Technical Report

November 26, 2025

Assessing water balances and adaptation potential at the regional scale in Switzerland

A report to the National Centre for Climate Services

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Abstract

This report assesses how climate change may alter the balance between water supply and water demand in Switzerland at the regional scale, and to what extent existing storage infrastructure and demand reduction can alleviate emerging water shortages. Building on the Hydro-CH2018 dataset, we combine hydrological simulations for 307 small catchments, aggregated into 22 mesoscale basins, with sectoral water-demand estimates across nine use categories. We analyse annual and seasonal water balances under normal (mean) and extreme dry conditions for a reference period (1981–2010) and a mid-century period (2045–2074) under RCP2.6, RCP4.5 and RCP8.5, and evaluate two stylised adaptation options: (i) enhanced use of storage in natural lakes and artificial reservoirs and (ii) an aggregate 60% reduction in non-ecological water demands.

Results indicate that, at the national and annual scale, water surpluses exceed shortages in all scenarios, with annual runoff generally exceeding total demand in all mesoscale basins under normal conditions. However, this apparent robustness masks growing seasonal and regional vulnerabilities. In summer, a number of Plateau basins begin to exhibit small but notable deficits under RCP8.5, driven by reduced summer runoff and relatively high demands from agriculture, public water supply and hydropower, while winter runoff generally increases. Under extreme dry years and dry summers, surpluses in presently water-rich Alpine basins shrink and deficits in some basins intensify.

Existing storage in reservoirs and regulated lakes can substantially mitigate shortages in many basins, but its potential is spatially uneven and insufficient to fully offset extreme summer deficits in some regions with high demand and limited local storage. Combining storage with strong demand reductions somewhat improves conditions, yet residual deficits remain. Overall, the findings highlight that Switzerland's future water challenges are primarily seasonal and regional to local management of water resources is important. Moreover, effective adaptation will require both optimised multi-purpose storage operation and targeted demand-side measures.

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Chapter 1

Background

This report has been produced in the context of the program "Decision-making basis for dealing with climate change in Switzerland: Information on cross-sectoral issues (NCCS-Impacts)" as part of the project "Costs of Climate Change in Switzerland". The project is managed by the consulting and engineering company EBP on behalf of the NCCS. This report is part of the mandate assigned by EBP to the research group Environment and Climate (Eclim) at the Department of Geography of the University of Zurich. Eclim has been mandated to assess the impacts originating from changes in the climate on human health, agriculture productivity, winter tourism and water availability and the effect of adaptation. This technical report details the work undertaken on the assessment of changes in water availability in Switzerland at the regional level without and with adaptation.

Chapter 2

Introduction

Climate change is increasingly experienced as change in water—through altered precipitation patterns, shifting seasonality of runoff, more frequent and intense droughts and floods, and warming waters—affecting societies and ecosystems worldwide [1, 2]. The IPCC's Sixth Assessment (WGII) finds robust evidence that climate change has already modified every component of the water cycle and that water-related risks will intensify with additional warming even under ambitious mitigation [1]. Globally, about four billion people face severe water scarcity for at least one month each year due to combined climatic and non-climatic drivers, highlighting the centrality of water security to human well being and economic activity [3].

Across Europe, water resources are under mounting pressure due to a combination of rising temperatures, shifts in snow and rainfall and growing demands, which lead to escalating droughts, and water scarcity alongside flooding damages [4]. Episodes such as the pan-European droughts of 2003, 2015, 2018, 2022 provide salient examples of multi-sector stress, namely crop yield losses, wildfires, forest degradation, disruption to shipping and water shortages [5]. The 2022–2024 period brought successive extremes, and by early 2023 the Alps' snow water equivalent was far below normal after an exceptionally warm, dry winter—reducing spring–summer melt contributions and heightening concern for water supply across perialpine regions [6].

Climate change is projected to intensify both dry and wet extremes as well as compound heat and dry extremes [7]. The European Joint Research Centre (JRC) calculated that by the end of the century, projected absolute drought losses for the EU+UK would rise to 170% under a global warming level of 1.5°C and to 250% under a global warming level of 2°C compared to the baseline 1981-2010. Under 3°C of global warming, annual losses would raise to 400% compared to the baseline [8]. Europe's state-of-water reports stress that adapting to concurrent scarcity, drought and flood risks is now a core management challenge [9].

Switzerland sits at the hydrological heart of the continent: the European Alps

generate high runoff relative to area and sustain downstream lowlands during summer, which is why the Alps are widely described as Europe's "water tower" [10]. Yet, despite this endowment, Switzerland has faced episodes of reduced water availability in recent years. The 2003 heatwave severely depressed soil moisture and crop yields and lowered river flows [11]. In 2018, drought severity in parts of northeastern Switzerland reached return periods exceeding a century for soil moisture, with compound low-flow deficits observed across many catchments [12, 13]. In 2023, extremely low Alpine snowpack and continued glacier loss (–4% volume in 2023 after –6% in 2022) signaled reduced seasonal buffering [14].

Understanding Switzerland future water risk requires considering both supply and demand. On the supply side, climate change is shifting the timing and magnitude of runoff: less snow accumulation and earlier melt redistribute flows from summer toward winter, while low flows and higher water temperatures become more frequent—affecting water ecology and use[14]. On the demand side, pressures come from multiple sectors. Agriculture's irrigation needs are projected to rise as summers warm and dry on the Swiss Plateau, even as summer runoff declines—intensifying seasonal competition [15, 16]. Public water supply depends predominantly on groundwater which is sensitive to prolonged dry spells and land-use pressures [17]. Hydropower Switzerland's electricity backbone—depends on seasonal inflows and storage; climate change alters inflow timing and can constrain hydropower generation [18, 19]. Tourism, especially winter sports, increasingly relies on snow making that raises localized water demand in the early winter low-flow period and may conflict with ecological and other uses [20].

Switzerland has likewise moved to operationalise drought monitoring and early warning nationally [21] and to implement a federal adaptation strategy and action plan that mainstreams water across sectors [22, 23]. Within an adaptation portfolio, re-operation and coordinated use of existing storage—both artificial reservoirs and regulated natural lakes—feature prominently for Alpine and perialpine basins. A nationwide Swiss assessment showed that, under current and future climates, summer water shortages are most likely on the Plateau north of the Alps and that regulated natural lakes often hold significant potential to alleviate local deficits; reservoirs can contribute where usable storage and connectivity align with demand hot-spots, though spatial mismatches and allocation rules limit the accessible fraction [24]. Recent work further demonstrates that lake-level management can modulate climate change impacts on outflows and levels in perialpine lakes, reinforcing the role of operating rules in adaptation [25]. National guidance notes that many Swiss lakes are regulated and can partly buffer climate-driven inflow shifts—again, within ecological and legal constraints [14]. At the same time, demand reduction—from irrigation efficiency and crop choices to leakage control, reuse, and targeted seasonal conservation—remains

essential to reduce peak deficits, especially during summer low-flow windows when ecological flows and hydropower operations also require water [26].

Against this backdrop, the present study evaluates Switzerland's water supply–water demand balance with and without climate change, and quantifies the effect of adaptation options centered on (i) strategic use and re-operation of storage in reservoirs and natural lakes and (ii) reduction of sectoral water demands (agriculture, public water supply, hydropower operations, tourism). In doing so, it builds on state-of-the-art evidence on climate-water balance in Switzerland and the growing body of evidence on adaptation feasibility and effectiveness. The report is organised as follows: Section 3 describes the methodology and data used for the study; Section 4 presents the results and finally Section 5 discusses the findings and outlines the main conclusions from the report.

Chapter 3

Methods

3.1 Methodology and data

Water availability under changing climatic conditions in Switzerland without and with climate change adaptation has been assessed building on the methodology in [27, 24]. This approach uses hydrological modeling to estimate current and future water supply in Switzerland at the meso-catchment scale. It then estimated water surpluses or shortages as the difference between water supply and water demand under normal and dry conditions.

Two main adaptation options to alleviate estimated water shortages are considered in this study, namely 1) the storage capacity of natural lakes and artificial reservoirs which also built upon [27, 24] and 2) a static reduction in total water demand.

In line with [24], a water availability framework with four main elements has been established: 1) water supply, 2) water demand, 3) water surplus/shortage and 4) adaptation through reservoir and natural lakes as well as reduced water demand. Each of the elements 1-3 is analysed in terms of yearly and seasonal distribution (i.e. summer and winter). Furthermore, the framework includes an assessment of extreme conditions.

Data on water supply, water demand and reservoirs volume have been obtained from the environmental data portal EnviDat [28]. This dataset provides runoff calculations from the PREVAH hydrological model [29] for 307 small catchments. The calibrated model is driven with daily meteorological data representing both a reference period (1981-2010) and a future period. The transient meteorological data for future climate scenarios is based on the CH2018 climate projections, which uses the EURO-CORDEX models and includes time-evolving (transient) simulations under different greenhouse gas scenarios (RCPs) [30]. These scenarios have been downscaled using quantile mapping methods for greater regional detail [30]. This dataset provides data for variables like temperature, precipitation, humidity, radiation, and wind speed for various Swiss meteorolog-

ical stations. For the scope of the present study, the future period corresponds to the thirty years window 2045-2074 with central year 2060. Three future climate scenarios are considered, namely RCP2.6 (10 model chains), RCP4.5 (13 model chains) and RCP8.5 (26 model chains). Henve, a total of 39 climate model chains are used to account for uncertainties arising from both emission scenarios and intra climate model variability.

The dataset described in [28] also contains monthly averages of water demand for the reference periods and a future period corresponding to 2070-2100 for the 307 small scale catchments. Since we are interested in the period 2045-2074 a linear interpolation is performed between the water demand in the control period and that at the end of the century. The linear interpolation is only performed for categories of water demand that are assumed to change in the future under future climate, namely irrigation, hydropower demand and winter tourism. No demographic change from the control period has been assumed in this study to keep consistent with other studies performed as part of the project. The possibility to include the shared socio-economic pathways (SSPs) in the water demand was considered, but at the time of the study there was no Swiss SSPs available at a scale necessary for this study (if at all). For the irrigation and hydropower demand the assumption were purely climate dependent and hence a linear interpolation was applied throughout.

Table 3.1: Overview on the nine categories of water demand and corresponding assumptions in the control period and future

Demand	Control	Future
Drinking water (households)	Drinking water demand from households estimated by multiplying the water use rate of 142 l per person and day with the number of inhabitants per catchment. Assumed constant over the year.	Estimated using population projections from [31]. Estimated also by keeping population as in the control period.

Drinking water (tourism)	Drinking water demand for tourism was estimated similarly to above multiplying the same water use rate by the number of overnight stays from BFS (Dec-Feb) and (Jun-Sept)	Estimated using population projections from [31]. Estimated also by keeping population as in the control period.
Industry second sector (manufacturing)	Industrial water demand was estimated by multiplying the water use rate (148 m^3) per employee with the number of employees per catchment.	Kept at the current level since no projections are available for this sector
Industry third sector (services)	Industrial water demand was estimated by multiplying the water use rate (85 m3) per employee with the number of employees per catchment.	Kept at the current level since no projections are available for this sector
Artificial snow production	Estimated by multiplying ski run area with the mean water demand per area (1200 m^3 per hectare) (only winter months)	Skiing areas below a certain altitude threshold will disappear due to unprofitability [32, 33] and assuming that the water consumption per hectare will increase to 1500 l (only winter months) assuming no technological improvements in the future.
Agriculture (livestock)	Livestock water demand was computed by multiplying the water use rate per unit of livestock (110l per day) with the number of livestock per catchment. Constant over the year.	No change

Agriculture (crop)	The irrigation water demand represents the difference between the crop water requirement and effective precipitation. Computed using time series derived by the hydrological model (April-Sept).	Estimated using potential evapotranspiration representing future climate conditions (39 model chains).
Ecology	Ecological flow requirements were considered by using a threshold flow value corresponding to the 95% quantile of daily discharges as prescribed by Swiss legislation (constant over the year)	No change
Hydropower	The water demand for hydropower production was estimated for each storage reservoir within Switzerland and then aggregated to basin- ide water demand. The monthly water demand was estimated by multiplying the monthly percentage change in storage content with the storage capacity of the reservoir, and by subsequently adding the monthly natural inflow to the reservoir. The monthly inflows were computed based on the catchment runoff simulated with the hydrological model PREVAH.	Future hydropower demand was computed with future reservoir inflows (39 model chains).

In accordance with the methodology in [24], water surplus/shortage are calculated as the difference between water supply and water demand. Normal conditions are assessed using the thirty years mean monthly values of the control and future period, while extreme conditions are assessed by comparing the supply in a dry year in the control period with the supply in a dry year in the the future period. For a representative dry year in the control period, the year 2003 has been selected. For a future dry year, the year with the corresponding minimum monthly flow across all future years and model chains has been selected. To find representative dry conditions for the summer and for the winter seasons, we

performed a univariate statistical analysis of the distribution of aggregated water discharge across all years and model chains. Extreme conditions were defined based on the lower tail of the distribution, corresponding to the 3rd percentile for summer and the 2.5^{the} percentile for winter, reflecting the generally less extreme variability in winter flows.

To simulate the effect of adaptation measures the following scenarios are considered:

- Low adaptation: water scarcity is alleviated through the water available in natural lakes and artificial reservoirs.
- High adaptation: water scarcity is addressed using the water available in natural lakes and artificial reservoirs combined with a 60% reduction of total water demand (excluding ecological demand)

The dataset available through EnviDat contained data on the storage capacities of natural lakes (using data from the Federal Office for the Environment - FOEN and calculations based on lake morphology) and artificial reservoirs (data from the Swiss Federal Office of Energy - BFE) for 307 small scale catchments. The total storage capacity at the catchment level is the sum of the capacities of all lakes and reservoirs within that catchment. For the purpose of our study, the amount available from natural lakes and drinking water reservoirs has been disaggregated at the monthly and seasonal scale and considered constant at those scale. The amount available from snow reservoir is included only for the winter months and the amount in the artificial reservoirs (which are mostly used for hydropower production) is split equally between the winter and the summer months. The potential of reservoirs and lakes for alleviating summer water scarcity is then quantified as the ratio between the total storage capacity in a catchment and the absolute water shortage under normal as well as extreme conditions. A ratio larger than 1 implies a high surplus of water from the reservoirs and lakes. A small ratio (<=1) imply that reservoirs and natural lakes have limited potential to alleviate shortages. For catchments with low reservoirs and natural lakes capacity (ratios <=1), a reduced water demand is applied to further alleviate shortages.

3.2 Study area

The dataset presented in [24] covers the entire territory of Switzerland, divided into 307 small-scale basins. For the purpose of this study, however, we aim to capture processes and effects at national to regional scales, which are more relevant for decision-making at both the cantonal and Swiss-wide levels. Therefore,

an aggregation from the local to the mesoscale is required. We aggregate water demand, supply, and reservoir potential from the 307 local catchments into 22 mesoscale catchments with areas ranging between 1000 and 5000 km^2. This mesoscale approach allows us to represent the variability of physical and meteorological conditions across Switzerland while maintaining a level of detail appropriate for policy and management decisions. To perform the aggregation, the local and mesoscale shapefiles are overlaid and each local catchment is assigned to a corresponding mesoscale unit. In cases where a local catchment overlaps with multiple mesoscale catchments, it is mapped to the catchment with the largest area of overlap. The effect of this spatial aggregation on total area is illustrated in Figure 3.1, while Figure 3.2 presents the final mesoscale basins with their corresponding names.

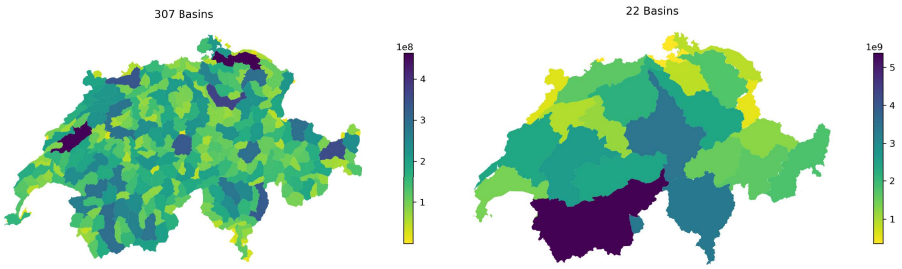


Figure 3.1: **Basins area in square metres.** The left panel shows the areas of the 307 local scale catchments; the right panel shows the areas of the 22 mesoscale catchments.



Figure 3.2: **Mesoscale catchments and names**. Map of the mesoscale catchments and their corresponding names.

Chapter 4

Results

4.1 Normal conditions

The annual water supply situation [mm/d] for normal (mean) discharge conditions for the control period (1982-2010) and for the future (2045-2074) is shown in Figure 4.1. The water regimes in Switzerland are influenced by glaciers and snow-melts in the Alpine regions showing high runoff in spring and summer and low run offs in winter; and by rainfall in the plateau regions showing low run off in summer and high run off in winter. It can also be noted how for normal conditions, the annual regimes to not differ substantially among the climate scenarios and between control and future period. To get a better sense of the discharge for different key seasons, Figure A.1 shows the discharge separated for the summer and the winter from the different periods and RCPs and as barplot. This also further confirms that even at the seasonal scale there is little difference from the present to the future and across climate scenarios.

The annual estimated volumes of water demand across all catchments are shown in Figure 4.2. The total volume corresponds to ca. 17000 10^6 m^3. The larger contributions to water demand are from ecology and hydropower followed by irrigation and to a lesser extend drinking water demand. The other contributions are comparatively smaller. However, there are considerable differences in contributions to water demand depending on the region and time of the year. This is clearly visible in Figures 4.3 and 4.4. The annual contributions for the future periods are shown in Figure A.2-A.5 of the Appendix A. It is important to stress that only irrigation, hydropower and snow production change in the future due to new climatic regimes.

The difference between water supply and total water demand per region provides the total water surplus/shortages also referred to as water balances. Under normal conditions, hardly any regions will be affected by water shortages at the annual scale (see Figure 4.5).

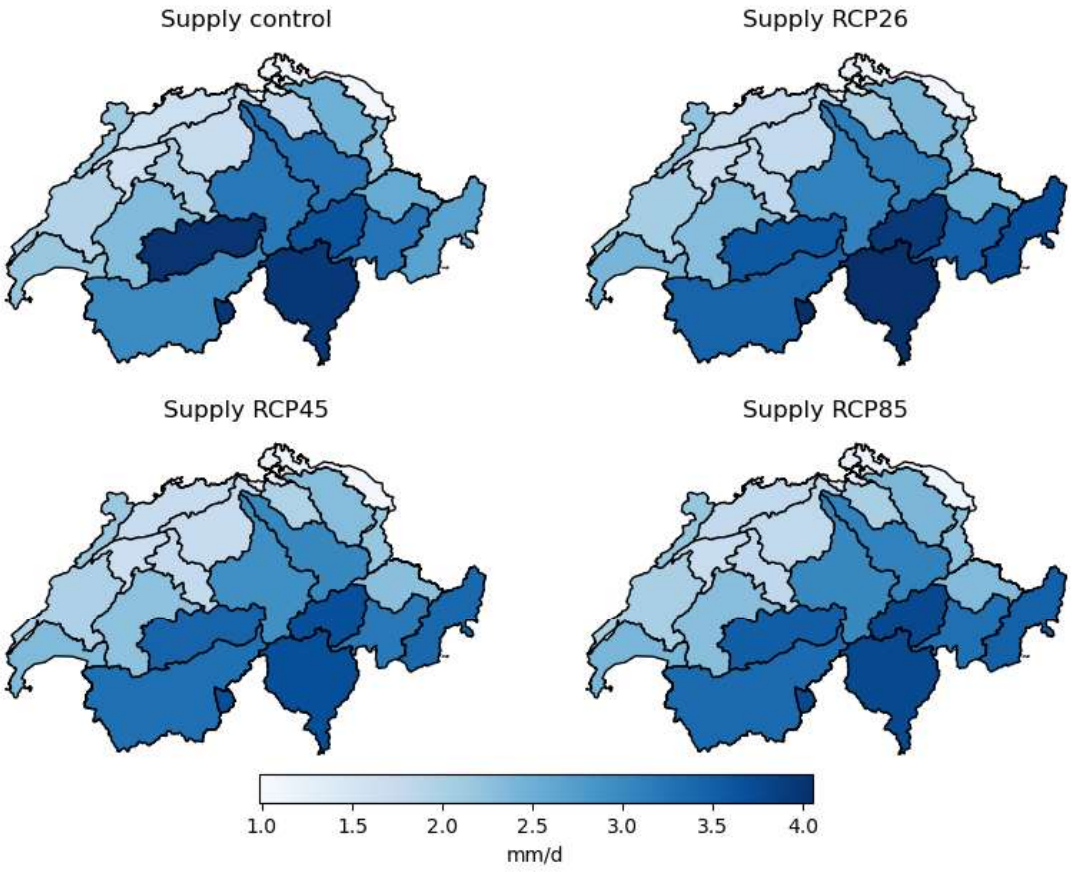


Figure 4.1: **Annual water supply normal discharge conditions**. Annual water supply computed for each of the 22 catchments for normal conditions (e.g. mean values). From the top right panels clockwise the figure shows the supply in the control period and for the three climate scenarios RCP2.6, RCP4.5, RCP8.5 respectively.

The water availability situation changes going from the annual to the seasonal scales. Water surplus/shortages for the summer (top) and winter (bottom) are provided in Figure 4.6. The water availability over the summer months is strongly affected by glacier melt. However this contribution diminishes more markedly under the climate scenarios RCP4.5 and 8.5 compared to RCP2.6. Overall the region Wal200 has the highest surplus which almost overshadows all the other contributions. The situation during the winter shows a more balanced water regime across regions and an increase in surplus for some regions under future climate conditions.

Looking at the data more in details confirms that a handful of regions may be confronted with water shortages over the summer months under RCP8.5, namely SSG200 (Sense Saane Guerbe), BiS200 (Bielersee) and LaL200 (Lac Leman). These

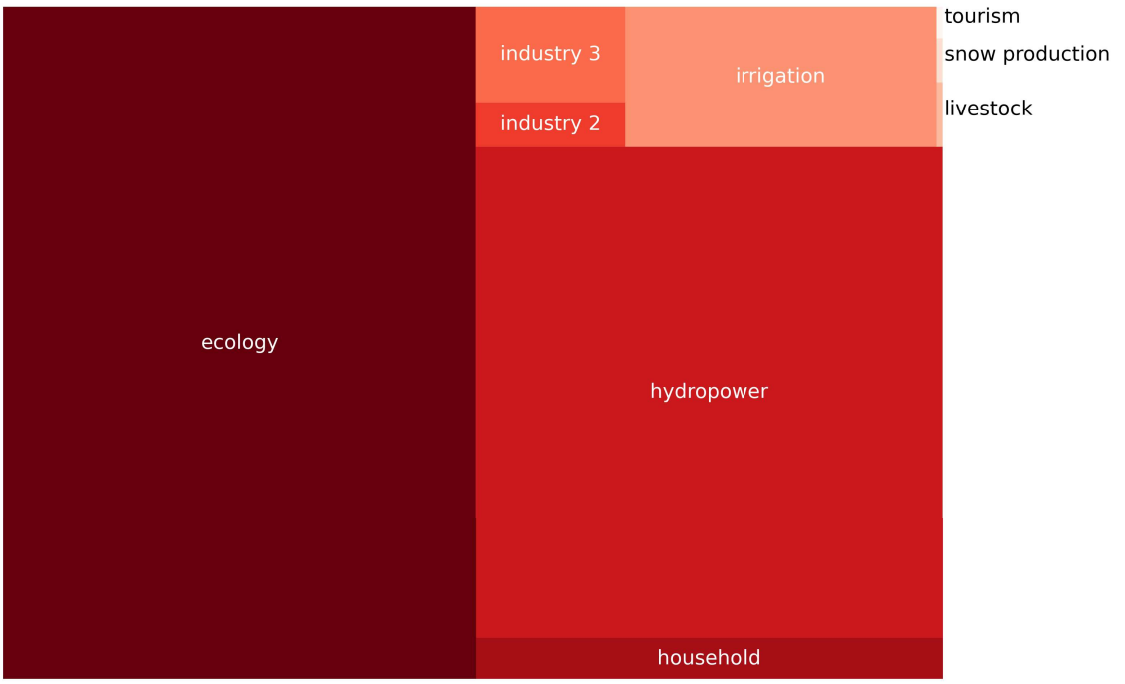


Figure 4.2: **Total annual water demand contributions**. Annual water demand volumes for all catchments (1981-2010).

regions of the plateau shows high demand for hydropower, irrigation and drinking water (see Figure A.5, but reduced supply through precipitation or glacier/snow melt over the summer (see Figure A.1).

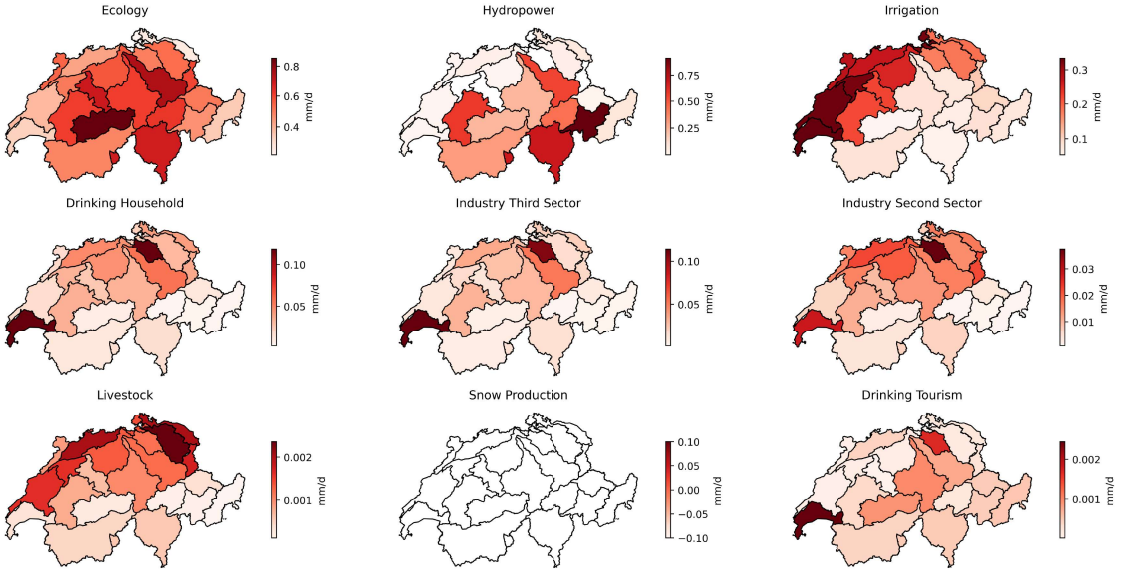


Figure 4.3: **Water demand contributions summer control**. Water demand contributions per each of the water-demand categories during the summer for the control period (1981-2010).

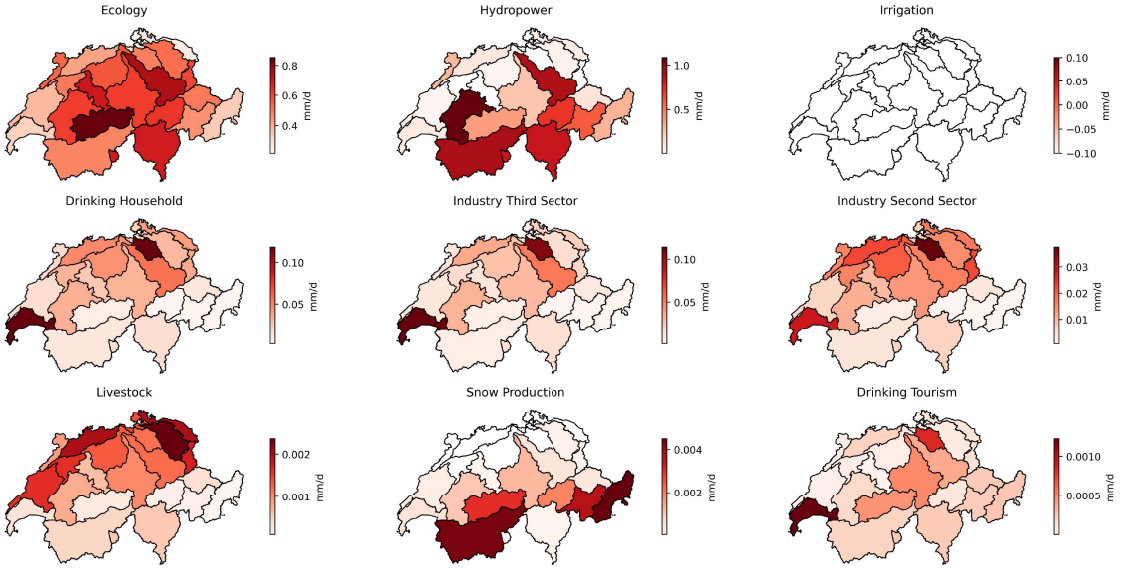


Figure 4.4: **Water demand contributions winter control**. Water demand contributions per each of the water-demand categories during the winter for the control period (1981-2010).

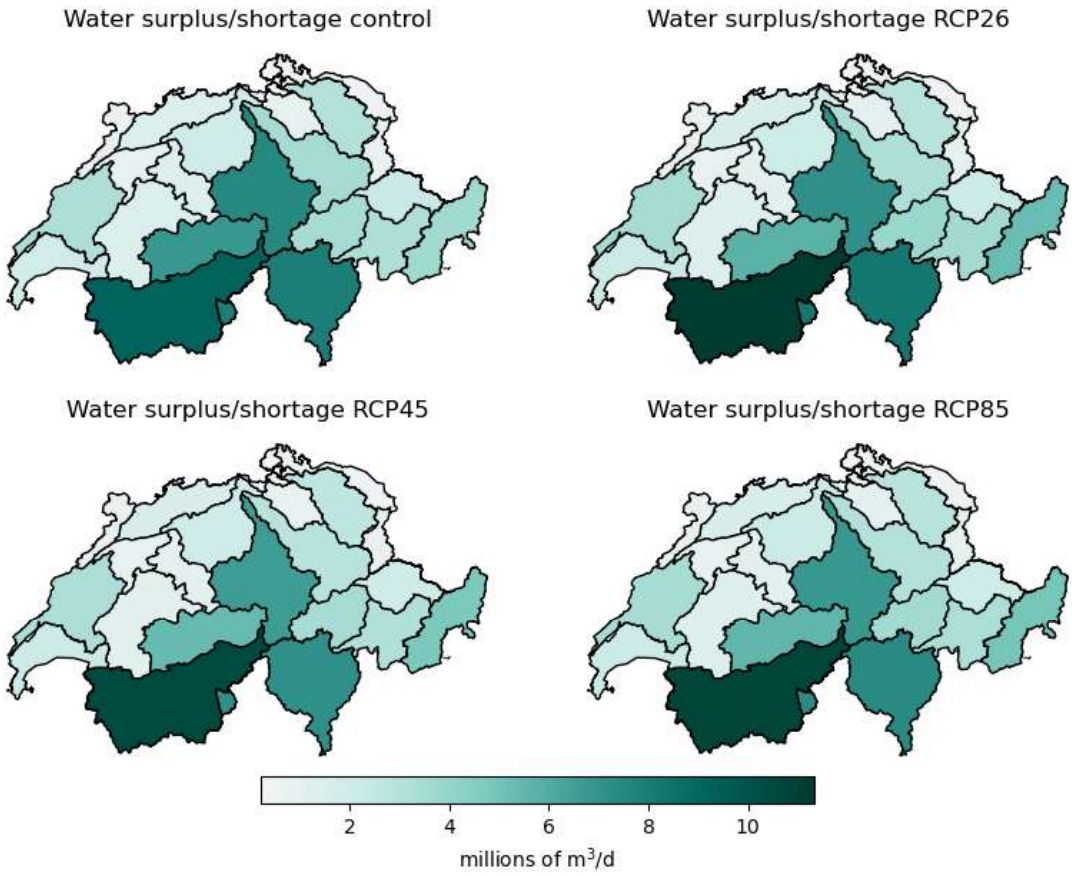
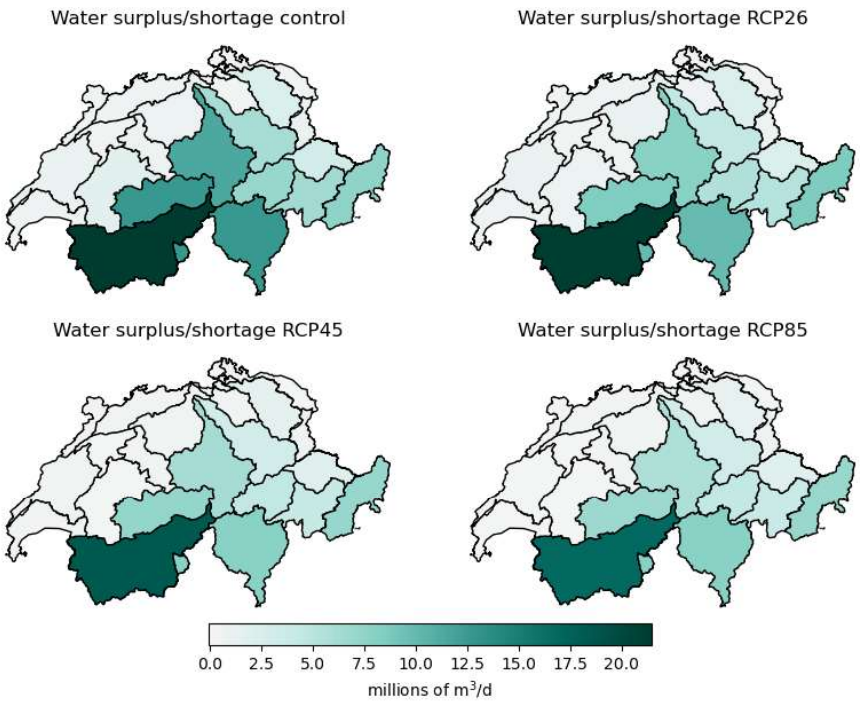
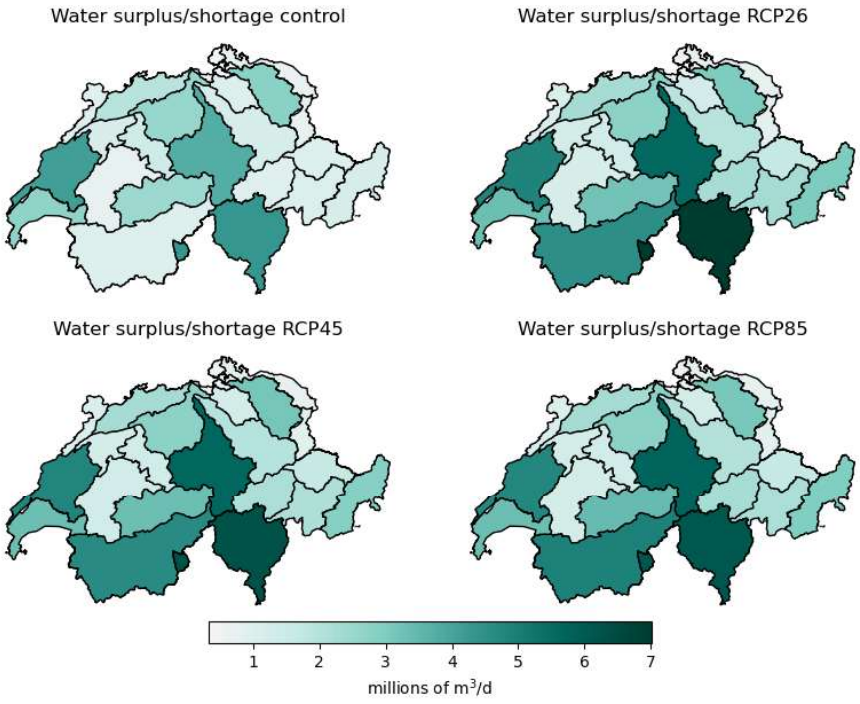


Figure 4.5: **Annual water surplus/shortage under normal conditions**. From top left clockwise: each panel shows water surplus/shortages in millions of m^3/day per each of the study regions. The lighter the color the smaller the surpluses. Negative values imply water shortages.



(a)



(b)

Figure 4.6: (a) Top panels shows the water shortages/surpluses over the summer months and lower panels (b) shows the shortages/surpluses over the winter months. From top left clockwise: each panel shows water surplus/shortages in millions of m^3/day per each of the study regions. The lighter the color the smaller the values. Negative values imply water shortages.

4.2 Extreme conditions

The annual water supply situation under extreme conditions is assessed by identifying a dry year for the present, i.e. 2003, and a corresponding dry year in the future (Figure 4.7). Estimates of water surpluses are lower for 2003 than under normal conditions. For an extreme year in the future, water surpluses are even less pronounced that they were for the year 2003 and certainly lower than compared to normal conditions in the future. For the year 2003, pronounced water surpluses are visible in the Wal200 (Valais) and ThS200 (Thunersee) and SeD200 reflecting the glacial and snow melt contributions. Moderate surpluses are also present in the southern-east basins. In contrast, much of the Swiss Plateau—shows values close to neutral, indicating relatively balanced water supply and demand in these densely populated or agricultural lowlands. In a corresponding future dry year, surpluses in the southern and western mountain regions are notably reduced and reduced water availability is more pronounced than for 2003. Some basins (e.g., SSG200) even show water shortages. The Plateau basins (e.g., Lim200, Lal200, BiS200, EmW200) exhibit small deficits or near-neutral balances, reflecting higher water demand in lowlands and urban agglomerations. Conversely, a few eastern Alpine basins (i.e. Eng200) maintain some small surpluses.

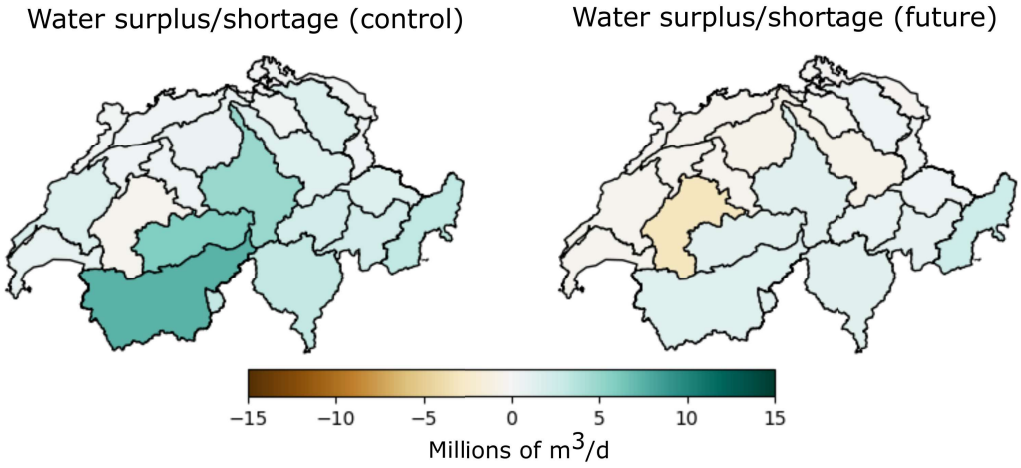
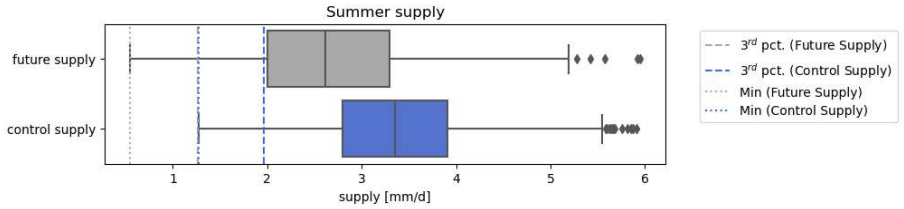


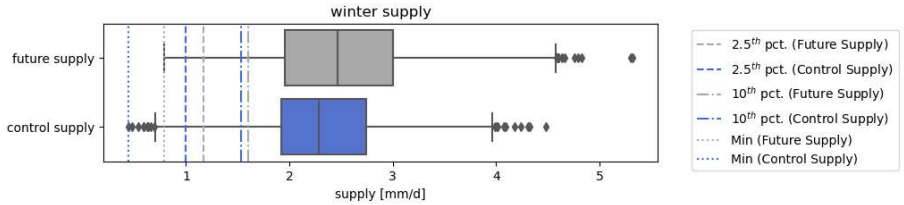
Figure 4.7: **Annual water surplus/shortage under extreme conditions**. The left panel shows an extreme dry year in the control period (year 2003) and the right panel shows an extreme dry year in the future period. Water surplus/shortages are provided in millions of m^3/day per each of the study regions. The lighter the color the smaller the surpluses. Negative values are shown by brownish colors.

Water availability in an extreme dry summer or dry winter is estimated us-

ing univariate frequency analysis of the aggregated water supplies in the present and in the future (across all years and model chains). The distributions of water supplies are shown in Figure 4.8. This figure shows boxplots comparing control (blue) and future (gray) water supply for two seasons — summer (a) and winter (b) — with additional percentile and minimum markers. For the summer (top figure), the future supply box (gray) is shifted to the left of the control one — meaning the median and quartiles of the distribution are lower in the future period than the control period. The whiskers (and outliers) extend further to the lower values (left) for future supply. The dashed and dotted lines (right legend) mark 3rd percentile (dashed) corresponding to a lower extreme (dry conditions) and minimum (dotted)- absolute minimum. It can be noted that a 3rd percentile in the future would correspond to the absolute minimum of the distribution in the control period. For the winter (bottom figure), the future supply median is slightly higher than the control period indicating that winter supply slightly increase under future conditions. The future supply also shows slightly larger spread, implying increased variability. Lower end percentiles, namely 2.5th percentile, 103th percentile, and minimum for both distributions are also shown. These show that extreme low-flow conditions (left-side tails) are slightly reduced in the future scenario. The summer corresponding to the 33rd percentiles and the winter corresponding to the 2.53th percentile are selected as representative of extreme dry conditions for both the present and the future.



(a)



(b)

Figure 4.8: (a) Top panels show the distribution of the water supply over the summer months and lower panels (b) show the distribution of the water supply over the winter months for both the control period (blue) and the future period (grey) with additional percentile and minimum markers as indicated in the legends to the right of the plots.

Water surplus/shortages for the summer (top) and winter (bottom) under extreme conditions are provided in Figure 4.9. During an extreme dry summer (3^{rd} percentile), the reference period exhibits surpluses in the high-Alpine south and parts of the central and eastern regions, with the largest positive values in the south-west. In contrast, future summers show a widespread reduction in availability: areas that were close to balance in the reference period over the Plateau and northern basins tend to shift towards small deficits, while only a few high-elevation regions remain clear net exporters of water. This pattern is consistent with weaker summer meltwater contributions and higher evapotranspiration, which reduce summer runoff and increase seasonal water stress. For an extremely dry winter (bottom row), the spatial gradients are weaker. In the reference period, mild shortages appear mainly in the southern Alpine regions, with near-neutral conditions elsewhere. In the future, winter shortages are largely alleviated and many regions move closer to balance or slight surplus. This reflects the projected shift from snow to rain in winter and earlier melt, which increases winter runoff even during dry conditions.

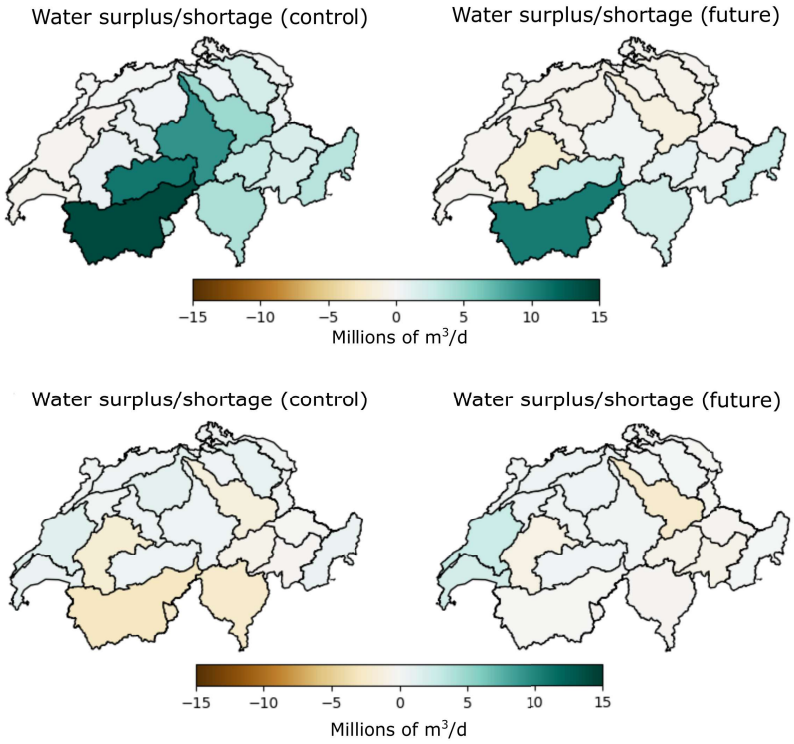


Figure 4.9: **Seasonal water surplus/shortage under extreme conditions**. The top panel shows an extreme dry summer and the bottom panel shows an extreme dry winter. The figures on the left in each panel correspond to conditions i the reference period, whereas the right panels corresponds to future conditions. Water surplus/shortages is provided in millions of m^3/day per each of the study regions. The lighter the color the smaller the values. Negative values imply water shortages.

4.3 Adaptation

In the previous sections we have explored the annual and seasonal water availability considering only natural water runoff under normal and dry conditions. In this section, we first present the role of natural lakes and reservoirs as an adaptation strategy to alleviate water scarcity. We refer to the alleviating capacity of water stored in natural lakes and reservoirs as "low adaptation", which implies the further integration and management change of existing reservoirs and natural lakes to further support water availability. The total water stored in different types of reservoirs in each of the 22 regions is provided in Figure 4.10.

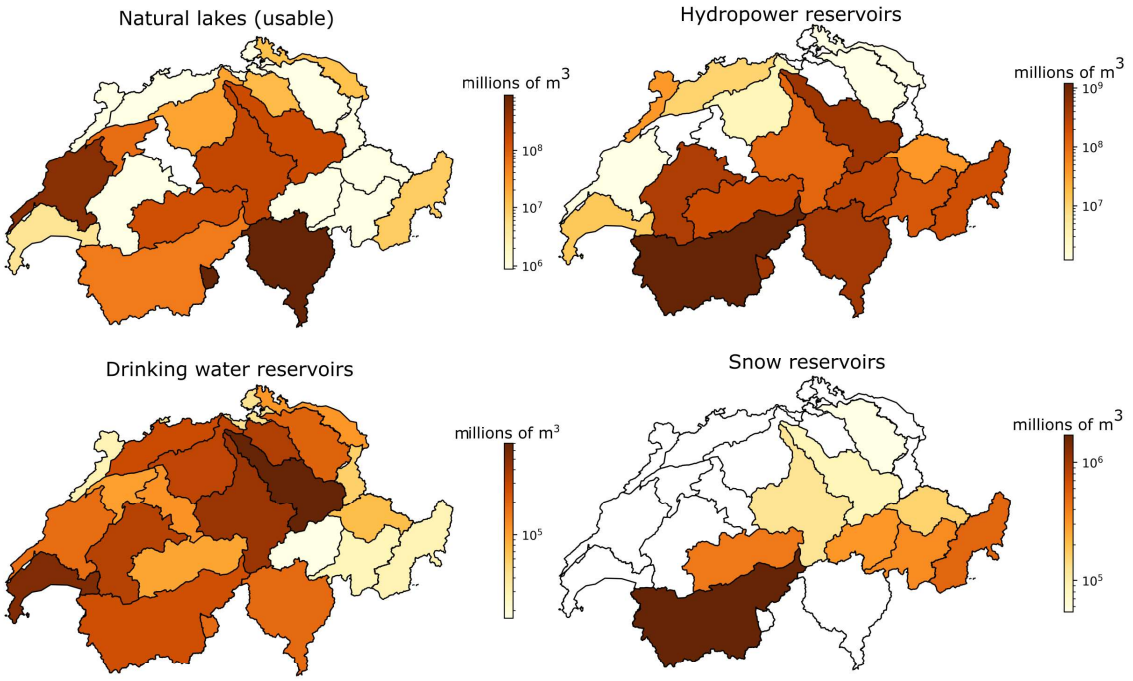
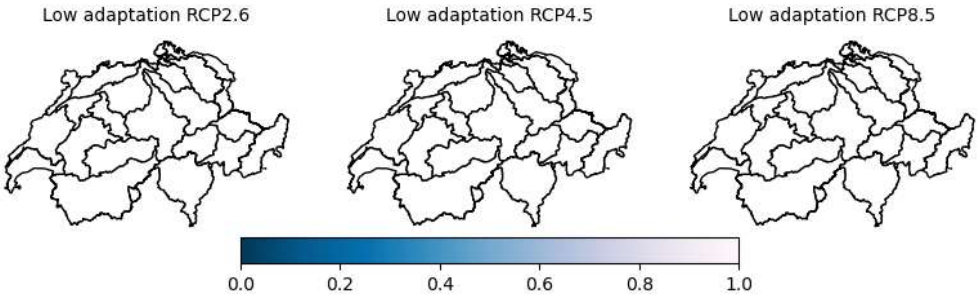


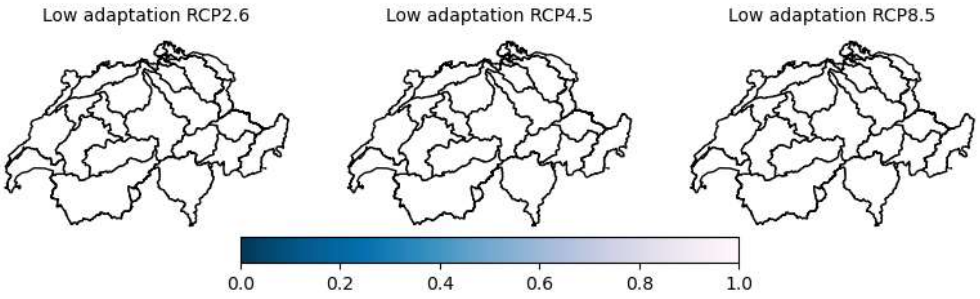
Figure 4.10: **Total volumes of water in reservoirs.** The figure shows the water available in natural lakes (only usable) and in three different types of reservoirs, namely hydropower reservoirs, drinking water reservoirs and snow reservoirs. The colour bar on the right of each plot provides different scales depending on the reservoirs. The units are in millions of cubic metres.

We recall that water shortages can be effectively mitigated when the ratio of available storage to shortage is high. Conversely, when this ratio is low (i.e. close to 0), the shortage exceeds storage capacity and the potential for alleviation is limited. Figure 4.11 shows the ratios under normal conditions. It is notable that

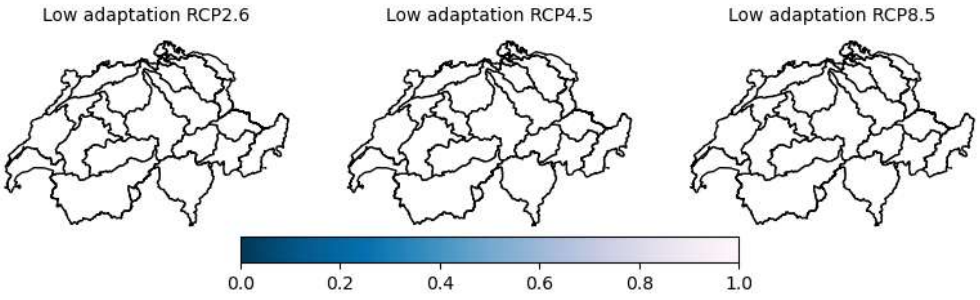
no region exhibit ratios lower than one and the alleviating potential of the reservoirs and natural lakes in this case is limited given that no shortages are detected in the first place.



(a)



(b)



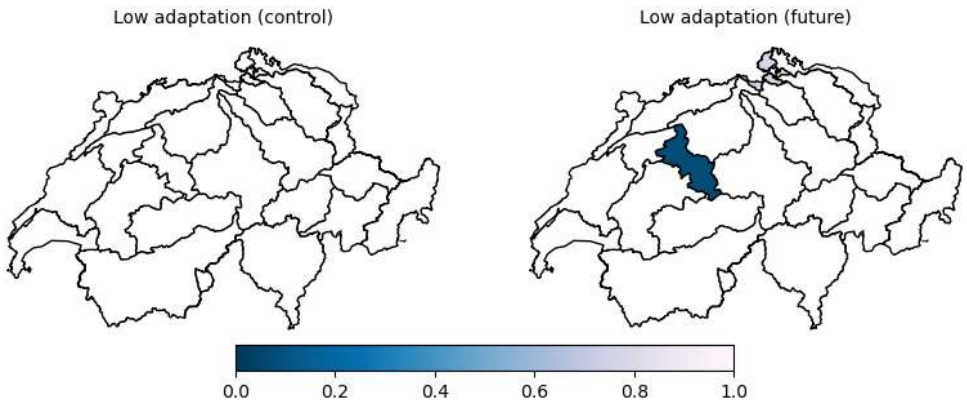
(c)

Figure 4.11: **Ratios under normal conditions**. (a) Top panels shows the yearly ratio of absolute water shortage vs. water available in reservoirs and natural lakes for the three climate scenarios. Panel (b) shows the same ratio for the summer months. Panel (c) shows the ratios for the winter months. White colors imply that the ratios are larger than 1 and hence that there is water surplus.

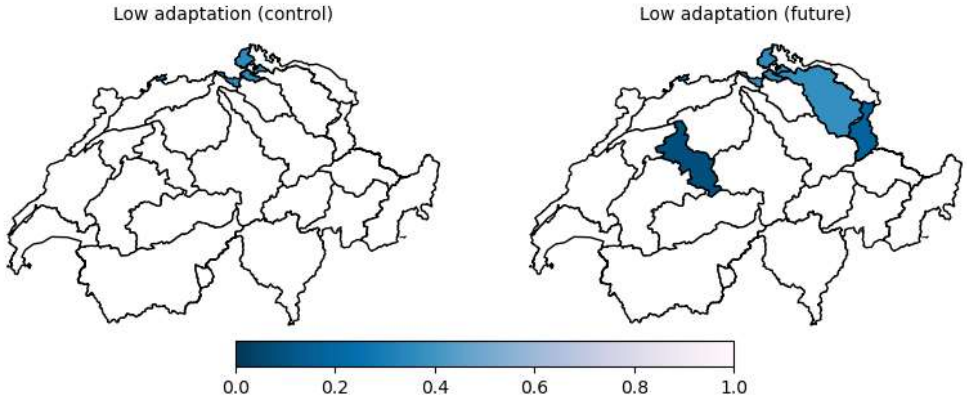
The situation is different under extreme dry conditions, since there are a handful of regions that exhibit low ratios. This implies that the absolute water shortages are higher than the capability of the reservoirs and natural lakes to alleviate such shortages. These are particularly pronounced both at the annual level and during summer months, whereas during winter months only the region VoA200 in the north east is mildly affected by potential shortages. The most affected regions during an extreme dry year are EmW200 and to a lesser extent NoW300. In the summer, the alleviating potential is limited in four regions, namely (in increasing order of shortages): NoW200, Th200, VoA200 and EmW200. These regions exhibit both water shortages and lower adaptation potential due to limited total "usable" water in reservoirs and natural lakes. It is important to notice that even when large natural lakes are present, these might be heavy regulated so that their resulting alleviating potential is comparatively low.

To further alleviate shortages during the summer months, an additional adaptation measure is considered. This corresponds to a 60% reduction in total water availability (excluding ecological demand). We apply this in addition to the alleviating potential of natural lakes and reservoirs to regions which exhibit ratios smaller than one.

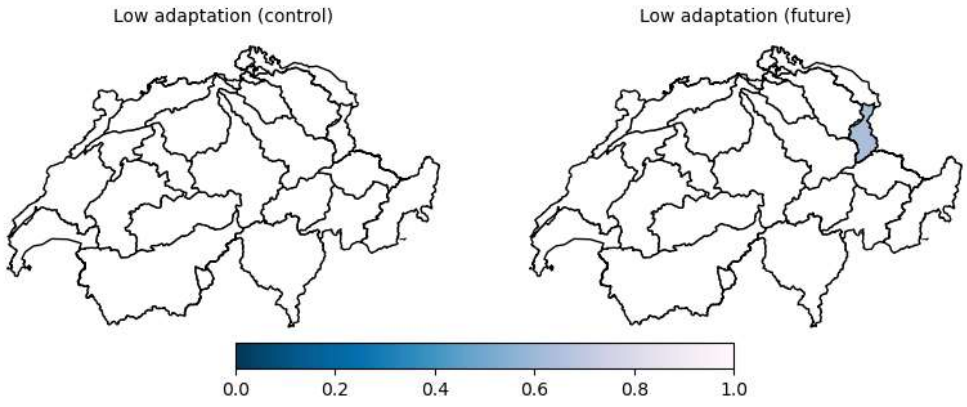
As a result of the reduction in demands, ratios between water in reservoirs and absolute water shortage become higher than 1 in NoW200, whereas in the other regions an improvement of the ratios between 50% to 70% although they still remain lower than 1.



(a)



(b)



(c)

Figure 4.12: **Ratios under extreme conditions**. (a) Top panels shows the yearly ratio of absolute water shortage vs. water available in reservoirs and natural lakes for the three climate scenarios (b) shows the same ratio for the summer months and (c) shows the ratio for the winter months. The left figures underpin conditions for the reference period and right figures for the future. White colors imply that the ratios are larger than 1 and hence that there is water surplus. The darker the color the lower are the ratios and hence the more pronounced is the shortage.

Chapter 5

Discussion and conclusions

This study set out to quantify how climate change alters the balance between water supply and water demand in Switzerland at a regional scale, and to assess to what extent existing storage infrastructure and demand reductions could alleviate emerging shortages. Using hydrological simulations for 307 small catchments aggregated into 22 mesoscale basins, driven by CH2018 climate scenarios and coupled with sectoral water-demand estimates, we analysed annual and seasonal balances under normal and extreme conditions, with and without stylised adaptation measures.

A key finding is that Switzerland as a whole is not projected to become water scarce at the annual scale by mid-century, even under RCP8.5, assuming stationary socio-economic conditions. Annual runoff remains high in the Alpine and pre-Alpine regions and, when integrated over a year, supply generally exceeds total demand in all mesoscale basins under normal conditions. However, this apparent robustness at the national and annual scale masks important seasonal and regional vulnerabilities which mostly emerge under extreme dry conditions. This results are in line with extant research which argue that under normal conditions hardly any region in Switzerland will be affected by water scarcity [24]. This is even more so the case at regional to national than at the local scale [27].

Seasonally, the picture is more nuanced. In summer, several Plateau basins – notably Sense–Saane–Gürbe (SSG200), Bielersee (BiS200) and Lac Léman (LaL200) – begin to exhibit small but non-negligible deficits under RCP8.5. These basins combine relatively modest summer runoff (little glacier contribution, reliance on rainfall) with comparatively high demands from agriculture, public water supply and hydropower. In winter, by contrast, future conditions tend to show slightly higher and more evenly distributed runoff, consistent with a shift from snow to rain and earlier melt, leading to increased winter surpluses in many regions. Thus, the main emerging signal is not an overall lack of water but a redistribution in time, from summer towards winter, and a growing mismatch between when water is available and when it is most needed. Previous studies in Switzerland

also highlighted seasonality shoft in water run off [34].

Under extreme conditions the vulnerabilities become more pronounced. The comparison between the dry year 2003 and a statistically comparable future dry year shows a clear reduction in surpluses, particularly in high-Alpine and southern regions where current surpluses are driven by glacier and snow melt. In the future dry year, several basins on the Swiss Plateau move from near-neutral balances to outright deficits, while even traditionally water-abundant basins such as Wal200 (Valais) show reduced surpluses. The frequency-based analysis of summer and winter low flows underlines this shift: a summer 3rd percentile event in the future corresponds roughly to the minimum of the control-period distribution, implying that drought-like summer conditions akin to or more severe than 2003 become more frequent. In winter, by contrast, even extreme dry conditions tend to be less critical in the future, because baseline winter flows increase. Here it is important to notice that the strong surplus in Valais shown in Figure 4.9 masks some important shortages which become may only become visible at the local scale as highlighted in [24].

The adaptation analysis highlights both the potential and the limitations of relying on existing storage and demand reduction. Under normal conditions, ratios of storage capacity (usable natural lakes and reservoirs) to absolute shortages exceed one in all basins; however, this is largely a formal result, since shortages are almost absent in the first place. Under extreme dry conditions, storage becomes more relevant: in Emme–Wigger (EmW200) and, to a lesser degree, Schwarzwald (NoW200), the available local storage is insufficient to fully offset simulated deficits. During an extreme dry summer, the alleviating potential is limited in four regions – NoW200, Th200, VoA200 and EmW200 – which combine substantial seasonal demand with low local storage volumes. This points to a spatial mismatch between where water is stored (often in high-Alpine hydropower reservoirs and regulated lakes) and where demand peaks (densely populated or agriculturally intensive lowlands)

The high-adaptation scenario, which couples the use of existing storage with a stylised 60% reduction in non-ecological demand, demonstrates that strong demand-side measures can reduce, but not always fully eliminate, deficits in the most exposed regions. In NoW200, the combination of storage and demand reduction is sufficient to raise the ratio of storage to shortage above one, while in EmW200, Th200 and VoA200, the ratios improve markedly but remain below unity. This indicates that even very ambitious demand reductions may not completely close the gap in all basins under extreme dry summers, especially where structural storage limitations and high demands coincide.

Overall, the results suggest a dual message. On the one hand, Switzerland remains a comparatively water-rich country at mid-century in terms of annual resources. On the other hand, seasonal and event-based water stress – particularly summer low-flow episodes on the Plateau – are projected to intensify, and

the capacity of existing storage to buffer these stresses is unevenly distributed in space. The results reinforce the view that future water risks in Switzerland arise less from absolute national scarcity than from spatial and temporal mismatches [27, 24], as well as from competition among uses. This has several implications for water management and climate adaptation.

Capitalising on the results of this study, the following recommendations are provided. First, adaptation strategies need to be explicitly seasonal. The projected strengthening of summer deficits alongside increasing winter surpluses points to the importance of measures that shift water availability in time. This support existing calls to revisit operating rules of multi-purpose reservoirs and regulated natural lakes to increase their buffering function for summer low flows, while respecting ecological and legal constraints [35, 34, 36]. The analysis suggests substantial theoretical potential in some basins; however, realising this potential will require cross-sectoral coordination between hydropower operators, water suppliers, agriculture, tourism and environmental authorities. This is a recurring theme at the European and Swiss level, namely multi-purpose systems necessitate governance structures and decision-making processes that integrate diverse objectives and actors [37]. The design of operating rules will need to balance energy supply security, flood protection and ecological flow requirements with increased summer water demand.

Second, adaptation priorities differ markedly between regions. High-Alpine basins with large storage volumes and relatively low consumptive use tend to retain surpluses even under extreme conditions, suggesting that their main challenges lie in hydropower operation, ecological impacts and downstream dependencies, rather than in regional scarcity. By contrast, Plateau basins with limited storage and high demands – such as EmW200 or VoA200 – are likely to remain hotspots of summer water stress. Here, the focus of adaptation may need to lie on improving irrigation efficiency, adapting cropping systems, enhancing groundwater recharge, diversifying water sources for public supply, and strengthening demand management during low-flow periods [38].

Third, the strong contribution of ecological flows and hydropower to total demand has important implications. Ecological flow requirements are legally prescribed minimum flows intended to protect aquatic ecosystems; in this analysis they are treated as non-reducible demand. This is a normative choice that reflects environmental legislation and policy goals [39]. It implies that much of the flexibility must be found in other sectors: agriculture, public water supply, industry, tourism and aspects of hydropower operation. At the same time, hydropower is largely non-consumptive at the annual scale, but its timing and storage effects mean that it can exacerbate seasonal scarcity if not coordinated with other uses [40].

Fourth, the high-adaptation scenario illustrates the magnitude of change required on the demand side to reduce extreme deficits. A 60% reduction in non-ecological

demand is clearly not a realistic short-term policy option but rather a stress test of what could be achieved through transformative changes in technology, behaviour and sectoral structures [41, 42]. In reality, different sectors have different potentials and costs for demand reduction, and equity considerations constrain how reductions can be distributed. Nonetheless, the scenario underscores that incremental efficiency improvements alone may be insufficient in some hotspots under severe drought conditions, and that discussions about more deeper shifts – for example, changes in cropping patterns, water savings – may be required [43]. Finally, the analysis underlines the importance of planning for extremes rather than averages. The differences between normal and extreme conditions in this study are substantial: regions that appear unproblematic when looking only at mean balances can experience marked deficits in extreme dry summers. As recent years in Europe have shown, such events have wide-ranging impacts on agriculture, energy, ecosystems and navigation [44, 38]. Integrating drought risk and low-flow scenarios into regional water management plans, emergency response protocols and investment decisions is therefore essential.

While the modelling framework provides a coherent national-scale picture, some limitations need to be recognised when interpreting the results and drawing policy conclusions. The study focuses on two 30-year windows (1981–2010 and 2045–2074) and defines extreme conditions based on percentiles of aggregated seasonal runoff distributions. This approach captures intra-period variability but does not explicitly address multi-year drought sequences. The aggregation from 307 small catchments to 22 mesoscale basins improves policy relevance and interpretability but inevitably masks local heterogeneities [27]. Water-supply systems, especially for small municipalities or specific irrigation districts, often operate at finer spatial scales than those analysed here. Local shortages in headwater catchments or small aquifers may be concealed within mesoscale surpluses, and local infrastructure constraints (e.g. limited transfer capacity) are not represented (see [24] for a finer grained analysis). The results therefore provide a regional-scale screening of vulnerabilities, not a substitute for detailed local assessments.

The representation of water demand is deliberately simplified. To remain consistent with other components of the overarching project, the study assumes no demographic or structural changes in most sectors, except for climate-driven changes in irrigation, hydropower and snowmaking. In reality, population growth, urbanisation, shifts in the economic structure, technological change and policy measures will all affect future water use [45]. Some trends (e.g. population growth, intensification of irrigation in response to warmer summers or technological improvement) could increase demand and thus amplify projected deficits, while others (e.g. efficiency gains, reduced industrial water use) could dampen them. The omission of socio-economic scenarios means that the results are best interpreted as climate-driven changes under constant socio-economic conditions, rather than as full projections of future water scarcity.

The storage-based adaptation analysis is stylised. The study relies on estimates of usable natural lake volumes and reservoir capacities and assumes that these volumes can be flexibly deployed to alleviate shortages within each basin. It also does not consider future changes in storage capacity driven by climate change. In practice, legal restrictions, ecological constraints, flood-protection requirements, hydropower contracts and technical limitations constrain how much of the storage can be devoted to drought alleviation, when and where. Furthermore, the analysis treats each mesoscale basin as largely self-contained, whereas actual water management includes inter-basin transfers, especially in hydropower systems.

The high-adaptation scenario applies a uniform 60% reduction to all non-ecological demands. This ignores sector-specific elasticities, costs and feasibility constraints. Finally, groundwater – a key source for public water supply in Switzerland – is not directly included in this study. The resilience or vulnerability of aquifers to prolonged droughts, changes in recharge or land-use change is therefore not explicitly assessed. Given the importance of groundwater for drought resilience, future work should integrate groundwater models or observational data more explicitly into national to regional scale assessments.

Despite some limitations, the study provides a coherent, spatially explicit assessment of how climate change may alter water balances and the scope for adaptation via existing storage and demand reduction across Switzerland. Three overarching conclusions emerge:

1) Annual national water availability remains robust, but seasonal and regional water deficit can be foreseen. Even under high-emission scenarios, Switzerland is projected to retain substantial annual water resources by mid-century. However, climate change shifts water availability from summer to winter and amplifies summer low-flow conditions, particularly on the Plateau. Water scarcity in Switzerland is therefore predominantly a seasonal and regional management challenge rather than a question of national-scale physical limits. 2) Existing storage offers relevant but spatially uneven adaptation potential, which must be complemented by demand-side measures. Regulated lakes and reservoirs can substantially alleviate deficits in many basins, particularly under moderate conditions. Under extreme dry summers, however, a few basins combine high demand with low local storage and remain vulnerable even when storage is fully mobilised. Strong demand-side measures, including improved efficiency, behavioural change and possibly structural changes in water-intensive activities, are required in these hotspots. 3) Planning for extremes and fostering cross-sectoral coordination are central to future water resilience. The largest challenges arise during extreme dry summers, when ecological, agricultural, hydropower and public supply needs coincide. Addressing these challenges calls for integrated water-resource management that explicitly considers drought risk, coordinates reservoir and lake operation across sectors and regions, and em-

beds water considerations into broader climate-adaptation, energy and land-use policies. Future research could extend this work in several directions: incorporating socio-economic scenarios and sector-specific adaptation pathways; representing groundwater and water-quality dynamics more explicitly; exploring alternative management strategies such as dynamic environmental-flow rules, nature-based storage, or new inter-basin connections; and analysing the joint impacts of multi-year droughts and compound heat-and-drought events. From a policy perspective, the results support the ongoing development of national drought monitoring, adaptation strategies and regional water-use planning, and provide a quantitative basis for prioritising regions and sectors where proactive adaptation is most urgent.

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Appendix A

Appendix

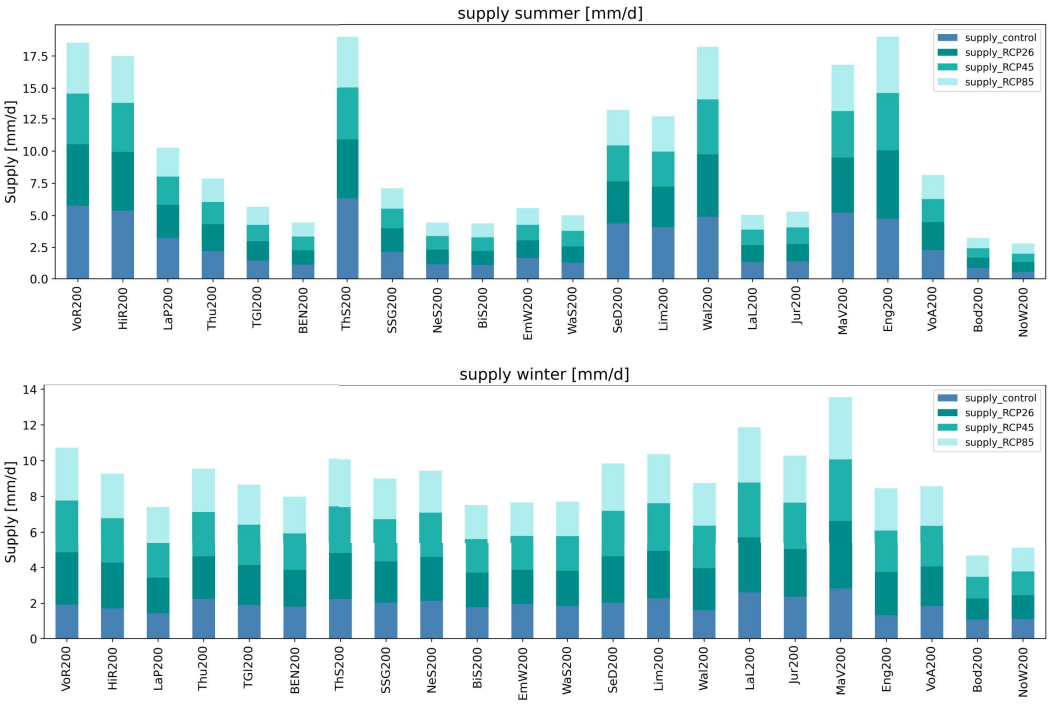


Figure A.1: **Stacked barplot of water supply normal discharge conditions**. Water discharge contributions per region for the control period and for the three climate scenarios. Top panel shows the summer discharge and bottom panel the winter discharge.

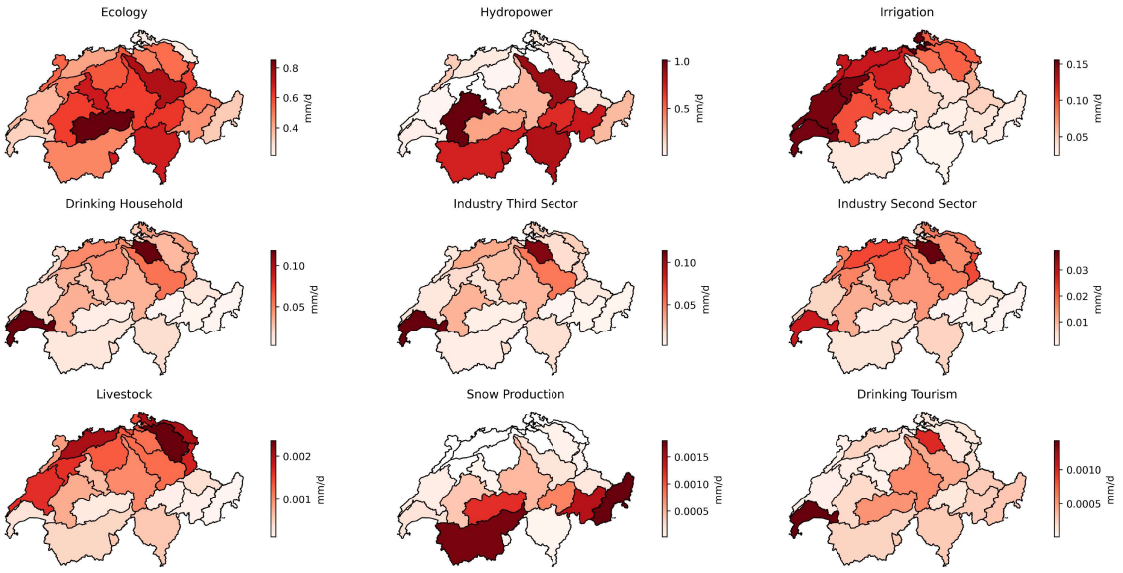


Figure A.2: **Annual water demand contributions control period**. Annual water demand per each of the water-demand categories for the control period (1981-2010).

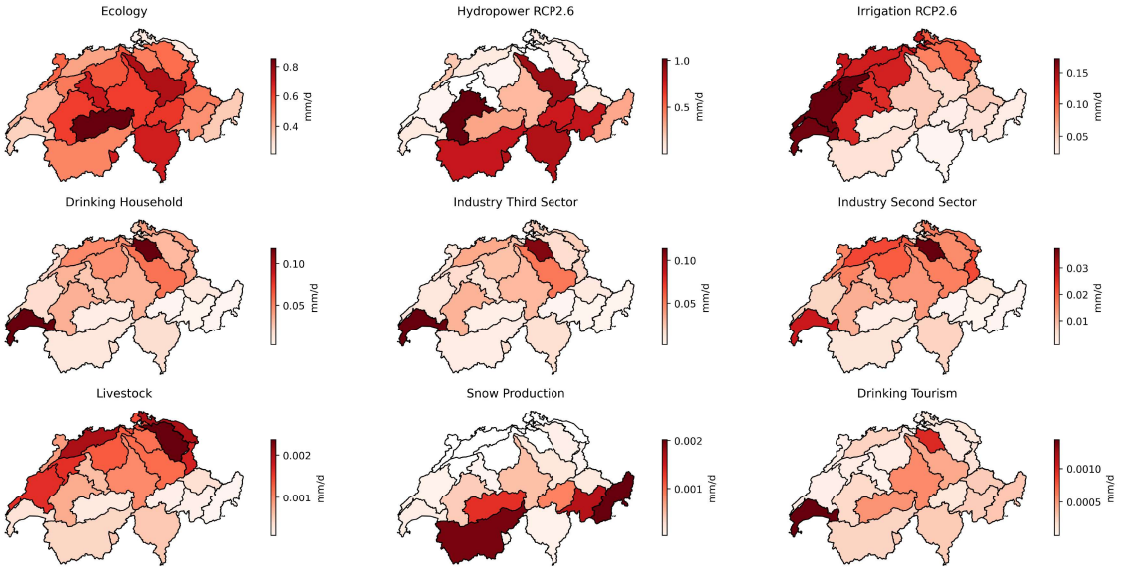


Figure A.3: **Annual water demand contributions RCP2.6**. Annual water demand per each of the water-demand categories for the future period (2045-2074).

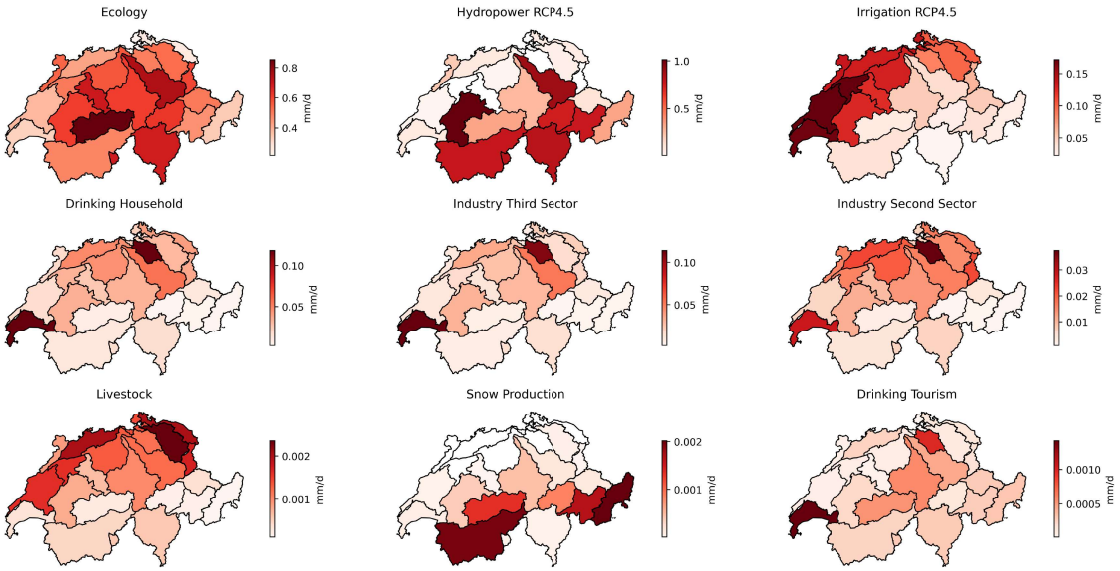


Figure A.4: **Annual water demand contributions RCP4.5.** Annual water demand per each of the water-demand categories for the future period (2045-2074).

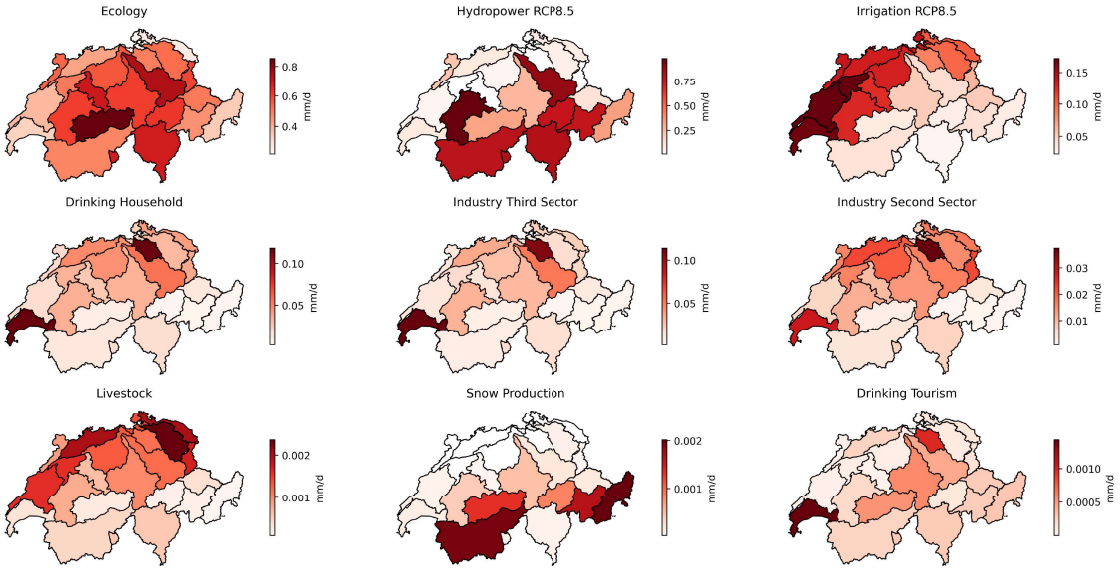


Figure A.5: **Annual water demand contributions RCP8.5.** Annual water demand per each of the water-demand categories for the future period (2045-2074).