

6 — Hydrological responses to climate change: river runoff and groundwater

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- river runoff
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– For all greenhouse gas scenarios, a shift in runoff regime type is projected to occur in most catchments in Switzerland, with lower summer runoff and higher winter runoff, but little change in the total annual volume.

– Limiting emissions to RCP3PD levels would reduce the impacts on mean winter and summer runoff by approximately half in comparison with scenario A2 for the period 2085 – but even under scenario RCP3PD runoff seasonality is likely to be altered.

– For groundwater temperature change, the medium estimates for the period 2085 under the three greenhouse gas scenarios range from +1 to +3°C. The warming, which could pose problems for groundwater quality and drinking water production, is accentuated in certain aquifers, especially in the mid- to long term (periods 2060 and 2085). Situations of no change in groundwater temperature, however, cannot be excluded given the assessed levels of uncertainty in the projections.

◀ Seasonal redistribution and increasing variability of runoff make water resource management challenging (Aare river after the dry spell in spring 2011; photo: Jérôme Wider, PLANAT).

6.1. INTRODUCTION

Due to its natural water storage capacity and its role as a source of water to its downstream neighbors, Switzerland is sometimes called the „water tower of Europe“. However, the effects of climate change, i.e., glacier melting (Chapter 5) and changes in precipitation (Chapter 3), are calling this role into question. Climate change also affects ecosystems and human well-being indirectly through impacts on water resources and water quality. River runoff and groundwater reservoirs are crucial for understanding and quantifying these impacts: runoff is essential for the functioning of ecosystems and for supplying water needed for hydropower production, irrigation, cooling, and other uses; groundwater provides Switzerland with 80% of its drinking water.

The impact of climate change on river runoff has recently been investigated as part of a comprehensive assessment for the whole of Switzerland (FOEN, 2012b). Here, this study is complemented by considering the effects of different greenhouse gas scenarios, by conducting a detailed and systematic assessment of the model uncertainties in runoff projections, and by performing simulations for an intermediate mid-century time period.

Studies addressing the impact of climate change on groundwater and groundwater quality in Switzerland are rare. Groundwater quality is crucially dependent on its temperature, and warming may affect groundwater biogeochemistry in a way that reduces its quality and suitability as a source of drinking water. Since the 1980s, at least some aquifers in Switzerland have shown a marked increase in groundwater temperature (on the order of 1°C) associated with a change in climate forcing (Figura et al., 2011). Here, groundwater temperature projections based on the CH2011 scenarios are presented for a limited selection of aquifers to provide a preliminary assessment of potential future groundwater warming.

6.2. METHODS

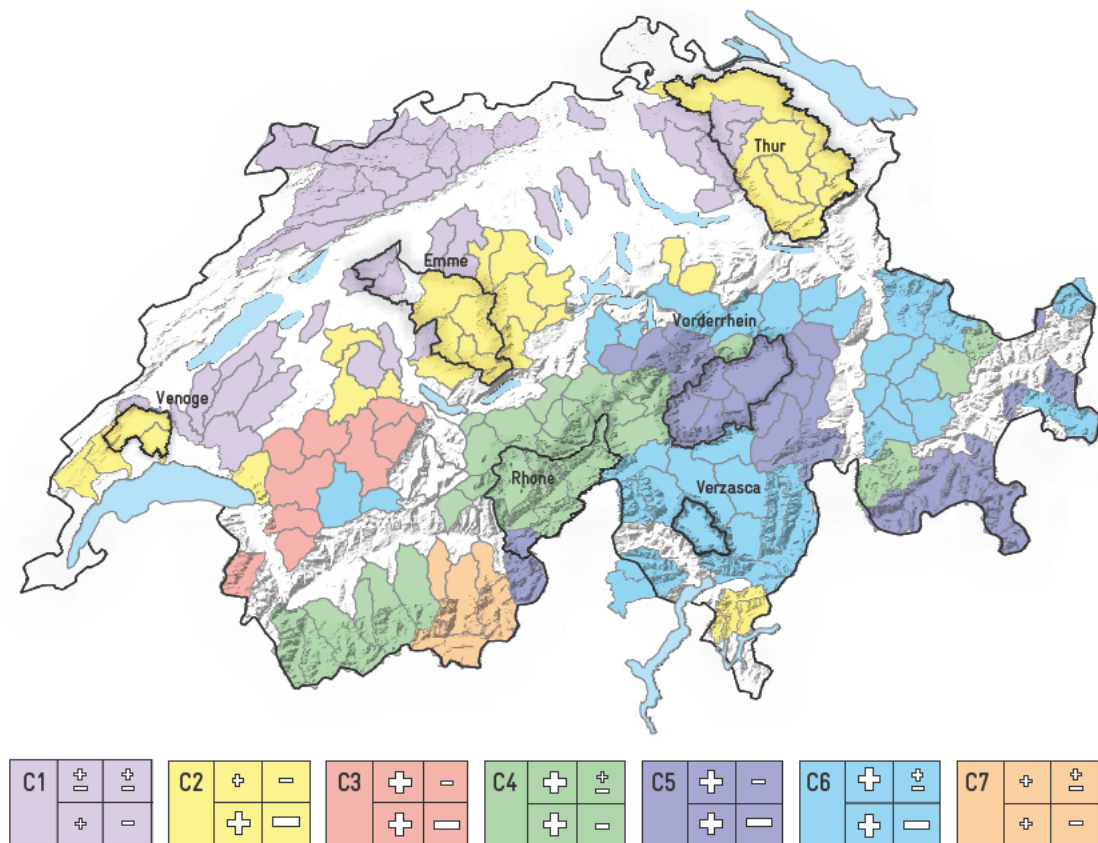
In a first step, **runoff** from 186 mesoscale catchments from all parts of Switzerland (20 – 1760 km² in size) is simulated under today's climate and under projected future climate conditions to determine overall hydrological changes and to delineate regions of similar hydrological response. Based on the A1B scenario, these Switzerland-wide simulations are performed for a reference period (1984–2005, slightly shorter than the CH2011 reference period) and two time periods in the near (2035) and far (2085) future using the downscaled DAILY-LOCAL dataset (Chapter 3). The hydrological model used is PREVAH-GIUB (Viviroli et al., 2009a; b). Resulting changes in runoff, precipitation, and air temperature are classified by applying a cluster analysis to group regions of similar runoff response. Seven different types of region with similar runoff responses are identified, here referred to as response types C1–C7 (Figure 6.1; Köplin et al., 2012). The discussion focuses on response types C1–C6, as C7 is strongly influenced by hydropower production, which follows economic rather than climate processes.

In a second step, this spatially comprehensive analysis is complemented by performing a more detailed analysis of six selected catchments (Rhône at Brig, Vorderrhein at Ilanz, Emme at Wiler, Thur at Andelfingen, Venoge at Ecublens, and Verzasca at Lavertezzo) representing four major response types with increasing degrees of glaciation (C2, C4, C5, C6, Figure 6.1). Three catchments (Emme, Thur, Venoge) classified mostly as belonging to the same response type (C2) are selected to account for within-type variability and to test the validity of the classification under different greenhouse gas scenarios. These six catchments are analyzed taking into account all greenhouse gas scenarios and time periods, the climate modeling uncertainties (Chapters 2 and 3), and partly the uncertainty in hydrological impact modeling. The analysis does not capture the uncertainties inherent to the impact model parameters, and only part of the downscaling uncertainty. For each catchment, the ensemble of 10 DAILY-LOCAL scenarios, as well as the lower, medium, and upper estimates of the DAILY-REGIONAL dataset (Chapter 3), are used to force four hydrological models of different complexity, structure, and parameterization. These hydrological models are, in order of increasing complexity:

HBV (Seibert and Vis, 2012), two versions of the model PREVAH (PREVAH-GIUB, Viviroli et al., 2009a; b; PREVAH-WSL, Kobierska et al., 2013), and WaSiM-ETH 8.0.1 (Schulla and Jasper, 2007). Data on glacier extent is provided by Linsbauer et al. (2013). The scaling methodology applied for transient glacier simulation approximates the scenarios RCP3PD and A2 in a way that may bias the runoff projections for the highly glaciated Rhône catchment. Consequently these greenhouse gas scenarios are not used for the Rhône catchment. Analysis of variance is used to distinguish between climate uncertainty (including natural variability) and impact uncertainty associated with the hydrological models (Chapter 2; climate uncertainty is not estimated for the Rhône catchment due to the incomplete coverage of the scenario range). The assessment focuses on changes in the annual cycle, as the available climate scenarios do not adequately capture changes in extremes.

Groundwater temperature projections are calculated for seven aquifers on the Swiss Plateau based on the empirical relationship between groundwater temperature and air temperature (Figure 6.2). Four of the aquifers studied are recharged mainly by riverbank infiltration (henceforth river-fed aquifers), and three by precipitation only (precipitation-fed aquifers). Two linear regression models are employed. One of these focuses on year-to-year correlations and yields separate estimates of annual mean groundwater temperature and monthly anomalies, whereas the other focuses on seasonality and yields direct estimates of monthly mean temperature. Both regression models are calibrated on historical measurement data that were only recently obtained (Schürch, 2011). The end of the calibration period is set at 2007 for all data sets, while the beginning of the calibration period varies depending on the length of the data available: for the three precipitation-fed aquifers (Kaeferberg, Laeufe, and Vorem Haag), the calibration periods begin in 1989, whereas for three of the four river-fed aquifers they begin earlier (1971 for Seewerben, 1978 for Signau, 1972 for Weieracker, and 1989 for Distelmatten).

Other factors such as the influence of river discharge on the temperature of infiltrating water are not accounted for and are treated as statistical uncertainty. Model performance



CH2014 study catchments



Relative changes in clusters

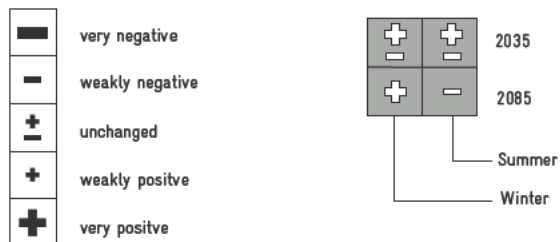


Figure 6.1: The seven runoff response types identified under the A1B scenario using the hydrological model PREVAH-GIUB (Köplin et al., 2012). Cluster C1 (light purple) corresponds to the Jura Mountains, cluster C2 to the catchments of the Swiss Plateau (yellow) and Ticino, and cluster C3–C7 (red, green, blue, and dark purple) to the alpine region with different degrees of glaciation. The boxes indicate the relative change in runoff in summer and winter in the scenario periods 2035 and 2085. The black contours indicate the six catchments selected for the in-depth study.

is evaluated by the goodness of fit to subsamples of the measurement dataset (validation data), after calibration based on the rest of the data (training data). The models perform better for the river-fed aquifers than for precipitation-fed aquifers. This is either because the relationship between groundwater temperature and air temperature is tighter in river-fed aquifers, or because the relevant measurement data series are longer. Box and transfer function models were also tested, but performed poorly in comparison to the linear regression models. Projections are calculated based on monthly mean air temperatures computed from the CH2011 DAILY-REGIONAL scenarios (including all three greenhouse gas scenarios and time periods).

6.3. RESULTS

The changes in runoff in Switzerland induced by climate change can be grouped into seven different response types (C1–C7, Figure 6.1) that mainly reflect the major geographical regions of Switzerland. Cluster C1 corresponds to the Jura Mountains, cluster C2 to the catchments of the Swiss Plateau and Ticino, and cluster C3–C7 to the alpine region, with different degrees of glaciation. Changes in runoff can be summarized as an increase in winter and a decrease in summer, with the total annual volume of runoff remaining approximately the same. Changes in runoff in autumn and spring are far less pronounced. These hydrological responses are summarized for each cluster in Figure 6.1. For catchments in clusters C3–C7, the thermally controlled melting of glaciers and snow governs the seasonal runoff. Here, the

projected warming affects seasonality by increasing the proportion of rain in winter precipitation, by resulting in earlier snow melt, and by decreasing the amount of snow and ice melted during the summer. Accordingly, these catchments shift from a snow-controlled (nival) regime to a more rain-controlled (pluvial) regime. This shift is less pronounced at higher elevations with a higher degree of glaciation (regions C4 and C7). The rainfall-controlled catchments in the Jura Mountains (C1) and on the Swiss Plateau (C2) show similar changes in seasonality, with the projected reduction of precipitation in summer and an increase of liquid precipitation in winter directly altering the runoff. In general, projected changes in Switzerland are more pronounced in alpine areas and in the distant future.

The robustness of the Switzerland-wide response signal is evaluated based on an uncertainty analysis for the six catchments selected for an in-depth study. Figure 6.3 presents the projected annual cycle and related uncertainty bands for these six catchments in comparison to the reference period for the A1B scenario in the distant future (2085). For all catchments, the uncertainty is large, but the salient hydrological responses described above remain valid: (i) earlier melting of snow and ice in both alpine catchments (Rhone and Vorderrhein); (ii) less summer runoff; and (iii) greater winter runoff in most catchments. Although the projected changes in the perialpine catchments (Emme, Thur) and in the catchment on the Swiss Plateau (Venoge) are comparatively small in absolute terms, the relative changes are considerable (Figure 6.3, bottom row). In the alpine Rhone catchment, the melting of residual glaciers prevents the occurrence of a decrease in summer runoff until the end of the century under the non-intervention scenario A1B.

The effect of climate change mitigation on the projected runoff is seen by comparing the different greenhouse gas scenarios (excluding the strongly glaciated Rhone catchment, for which only the A1B projections are available; Figure 6.4). Changes in runoff are projected to appear by the first scenario period (2035) irrespective of the greenhouse gas scenario. Differences between the mitigation (RCP3PD) and the non-intervention (A1B and A2) greenhouse gas scenarios become clear in the mid-century period (2060), when the effects of climate change are also greater. For the end of the century



Figure 6.2: Map showing the location of the aquifers studied. Blue: river-fed aquifers. Green: precipitation-fed aquifers.

(2085), a further increase in the impacts of climate change is projected, and differences appear between A1B and A2. Limiting emissions to RCP3PD levels would reduce the impacts on runoff in summer and winter, when the change is strongest, by approximately a factor of two in comparison to the impacts projected for scenario A2 for 2085. This potential reduction of the impact is independent of the response type (Figure 6.4, bottom row).

The uncertainty in the runoff projections for the non-glaciated catchments is dominated by the uncertainties in the climate models and by the natural variability of the climate (Figure 6.5). Within high alpine catchments, differences in the complexity of the glacier and snow melt routines, as well as differences in the representation of reservoirs in the hydrological models, are crucial and associated with high uncertainties, but the sign of the change

remains consistent across all model chains of the DAILY-LOCAL data set (Chapter 3). This finding is relevant for future studies and for the interpretation of past studies that rely on a single hydrological model. In the lowlands, the ensemble mean indicates an increase of winter runoff but high uncertainties make the sign of the change inconclusive. In the mountain catchments, low winter runoff implies high uncertainties in the relative runoff change. The uncertainties in the summer runoff projections remain relatively stable whereas uncertainties in the winter runoff tend to increase with time.

The three lowland catchments of the same response type show similar behavior. This finding supports the clustering derived from the spatial analysis (Köplin et al., 2012; Figure 6.1) and justifies the extrapolation from the selected set of six catchments to the response types identified in the Switzerland-wide study.

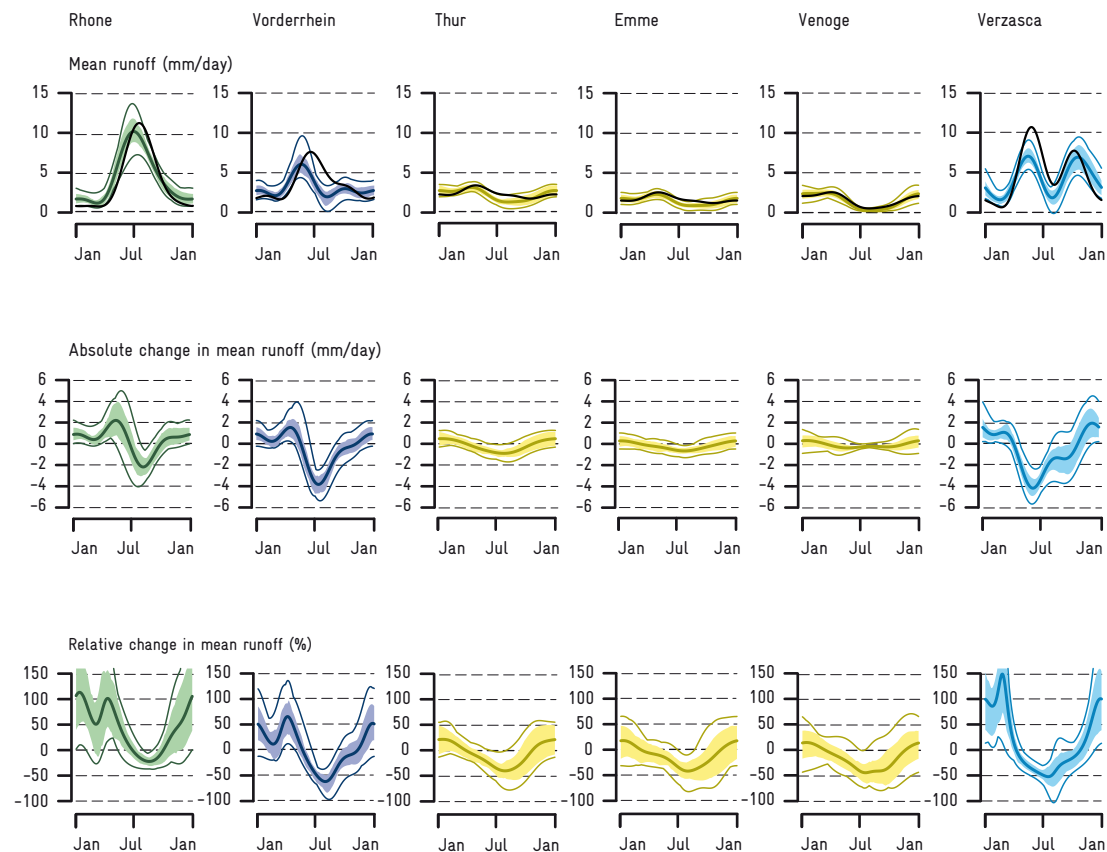


Figure 6.3: Mean runoff (top row) over the reference period (black) and the scenario period 2085 (colored) for scenario A1B, and the corresponding absolute change (middle row) and relative change (bottom row). For projected runoff, the mean over the uncertainty range is shown (bold colored line) along with the standard deviation (shaded) and the minima/maxima (thin lines). Colors indicate the runoff response types for each catchment according to Figure 6.2.

Based on the CH2011 climate projections, **groundwater warming** can be expected in all aquifers studied, but (with the exception of Distelmatten) there are marked differences between river-fed and precipitation-fed aquifers (Figure 6.6). According to the medium estimates, by the end of the century the latter are projected to warm by $< 1^{\circ}\text{C}$ on average while the former are projected to warm by $1\text{--}3.5^{\circ}\text{C}$. However, the results do not indicate clearly whether the relatively slight warming projected for precipitation-fed aquifers results from a weak coupling of groundwater temperature to air temperature or from the comparative shortness of the data sets. Taking into account the uncertainty in the projections, it is possible that groundwater temperatures will increase by up to 7°C in river-fed aquifers and by up to 2°C in precipitation-fed aquifers in any given year of the projection period 2085. However, as a result of the large uncertainties involved, the projections do not exclude a situation in which no warming, or even a slight cooling, might take place. Comparison of the groundwater temperature projections under the three different greenhouse gas scenarios shows that they are very similar for the 30-year period centered on 2035, but diverge later (Figure 6.6). With regard to seasonality, the two regression models are not always consistent; however, there is a clear tendency for warming to be strongest in summer and autumn. The uncertainty associated with the projections results mainly from the uncertainty inherent in the statistical predictability of groundwater temperature from air temperature, which is responsible for 70–80% of the total projection uncertainty. The remaining 20–30% of the total projection uncertainty results from the difference between the lower and upper estimates of the CH2011 projections. The impact uncertainty is larger in most river-fed aquifers than in precipitation-fed aquifers because of the stronger coupling with the naturally varying air temperatures.

6.4. IMPLICATIONS

The total annual **runoff** volume in Switzerland is projected to remain approximately the same as it is now. However, at the regional scale, e.g., in highly glaciated alpine valleys like the Rhone catchment, this will be partly at the expense of retreating glaciers. This general

statement is especially true for the northern part of the Alps. In the Ticino and the southern Valais however, the annual runoff volume will decrease (FOEN, 2012b). The relative stability of the long-term annual runoff over time is related to the smallness of the projected changes in annual precipitation rates, supplemented by the contribution of glacier melt in glaciated catchments.

A seasonal redistribution of runoff is projected under all greenhouse gas scenarios, and will affect summer and winter runoff in all catchments. This confirms and corroborates previous findings (IPCC, 2007b; FOEN, 2012b) and has already been described qualitatively twenty years ago (VAW, 1990; Occc, 2007). In the present study, the hydrological responses to climate change have been quantified using the latest and most comprehensive modeling approach. Furthermore, this study demonstrates that the response patterns are robust with respect to the considerable uncertainties that result from the choice of climate and hydrological models.

Although the long-term annual runoff will remain approximately constant, the year-to-year variability and the seasonal redistribution of discharge suggest some challenges for water resources management. Year-to-year variability, which may significantly affect water management, has not yet been investigated thoroughly because of the limitations of the downscaling method (Chapter 3). Concerning seasonal redistribution, the FOEN report (FOEN, 2012b) as well as Meyer (2012), showed for the Swiss Plateau that an increase in the duration of dry spells in summer might lead to water shortages like those that occurred in the summer of 2003. As shown in the present study, these water shortage situations are further exacerbated by the projected groundwater temperature increase, which can affect groundwater quality. In all regions of Switzerland, water scarcity in summer has additional implications for agriculture and ecosystems, drinking water supply and hydropower production (SGHL and CHy, 2011). For instance, Holzkämper et al. (2013a) showed that the positive effects of climate warming on agricultural yield are suppressed by water stress in extremely dry years like 2003. Still, in a continental context, the threat of drought stress is less for Switzerland than for southern and eastern Europe (IPCC, 2007b).

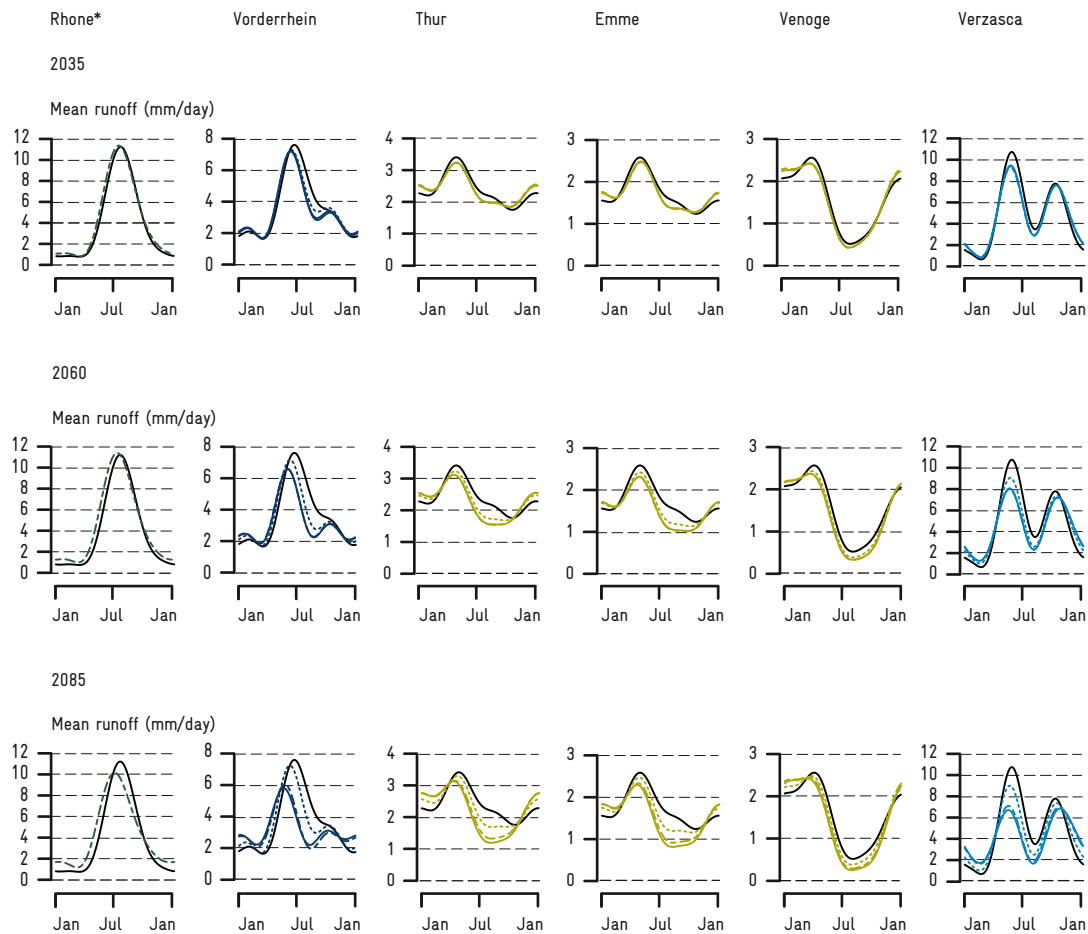


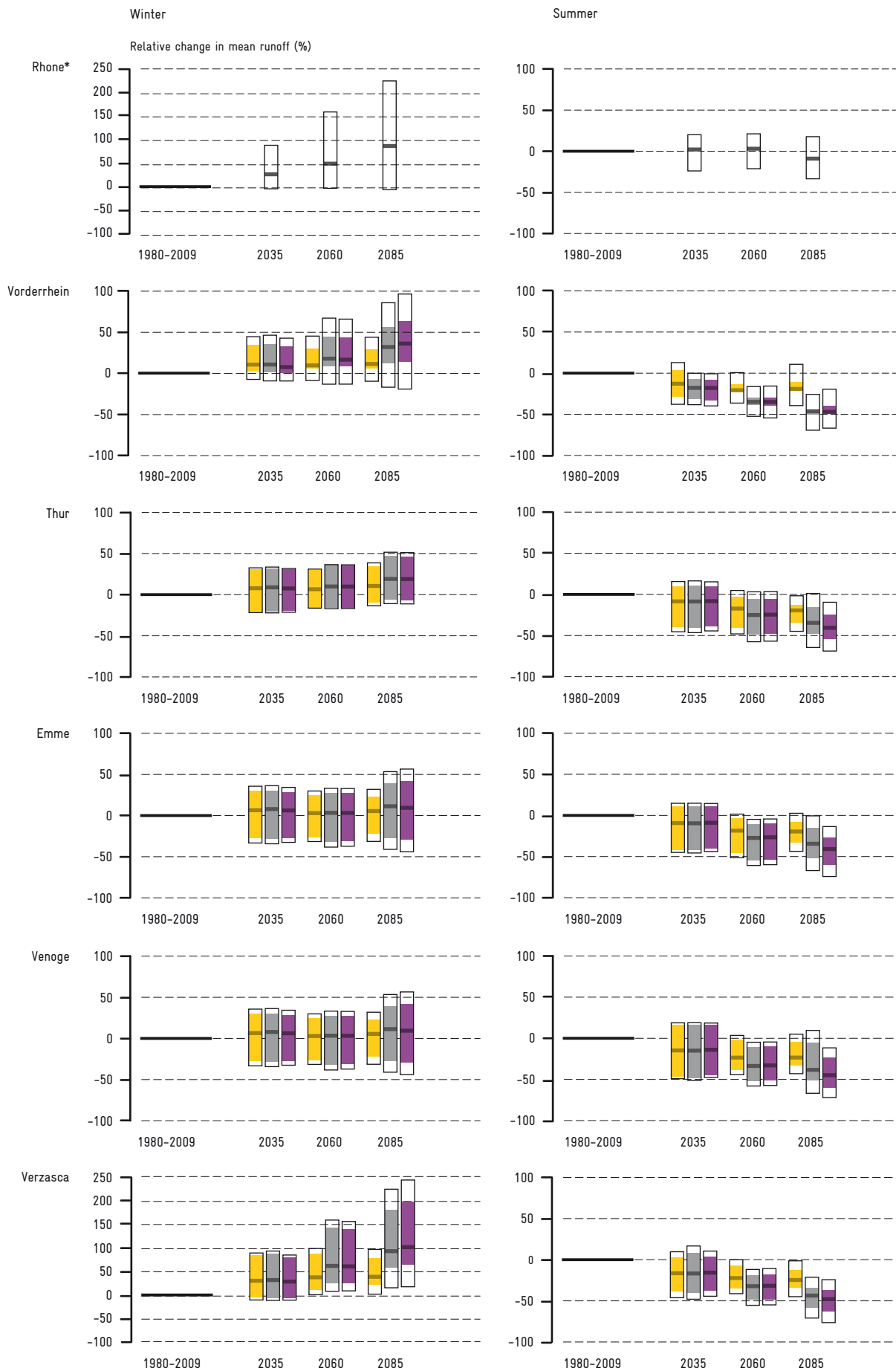
Figure 6.4: Mean runoff over the reference period (black) and the three CH2011 time periods (colored) and greenhouse gas scenarios A2 (solid), A1B (dashed), and RCP3PD (dotted). The lines represent means over 24 simulations; the uncertainty range is not shown. Colors indicate the runoff response types for each catchment according to Figure 6.2.

*Scenarios A2 and RCP3PD are not shown for the Rhone catchment due to potential bias (section 6.2).

Climate change, and especially the higher temperatures associated with climate change, will cause a shift in the runoff regime from nival to pluvial in catchments that are not strongly influenced by glacial meltwater. Accordingly, an increase in the variability of runoff throughout the year and from year to year, resulting in lower stability and lower predictability, is another challenge that will need to be met in the future. A more flexible and adaptive water management will be needed to deal with a more irregular and longer flood season (Köplin et al., 2014) and an expected increase in the frequency of occurrence of extreme events such as droughts and floods. Joint regional governance of water resources and water management across political boundaries can

balance water demand and water availability at the local scale. Furthermore, multifunctional storage that – apart from hydropower production – can be used for drinking water supply, irrigation, artificial snow production, and flood retention might be a viable solution. Again, regional and multi-user agreements have to be established, which is not an easy task also from a political point of view.

The implications for hydropower production have been studied by Hänggi et al. (2011a; b). They considered the direct effect of changes in runoff on hydropower production across Switzerland from the reference period 1980–2009 to the period 2035 (under scenario A1B), assuming current production schemes and



electricity markets. For winter they find an increase of 10% in hydropower production, for summer a decrease of 4 to 6%, and overall for the whole year a slight increase of 0.9 to 1.9%. Despite these encouraging results, adverse impacts of climate change, especially in the mid- (2060) and long term (2085) for single hydropower stations, cannot be excluded.

Although this study presents detailed and comprehensive results, more research is needed to determine how changes in climate variability and climate extremes will affect runoff, as changes in climate variability are not captured in the climate change scenarios used (Chapter 3). Furthermore, uncertainties related to the internal model parameters and a broader spectrum of downscaling methods should be addressed in future studies.

It is worth emphasizing that the present study shows that mitigation of greenhouse gases can reduce the change in runoff in winter and summer by about a factor of two. With regard to the implications summarized above, mitigation can help considerably in attenuating the adverse effects of climate change. Still, some changes will occur and will require adaptation. Thus, future modeling studies should couple hydrological impact models with models for water resource management, irrigation, hydropower production, etc., to quantify the impact of hydrological change on society, the economy, and ecosystems.

Although the models do not perform equally well for all aquifers, the projections clearly indicate that **groundwater temperatures** in river-fed aquifers, which account for approximately 30% of Swiss drinking water production, will increase strongly. The main reason for this groundwater warming is the warming of the rivers that feed the aquifers. Various studies show that higher temperatures affect microbiological activity during the infiltration of river water (Sprenger et al., 2011; Figura

et al., 2013), and in Switzerland during the unusually hot, dry summer of 2003, oxygen consumption was observed to increase with increasing groundwater temperature to such an extent that groundwater anoxia resulted (Hoehn and Scholtis, 2011). This could pose problems not only with respect to groundwater quality (Sprenger et al., 2011), but also with respect to drinking water production as a result of the possible clogging of pumping wells with manganese and iron precipitates (Hunt et al., 2002). To assess the impact of climate warming on oxygen concentrations and on the redox state of groundwater, monitoring at riverbank infiltration sites needs to be continued and intensified in the future. Furthermore, because the groundwater temperature projections rely solely on statistical relationships and are subject to relatively large uncertainties, further studies need to focus on constructing adequate models for groundwater temperature based on field experiments and long-term monitoring.

According to the present study, Switzerland will retain its role as Europe's water tower, but as summer runoff and drinking water become more vulnerable in the course of the next century, adaptation measures, such as improving the efficiency of water usage, storage, and distribution, will need to be implemented to prevent water shortages. Immediate reduction of greenhouse gas emissions as expressed in the RCP3PD scenario can greatly reduce these impacts.

< **Figure 6.5:** Relative change in mean runoff projected for winter (DJF, left) and summer (JJA, right). Greenhouse gas scenarios are indicated by the colors yellow (RCP3PD), grey (A1B), and purple (A2). The black boxes and the horizontal line in the middle of each box show the range and the mean of the ensemble, respectively. The shaded range indicates the climate uncertainty including the effect of natural variability. Note the wider scale of the y-axis for the Rhone and Verzasca for winter.

*Scenarios A2 and RCP3PD and the climate uncertainty range for A1B are not shown for the Rhone catchment because of potential bias (section 6.2).

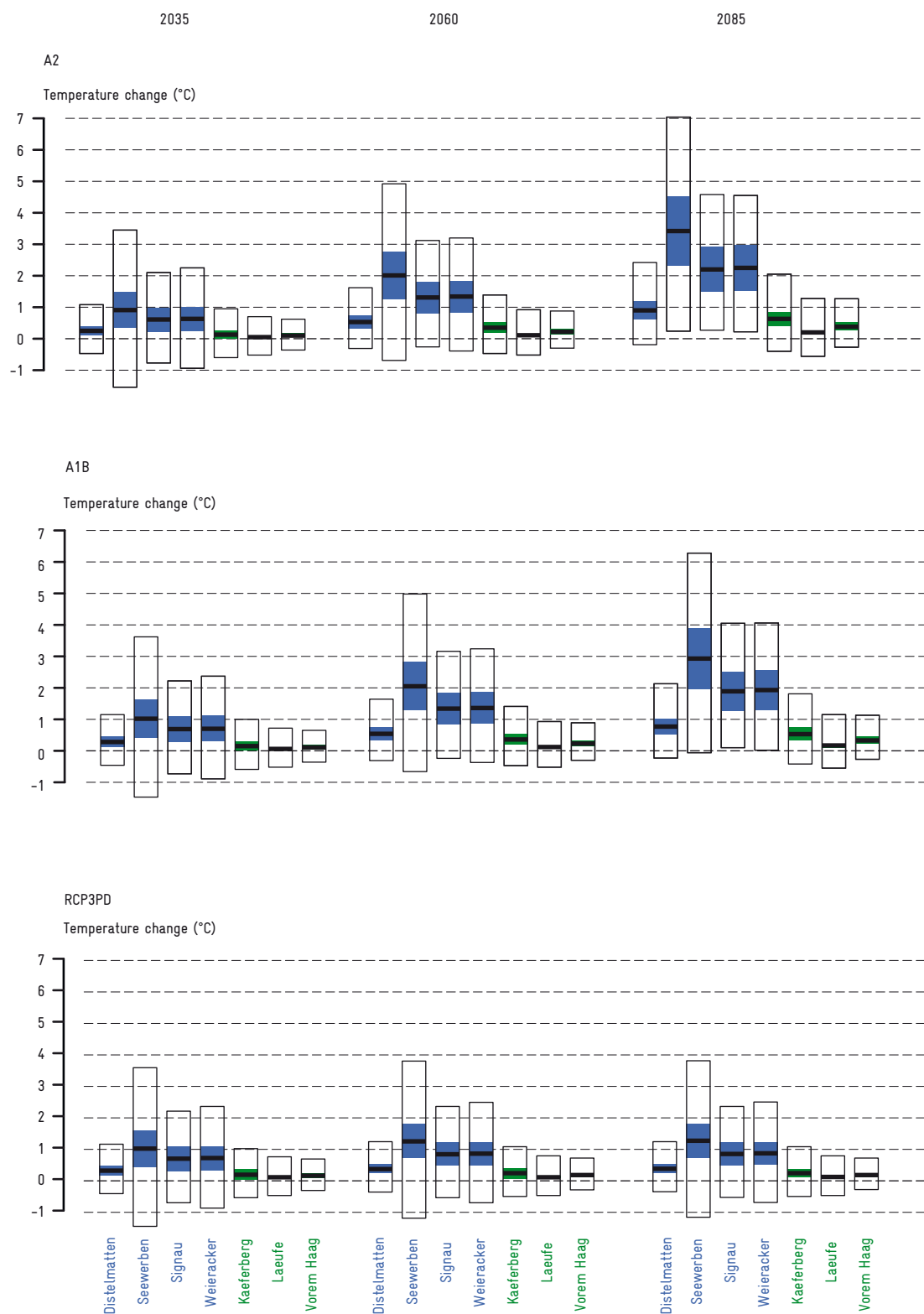


Figure 6.6: Projected groundwater temperature change for each of the three CH2011 climate scenarios and time periods. Shown are the averaged projections of the two linear regression models. Blue: river-fed aquifers. Green: precipitation-fed aquifers. The colored region of each box shows the uncertainty associated with the climate projections, and the black outline shows the combined uncertainty of the temperature change in any given year of the corresponding future period, including both climate and impact uncertainty.