regular updates to the hydrological scenarios
The measures to adapt to climate change are geared towards the hydrological scenarios and in some cases are very long term. Frequent updating of the scenarios might therefore complicate adaptation. They should only be updated when relevant changes in the water balance occur. What changes are relevant must be decided in dialogue with the users. Some reasons for major changes in the hydrological scenarios could be: findings from new generations of climate scenarios, new process knowledge or improved basic data availability. This requires operationalisation of the computation of hydrological scenarios (like the climate scenarios) and monitoring of the scientific developments within the NCCS.

Better orientation of existing monitoring on climate issues

Good databases on climate, water balance, water management and regional characteristics are essential both for research and for the computation of scenarios and implementation of adaptation measures associated with water. In order to be able to monitor and record climate-related changes in the water bodies, there is a need for long and homogenous measurement series which are influenced as little as possible in water management terms (i. e. by human uses). It is therefore very important for measurement series which meet these criteria to be continued. This cannot be taken for granted, because existing monitoring sites often have to be abandoned or moved, e. g. due to hydraulic projects for better flood protection, to expansion and restructuring of hydropower uses or to make monitoring more practicable.

In the past, hydrological parameters (e. g. runoff, water table) were generally monitored for purposes of water use, flood protection or water protection rather than for the effects of climate change. This means that some climate-relevant parameters and catchments are under-represented in the networks. Mainly affected by this are alpine glaciated regions for flow monitoring and small watercourses on the Swiss Plateau for the water temperature network. In the large lakes, continuous recording of temperature-depth profiles must be increased. There is a lack of basic research or a total absence of monitoring for lakes in the alpine region which are just beginning to form as a result of glacier retreat. The data situation for sediment transport and soil moisture is also unsatisfactory.

At international level, data on many climate-relevant measuring series is collected and made available by the Global Climate Observing System GCOS[8]. In Switzerland various institutions operate monitoring networks which overall give a very broad view of the effects of climate change. The aim of GCOS Switzerland is to maintain these climate-relevant series and to develop and coordinate them as necessary.

Important databases are lacking or inadequate

The hydrological modelling and modelling of developments in agriculture, forestry and ecology form the basis for various adaptation measures. All these models need basic data, which is currently non-existent or not of sufficient quality and resolution. The central focus is to have consistent, comprehensive information on soil, geology and land use. The main priority here is to collect nationwide soil information.

Data on the current use of water by agriculture, tourism and industry and commerce is not currently collected systematically by most cantons. Socio-economic future scenarios from which the future development of water consumption could be deduced also exist only in part. Water consumption by both individual users and large sectors should be known, to form the basis of long-term adaptation of water management to climate change. Only by detailed knowledge of consumption patterns can supply networks be suitably designed and the use of water be balanced with its long-term availability.

Likewise not consistently collected in Switzerland is data on the effects already observed of climate change on water management, for instance where and when water abstraction bans have to be imposed at times of low water. Some data exists at cantonal, regional and local level and among private stakeholders, but its recording and collection are not consistent or standardised. Water management information is very important for adaptation to climate change and there is a need for data collection on climate impacts to be coordinated and made available centrally.

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9 Conclusion: Need for climate protection and adaptation to climate change

The effects of climate change on the water resources can already be felt today and will intensify in future. If climate change continues unabated, water bodies will suffer great changes, with serious negative effects on water ecology and management. If the targets in the Paris Agreement are successfully achieved and global warming is limited to well below 2 °C, many of these changes can be prevented and it will be easier and less expensive to adapt to those that remain.

The results of Hydro-CH2018 show that runoff will increase in winter and further decrease in summer. The glaciers will also continue to shrink and less and less snow will fall. Extreme hot and dry periods will occur more frequently in summer and lead to water shortage situations. The water temperatures will increase, with some serious consequences for aquatic organisms. But there is still uncertainty about future developments, such as the frequency of extreme hydrological events or the reaching of ecological tipping points at which fundamental and irreversible changes occur. For better assessment of future developments, it is essential to monitor the changes, improve the knowledge bases and possess reliable hydrological scenarios. The foundation for this is to secure and further develop robust hydrological measuring infrastructure with reliable data series. Drought and low flow predictions which use new digitalisation and remote sensing methods are also necessary.

Protection of the water bodies, water use, flood protection and agriculture must face the challenge of the new hydrological conditions with their changes in water availability. However, substantial differences exist on the scale of the changes, depending on whether the future climate evolves according to a scenario with or without global climate protection measures, as shown by a comparison of the scenarios for watercourses in summer, for example. With resolute climate change mitigation, the temperature increase in the Swiss Plateau watercourses can be limited by the end of the century to below 2 °C and the decrease in summer runoff to 20%. Without climate change mitigation the Swiss Plateau rivers would warm by around 4.5 °C and the summer runoff would decrease by up to 50% – even in the long-term average. This would cause small watercourses to fall dry more frequently. Warming and decreases in runoff on that scale would change the water bodies in a way never before experienced, at least in summer. Today's aquatic ecosystems and the composition and distribution of species would change fundamentally and inexorably.

Limiting climate change is thus also important from the perspective of the water bodies. To enable the ecosystems to continue to fulfil their basic functions in the distant future, foresighted water planning water bodies is critical. The renaturation programme now under way for revitalisation of water bodies and ecological restoration of hydropower, the guarantee of appropriate residual flow, the upgrading of water treatment plants and the reduction in substance inputs from agriculture are all central in reducing pressure on the water bodies. That pressure will increase further with climate change, which makes it even more vital to protect and promote water bodies which are as natural as possible.

The demand for service water, particularly by agriculture, will rise sharply in times when availability will be scarcer. In many places it will no longer be possible to maintain the current systems and uses and they will have to be adapted. In agriculture, for instance, this can be achieved by cultivating drought- and heat-resistant crops or varieties, more efficient use of water or new infrastructure to store and supply water. In industry and commerce, it is important to develop and promote water-saving technologies and processes. Regional water supply plans covering all the user sectors are also necessary to prevent local shortages.

The mountains will suffer extremely severe changes. The rise in the zero-degree isotherm will affect winter tourism, with potentially significant negative consequences for the tourism industry. On the other hand, opportunities will be created for summer tourism in the Alps and on the water. Natural hazards will increase, due to glacier melt, permafrost warming and more intensive heavy rainfall. Integrated risk management is already addressing these hazards.

New lakes, watercourses and wetlands will appear in the mountains. These are of great ecological significance, but could also be used to generate electricity. It is therefore important to launch a national, cross-sectoral process to clarify how to handle these changed landscapes in the future. The hydrological transformation in the mountains will also impact neighbouring countries, where numerous users rely on the water from Switzerland.

Nature and water use, flood protection and water protection have already begun to adapt to the changed conditions. With the strategy 'Adaptation to climate change in Switzerland' (Swiss Confederation 2012), the Federal Council created the framework for a coordinated procedure. It contains the targets for adaptation and describes the greatest challenges and the scope for action to adapt at federal level. The adaptation strategy was implemented by the first action plan for the years 2014 to 2019 (Swiss Confederation 2014). The second action plan adopted in 2020 governs implementation in the years 2020 to 2025 (Swiss Confederation 2020).

The results from Hydro-CH2018 – where already available – were included in the preparation of the 2020–2025 action plan (Table A-3). However, for successful adaptation the climate-related changes in the water balance must not take place too quickly. From a water body perspective, it is clear: climate protection is not an option, it is a necessity! Far-reaching changes can only be prevented and the costs of adaptation can only be limited by concerted climate protection.

Climate change is a global phenomenon. The Paris Agreement adopted on 12 December 2015 at the Paris climate conference obliges the signatory parties to keep global warming below 2 °C and to aim for maximum warming of 1.5 °C. Switzerland ratified the Agreement on 6 October 2017 and made a commitment to reduce emissions by 50% from their 1990 levels by 2030. By 2050, greenhouse gas emissions are to be reduced to net zero. But at the same time adaptation to climate change must be driven forward forcefully.

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11 Glossary

Biodiversity
Biodiversity comprises the different life forms (species of animals, plants, fungi, bacteria), the various habitats in which species live (ecosystems such as water bodies) and the genetic diversity within the species (e. g. subspecies, varieties and breeds).

Emission scenarios: RCP2.6, RCP8.5
Possible future development pathways of anthropogenic emissions of greenhouse gases and aerosols. The latest emission scenarios (Representative Concentration Pathways, RCP) indicate how the greenhouse gas and aerosol concentrations must develop in order to achieve a specific climate target. 2.6 and 8.5 represent the expected radiative forcing in the year 2100 in W/m^2.
RCP2.6: concentration pathway with resolute climate change mitigation conforming to the Paris Agreement
RCP8.5: concentration pathway without climate change mitigation measures

Feedback effects
Reaction of a system to a change: a positive feedback is a self-reinforcing process; a negative feedback means that a change is balanced by an opposite reaction.

Heavy precipitation
Heavy precipitation is precipitation which has high intensity relative to its duration. Heavy precipitation events can be either precipitation with short duration and high intensity or precipitation lasting for several hours or days with high rainfall amounts. In addition to duration and frequency, the size of the area affected by the heavy precipitation is also critical.

Hydropeaking
Temporary and frequent changes in flow due to turbining of reservoir water in hydropower plants for electricity production. Hydropeaking sections are watercourse sections affected by these fluctuations in runoff.

NM7Q
The annual minimum flow rate averaged over 7 days. Averaging over several days makes this low flow parameter less susceptible than others to measurement errors or short-term anthropogenic influences.

PKD
PKD is the abbreviation (Proliferative Kidney Disease) for a kidney disease occurring in certain species of fish. The disease can be fatal if the water temperature exceeds 15 °C for extended durations.

Q_{347}
Under Article 4 Waters Protection Act, the flow rate Q_{347} is the flow rate which, averaged over ten years, is reached or exceeded on an average of 347 days (95^{th} percentile) per year and which is not substantially affected by damming, abstraction or inflow of water.

Runoff regime: glacial, nival, pluvial
Characteristic seasonal runoff variations in a watercourse, which is dependent on meteorological factors and the characteristics of the catchment. Glacial regimes are characterised by the glacier melt in summer, nival regimes by the snow melt in spring, pluvial regimes by the interplay of rain and evaporation.

Surface runoff
Surface runoff is rainwater which does not percolate, particularly during heavy precipitation, but runs along the open ground and can cause damage.

Water management
Water management comprises all the human activities for use of the water, protection of the water and protection against hazards from the water.

12 Annex

Table A1: Models used in the Hydro-CH2018 project

Model	Approaches used	Calibration	Spatial resolution	Temporal resolution	Bibliography
PREVAH-WSL	Evaporation: Penman-Monteith Runoff formation: PREVAH HBV type Snow melt: degree-day-extended (Hock 1999) Glacier ice melt: degree-day extended (Hock 1999). Only the extent of the glacier is considered. Glacier extent is updated every 5 years with data from Zekollari et al. (2019)	Calibration using measured discharge. Regionalisation for regions without discharge monitoring by Kriging.	Swiss political raster 500 × 500 m Swiss hydrological raster 200 × 200 m	1 day	Brunner et al. 2019c Speich et al. 2015
PREVAH-UniBE	Evaporation: Hamon Runoff formation: PREVAH HBV type Snow melt: degree-day (Hock 1999) Glacier ice melt: degree-day extended (Hock 1999). Only the extent of the glacier is considered. Glacier extent is updated every 5 years with data from Zekollari et al. (2019)	Calibration using measured discharge. No regionalisation.	HRU-based; 93 catchments	1 day	Viviroli et al. 2009
HBV Light-UniZH	Evaporation: Hamon Degree-day approach for snow- and glacier ice melt Glacier changes simulated by the Huss-dH approach (Seibert et al. 2018a)	Calibration using measured discharge, snow line from MODIS, glacier volume. Regionalisation of flow modelling parameters for regions without flow monitoring.	Semi-distributed, HRU-based; 190 glaciated catchments	1 day	Seibert and Vis 2012 Seibert et al. 2018a
COSMO-CLM[2] ETH Zurich coupled regional climate model			Europe on a 0.44 × 0.44° (50 km) raster	1 day	Davin et al. 2011
Simstrat (v. 2.1.2) Eawag	One-dimensional (vertically resolved) hydrodynamic model	Calibrated using measured temperatures for 27 of the 29 lakes simulated	0.5 m (vertical)	10 minutes	Goudsmit et al. 2002 Gaudard et al. 2019
Snowpack/Alpine3D, StreamFlow EPFL	Physically based approaches. Retention time of water in the soil is parameterised according to Corrola (2015) and water concentration according to Gallice et al. 2016.	Snowpack/Alpine3D: no calibration Streamflow: calibration of retention time of water in soil and soil heat flux	Snowpack/Alpine3D: 100 or 500 m Streamflow: 100 or 500 m	1 hour	Lehning et al. 2006 Gallice et al. 2016
Hydrogeosphere Neuchâtel Uni	Evaporation: current evapotranspiration Soil water-groundwater flow modelling fully coupled Groundwater: spatially distributed flow field according to Darcy's law Runoff: runoff in river system, snow melt: degree-day	Calibration using measured snow depths, discharge and groundwater levels	Finite elements (2 to 100 m)	1h to 1 day	Brunner and Simmons 2012

Model	Approaches used	Calibration	Spatial resolution	Temporal resolution	Bibliography
Feflow©, ArcMap© Basel Uni	'Raster analysis', 'Hydrology tool' (ArcMap©), flow time derived from computed flow lengths and Darcy flow velocities 'GeoTher' tool (Alcaraz et al. 2016)	Basel-Stadt: calibration and validation based on hydraulics and temperature data from >100 GW monitoring stations	5 to 25 m	1 day	Diersch 2014 Alcaraz et al. 2016 Epting et al. 2013 Mueller et al. 2018
PREVAH-WSL, coupled with forest development model	Evaporation: Penman-Monteith Runoff formation: PREVAH HBV type Snow melt: degree-day extended (Hock 1999) Glacier ice melt: degree-day extended (Hock 1999). Glacier changes simulated using the Huss-dH approach	Calibration using measured discharge. Regionalisation for regions without discharge monitoring by Kriging.	200 × 200 m 6 large regions in different climate regions of Switzerland and alternation between south and north facing slopes.	1 day	Speich et al. 2015 Speich et al. 2020
Topkapi-ETH ETHZ operated by AWE-GEN-2d weather generator	Spatially distributed and physically explicit model Evaporation: Priestley-Taylor Wave process in the channel: kinematic wave (Fatichi et al. 2015) Snow melt and glacier ice melt: temperature index method (Pellicciotti et al. 2005)	Calibration using measured discharge	100 m raster for Thur, Kleine Emme and Maggia	1 hour, downscaling with weather generator	Fatichi et al. 2015 Peleg et al. 2017 Peleg et al. 2019 Peleg et al. 2020
Plant growth model CropSyst	Evaporation: Penman-Monteith Soil water content: cascade model (daily)	Calibration using statistical input data	Field scale	1 day	Stöckle et al. 2003

Table A2a: RCP8.5 climate mode chains used for hydrological modelling

Some climate model chains are available in two spatial resolutions: EUR-11 or 0.11° marked x and EUR-44 or 0.44° marked (x).

Global climate model GCM	Model run	Regional climate model RCM	PREVAH-WSL	PREVAH-UniBE	HBV Light-UniZH	Soil ETH Zurich	Lake Eawag	Water temp. EPFL	UniNE GW recharge	UniNE alpine HSG	UniNE alpine HSG	Basel Uni	Topkapi-ETHZ	HSG Agriadapt	Cropsyst Agriadapt	WSL Forest development
eCHEC-EC-EARTH	r1i1p1	KNMI-RACMO22E	x	x	x	(x)	x	(x)								x
	r3i1p1	DMI-HIRHAM5	x(x)	x(x)	x	x	x	x					x		x	x(x)
	r12i1p1	CLMcom-CCLM4-8-17		x	x	x							x			
	r12i1p1	CLMcom-CCLM5-0-6	x	x	x	(x)	x									x
	r12i1p1	SMHI-RCA4	x(x)	x(x)	x	x	x		x				x			x(x)
MOHC-HadGEM2-ES	r1i1p1	KNMI-RACMO22E	x	x	x	(x)	x	(x)							x	x
		CLMcom-CCLM4-8-17	x	x(x)	x	x	x						x		x	x
		CLMcom-CCLM5-0-6	x	x	x	(x)	x	(x)								x
		SMHI-RCA4	x(x)	x(x)	x	x	x		x		x		x			x(x)
		ICTP-RegCM4-3			x	(x)										
MPI-M-MPI-ESM-LR	r1i1p1	CLMcom-CCLM4-8-17		x(x)	x	x							x			
		CLMcom-CCLM5-0-6	x	x	x	(x)	x									x
		MPI-CSC-REMO2009		x(x)									x			
		SMHI-RCA4	x(x)	x(x)	x	x	x	(x)	x	x	x	x	x		x	x(x)
	r2i1p1	MPI-CSC-REMO2009		x(x)	x	x										
MIROC-MIROC5	r1i1p1	CLMcom-CCLM5-0-6	x	x	x	(x)	x									x
		SMHI-RCA4	x	x	x	(x)	x	(x)	x						x	x
CCCma-CanESM2	r1i1p1	SMHI-RCA4	x	x	x	(x)	x	(x)	x	x	x					x
CSIRO-QCCCE-CSIRO-Mk3-6-0	r1i1p1	SMHI-RCA4		x	x	(x)	x		x					x	x	
IPSL-IPSL-CMSA-MR	r1i1p1	SMHI-RCA4		x(x)	x	x	x						x			
NCC-NorESM1-M	r1i1p1	SMHI-RCA4	x	x	x	(x)	x									x
NOAA-GFDL-GFDL-ESM2M	r1i1p1	SMHI-RCA4		x	x	(x)	x									

Table A2b: RCP2.6 climate model chains used for hydrological modelling

Some climate model chains are available in two spatial resolutions: EUR-11 or 0.11° resolution x and EUR-44 or 0.44° marked (x).

Global climate model GCM	Model run	Regional climate model RCM	PREVAH-WSL	PREVAH-UniBE	HBV Light-UniZH	Soil ETH Zurich	Lake Eawag	Water temp. EPFL	UniNE GW recharge	UniNE Alpine HSG	UniNE Alpine HSG	Basel Uni	Topkapi-ETHZ	HSG Agriadapt	Cropsyst Agriadapt	WSL Forest development
ICHEC-EC-EARTH	r1i1p1	KNMI-RACM022E														
	r3i1p1	DMI-HIRHAM5	x	x(x)	x		x	(x)						x	x	x
	r12i1p1	CLMcom-CCLM4-8-17														
	r12i1p1	CLMcom-CCLM5-0-6														
	r12i1p1	SMHI-RCA4	x(x)	x(x)	x		x									x(x)
MOHC-HadGEM2-E	r1i1p1	KNMI-RACM022E	x	x	x		x	(x)							x	x
		CLMcom-CCLM4-8-17														
		CLMcom-CCLM5-0-6														
		SMHI-RCA4	x	x	x		x									x
		ICTP-RegCM4-3														
MPI-M-MPI-ESM-LR	r1i1p1	CLMcom-CCLM4-8-17														
		CLMcom-CCLM5-0-6														
		MPI-CSC-REMO2009		x(x)												
		SMHI-RCA4	x	x	x		x	(x)				x			x	x
	r2i1p1	MPI-CSC-REMO2009		x(x)	x											
MIROC-MIROC5	r1i1p1	CLMcom-CCLM5-0-6														
		SMHI-RCA4	x	x	x		x	(x)							x	x
CCCma-CanESM2	r1i1p1	SMHI-RCA4														
CSIRO-QCCCE-CSIRO-Mk3-6-0	r1i1p1	SMHI-RCA4														
IPSL-IPSL-CMSA-MR	r1i1p1	SMHI-RCA4														
NCC-NorESM1-M	r1i1p1	SMHI-RCA4	x	x	x		x									x
NOAA-GFDL-GFDL-ESM2M	r1i1p1	SMHI-RCA4														

Table A-3: Adaptation measures at federal level

Measures related to water management and water bodies in the first and second action plans AP1 and AP2 and their implementation status (Swiss Confederation 2014 and 2020) are presented.

	Number	Name	2020 status
Water	AP2-w1	Collection of Swiss water requirement data	New measures
	AP2-w2	Review of the water protection measures in terms of climate change	
	AP1-w1	Planning instruments for water resource management	Ongoing
	AP1-w3	Networking and security of the water supply	
	AP1-w4	Potential of water retention and reservoirs	
	AP1-w5	Lake regulation	
	AP1-w6	Swiss lake and reservoir management in the international context	
	AP1-w7	Consideration of changes in discharge and temperature regimes for urban drainage	
	AP1-w10	Early detection of drought	
	AP1-w2	Boundary conditions for water management in the catchment – promotion by communication, knowledge transfer and education	Completed
	AP1-w8	Heat discharge into water bodies	
	AP1-w9	Water quality – preventing further impairment of water bodies by heavy precipitation or crop irrigation	
	AP1-w11	Correction of Basel–Birsfelden navigation channel	
Natural hazards	AP1-n1	Monitoring of hazard processes	Ongoing
	AP1-n2	Awareness of hazards and risks	
	AP1-n3	Designing robust and tailored protective measures	
	AP1-n4	Implementing spatial planning measures: reducing damage potential by risk-based spatial planning	
	AP1-n5	Managing natural events successfully	
	AP1-n6	Increasing natural hazard awareness, education and research on natural hazards	
Soil	AP2-s1	National soil mapping implementation concept	New measure
Agri-culture	AP1-l1	Optimised use of suitable varieties and breeds including dealing with harmful organisms	Ongoing
	AP1-l2	Responsible use of soil and water	
	AP1-l3	Preparation of basics for location-compatible management	
Energy	AP1-e4	Studies on the effects of climate change on hydropower use including raising the awareness of those affected	Ongoing
	AP1-e5	Inclusion of the effects of climate change in dam supervision	Completed
	AP1-e6	Review of the regulations on return of cooling water	
Bio-diversity	AP2-b7	Shade creation through planting	New measure
	AP1-b3	Ensuring ecological minimum requirements and evaluation measures for habitats very reliant on sufficient water supplies	Completed
Basics	AP2-wg4	Analysis of the effects of climate change on Switzerland – CH-Impacts	New measure
	AP1-wg1	Regular production of regional climate scenarios for Switzerland	Ongoing
	AP1-wg2	Hydrological principles and scenarios for adaptation to climate change	
	AP1-wg3	Concept for the collection of soil data	Completed