Hydrological impacts of climate change in Switzerland during the 21st century

Inauguraldissertation
der Philosophisch-naturwissenschaftlichen Fakultät
der Universität Bern

vorgelegt von
Nina Köplin
von Deutschland

Leiter der Arbeit:
Prof. Dr. R. Weingartner

Co-Leiter:
Dr. B. Schädler

Geographisches Institut der Universität Bern
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Prof. Dr. S. Decurtins
Summary

Within this thesis, the climate change impacts on the water balance components of Swiss mesoscale catchments were assessed as well as the relative importance of forest and glacier change on the projected runoff. Additionally, changes in high flow conditions were examined. The hydrological modelling system PREVAH was used to study the changes in the hydrological variables. The model parameters were calibrated for catchments where measured discharge records in hourly resolution are available. By regionalization, the calibrated parameter sets were then transferred to catchments without or with influenced discharge data. The resulting extensive set of 189 study catchments represents the different regime types in Switzerland. To assess future changes, ten climate model chains were applied, each consisting of a global climate model (GCM) and a nested regional climate model (RCM). The climate scenario data were provided by the CH2011 initiative and are driven by the A1B emission scenario. The GCM-RCM data were post-processed and interpolated to the dense network of meteorological station sites in Switzerland, i.e. to 188 temperature and 565 precipitation stations. Two scenario periods in the 21st century were assessed relative to the control period 1984–2005: the near future from 2025–2046 and the far future from 2074–2095. The projected changes in the climate variables can be briefly summarized as follows: summer precipitation decreases and winter precipitation increases whereas temperature increases in general. The projected changes are more pronounced in the far future period.

Catchments with a mean altitude between 1000 to 2500 m a.s.l. show most pronounced changes in mean monthly runoff. This is the result of changes in snow accumulation and snow- and ice-melt and is therefore mainly a result of the strong temperature increase. The hydrological change in catchments with a mean elevation below 1000 m a.s.l. is largely determined through (the less clear) precipitation change. In catchments with a glaciation of more than 10 % in the control period, the projected summer runoff highly depends on glacier retreat. Changes in forest cover alter the evapotranspiration and thereby extract water from the hydrological cycle. The indirect effect on the runoff, i.e. a lowering of the projected runoff, is however small in the analysed 15 case study catchments. The seasonality of floods changes substantially in snow-fed catchments that show a clear change in regime type. The clear summer seasonality in those catchments changes to a non-distinct seasonality with floods during the whole year but with a tendency to winter. The magnitudes of mean annual high flows increase in general, although changes in the frequency and intensity of precipitation were kept constant. That is, changes in the mean annual cycle of the climate variables alter high flow conditions, already.

The projected changes are valid for mesoscale catchments in Switzerland and other mid-latitude mountainous regions. They provide valuable quantitative information on hydrological climate change impact and contribute to the scientific basis that is necessary to develop sound and sustainable adaptation measures.
Zusammenfassung


Die projizierten Änderungen sind sowohl für mesoskalige Gebiete in der Schweiz als auch für andere gebirgige Regionen der mittleren Breiten gültig. Die Resultate stellen wertvolle quantitative Informationen zu den hydrologischen Auswirkungen der Klimaänderung dar und
tragen zu den wissenschaftlichen Grundlagen bei, welche die Basis für fundierte und nachhaltige Anpassungsmassnahmen bilden.

**Acknowledgements**

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**Dank**

Ich habe es mit meiner Dissertation am GIUB in Bern gut getroffen, einigen Personen möchte ich dafür persönlich danken:

Rolf für seine Weitsicht and Genauigkeit, die einen stetig dazu anregt, das Fertige neu zu überdenken. Das verblüfft mich immer wieder.

Bruno für seine Erfahrung, seinen Scharfsinn und die Art wie er ist. Der Betreuer einer Doktorarbeit sollte so sein wie du.

Dani für sein Engagement über das Muss hinaus. Ohne deine Arbeit hätte es diese hier so nicht gegeben.

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Mama und Papa, dass sie mir alle Freiheiten gelassen haben, mit dem Wissen und Vertrauen, dass ich meinen Weg gehe.

Es ist alles nur halb so schwer, wenn das Wichtigste schon stimmt. Danke, Thomas.
# Table of contents

Summary .................................................................................................................. iii
Zusammenfassung ................................................................................................ iv
Acknowledgements ............................................................................................... v
Dank ....................................................................................................................... v
Table of contents ................................................................................................... vi
Figures .................................................................................................................. viii
Tables ................................................................................................................... ix

## INTRODUCTION

1 Object of research .............................................................................................. 2
2 CCHydro ........................................................................................................... 3
3 Research questions ............................................................................................ 4
4 Structure of the thesis ....................................................................................... 4

## PART I DATA & METHODS

I-1 Study catchments and data ............................................................................ 8
I-2 Hydrological model ........................................................................................ 9
I-3 Calibration ..................................................................................................... 10
I-4 Regionalization ............................................................................................. 12
I-5 Validation ...................................................................................................... 13
I-6 Climate scenarios .......................................................................................... 17
I-7 Glacier and forest scenarios ......................................................................... 19

## PART II SENSITIVITY

II-1 Introduction ................................................................................................... 22
II-2 Study area and data ..................................................................................... 23
II-3 Methods ....................................................................................................... 27
II-4 Results .......................................................................................................... 30
II-5 Discussion and conclusions ....................................................................... 39

## PART II SUPPLEMENT

45
# Table of Contents

## PART III  LAND COVER
- III-1 Introduction ................................................................. 52
- III-2 Study area and data ........................................................ 53
- III-3 Methods ........................................................................ 60
- III-4 Results ........................................................................... 63
- III-5 Discussion ...................................................................... 70
- III-6 Conclusion ...................................................................... 72

## PART IV  FLOODS
- IV-1 Introduction ..................................................................... 74
- IV-2 Data and Methods ............................................................ 75
- IV-3 Results and Discussion .................................................... 77
- IV-4 Conclusions and outlook ................................................ 86

## SYNTHESIS
- 1 Climate change sensitive catchments .................................... 90
- 2 Additional impact of glaciers and forests ............................. 92
- 3 Future flood seasonality ......................................................... 93
- 4 Research questions .............................................................. 95
- 5 General conclusions and outlook .......................................... 97

## REFERENCES
- Erklärung .................................................................................. 113
- Curriculum Vitae ..................................................................... 115
Figures

**PART I  DATA & METHODS**

- Fig. 1. Mesoscale catchments for calibration and regionalization .......................................................... 8
- Fig. 2. Schematic of the PREVAH model structure .................................................................................. 10
- Fig. 3. Iterative search algorithm ............................................................................................................. 12
- Fig. 4. Validation of calibration .................................................................................................................. 14
- Fig. 5. Overview of catchments for validation of regionalization .............................................................. 15
- Fig. 6. Validation of regionalization .......................................................................................................... 16
- Fig. 7. Spatial distribution of climate change signals .................................................................................. 19

**PART II  SENSITIVITY**

- Fig. 8. Overview of the study region ........................................................................................................ 24
- Fig. 9. Correlation analysis of physiographic catchment properties .......................................................... 29
- Fig. 10. Cluster analysis for hydro-climatological change signals ............................................................ 31
- Fig. 11. Parallel coordinates plot of the physiographic catchment properties ........................................ 32
- Fig. 12. Hydro-climatological change signals per cluster ........................................................................ 33
- Fig. 13. RDA-biplots for all catchments ..................................................................................................... 36
- Fig. 14. RDA results for the far future period and single clusters ............................................................... 38
- Fig. 15. Additional cluster analysis – Variables ......................................................................................... 46
- Fig. 16. Additional cluster analysis – Methods .......................................................................................... 47

**PART III  LAND COVER**

- Fig. 17. Spatial and altitudinal distribution of the case study catchments .................................................. 54
- Fig. 18. Relative proportion of land cover types ....................................................................................... 56
- Fig. 19. Schematic of the modular model structure of PREVAH .............................................................. 59
- Fig. 20. Schematic of scenario coupling ..................................................................................................... 61
- Fig. 21. Comparison of water balance components for the non-glaciated catchment 5 ......................... 64
- Fig. 22. Comparison of water balance components for the glaciated catchment 9 .................................. 65
- Fig. 23. Comparison of relative net changes .............................................................................................. 67
- Fig. 24. ANOVA for the annual cycles of monthly change values ............................................................ 69

**PART IV  FLOODS**

- Fig. 25. Comparison of simulated and observed specific discharge ............................................................ 78
- Fig. 26. GCM spread of $H_{\text{MEAN}}$ and $H_{\text{MAX}}$ .............................................................................. 79
- Fig. 27. Boxplots of specific discharges of all 189 catchments ................................................................ 80
- Fig. 28. Spatial representation of change in $H_{\text{MEAN}}$ and $CV$ ................................................................ 81
- Fig. 29. Seasonality vectors for control, near future and far future period .............................................. 83
- Fig. 30. Detailed analysis of seasonality change for five case study catchments ........................................ 84

**SYNTHESIS**

- Fig. 31. Overview of case study catchments shown in the synthesis section ............................................. 90
- Fig. 32. Spread of control and scenario period runoff – Sensitivity ........................................................... 91
- Fig. 33. Spread of control and scenario period runoff – Land cover .......................................................... 93
- Fig. 34. Extended seasonality analysis in the five case study catchments ................................................. 94
Tables

PART I  DATA & METHODS
Table 1. Grouping of parameters for successive pair-wise calibration ........................................... 11
Table 2. Parameterization of regionalization; northern and southern alpine ........................................... 13
Table 3. Applied climate model chains from the ENSEMBLES project ........................................... 18

PART II  SENSITIVITY
Table 4. Physiographic catchment properties .......................................................................................... 26
Table 5. Summary of runoff change per cluster ......................................................................................... 37

PART III  LAND COVER
Table 6. Nomenclature of scenario combinations .................................................................................... 57

PART IV  FLOODS
Table 7. Applied climate model chains from the ENSEMBLES project ........................................... 79
Table 8. Summary of changes in seasonality for the five case study catchments ............................................. 86
INTRODUCTION
1 Object of research

In recent years, the need to integrate climate change adaptation-actions into national planning has been recognized and transferred into international conventions (UNFCCC, 2008). In the Cancun Adaptation Framework (CAF; UNFCCC, 2010) the Parties agreed “[...] that adaptation is a challenge faced by all Parties, and that enhanced action and international cooperation on adaptation is urgently required [...]”. Switzerland therefore adjusted its climate policy and issued an adaptation strategy, which consists of two phases (FOEN, 2012a). First, the aims, fields of action and main challenges were defined. Overall challenges that affect not only water resources management but the whole society are increasing summer droughts and an increasing flood risk. The second phase, which should be finished by the end of 2013, shall provide specific action plans how to reach the determined aims.

One way to obtain the scientific basis required for adaptation strategies are so called top-down impact studies that apply state of the art climate model data to impact models and evaluate the changes in the targeted variables. The Swiss Climate Change Scenarios CH2011 constitute the most recent basis for impact studies in Switzerland (CH2011, 2011). They provide post-processed climate scenario data for the local scale, i.e. at every temperature and precipitation station in Switzerland. Briefly speaking, the clearest changes for Switzerland are generally increasing temperatures and decreasing summer precipitation at the end of the 21st century as well as increasing winter precipitation in the same period. Compared to the change signals of the near future, those for the far future period, i.e. the late 21st century, are much clearer.

Switzerland is an ideal region to study the impacts of climate change on the hydrology for various reasons. First of all, mountains are environments that react very sensitive to changes in climate and an impact is already perceptible as glaciers retreat and snow line altitude increases. European glaciers, for example, lost 65 % of their mass since the end of the Little Ice Age in 1850 (Schädler and Weingartner, 2010). Another important feature of mountains is that temperature and precipitation, as well as vegetation, soils and slope change with altitude, which constitutes a heterogeneous environment with steep gradients. These climatic and physiographic characteristics of mountains clearly govern hydrological processes (Weingartner et al., 2003), which is why a wide range of hydrological regime types can be found on a rather small area (Wehren et al., 2010). This, too, makes mountainous areas an ideal and exciting study region for climate change impacts. Moreover, it is not only important for the directly affected region to know how the hydrology might change: “[...] the implications of climate change in mountains will reach far beyond mountain areas” (Kohler and Maselli, 2009). The Alpine Rhine, for example, contributes 34 % of the total runoff of the Rhine, but its relative catchment area comprises only 15 % (Viviroli and Weingartner, 2004). Finally, precipitation and runoff are measured in relatively dense networks in Switzerland (Weingartner et al., 2007). Switzerland can therefore be regarded a “privileged region” for climate impact studies (Beniston, 2006).

Recently, a large number of climate impact studies were conducted in Switzerland (e.g., Hänggi, 2011; Horton et al., 2006; Jasper et al., 2004 and Schaeffli et al., 2007 to name just a
few). Although each study has a specific focus, both thematically and spatially, one can summarize the main findings that are repeatedly stated: in a warmer future, the proportion of liquid precipitation increases whereas that of solid precipitation decreases. This leads to changes in the regime type of a catchment. In snow-fed catchments, an earlier snow melt due to higher temperatures provokes a shift of the annual maximum to an earlier time in the year. Summer runoff will decrease substantially, mostly as a result of decreasing summer precipitation and due to the relative snow melt deficit. These are some of the most obvious hydrological changes anticipated for the 21st century.

Most of the studies mentioned above are detailed case studies that study the uncertainty of the climate model input (e.g., Finger et al., 2012; Kunstmann, et al. 2004; Jasper et al., 2004; Rössler et al., 2012) or case studies with a specific focus, e.g. on changes in glacier runoff (Farinotti et al., 2011, Huss et al., 2010) or on hydropower production (Finger et al., 2012; Hänggi, 2011; Schaeffli et al., 2007). What is missing so far is a comprehensive assessment of the various catchment types in Switzerland. This thesis is a contribution to bridge this gap.

It is part of a national research project (CCHydro, see next section) that is one in a series of nationwide and international research projects in recent years that elaborated on climate change impact on the hydrology. The project “Climate change and hydropower generation in Switzerland”, for example, sought to establish a sound database for future management of hydropower production (SGHL and CHy, 2011). The AdaptAlp project focused on natural hazard management and climate change adaptation in the Alpine arc with extensive transnational collaboration (Korck et al., 2011). The large-scale ACQWA project (Assessing Climate impacts on the Quantity and quality of WAter; ACQWA, 2012) studies the impacts of climate change on the hydrology, particularly the subsequent effects on the social, economic and political systems. The latest of those climate impact projects in Switzerland is the mentioned project CCHydro, which will be discussed in more detail in the following section.

2 CCHydro

The present study is part of the recently finished national research project Climate Change in Switzerland – Hydrology (CCHydro; Volken, 2010), which was initiated by the Federal Office for the Environment (FOEN) in 2008. The synthesis report (FOEN, 2012b) provides a detailed overview of the various topics covered in the project. The overall aim of CCHydro was to assess the variety of possible climate change impacts on all kinds of hydrological systems in Switzerland. The project should contribute to the scientific basis for the Swiss adaptation strategy (FOEN, 2012a).

Several research institutions were involved, each of them accounting for a specific aspect of hydrological change, e.g. alterations of the natural runoff of large basins, changes of the peak flow and low flow conditions or glacier retreat. All subprojects applied the abovementioned CH2011 climate scenarios which ensures comparability of the individual studies and their
results. For the same reason, the derived scenarios of glacier retreat are used in those subprojects where they were relevant.

In the subproject presented in this thesis, changes in the water balance of mesoscale catchments were analysed to identify those catchments exhibiting sensitivity to a change in climate. The relative importance of glacier retreat and forest change on the hydrological projections was studied in detail for a selection of case study catchments that represent the variety of hydrological response types in Switzerland. Finally, changes in high flow conditions, in particular changes in the seasonality of floods were assessed.

3 Research questions

The three aspects of the study, climate sensitivity, land cover influence and flood seasonality, are studied for the entire area of Switzerland and addressed with the following research questions:

1. Are there catchments that are particularly sensitive, i.e. that show a strong response to changes in climate, and what are the dominant processes that cause a sensitive response?

2. Does a climate induced change in land cover, i.e. changes in forest and glacier extent, impact on the hydrology additionally, and how does this change compare to the hydrological change caused by the climate signal alone?

3. Does the flood runoff of catchments and in particular their flood seasonality change due to changes in the mean annual cycle of precipitation and temperature?

4 Structure of the thesis

This introduction provides only a short overview on the topic and its broader perspective. The following parts I to IV, which constitute the main part of the thesis, consist of four research articles prepared within the project. The three papers that comprise parts II to IV answer the three research questions stated above.

**Part I, DATA BASIS**, gives an overview on the general set up and a description of the data used within the study. It covers the preprocessing as well as the calibration, regionalization and validation of the simulated data and briefly summarizes the applied climate, glacier and forest scenarios.

In **part II, SENSITIVITY**, the projected hydrological change of the study catchments is first classified by means of cluster analysis to identify regions with similar change signals. Those regions are then analysed for their sensitivity to climate change and for the dominant processes that constitute the hydrological change. Part II is followed by a supplement that enlarges upon the impact of different configurations of the applied clustering. This is to verify the suitability of the chosen clustering method.
In part III, LAND COVER, the relative importance of climate induced changes in land cover, i.e. glacier and forest change, are examined. The necessary scenarios of glacier retreat were provided within CCHydro (Linsbauer et al., 2012). Forest scenarios that reflect different processes, e.g. an increase in tree line or forest ingrowth on abandoned areas, are compiled for this part of the thesis, specifically.

Part IV, FLOODS, studies changes in flood magnitudes and in more detail changes in flood seasonality as a result of the projected changes in climate.

In the synthesis section, the key results of parts II to IV are summarized and reflected. General conclusions are drawn and an outlook on possible future research is provided.
PART I DATA & METHODS

This first part of the thesis is based on a paper published in Advances in Geosciences (Köplin et al., 2010). The paper is not integrated in its original form because some parts of the study setup have changed, meanwhile, for example the number of climate scenarios in use (now 10 instead of 16) as well as the reference period and the number of scenario periods assessed (now 2 instead of 1). The paper provided an overview on the project and was published when final results were not yet at hand. Therefore, its content was modified, complemented where necessary (e.g. validation of regionalization in southern alpine areas) and rearranged.

First, the study catchments and available data are introduced followed by the hydrological model used in this study. Then, the calibration and regionalization of the model parameters and their validation is described. The subsequent section on climate scenarios is complemented by short sections on scenarios of glacier and forest change.

I-1 Study catchments and data

As stated in the introduction, Switzerland is an ideal domain to study the impacts of climate change on the hydrology of mesoscale catchments. It has a variety of different catchment types and analysing them all facilitates assessing the range of possible hydrological impacts of climate change. In hydrological modelling, the parameter sets of catchment models have to be calibrated on measured records, most often on measured discharge like in this study. The number of catchments with natural or uninfluenced discharge records in Switzerland is, however, limited due to hydropower production (Margot et al., 1992), and their spatial distribution is unbalanced, which is most obvious in mountainous regions (cf. Fig. 1, filled blue and orange areas). To assess the range of different catchment types, the model parameters of calibrated catchments are transferred to both, catchments without and catchments with influenced discharge records by regionalization. Thereby, we obtain parameters for a comprehensive set of mesoscale catchments (hatched areas in Fig. 1) that represent the variety of catchment types in Switzerland. In total, 189 regionalized catchments are studied having an average area of 250 km$^2$ and ranging from 20 to 1760 km$^2$. Their mean altitudes vary between 440 and 3020 m a.s.l. and they are so called water balance basins as introduced and defined by Schädler and Weingartner (1992). For these basins, the long-term mean annual values for the water balance components were estimated (Schädler and Weingartner, 2002), which allows for the comparison with the simulated data (see later in this part). Catchments located downstream of larger lakes are not considered because their hydrographs are influenced too strongly by lake management.

Fig. 1. Mesoscale catchments for calibration (solid) and regionalization (hatched) and meteorological network of Switzerland. The catchments north of the alpine ridge are displayed in blue, the southern alpine catchments are shown in orange. Note that a few catchments in northwest and west Switzerland belong to the Rhone basin draining southward.
Note, that the calibration and regionalization procedures described in the following sections were developed for and applied to northern alpine catchments, i.e. the Swiss Rhine and its tributaries (Viviroli, 2007). For this thesis, calibration and regionalization was extended and applied to southern alpine catchments, additionally. By *southern alpine*, all catchments located south of the main ridge of the Alps are meant, which incorporates catchments in the inner alpine valleys in cantons Valais and Grisons, too, and not as usual canton Ticino, alone.

For model calibration, hourly discharge records are used that cover at least 5 years of continuous measurement in the period from 1983 to 2005 (one year warm-up included, i.e. the evaluation will based on the period 1984–2005). The decision on this simulation period is based on data availability: the high resolution meteorological network (ANETZ, cf. Fig. 1), for example, was more or less fully established in 1983 and was considerably revised after 2005, including decommission or dislocation of some stations, in the course of the establishment of the new high resolution SwissMetNet (SMN; MeteoSwiss, 2005). Focusing on the period from 1983 to 2005 guarantees a consistent data base for model forcing. The discharge records are provided mostly by the FOEN (2008) and partly by cantonal authorities. Further input data for the modelling and regionalization are a digital elevation model as well as maps of land use and soil properties, all provided by the SFSO (2003).

The meteorological input variables are air temperature (°C), precipitation (mm h⁻¹), relative humidity (%), wind speed (m s⁻¹), global radiation (W m⁻²) and relative sunshine duration (–). Depending on the type of meteorological station, the resolution of the data is hourly to daily. For 77 stations of the automatic meteorological network (ANETZ) all variables are available in hourly resolution, while 84 climate stations and 668 precipitation gauges register data in 6 h resolution or daily, respectively (data provided by MeteoSwiss, 2008). The model input is mainly based on high resolution ANETZ data and complemented by the other records.

**I-2 Hydrological model**

The hydrological modelling system PREVAH (Precipitation-Runoff-EVAporation-HRU related model; Gurtz et al., 1999; Viviroli et al., 2009a; Zappa and Gurtz, 2003) is a semi-distributed and conceptual yet process-oriented model that is run on the basis of hourly meteorological input, and at a spatial resolution of 500 × 500 m². An extensive documentation of the hydrological model and its pre- and post-processing tools is available in Viviroli et al. (2007; 2009a). In this section, only the basic components are covered. We use this model in our study because it has been developed to particularly suit conditions in mountainous environments (Gurtz et al., 1999). Furthermore, PREVAH has shown to be a reliable and flexible tool for various scopes of application and climate conditions ranging from drought analysis over water balance modelling to flood estimation and forecasting (Viviroli et al., 2009a).
Fig. 2. Schematic of the PREVAH model structure with tuneable parameters, storage modules and hydrological fluxes (Viviroli et al. 2009a).

The basic conceptualization of PREVAH includes an HBV model component (Bergström, 1976; Lindström et al., 1997) that is implemented with the semi-distributed approach of hydrological response units (HRUs; Ross et al., 1979). Further modules supplement the model structure, each of which represents an individual process of the hydrological cycle, e.g. interception, soil water storage, groundwater fluxes or snow- and glacier-melt (Fig. 2). The specific characteristics of 22 different land cover types are parameterized a priori.

To run the model, the meteorological station data have to be interpolated, first, and the spatially distributed meteorological variables are averaged to 100 m altitude zones, afterwards. In this study, interpolation is carried out on the basis of Detrended Inverse Distance Weighting (DTIDW), where detrending means an elevation dependent regression of the climate variables.

I-3 Calibration

The basics of the methods involved are explained in this section; the calibration procedure is described in detail in Viviroli et al. (2009b). As stated above, at least five years of discharge data in hourly resolution are needed within the period 1983 to 2005. A five-year calibration period which proved suitable in the study by Viviroli et al. (2009b) was chosen (with one year...
warm-up included), to capture the discharge variability of a catchment. Where possible, the calibration period covers the five years from 1993 to 1997. For catchments where these data are not available, an alternative five year period within the modelling period 1983 to 2005 is chosen. Catchments are calibrated using an iterative search algorithm which is applied to maximize objectivity of the calibration procedure. The parameter pairs are given in Table 1 in the order they are calibrated.

Table 1. Grouping of parameters for successive pair-wise calibration of PREVAH (Viviroli et al., 2009b).

<table>
<thead>
<tr>
<th>Pair</th>
<th>Parameter</th>
<th>Parameter description</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>PKOR</td>
<td>Precipitation adjustment</td>
<td>%</td>
</tr>
<tr>
<td></td>
<td>SNOKOR</td>
<td>Snow adjustment</td>
<td>%</td>
</tr>
<tr>
<td>2</td>
<td>T0</td>
<td>Threshold temperature snowmelt</td>
<td>°C</td>
</tr>
<tr>
<td></td>
<td>TMFSNOW</td>
<td>Temperature melt factor for snow</td>
<td>mm d⁻¹ K⁻¹</td>
</tr>
<tr>
<td>3</td>
<td>T0</td>
<td>Threshold temperature snowmelt</td>
<td>°C</td>
</tr>
<tr>
<td></td>
<td>RMFSNOW</td>
<td>Radiation melt factor for snow</td>
<td>mm h⁻¹ K⁻¹ W⁻¹ m²</td>
</tr>
<tr>
<td>4</td>
<td>SGR</td>
<td>Threshold storage for surface runoff</td>
<td>mm</td>
</tr>
<tr>
<td></td>
<td>K0H</td>
<td>Storage time for surface runoff</td>
<td>h</td>
</tr>
<tr>
<td>5</td>
<td>K1H</td>
<td>Storage time for interflow</td>
<td>h</td>
</tr>
<tr>
<td></td>
<td>PERC</td>
<td>Percolation rate</td>
<td>mm h⁻¹</td>
</tr>
<tr>
<td>6</td>
<td>CG1H</td>
<td>Storage time for quick base flow</td>
<td>h</td>
</tr>
<tr>
<td></td>
<td>SLZ1MAX</td>
<td>Maximum content of the quick base flow storage</td>
<td>mm</td>
</tr>
<tr>
<td>7</td>
<td>K2H</td>
<td>Storage time for slow base flow</td>
<td>h</td>
</tr>
<tr>
<td></td>
<td>PERC</td>
<td>Percolation rate</td>
<td>mm h⁻¹</td>
</tr>
<tr>
<td>8</td>
<td>ICETMF</td>
<td>Temperature melt factor for ice</td>
<td>mm d⁻¹ K⁻¹</td>
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<tr>
<td></td>
<td>ICERMF</td>
<td>Radiation melt factor for ice</td>
<td>mm h⁻¹ K⁻¹ W⁻¹ m²</td>
</tr>
</tbody>
</table>

* For glaciated catchments only.

A total of 12 tuneable parameters (14 for glaciated catchments, Table 1) are calibrated pairwise and sequentially. Every model run is evaluated automatically using a combination of a Nash-Sutcliffee-Efficiency (NSE; Nash and Sutcliffe, 1970) with its logarithmic derivate (NSEln) and a mean annual volumetric deviation (VDa) between observed and simulated runoff (Viviroli et al., 2009b). In each iteration step performed during a calibration, the best model run defines the limits of a reduced parameter space to be tested in the subsequent step (cf. Fig. 3). The tuneable parameters are calibrated for standard and flood conditions, the latter realised through an additional calibration run and evaluation of peak-flow-sensitive scores (Viviroli et al., 2009b). Both parameter sets (standard and flood calibration) are used for further investigations in this thesis.
I-4 Regionalization

The parameter values obtained through calibration are transferred to ungauged catchments, i.e. catchments without or with influenced records. The regionalization scheme developed for the northern alpine catchments (Viviroli et al., 2009c) was extended and applied to southern alpine catchments in this study, as mentioned earlier. It is a combination of three different approaches of parameter regionalization, namely Nearest Neighbours (parameter transfer from catchments similar in attribute space), Kriging (parameter interpolation in physical space) and Regression (parameter estimation from relations to catchment attributes).

A total of 82 attributes are collected for every catchment, e.g. geologic, physiographic or hydro-geologic attributes. They were chosen to describe the catchment characteristics best with a view to relevant hydrological, climatological and physiogeographic properties. Sets out of these 82 attributes are used in the individual regionalization approaches. The resulting hydrographs of each method are combined to one hydrograph by averaging them for each time step, i.e. hour. Averaging is done by computing the hydrographs’ median or mean depending on the respective purpose. For the Nearest Neighbours, first the resulting hydrographs of the five most similar parameter sets are averaged. This resulting hydrograph is then combined with those of the Kriging and Regression method. In other words, the model has to be run seven times to regionalize the hydrograph for a study catchment.

It was not clear from the start that the regionalization procedure developed for northern alpine catchments works reasonable in the southern alpine region because of the limited number of calibrated donor catchments there. This is why we tested different parameterizations of the individual regionalization procedures, which will be briefly covered in the following. In general, the whole set of calibrated northern and southern alpine donor catchments was used in the south for each of the three regionalization methods. In some configurations, the pool of donor catchments was subdivided according to elevation or climate region. That is, only catchments
situated within the same climate or elevation region can be used as donor catchment. For the Nearest Neighbours, five configurations were tested, three for the Kriging method and two for Regression. This amounts to 30 different combinations of the three regionalization methods (5 × 3 × 2) that were all evaluated for their goodness-of-fit in simulating the discharge of the gauged southern catchments. The combination that yielded best results in the southern alpine region is less restrictively parameterized than that for the northern alpine region (cf. Table 2). In other words, more catchments could function as donor catchment for a specific ungauged catchment south of the Alps. This is explained by the limited availability of calibrated parameter sets in the southern region (cf. Fig. 1).

Table 2. Parameterization of regionalization methods for northern and southern alpine catchments.

<table>
<thead>
<tr>
<th>Regionalization method</th>
<th>Parameterization/constraints northern alpine</th>
<th>Parameterization/constraints southern alpine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nearest Neighbours</td>
<td>3 elevation zones, break at 1000 m a.s.l.</td>
<td>2 elevation zones, break at 1550 m a.s.l.</td>
</tr>
<tr>
<td>Kriging</td>
<td>Search radius 100 km or maximal 10 donor catchments</td>
<td>Search radius 200 km or maximal 25 donor catchments</td>
</tr>
<tr>
<td>Regression</td>
<td>3 elevation zones, break at 1000 m a.s.l.</td>
<td>2 elevation zones, break at 1550 m a.s.l.</td>
</tr>
</tbody>
</table>

In conclusion, some restriction, for example the subdivision into two elevation zones, is necessary to guarantee reasonable results, but the pool of donor catchments has to be widened for the less represented southern region. This might affect the quality of the simulations in the south, which will be discussed in the next section.

I-5 Validation

We compare the results for the northern and southern alpine catchments in this section. Within the study for the northern alpine region (Viviroli, 2007), a total of 140 catchments were calibrated successfully. Out of this 140 calibrated catchments, 49 served as representative catchments for extensive evaluation due to their long gauge records covering the complete modelling period from 1983 to 2005 (Viviroli et al., 2009b). Those 49 catchments are compared to the calibrated southern alpine catchments, where, in contrast, 23 catchments constitute the total set of successfully calibrated catchments: although we calibrated 36 catchments in the southern area, we had to dismiss 13 due to poor model efficiencies after calibration. In comparison with the northern catchments, where only 19 out of 159 calibrations failed, the proportion seems relatively high. This can be partly attributed to quality issues of the discharge records, which contain several periods with missing data, for example. Moreover, the interpolation of meteorological station data turned out to be a challenging task, owing to the marked topography in this part of Switzerland and the rather sparse distribution of ANETZ
stations. Still, the calibration results of the 49 representative northern alpine and 23 successfully calibrated southern alpine catchments are compared in the following section to analyse them for possible systematic differences.

I-5.1 Calibration

Without exception, the medians of NSE and NSE\textsubscript{ln} are higher for the southern alpine catchments (Fig. 4, red boxes) compared to those of the northern alpine catchments (blue boxes). At the same time, the distributions of these efficiency scores are rather skewed. This suggests that the calibration results are more uniform for the northern alpine catchments. The comparatively small volumetric deviation of the southern alpine catchments might be ascribed to the effort we have made, identifying the best sample of meteorological stations for interpolation, which has been an essential step with respect to the small number of only 36 catchments for calibration, here. This time-consuming procedure, however, was beyond the scope of the previous study by Viviroli et al. (2009b), where an extensive set of 159 catchments was calibrated. The comparison of the overall model scores for the northern and southern alpine catchments suggests that the iterative calibration procedure is capable to yield robust parameter estimation for the southern alpine region as well. The outliers of the southern alpine catchments can be attributed to short time series of measured discharge. For the northern alpine catchments the outliers are found mainly among very small catchments (< 40 km\textsuperscript{2}) with particularly quick reaction to intense precipitation.

Fig. 4. Box plots for linear and logarithmic Nash-Sutcliffe-Efficiency (NSE, NSE\textsubscript{ln}) and mean annual volumetric deviation (VD\textsubscript{a}) for 49 representative northern alpine catchments (blue boxes, Viviroli et al., 2009b) and 23 southern alpine catchments (red boxes) in calibration (cal) and validation (val) periods for standard and flood calibrated parameter sets. Circles denote outliers (distance from upper or lower quartile is greater than 1.5 times the quartile range).
I-5.2 Regionalization

Out of 189 regionalized catchments, 29 coincide with a gauge at their outlet (see Fig. 5) that measures in hourly resolution and that covers the simulation period from 1984 to 2005 (evaluation is done without the warm-up year 1983, cf. Sect. I-1). These records were used to assess the goodness of the regionalization procedure for the southern alpine catchments and compare it to that of the northern catchments.

![Catchments diagram](image)

**Fig. 5.** Regionalized northern (blue) and southern alpine catchments (orange). The 29 catchments where additional measurements are available in hourly resolution are highlighted. For catchments marked with an asterisk, long-term mean water balance data are available (see later in this section).

We evaluated the regionalized simulations for standard (MQ) and flood (HQ) parameter sets. For the MQ parameters we combined the seven regionalized hydrographs (cf. Sect. I-4) twice by computing the mean and the median per time step. The combination by the mean is an unweighted representation of the seven original hydrographs, the median, on the contrary, allows excluding outliers. All median NSE values (Fig. 6) are $\geq 0.75$ which shows the overall good representation of the runoff behaviour through regionalized hydrographs. As with the calibration, few outliers are observed evaluating the regionalization and the spread for the southern alpine catchments is larger as it is larger for the HQ parameters opposed to the MQ parameters. The median volumetric deviation ranges from 0.9 % for the northern MQ parameter sets to 7.7 % for the northern HQ parameter sets, which is acceptable because the HQ parameter sets are trimmed to meet the peaks and are not used for evaluation of changes in the water balance components. Only three outliers show large deviations.
Viviroli (2007) furthermore evaluated the results for the 49 representative northern alpine catchments (cf. Sect. I-5) by cross-validation with the jack-knife technique. A median NSE of 0.72 for the calibration on standard and 0.69 for that on flood conditions showed overall good model performances. As demonstrated in Viviroli et al. (2011), another way to estimate the quality of the simulated discharge is to compare it to the long-term annual mean values that were compiled for all study catchments for the period 1961–1990 (Schädler and Weingartner, 2002). These water balance data are rated with respect to their plausibility and assigned to four classes of decreasing reliability. We compare only catchments of class 1 (marked with an asterisk in Fig. 5) having the highest plausibility, which applies to 84 northern and 38 southern alpine catchments. Here, we only assessed the calibration on standard conditions. It should be noted, however, that the reference periods (1961–1990 opposed to 1984–2005) differ, which could affect the result.

The mean annual runoff of the northern alpine catchments deviates only -3 % from that of the water balance basins, with a standard deviation of 15 %, though. The results for the southern alpine catchments differ stronger: on average, the annual runoff is 17 % higher than that of the water balance basins. Without the most south-western catchments in canton Valais, however, the deviance is smaller and the southern catchments only show a 9 % higher annual runoff with a standard deviation of 16 %, though. The strong overestimation of runoff in south-western catchments can be attributed to edge effects, on the one hand, that affect the quality of the regionalization results in this area. On the other hand, this area with the highest mountains in Switzerland is clearly underrepresented by meteorological stations (cf. Fig. 1). Those catchments and their hydrological projections have to be regarded being less plausible, therefore, although the differing reference periods have to be considered, too, of course. The simulation period and the reference period in Schädler and Weingartner (2002) overlap only 7
Admittedly, the annual runoff in Switzerland did not change significantly in the 20th century in general (Schädler, 2010), but for these high alpine catchments in southern Valais that are strongly characterized through melt processes, an effect of a negative glacier mass balance, for example, is possible. Regardless of the differing reference periods, we nevertheless compared the regionalized catchments to the long-term water balance data, to additionally evaluate the simulations. This comparison showed that the majority of catchments reproduce the estimated mean annual runoff adequately.

To conclude, the regionalization procedure that combines three different approaches yields robust and plausible results for the majority of catchments considered, both for the northern and southern alpine catchments. Despite the sparse database in the southern alpine region, the model parameters could have been regionalized, and the resulting set of 189 study catchments that evenly cover the variety of catchment types in Switzerland constitute a valuable database suited for the further analysis in this study.

I-6 Climate scenarios

In recent years, it has become state of the art in climate impact studies to apply dynamically downscaled data of global climate models (GCM). Dynamical downscaling is most often achieved by nesting a spatially higher resolved regional climate model (RCM) into the global climate model. The RCMs employed in this study provide data at daily resolution for 25 km grid cells (CH2011, 2011). This spatial resolution (625 km$^2$ cell area) is still too coarse for the application in hydrological impact studies in mesoscale catchments, though. Another problematic issue related to GCM-RCM model chains are substantial biases of the model outputs. The scenario data provided by the CH2011 initiative are therefore post-processed using an extended delta change method, where a spectral smoothing is applied to filter the annual cycle of change signals (Bossard et al., 2011). The CH2011 data are furthermore interpolated to the much denser network of observation sites, having an average density of one station per 60 km$^2$ for precipitation, for example. This allows for a consistent hydrological model forcing with interpolated meteorological station data for the control and scenario period.

A total of ten GCM-RCMs from the ENSEMBLES-project (van der Linden and Mitchell, 2009) are applied in this study (for names see Table 3). All model chains are forced with the A1B emission scenario. For each meteorological station, the mean annual cycle of the delta change signal has been calculated for the scenario periods 2021 to 2050 (hereafter called near future) and 2070 to 2099 (far future) relative to the reference period 1980 to 2009. The observed time series of temperature and precipitation are scaled with the delta change signals to generate a set of climate scenarios with which the model is run for the regionalized catchments. Thereby, the resulting scenario periods for the hydrological modelling are 2025–2046 and 2074–2095 because of the slightly differing hydro-meteorological data records (cf. Sect. I-1, reference period 1984–2005).
As stated above, the delta change signals are calculated for precipitation and temperature only. Changes in the other hydro-meteorological variables that are needed to run the hydrological model are not accounted for. For those variables, the control period records are used, which is a very rough simplification, of course. However, as temperature and precipitation are the hydrologically most relevant climate variables, and the most sensitive tuneable model parameters rely on these variables, too, this simplification is justifiable and has often been made (e.g. Boé et al., 2007; Horton et al., 2006; Huss et al., 2008).

Table 3. Applied climate model chains from the ENSEMBLES project, post-processed and provided by the CH2011 initiative (CH2011, 2011).

<table>
<thead>
<tr>
<th>Institution</th>
<th>GCM</th>
<th>RCM</th>
</tr>
</thead>
<tbody>
<tr>
<td>CNRM</td>
<td>ARPEGE</td>
<td>ALADIN</td>
</tr>
<tr>
<td>DMI</td>
<td>ECHAM5</td>
<td>HIRHAM</td>
</tr>
<tr>
<td>ETHZ</td>
<td>HadCM3Q0</td>
<td>CLM</td>
</tr>
<tr>
<td>HC</td>
<td>HadCM3Q0</td>
<td>HadRM3Q0</td>
</tr>
<tr>
<td>ICTP</td>
<td>ECHAM5</td>
<td>REGCM</td>
</tr>
<tr>
<td>KNMI</td>
<td>ECHAM5</td>
<td>RACMO</td>
</tr>
<tr>
<td>MPI</td>
<td>ECHAM5</td>
<td>REMO</td>
</tr>
<tr>
<td>SMHI</td>
<td>BCM</td>
<td>RCA</td>
</tr>
<tr>
<td>SMHI</td>
<td>ECHAM5</td>
<td>RCA</td>
</tr>
<tr>
<td>SMHI</td>
<td>HadCM3Q3</td>
<td>RCA</td>
</tr>
</tbody>
</table>

In the following, we summarize the climate changes according to the CH2011 climate scenarios for Switzerland, briefly; all values correspond to the ensemble mean. The signals of the far future (Fig. 7) are clearer than that for the near future period. In the far future period, the temperature increases by 2.7–4.1 °C, on average, depending on the region (north or south). Summer mean precipitation decreases by 18–24 % and winter precipitation increases between 3 and 20 %, again, depending on the region. For the change in winter precipitation, the model agreement is less strong, though (cf. Fig. 7). The changes for the near future period are less pronounced, in general, but the overall pattern of decreasing summer precipitation and increasing winter precipitation as well as generally increasing temperatures is observed for that period, too.

The applied delta change method is a post-processing procedure that gives more weight to the observation and to changes in the atmospheric mean state. The impact of changes in the frequency and intensity of the climate variables cannot be studied with the delta change method: the sequence of wet- and dry-days, for example, does not change in the scenario. For the analyses in parts II and III, this limitation is acceptable; we study changes of the water balance components on the mean annual cycle of monthly values, there. The last paper in part IV, on the contrary, studies changes in flood seasonality. The wet-day frequency and intensity is, of course, crucial when discharge extremes are concerned. The flood seasonality, however,
depends less on the frequency and is more determined by changes in the flood generating processes, i.e. changes in the precipitation regime and the ratio of liquid to solid precipitation.

Fig. 7. Exemplary spatial distribution of the climate change signals for individual stations (CH2011 2011); temperature (left) and precipitation (right) for winter (top) and summer (bottom) of the far future. The background shading indicates the model agreement in change simulated by the individual chains. Dark shading indicates a high model agreement.

I-7 Glacier and forest scenarios

It is mandatory to account for glacier retreat when studying hydrological change in high-mountain areas. Within CCHydro, glacier retreat scenarios for all Swiss glaciers were derived according to the projected temperature increase (Linsbauer et al., 2012). The calculated retreat is based on a shift of the equilibrium line altitude (ELA, Paul et al., 2007), which divides the glacier area in Switzerland at a ratio of 40 to 60 % (ablation to accumulation area), on average (WGMS, 2011). The ELA rises by 150 m per 1 °C temperature increase. A mean response time of 50 years is assumed for all glaciers, which causes large glaciers to retreat too fast and small glaciers too slowly. Nevertheless, for the majority of glaciers, this average response time is adequate. Although simplified, the parameterization of the glacier retreat model is physically robust and applicable at regional scales (Linsbauer et al., 2012).

The glacier scenarios are incorporated in all analyses in this study, but their additional impact on the runoff projections is explicitly analysed in part III of the thesis. For this part, additional forest scenarios were developed that account for an increase of the tree line due to
higher temperatures, an ingrowth of forests where former land was abandoned and an increase of the soil depth under forests. Those scenarios were calculated for the far future only and are described in detail in part III.
PART II SENSITIVITY

We propose an approach to reduce a comprehensive set of 186 mesoscale catchments in Switzerland to fewer response types to climate change and to name sensitive regions as well as catchment characteristics that govern hydrological change. We classified the hydrological responses of our study catchments through an agglomerative-hierarchical cluster analysis. We related the dominant explanatory variables, i.e. the determining catchment properties and climate change signals, to the catchments’ hydrological responses by means of redundancy analysis. All clusters except for one exhibit clearly decreasing summer runoff and increasing winter runoff. This seasonal shift was observed for the near future period (2025–2046) but is particularly obvious in the far future period (2074–2095). Within a certain elevation range (between 1000 and 2500 m a.s.l.), the hydrological change is basically a function of elevation, because the latter governs the dominant hydro-climatological processes associated with temperature, e.g. the ratio of liquid to solid precipitation and snow melt processes. For catchments below the stated range, hydrological change is mainly a function of precipitation change, which is not as pronounced as the temperature signal is. Future impact studies in Switzerland can be conducted on a reduced sample of catchments representing the sensitive regions or covering a range of altitudes.

II-1 Introduction

The latest climate scenarios for Switzerland project a summer mean temperature increase of 3.7–4.1 °C and a summer mean precipitation decrease of 18–24% for the A1B emission scenario and the late 21st century (CH2011, 2011). These changes in climate will inevitably induce changes in Switzerland’s hydrology because the hydrological cycle is closely connected to the climate system. This was demonstrated in numerous studies covering a range of different foci and scales, from rather detailed and local-scale case studies (e.g., Finger et al., 2012; Graham et al., 2007; Hänggi, 2011; Huss et al., 2008; Jasper et al., 2004; Kunstmann et al., 2004; Schaefli et al., 2007) to broader analyses at the regional or continental scale (e.g., Bergström et al., 2001; Christensen and Lettenmaier, 2007; Dankers and Middelkoop, 2008; Hamlet, 2011).

With the “Bali Action Plan”, the United Nations Framework Convention on Climate Change (UNFCCC) identified the need to integrate adaptation actions into sectoral and national planning (UNFCCC, 2008). Switzerland, as a party to the Convention, adjusted its climate policy according to the UNFCCC obligations and formulated a Swiss adaptation strategy, where water resources management was identified as one of nine sectors specifically affected by climate change (FOEN, 2010). Among others, the adaptation strategy includes frequent updates of climate-impact studies according to the most recent climate scenarios. The latest of those impact studies is the joint research project “Climate Change and Hydrology in Switzerland” (CCHydro; Volken, 2010), which the study presented here is part of.

A comprehensive hydrological climate-impact study, however, that accounts for all sources of uncertainties is an utmost demanding task in terms of computational power and time. Ideally, it would involve a series of different greenhouse gas emission scenarios forcing different general circulation models (GCMs), into which different regional climate models (RCMs) are nested. The regional climate models, in turn, would be downscaled with different downscaling procedures to drive a number of hydrological models, each having a series of different parameter sets and being run for different catchment types. This extensive modelling setup would allow a complete integration and quantification of all possible sources of uncertainty along the impact-modelling chain. The associated heavy workload, however, is far beyond the means and would even increase with forthcoming generations of climate scenarios that are likely to be available in a higher spatial and temporal resolution.

Obviously, it is impossible to execute this idealized impact-modelling chain whenever a new generation of climate scenarios is available, and ways to simplify the procedure are indispensable. Therefore, the aim of this study is to ease the multi-dimensional task of impact modelling by reducing the catchments to a few distinct response types and assessing their specific climate-sensitivity, for example. This facilitates to conduct future impact studies only in the most affected regions, which eases the workload to a great extent.

To achieve a dimension reduction, we first classify a comprehensive set of catchments based on their hydrological responses to climate change to answer our first research question: (1) Are there certain types of hydrological responses, i.e. can the catchments be grouped into
fewer response types? We assume a differentiation and, therefore, a possible grouping of the catchments due to their hydrological responses, because Wagener et al. (2007) identified the response behaviour as the “[…] main differentiating metric between catchments”. In a second step, the resulting response types are analysed to find out (2) which response types are specifically sensitive to changes in climate. Finally, we assess the relative impact of climate change signals and catchment properties on the hydrological response to test (3) if there are general causal relationships between hydrological responses to climate change and catchment properties. We want to assess this relative impact of climate and catchment properties, because the climate change signal might not be the only factor determining the hydrological response to climate change. Sawicz et al. (2011) found, for example, “[…] that soil properties will modify the impacts of climate change on hydrologic regimes, which means that changes in precipitation and temperature will not impact the streamflow response equally”. If there are such modifying catchment characteristics like soil properties or other physiographic signatures in our study region, then the entity of catchments to be analysed can be reduced to a sample that is representative for the determining properties. One approach to relate catchment characteristics to hydrological response is to classify catchments according to their physiographic properties and compare them to the classification of the hydro-climatological response (see e.g., Ley et al., 2011). Here, we relate the hydrological response to both the catchment properties and the climate change signals by means of redundancy analysis, a constrained ordination method widely used in vegetation ecology that has been demonstrated to be effectively applicable to hydrologic data, too (Ali et al., 2011).

Based on the latest climate scenario data for Switzerland, we apply the proposed procedure to an extensive set of 186 mesoscale catchments that represent the variety of Switzerland’s hydrological systems. With a view on practical application, the reduction of the variety of hydrological responses to the most important types will facilitate identification of regions where adaptation measures should be applied to with priority.

**II-2 Study area and data**

We studied 186 catchments in Switzerland (study catchments, Fig. 8) that cover an area of 63 % (25 865 km$^2$) of the country. Switzerland has a variety of different landscape types, from the Jura limestone range in the northwest over the rather flat Swiss Plateau and the high alpine area, which constitute a continental drainage divide, to the inner alpine valleys and the southern alpine region with their distinct climates. Because of this heterogeneous landscape structure, a range of different catchment types evolved, which is reflected in the catchments’ mean elevations, for example, ranging from 438 to 3024 m a.s.l. The study catchments have an average area of approximately 250 km$^2$.

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1 Note that we excluded three catchments (the Kander) from the analysis in this study because they built an own cluster in the analysis, which was attributed to issues with the interpolation of the projected climate variables in these catchments.
We used hourly discharge measurements for the period from 1983 to 2005 (FOEN, 2008) to calibrate and validate our hydrological model for 163 catchments (calibrated catchments in Fig. 8). Discharge data are available for more catchments than those calibrated here, but in the alpine areas, for example, hydropower production biases the discharge measurements, which is why we could not use these data for model calibration.

Meteorological data are available in hourly to daily resolution, depending on the type of meteorological station (Fig. 8). For the 77 stations of the automatic meteorological network, the data are available in 1 h resolution, while 84 climate stations provide data two or three times a day, and 668 precipitation gauges measure with a daily resolution (cf. Fig. 8; MeteoSwiss, 2008). Model forcing is mainly based on the 77 meteorological stations with hourly data and complemented by other stations with data at lower temporal resolutions.

Fig. 8. Overview of the study region. Note that the study catchments (white borders) and the calibrated catchments are partly superimposed. The calibrated catchments are located within the red hatched areas, but their watershed boundaries are not delineated to enhance legibility.
II-2.1 Model data

We used the hydrological modelling system PREVAH (Precipitation-Runoff-EVApotranspiration-Hydrotepe-based model; Viviroli et al., 2009a) that is semi-distributed because it relies on the concept of hydrological response units (HRUs) and that is process-oriented as it incorporates, for example, combined temperature-radiation modules for snow and ice melt. In this study, PREVAH is run on the basis of hourly meteorological input (temperature, precipitation, relative humidity, wind speed, global radiation and sunshine duration) and at a spatial resolution of $500 \times 500m^2$. We extended an existing set of 140 calibrated northern alpine catchments (Viviroli et al., 2009b) to southern alpine catchments (Köplin et al., 2010) following the calibration procedure designed by Viviroli et al. (2009b). Thus, we obtained a comprehensive set of 163 calibrated catchments representing the variety of catchment types in Switzerland. The evaluation of the calibration results for the northern and the southern alpine catchments is described in detail in Viviroli et al. (2009b) and in Köplin et al. (2010), respectively.

The 163 calibrated model parameter sets were used to regionalize runoff simulations for ungauged catchments, subsequently. For this, we used a regionalization scheme by Viviroli et al. (2009c) developed for flood estimation in small- to mesoscale catchments in Switzerland (Viviroli and Weingartner, 2011). The scheme combines three different regionalization methods (nearest neighbours, kriging and regression) by averaging the model output of the respective simulations for every time step, i.e. for every hour. To be precise, the simulated runoff time series of five model runs based on calibrated parameter sets of the five nearest neighbours (near in the attribute space) as well as the simulated runoff of two model runs based on parameter sets derived by kriging and regression were combined by computing the mean of the seven time series. As a result of this procedure, the regionalized simulated runoff of a catchment is not based on a single but on seven different parameter sets. It should be noted that we regionalized the runoff simulations not only for the ungauged catchments, but for all our study catchments, even for those where discharge measurements were available. We did this to guarantee a homogeneous database for our further analysis. This means that the pools of calibrated and regionalized catchments partly overlap in space (cf. Fig. 8). The regionalization of the catchments with available discharge measurements allows for a validation of the regionalization procedure using the jack-knife technique, a cross-validation approach that showed good model efficiencies for the regionalized runoff, e.g. a median Nash-Sutcliffe efficiency (NSE) of 0.72 for the tested catchments (see Viviroli et al., 2009c for details).

Although the absolute numbers of calibrated (163) and regionalized (186) catchments do not differ substantially, their spatial distribution does (cf. Fig. 8): the calibrated catchments encompass an overall smaller area because of their smaller average size ($110 \text{ km}^2$ opposed to $250 \text{ km}^2$ for the regionalized catchments) and, besides, the calibrated catchments are unevenly distributed, which is why regionalization could significantly extend our catchment database to high and southern alpine areas. Since the high alpine areas are expected to be areas that are most vulnerable to changes in climate (Birsan et al., 2005; Viviroli et al., 2011), regionalization was a prerequisite in this study.
Physiographic catchment properties

The physiographic properties that will be used to characterize the catchments (Table 4) were derived from the HRU-based spatial information gathered during the pre-processing of the data for the hydrological model. The data are gained from a digital elevation model (DEM, 100 × 100 m$^2$), a soil map (1 : 200 000) and a land use map (100 × 100m$^2$), all provided by the Swiss Federal Statistical Office (SFSO, 2003). The digital maps are joined and provided at a spatial resolution of 500 × 500 m$^2$. For use as characterising properties, the HRU-based data are summed up to the catchment scale.

Table 4. Physiographic catchment properties.

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
<th>Unit</th>
<th>Scale type</th>
</tr>
</thead>
<tbody>
<tr>
<td>catch_area</td>
<td>Catchment area</td>
<td>km$^2$</td>
<td>Ratio</td>
</tr>
<tr>
<td>mean_alt</td>
<td>Mean altitude</td>
<td>m a.s.l.</td>
<td>Ratio</td>
</tr>
<tr>
<td>elv_range</td>
<td>Elevation range (altitude$<em>{max}$ – altitude$</em>{min}$)</td>
<td>M</td>
<td>Ratio</td>
</tr>
<tr>
<td>mean_slo</td>
<td>Mean slope of the catchment</td>
<td>°</td>
<td>Ratio</td>
</tr>
<tr>
<td>mean_afc</td>
<td>Mean available field capacity</td>
<td>Vol%</td>
<td>Ratio</td>
</tr>
<tr>
<td>mean_sdp</td>
<td>Mean soil depth</td>
<td>m</td>
<td>Ratio</td>
</tr>
<tr>
<td>gl_ctrl_rel</td>
<td>Relative glaciated area (control period)</td>
<td>%</td>
<td>Ratio</td>
</tr>
<tr>
<td>gl_near_rel</td>
<td>Relative glaciated area (near future, 2025-2046)</td>
<td>%</td>
<td>Ratio</td>
</tr>
<tr>
<td>gl_far_rel</td>
<td>Relative glaciated area (far future, 2074-2095)</td>
<td>%</td>
<td>Ratio</td>
</tr>
<tr>
<td>domnt_asp</td>
<td>Dominant aspect class (the mode of the aspect classes, 1=North, 2=East, 3=South, 4=West)</td>
<td>–</td>
<td>Nominal</td>
</tr>
<tr>
<td>domnt_lu</td>
<td>Dominant land use (the mode of the land use types, 1=coniferous forest, 2=deciduous forest, 3=mixed forest, 4=pasture, 5=bare ice, 6=rock, 7=sub-alpine meadow, 8=coniferous forest/rock)</td>
<td>–</td>
<td>Nominal</td>
</tr>
</tbody>
</table>

II-2.2 Scenario data

Climate scenarios

We applied climate scenarios of expected changes (deltas) in the annual cycle of temperature and precipitation that are part of the latest release of downscaled climate scenarios for the area of Switzerland (CH2011, 2011). The change signals between the control (1980–2009) and the scenario periods (2021–2050 and 2070–2099) were provided for each day of the year and each observation station in Switzerland (Bosshard et al., 2011). For every station site, a total of ten model chains from the ENSEMBLES-project (van der Linden and Mitchell, 2009) were analysed, each consisting of one of five GCMs driving one of eight RCMs, whereas all
model chains assume the SRES A1B emission scenario. Bosshard et al. (2011) applied a spectral smoothing method to filter the annual cycle of change signals, which resulted in considerably better representations of the climate change signals’ annual cycle compared to the commonly applied moving averaging window. A bias correction of the climate model output is implicitly incorporated in this downscaling method.

**Scenarios of glacier retreat**

In addition to the climate scenario data itself, we accounted for the accompanying glacier retreat, too. The scenarios assume a mean response time of 50 years. The increase in equilibrium line was calculated according to three different temperature increases (a low, a middle and a high increase) that were classified from the range of all temperature increases of the climate scenarios in use. Further details on the methodology can be found in Paul et al. (2007) and in Linsbauer et al. (2012).

**Hydrological projections**

The observed time series of precipitation and temperature were scaled with the annual cycles of climate change signals. Thereby, we generated a set of climate scenarios with which we ran the catchment models. We simulated the runoff for the control period from 1984 to 2005 and for the two scenario periods from 2025 to 2046 (near future) and 2074 to 2095 (far future) for every catchment and climate scenario. These periods slightly differ from the climate scenario periods, because they are based on the calibration and validation period of the hydrological model. We calculated the mean annual cycle of monthly runoff and derived the monthly change signals, afterwards, being the ratios of scenario runoff over control period runoff. We aggregated the simulated hourly time series to mean annual cycles of monthly values, because the focus is on changes in the hydrological regime, here, and not on peak flows, for example. Finally, we computed the ensemble mean of the ten hydrological projections per catchment and scenario period.

**II-3 Methods**

The analysis in this study consists of three steps that are explained in this section: (1) the classification of catchments through cluster analysis based on the catchments’ hydro-climatological change signals, (2) the evaluation of the clusters’ climate-sensitivity and (3) the mapping of hydrological change to both the climate change signals and the catchment properties by means of redundancy analysis.

For the remainder of this paper, we will refer to three distinct change signals mentioned in the previous paragraph that are specified at this point: (A) the climate change signal comprising annual cycles of monthly temperature and precipitation deltas, (B) the hydrological change signal consisting of the annual cycle of monthly runoff deltas, and (C) the hydro-climatological change signal combining signals A and B. For all change signals, the ensemble means of the ten
different projections are computed, thus providing single annual cycles per catchment that result from the spread of the ten scenarios.

We used the R version 2.14.1 (R Development Core Team, 2012) for our analyses in general and in particular the R package vegan, version 2.0-2 (Oksanen et al., 2011) for the redundancy analysis.

II-3.1 Cluster analysis

We classified the study catchments with respect to their hydro-climatological change signals, because the same climate signal might cause different hydrological signals in different catchments: considering all signals together facilitates distinguishing clearer clusters. The hydro-climatological change signals were clustered threefold: for the near and the far future period alone and for both periods in combination.

We applied a hierarchical agglomerative clustering based on Ward’s minimum variance method. This algorithm starts with $n$ clusters, i.e. as many clusters as catchments considered, and successively merges the individuals based on their similarity that is measured by Euclidean distances. More precisely, the sum of the squared distances among the members of a cluster, divided by the number of the members, is to be minimized (see e.g., Borcard et al., 2011). The result of this kind of clustering method is always a dendrogram, a tree-like graph where every fusion of two branches (i.e. the merging of two clusters) indicates a level of generalization. The length of a branch can be interpreted as the dissimilarity between clusters and can be used to assist in deciding on the number of clusters $k$. The decision on $k$, however, remains a subjective choice to a certain extent, and there is not one objectively right solution (Leyer and Wesche, 2007). It has to be stated that there are various clustering methods (see e.g. Borcard et al., 2011 for an overview) and none of them can be objectively rated as the best method (Hannah et al., 2005). A number of studies that tested different clustering methods for their use in catchment classification found that Ward’s minimum variance method yields robust and physically meaningful results (e.g. Bower et al., 2004; Gobena and Gan, 2006; Kingston et al., 2011). Therefore, we chose this method for our study.

II-3.2 Physiographic catchment properties

The resulting clusters were characterized by the catchment properties mentioned above. We reduced the set of quantitative variables (“ratio scale” in Table 4) by means of correlation analysis (Fig. 9) to exclude those variables that share the same or similar information. A Pearson’s correlation coefficient ($r$) or Kendall’s tau ($\tau$) higher than 0.7 indicates high correlations (Leyer and Wesche, 2007), and one of the correlated variables is dismissed from further analysis.
Mean slope, mean field capacity and mean soil depth are highly correlated among each other. Because field capacity and soil depth are variables derived from the soil map that has a relatively low spatial resolution (see Sect. II-2.1), they are assumed to be less precise and are excluded from the set of catchment properties. Mean slope is also highly correlated with mean altitude, but they are both used in further analysis because they are expected to impact different hydrological processes, i.e. the slope is supposed to rule runoff generating processes, whereas the mean altitude (as an indicator of temperature) governs, for example, snow and glacier melt processes. From the two correlated variables mean altitude and elevation range, we apply mean altitude in our further analysis because of its superior significance for hydrological processes.
the variables dominant aspect and dominant land use are used in further analysis, but they are not tested for correlations because they are of nominal scale.

II-3.3 Redundancy analysis

Redundancy analysis (RDA) is the canonical or constrained version of a principal components analysis (PCA) and combines multiple linear regression with classical ordination; for a detailed explanation, see Borcard et al. (2011) and Legendre and Legendre (1998). Briefly, while classical ordination is a method of dimension reduction designed to extract the dominant structures in a single data set, constrained ordination extracts that part of the variation of a data set that is a function of the variation in another data set (Borcard et al., 2011). In other words, constrained ordination only describes the variation of the data that can be explained by the constraints (Oksanen et al., 2011). The canonical axes that are derived represent linear combinations of the explanatory, i.e. the constraining variables that best explain the variation in the matrix of the response variables (Borcard et al., 2011; Legendre et al., 2011).

We used this canonical ordination method primarily as a graphical tool in our study, like Oksanen et al. (2011) suggested, although the quantitative information associated with the RDA-axes was employed to evaluate the reliability of the derived relationships. Each RDA-axis explains a certain amount of the total variance of the response variables, which is equivalent to an $R^2$ in multiple regression. This $R^2$ is biased, though, and one should, therefore, compute an adjusted $R^2_{adj}$ (for details, see Borcard et al., 2011).

In a first step, all catchments were assessed together to gain insight into the overall governing structures in the data set. In doing so, redundancy analysis was used to verify the results of the cluster analysis: if the catchments of a cluster are grouped together in the RDA, too, one can assume a robust clustering of the catchments. Then, the clusters were separately analysed to assess the cluster-specific dominant explanatory variables. The response variables were the hydrological change signals, whereas the matrix of explanatory variables consists of the climate change signals and the physiographic catchment properties. To reduce the number of explanatory variables, the monthly climate change signals were aggregated to seasonal signals by computing the seasonal mean. This was necessary because for $m$ (number of explanatory variables) approaching $n$ (number of objects, i.e. catchments), the constraints become meaningless and the RDA is more similar to a PCA (Oksanen et al., 2011).

II-4 Results

II-4.1 Cluster analysis and sensitive catchments

The catchments’ hydro-climatological change signals were clustered for the near and the far future period alone and for both periods together (Fig. 10). The number of clusters $k$ was determined with the aid of the resulting dendrograms as well as our knowledge about the study region: the climatically distinct southern alpine region with its typical two-peaked hydrological
The clusters of all three versions are spatially coherent, and the distribution of the clusters mirrors the landscape types depicted in Fig. 8 to a certain degree. Comparing the clusters of the near and the far future, altogether 55 catchments are assigned to different clusters between those periods (referred to as changing catchments). Particularly remarkable are the catchments that switch to C6 in the far future, because this cluster was the southern alpine cluster mentioned above that we wanted to separate from the others. Analysis of the switching catchments’ hydrological regime, however, revealed that their regime switched to the two-peaked southern regimes, too (FOEN, 2012b), which explains their grouping in the far future period. Another interesting feature is the combined clustering preserves either the clusters of the near or the far
future and does not generate completely new clusters. In most cases, the clustering of the far future is preserved in the combined clustering, though, this might be ascribed to the clearer hydro-climatological signal in that period. For our further analyses, we use the clustering based on both periods in combination (Fig. 10, lower panel).

The physiographic properties of the clustered catchments are summarized in a parallel coordinates plot (Fig. 11). Each parallel axis displays the range of values of a physiographic variable, and each curve represents a single catchment with its characteristic properties. The curves are colour-coded according to the cluster a catchment belongs to. The graph can be read from left to right examining, for example, the mean values of a single cluster (coloured circles) or it can be studied axis-wise comparing the clusters with respect to a specific variable.

![Parallel coordinates plot](image)

**Fig. 11.** Parallel coordinates plot of the physiographic catchment properties (for abbreviations and class descriptions of the nominal variables dominant aspect and dominant land use see Table 4). Each parallel axis displays one physiographic variable, and each curve represents a catchment. The curves are colour-coded according to the cluster a catchment is assigned to.

The variable catchment area does not differ much amongst the clusters. In other words, the clusters’ mean values vary around the overall mean. Unlike the catchment area, mean altitude and mean slope are two variables that clearly distinguish the clusters. The high correlation of those two variables (Fig. 9) is visible in the parallel coordinates plot, too. The clusters with glaciated catchments can be subdivided into two clusters (C4 and C7) that are still considerably glaciated in the far future, one intermediate cluster (C5) and two clusters (C3 and C6) that are projected to be nearly ice-free by the end of the century. The clusters’ modes for the nominally scaled variable dominant aspect also depict a clear pattern. Clusters C1 to C3, which are situated north of the Alpine ridge, are mostly north-exposed. Catchments in C5, which generally drain
eastwards, are east-exposed (aspect class 2), accordingly. The other clusters are mainly west-exposed. For dominant land use, a correlation of the clusters’ modes with their mean elevation can be observed. In C1 and C2, having a mean elevation of 1000 m a.s.l. and less, the dominant land use is pasture. C3 and C6 are mainly covered with subalpine meadow and are situated between 1500 and 2000 m a.s.l. For clusters situated above 2000 m a.s.l. on average (C4, C5 and C7), the dominant land use is rock.

Fig. 12. Hydro-climatological change signals per cluster (absolute temperature, precipitation and runoff change, rows 1 to 3 from top), relative runoff change (4th row) and absolute monthly runoff (bottom row) for the control period (CTRL, dashed lines), the near future period (SCE, solid lines in left column) and the far future period (SCE, solid lines in right column). The change signals are given as absolute values to facilitate direct comparison with the absolute monthly runoff.
The hydro-climatological change signals of the clusters (Fig. 12, rows 1 to 4 from top) show clear annual cycles with maxima in summer for temperature and minima in summer for precipitation and runoff. The rather slight changes that can be observed for the near future period are visibly amplified in the far future for all change signals. The amount of decreasing summer precipitation is considerably smaller than that of the summer runoff, which means that the temperature change signal determines the change in runoff to a large extent. Unlike the climate change signals that hardly differentiate among the clusters, the hydrological change exhibits an obvious spread. This confirms our assumption that the same climate change signal, indeed, can induce very different hydrological responses.

Concerning climate sensitivity in the near future period, the clusters can be regarded as non-sensitive. Although slight changes in near future runoff can be observed for all clusters except C1 (Jura Mountains, Swiss Plateau), these changes are negligible with respect to the absolute monthly runoff (see lower left panel in Fig. 12). In the far future period, C1 stays insensitive to the clear changes in climate. Although the relative change in the summer of the far future is comparable to that of the other clusters (fourth row from top in Fig. 12), this change is still a small absolute deviance (-25 % but only -10 mm month$^{-1}$). On the contrary, C2, which experiences about the same climate change in the far future period as C1, exhibits discernible absolute and relative changes in runoff. The physiographic properties that differ between those clusters are mean altitude and mean slope, which indicates an influence of those variables on the projected hydrological change. The yearly peak runoff of C5 and C6 is shifted one month earlier and is projected to significantly decrease in the far future (lower right panel in Fig. 12). The shift in peak runoff applies to C4, too, with the exception that the peak is projected to increase, here. The most obvious difference between C4 and C5/C6 is their glaciation, which is on average still 10 % for C4 in the far future, whereas the mean values of C5 and C6 are 3 % and nearly zero, respectively. Moreover, C4 has a higher mean altitude than C5 and C6, meaning that increasing winter precipitation is to a certain extent solid precipitation causing increasing snowmelt in spring. This, together with a still existing glacier melt, explains the increasing yearly peak runoff. This is not true, however, for C7, the cluster with the highest mean altitude and glaciation, where the projected peak runoff decreases in the far future. This decrease is the result of the smaller glaciated area compared to the control period (that applies to the other glaciated cluster, too, of course) as well as the decreasing summer precipitation. C7 does not show the increase in spring runoff that C4 exhibits because of the high mean altitude of this cluster and therewith the low mean temperature: the temperature is low enough to preserve the control period’s ice-fed regime in the far future period. Moreover, temperature is the reason why winter runoff does not increase significantly in C7, too, because the ratio of liquid to solid precipitation does not change markedly. That is, the mean altitude of a catchment and therewith the temperature are features that strongly determine hydrological change.

II-4.2 Redundancy analysis

The redundancy analysis confirms the results of the cluster analysis because the same catchments are grouped together in the RDA-biplot, too (Fig. 13, upper panel). It should be
noted that the catchments are only colour-coded according to the corresponding cluster, but the cluster itself was not a constraint in the RDA. Besides this obvious result, biplots are interpreted according to certain rules (cf. e.g., Borcard et al., 2011; Leyer and Wesche, 2007; Oksanen et al., 2011 and see the RDA schematic in Fig. 13):

1. Only the first two (and most important) canonical axes are displayed; their proportion of explained variance of the dependent variables is given as $R^2_{adj}$.

2. A constraining variable’s vector points to the direction of the variable’s gradient, and the arrow’s length, projected on each of the two canonical axes at a right angle, indicates the strength of this variable. The absolute length of a vector has no meaning, but it can be assessed relative to the length of the other vectors.

3. The response variables (i.e. the catchments, Fig. 13, upper panel, or the monthly runoff change signals, lower panel) are projected at a right angle on a constraining variable’s vector. They are ordered along the vector according to the relative importance the constraint has for the response variable.

4. Distances between the response variables and the centroids of nominally scaled constraining variables (here: aspect and land use) approximate their Euclidean distances in the multidimensional space; the nearer a response variable to the constraint’s centroid, the more of the variance is explained by the constraint.

The analysis of the entire set of catchments (Fig. 13) provides insight into the general structure of explanatory and dependent variables. The overall $R^2_{adj}$ is 0.79, meaning that the variance of explanatory variables explains roughly 80% of the variance of the dependent variables. This is a fairly high value that indicates we have assessed the important constraints in our analysis. The first RDA axis accounts for the major part, i.e. 63% of the variance, and this axis is strongly determined by mean altitude, mean slope and summer and autumn temperature change of both periods. The second RDA axis, in contrast, explains only 8% of the variance of the response variables.

The set of catchments is divided into northward (C1, C2, C3 and C7, Fig. 13, upper panel) and south- and eastward exposed catchments (C4, C5, C6). Furthermore, the colour-coded clusters are distributed along the first RDA axis from right to left, roughly sorted depending on their mean altitude. At the same time, they are spread in relation to land use type that itself is a function of elevation. For highly elevated catchments (C4, C5, C6), the importance of the temperature change is proportionately higher, too. The highest catchments, however, exhibit strikingly different behaviours (C7 in Fig. 13, upper panel); these catchments’ hydrological change signals depend on the precipitation delta and on glaciation, which matches our findings from the cluster analysis. The dispersion of catchments along the second RDA axis is mainly a function of glaciation for the high elevated catchments (C4 and partly C5 and C7) as well as a function of spring temperature change for the catchments at lower elevations (C2, C3, C6 and partly C5), indicating an influence of snowmelt processes on the hydrological response for the latter ones.
Fig. 13. RDA-biplots for all catchments and both scenario periods. At the top of the legend, a schematic of an RDA with its different components is given (cf. Sect. II-4.2 for interpretation rules). The upper panel shows a biplot of the catchments; the lower panel displays the same results but with respect to monthly runoff changes (Delta Q). The vectors of the seasonal Delta T and P are indicated with abbreviations “wi”, “sp”, “su” and “au”. Both change signals are displayed for the near (orange and light blue) and the far (red and dark blue) future. The adjusted $R^2$ ($R^2_{adj}$) is the proportion of variance of the response variables explained by the constraining variables.

Regarding the hydrological change signals (Fig. 13, lower panel), the variance of the near future’s change signals is generally smaller compared to those of the far future because they are
distributed around the origin of the RDA axes. This reflects the lower climate sensitivity during the near future period that we found in cluster analysis. The land use type does not constrain the monthly hydrological change; it seems to be only characterising for the entire annual cycle of change signals (represented by the centroid of a catchment). There is a strong dependence of spring and summer runoff change on the glaciation of a catchment. The change in winter and spring runoff is also a function of the catchments’ mean altitude and is thereby a function of winter and spring temperature change, determining the ratio of liquid to solid precipitation as well as snowmelt processes. Whereas the summer precipitation delta has an influence on changes in summer runoff, the other seasonal precipitation deltas do not determine hydrological change.

For the analysis of single clusters, the set of constraining variables had to be further reduced because the \( n \) of single clusters is smaller (cf. Sect. II-3.3). First of all, we assessed only the sensitive far future period and excluded dominant land use and catchment area from the set of constraints, because they showed to be less important for the monthly runoff change (cf. Fig. 13, lower panel). C3 and C7 were not analysed at all because their number of cluster members was too small as opposed to the number of constraining variables. In fact, there would have been more constraints than objects to explain. The results of the redundancy analysis for single clusters (Fig. 14) are summarized in Table 5.

**Table 5.** Summary of summer (JJA), winter (DJF) and yearly (a) runoff changes \((Q)\) per cluster and scenario period (near, far) and evaluation of the constraints from redundancy analysis. Explanation of symbols: increase/decrease \(< 10\% \,(\approx),\ 10\text{-}29\% \,(+/-),\ 30\text{-}50\% \,(+++/-),\ > 50\% \,(+++/---)\). Yearly peak increased \((\uparrow)\), decreased \((\downarrow)\) or shifted earlier \((\leftarrow)\). Influence of constraint (x), strong influence of constraint (xx). For influence of the climate change signal \((\Delta T, \Delta P)\), the respective seasons are indicated. \(R^2_{adj} = \) proportion of variance explained by constraints.

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<th>C1</th>
<th>C2</th>
<th>C3*</th>
<th>C4</th>
<th>C5</th>
<th>C6</th>
<th>C7*</th>
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<td>(Q_{JJA,\ near})</td>
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<td>(Q_{a,\ near})</td>
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<td>(\text{Peak}_{a,\ near})</td>
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<td>0.61</td>
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*C3 and C7 were not separately analysed in redundancy analysis because of the too small numbers of cluster members.*
Fig. 14. RDA results for the far future period and single clusters. Clusters three and seven were not analysed because of their too small numbers of cluster members. For explanation of the vector names see Fig. 13. Note that clusters one and two are not glaciated and therefore miss glaciation as a constraining variable.
C1 and C2 are the only clusters where a clear impact of mean slope on the monthly runoff change was observed. At the same time, precipitation change influences the change in runoff during the whole year in those two clusters. This suggests that hydrological processes that are related to the slope of a catchment are dependent on the precipitation delta. In C2, the winter temperature delta is important for runoff change, too, indicating an additional impact of an altered ratio of liquid to solid precipitation, here. The small (> 10 %, C1) to medium (> 30 %, C2) seasonal changes in runoff in the far future period are averaged out over the whole year. This is different for C4 to C6, where a small (> +10 %) to large (> +50 %) increase in the far future’s yearly runoff was projected despite of decreasing summer runoff. This yearly increase is highest for the highly glaciated C4. Mean altitude is important in all clusters tested separately, but its impact is less pronounced in C4, where the glaciation is most important. In summary, the RDA for single clusters underlines our previous findings where mean altitude and thereby the temperature of a catchment are the dominant factors determining hydrological change.

II-5 Discussion and conclusions

We introduced an approach to reduce a comprehensive set of 186 catchments in Switzerland to fewer response types to climate change. We then inferred general relationships between catchment characteristics, climate change signals and the hydrological responses of the catchments in order to extract the dominant processes that govern hydrological change. The motivation for this study is the adaptation policy that demands hydrological projections, which should support the decision-making on necessary adaptation measures. Hydrological climate-impact studies that provide these projections are highly demanding with respect to computational power and time, however. To simplify future impact studies in Switzerland, we deduced characteristic catchment properties that constitute the hydrological change to a large extent and identified climate-sensitive regions, so that future impact studies can be conducted on a reduced sample of catchments that represent the determining properties and sensitive regions.

In the following, we want to discuss our results with respect to the research questions outlined in the introduction, then evaluate the results’ significance for adaption measures and review some sources of uncertainty we did not cover in our analysis. Finally, we propose possible directions where future research could focus on.

II-5.1 Research questions

In our first research question we sought a grouping of hydrological response. By means of cluster analysis, we grouped the catchments into seven distinct response types. This means that future impact studies for the entire area of Switzerland can be conducted on a subset of catchments representing the different response types.

Regarding the second question that aimed at the response types’ climate-sensitivity, we found that all clusters except for one exhibit a clear shift of the annual runoff distribution in the
far future period: summer runoff decreases significantly, whereas winter runoff increases. This shift acts on specific regimes, though, which alters the effect with respect to the absolute monthly runoff. Significant yearly increases in runoff were observed for the high alpine region in addition to the clear seasonal shift. Cluster 1 (C1), which encompasses catchments in the Jura ranges and in parts of the Swiss Plateau, is not sensitive to climate change, neither during the near (2025–2046) nor the far future period (2074–2095). To summarize, all clusters except for C1 have to be regarded as climate-sensitive in the far future period and their response to climate change is cluster-specific. To reduce the workload of future impact studies, one could focus on catchments in the sensitive regions and assess only the far future period, provided that the near future is not of particular interest.

The third research question aimed at deriving general causal relationships between the hydrological response to climate change and characteristic catchment properties. We conclude that the main determining feature is the catchments’ mean elevation, which e.g., Birsan et al. (2005) and Renner and Bernhofer (2011) found, too. Within a certain range of the catchments’ mean altitudes, between 1000 and 2500 m a.s.l., the hydrological change can be regarded as a function of elevation and, therefore, as a function of temperature change. Because elevation governs the mean annual temperature of a catchment, it governs the associated dominant hydro-climatological processes, too, which are above all the partitioning of liquid and solid precipitation and the determination of snow accumulation and snow melt. Nijssen et al. (2001) discovered a similar causal relationship between the hydrological response and the latitude of a catchment: more northern catchments, i.e. colder and more snow-dominated catchments, exhibit “[…] the largest changes in the hydrological cycle […]”. For catchments in our study with a mean altitude below 1000 m a.s.l., hydrological change is mainly a function of precipitation change which is not nearly as pronounced as the temperature signal is and which is why they are less climate-sensitive. Catchments with a mean altitude above the threshold of approximately 2500 m a.s.l. exhibit a different behaviour: at these elevations, even strong increases in temperature do not shift the mean annual temperature of a catchment strongly enough, so that snow accumulation and ablation processes would be substantially altered and a change in regime would succeed. This effect was observed by Nijssen et al. (2001), too, but for the most northern (i.e. the coldest) catchments in their study, where “[…] even for a relatively large increase in temperature, winters will remain quite cold with temperatures generally well below freezing”. This means that the sample of catchments considered in future impact studies should include catchments at different altitudes and, therefore, with different mean temperatures, even if they are situated in the same response region because of the superior importance of this integral catchment characteristic.

II-5.2 Significance for adaptation measures

In the following, we discuss the general suggestions for future impact studies outlined in the previous section with respect to water resources management and adaptation strategies. Adaptation is a process that has to be dealt with locally and with a distinct focus. We focused on changes in the mean annual cycle, here, and assessed the high alpine regions (C4, C5 and partly
C6) to be specifically sensitive to changes in climate, which implies a potential need for adaptation. This sensitive hydrological response, however, can actually be advantageous if the focus is on hydropower production, which is the main economic factor in these regions. Hänggi and Weingartner (2012) concluded, for instance, that a more balanced runoff regime is favourable for hydropower production, although they recommend that each hydropower plant should be analysed separately. Conversely, we assessed C1 to be insensitive to climate change based on the analysis of changes in the mean annual cycle. Meyer et al. (2012), however, who focused on low flow events, detected a significant low flow vulnerability of catchments in this particular region. This underlines the importance of a clear focus and a tailored study setup when suggestions for adaptation measures are requested. As a last example, C2 encompasses areas in the Swiss Plateau where conflicts between the water use for agriculture, drinking water supply and ecological requirements might emerge in the future. With regard to seasonal and annual changes, this cluster is not as climate-sensitive as the alpine clusters are, but the projected runoff still considerably decreases in late spring and summer when water demand by the concurrent users is usually highest.

II-5.3 Sources of uncertainty

We assume that the primary source of uncertainty associated with hydrological climate-impact modelling comes from climate models, which had been demonstrated by e.g., Arnell (2011), Kay et al. (2009), Teutschbein and Seibert (2010) and Wilby and Harris (2006). By applying ten different combinations of GCM-RCMs, we accounted for a spread in the hydrological projections caused by the climate models and omitted the other uncertainty sources mentioned in the introductory part to direct our efforts towards assessing as many different catchment types as possible instead.

The climate scenarios in our study do not include changes in the frequency and intensity of the climate variables, though, because they were derived with the delta change approach which only accounts for changes in the mean annual cycle of temperature and precipitation. This is a drawback, of course, with respect to the assessment of extremes (that we did not aim at). On the other hand, these rather moderate scenarios might constitute an advantage with respect to the validity of the model parameters: Vaze et al. (2010) showed, for instance, that model parameters can yield reasonable results if applied in impact studies with rather moderate precipitation changes, which is true for our climate scenarios.

Nevertheless, the calibrated model parameters are the crucial source of uncertainty associated with the hydrological model. As Merz et al. (2011) elaborated, calibrated model parameters are only valid for the period they were calibrated for, and “[…] care needs to be taken when using calibrated parameters for predictions of the future”. They refer to the stationarity problem, here, which is related to hydrological model parameters. We assume, however, that the employed regionalization procedure might mitigate the adverse effects of stationary model parameters: the simulated hydrograph is virtually detached from one distinct set of model parameters. In other words, the seven different parameter sets that were applied to regionalize the runoff reflect model parameter uncertainty.
The land use is treated as a static catchment property in our study, although one can argue that land use will change under a changing climate and will impact on the hydrological response itself, which is likely to be true. The land use being a static catchment property in our model is therefore a rough simplification, which is why the effects of climate-induced changes in land use, e.g. an increase in tree line or an extended growing season, are foci of another study (Köplin et al., 2012b).

The results of the cluster analysis depict only one possible grouping of the study catchments, because there is no distinct objective solution in catchment classification (Leyer and Wesche, 2007). In fact, the borders between the catchments are most likely less sharp, as they seem to be in the spatial visualization in Fig. 10. Nevertheless, the clustering seems to be robust because the catchments are similarly clustered in the RDA that was run independently from the cluster analysis.

The results of the RDA, on the other hand, certainly strongly depend on the set of constraints applied, and we may have missed other, possibly more important constraining variables. One can also argue that the catchment properties we chose are not characteristic for the clusters, which can be assumed from the substantial within-cluster spread of some variables depicted in Fig. 11. The comparatively high values for $R^2_{adj}$ indicate, however, that we captured a significant amount of variance explained through the constraints.

**II-5.4 Further research**

We showed just one possibility to reduce the workload in hydrological climate-impact studies, and there are several options to widen or modify our analysis. The cluster analysis could be tested for its robustness, for example, by separately clustering the hydro-climatological change signals of each climate scenario and comparing the results to the clustering based on the ensemble mean that we applied here. Moreover, different clustering methods could be tested, e.g. a fuzzy clustering that would account for smooth transitions between the clusters. An option to widen our study is to select a sample of catchments according to the suggestions mentioned above and consider additional uncertainty sources like, for instance, different hydrological models or calibrated parameter sets. Moreover, it would be interesting to apply the proposed procedure to all catchments but driven by climate scenarios that account for frequency and intensity changes, too, and compare the results to our findings. Presumably, we extracted essential components of hydrological change in Switzerland because we applied the basic changes in the annual cycles of temperature and precipitation. There might be other processes, though, that emerge with frequency and intensity changes of the climate variables that would be important for the assessment of extremes, for example.

A different approach to assess hydrological change would be to test a range of plausible changes in climate (derived from climate models) for their threshold exceedance of safety margins, for example (Prudhomme et al., 2010; van Pelt and Swart, 2011; Wetterhall et al., 2011). That is, this is a sensitivity analysis of a hydrological system to different climate changes rather than an impact analysis of climate change on hydrology. This approach has only recently
gained attention for use in adaptation strategies (van Pelt and Swart, 2011) and offers an addition to the top-down approach applied in this study. However, it is not a substitute for climate impact studies, as it cannot account for the complete storyline of climate change that an ensemble of GCM-RCMs depicts.

It has to be stated that our findings are only valid for the study domain considered, but they are likely to be valid for other alpine regions in Europe, as well. Moreover, the proposed procedure is applicable to any desired study region and helps to understand and structure the hydrological change in the particular area of interest.
In the previous analysis, we clustered the catchments based on an equally weighted combination of the three monthly change signals of temperature, precipitation and runoff. It might be possible that this combination gives too much weight to the climate change signal, though, because it is sampled twice through temperature and precipitation. Therefore, we tested and compared the results of the cluster analysis using the same cluster method as in the paper for the three signals individually and for a combination of the three with double weighted runoff change.

Another factor that significantly influences the result of the cluster analysis is the cluster method itself. We, therefore, tested another widely used cluster method, the $k$-means clustering, and compared the results to the hierarchical-agglomerative clustering applied in the paper. Moreover, we assessed different configurations of both cluster methods to evaluate their effects on the cluster analysis results.
Some preliminary notes on the interpretation of Fig. 15 and Fig. 16: when analyzing the differences of the cluster methods and configurations, it has to be mentioned that a cluster’s colour and name (i.e. number) is always assigned arbitrarily; only the grouping of catchments is determined by the cluster analysis. We tried to colour those regions the same that are grouped similarly in different clustering versions to ease comparison. For example, the catchments in the north-western part of Switzerland are the green cluster C1 in every panel of Fig. 15 and Fig. 16, although its extent, i.e. the number of catchments in the cluster, varies in the different versions. For the cluster versions in Fig. 16, the spatial stationarity of clusters C2 to C7 was less easily achieved, though, due to rather different results of the various clusterings. Another important fact is that every clustering version in this supplementary section is based on a fixed number of seven classes because the different methods and configurations are compared and not the effect of the number of classes $k$. The $k$ would have an effect on the outcome itself, of course.

**Fig. 15.** Clustering results for individual change signals (left column, near and far future combined), absolute monthly runoff (of combined control and scenario periods, top-right) and two combinations of all three change signals with different weights. The bottom-right panel is equal to the combined clustering in the paper (Fig. 10). The catchments that change clusters in the combined clustering versions (middle- and bottom-right) are highlighted by triangles.
For the northern alpine area, the three cluster analyses of individual change signals (left column Fig. 15) mostly preserve the pattern of the cluster map in the lower-right corner that was used in the paper. Differences can be observed for the eastern Alps, though. The Delta $Q$-map is rather irregular and the clusters are spatially less coherent whereas the precipitation and temperature signals alone produce spatially coherent and equally sized clusters that mirror an altitudinal gradient. The clustering of the absolute monthly runoff of control and both scenario periods partly reflects the regime types (Weingartner and Aschwanden, 1992). The combined clustering with double-weight on runoff change shows a very similar pattern to the equally weighted version, except for catchments in the western part of Switzerland. The combined clustering with equal weights used in the study is most similar to the clustering of Delta $T$ alone, indicating a strong effect of temperature on the clustering. In the south-eastern part, however, runoff change seems to have an additional impact, too. Despite these observed differences, the overall pattern of the individual configurations shows similar structures.

**Fig. 16.** Comparison of hierarchical (top and middle row) and $k$-means clustering (bottom row) with different distance measures (Euclidean and Manhattan), different agglomeration methods (Ward, complete) and configurations (number of iterations). See the text for further details. The combination of distance measure and agglomeration method marked with an asterisk was used in the paper.
The additional cluster methods tested here (Fig. 16) represent two main families of cluster analyses: partitioning and agglomerative clustering. The main difference between the two clustering algorithms is the time the number of classes $k$ has to be determined: in partitioning cluster algorithms it is before the clustering, whereas $k$ can be determined afterwards in agglomerative clustering. The a priori definition of $k$ significantly affects the result of the cluster analysis (see Borcard et al., 2011 for detailed explanations of the different clustering methods). Again, $k$ was fixed to seven classes, here, to compare the results of the different methods and configurations to the clustering applied in the paper. The effect of $k$ is not examined.

The two clusterings with Euclidean distance (middle row in Fig. 16) show a similar pattern in the alpine and southern areas, whereas the grouping of the northern alpine areas seems to depend more on the agglomeration method (Ward’s and complete). Overall, the results for different distance measures with the same agglomeration method tend to be more similar, though. That is, the agglomeration method determines the structure and size of the clusters (Borcard et al., 2011): complete linkage results in some rather large clusters (e.g. C1) and some very small (e.g. C3 or C7) whereas Ward’s minimum variance method yields more equally sized groups. Consequently, the choice of the agglomeration method is more crucial than that of the distance measure, which can be attributed to the way the clusters are merged: with the complete linkage method or furthest neighbour sorting (Borcard et al., 2011) two objects or groups are combined if the largest distance between any two objects of the groups is smaller than the respective distance to any other object of another group. Thereby, all objects in the merged group are linked, implicitly. In Ward’s minimum variance method, objects or groups are merged by minimizing the sum of the squared distances among the members of a cluster, divided by the number of the members (cf. Sect. II-3.1).

The non-hierarchical $k$-means partitioning (bottom row in Fig. 16) assigns the objects to an a priori determined number of clusters $k$ with randomly chosen cluster centres in the attribute space. This procedure is repeated $n$ times (number of iterations). The grouping is evaluated with Ward’s minimum variance, too, but the main difference is, of course, the a priori decision on $k$. With few iterations (lower-left panel in Fig. 16), two large clusters result (C2 and C6) and several patchy and small clusters. With 10 and 15 iterations, the resulting patterns are very similar to the clustering applied in the paper.

In conclusion, the additional cluster analyses in this supplement demonstrated clearly that there is not one optimal cluster method, but there are some methods that are better suited for the purpose in this study than others. We sought a generalization of the individual change signals, or in other words, rather equally sized clusters. We applied a hierarchical-agglomerative clustering method in the previous analysis because of its independence from $k$. The combination of Ward’s minimum variance method with Euclidean distances as similarity measure applied in the paper is recommended for catchment classification in hydrology by several studies because it produces physically meaningful clusters (cf. Sect. II-3.1). A combination of Manhattan distance and Ward’s method would have yielded comparable results. So, ultimately, the choice of the clustering method, the used algorithm and the distance metric is arbitrary and has to be made with consideration of the data and the respective purpose. The choice of the variables to
cluster is likewise crucial. The combination of the three change signals showed to produce slightly different clusters than the individual variables alone. This means that the combination of the signals contains additional information and is therefore useful.
Changes in land cover alter the water balance components of a catchment. Therefore, hydrological climate impact studies should also integrate scenarios of associated land cover change. We applied scenarios of glacier retreat and forest cover increase that were derived from the temperature signals of the climate scenarios used in this study. The relative importance of each of the three types of scenarios (climate, glacier, forest) is assessed through an analysis of variance (ANOVA). The results show that even an extreme change in forest cover is negligible with respect to changes in runoff, but it is crucial as soon as evaporation or soil moisture is concerned. For the latter two variables, the relative impact of forest change is proportional to the magnitude of its change. For changes that concern 35% of the catchment area or more, the effect of forest change on summer evapotranspiration is equally or even more important than the climate signal. For catchment with a glaciation of 10% or more in the control period, the glacier retreat significantly determines summer and annual runoff. The most important source of uncertainty in hydrological climate impact studies is the climate scenario, though, and it is highly recommended to apply an ensemble of climate scenarios in impact studies.


² Please note that this version is the discussion paper in HESSD. For the final revised version, please consult the Hydrology and Earth System Sciences homepage.
III-1 Introduction

Changes in land use and land cover alter the hydrology of a catchment through changes in evapotranspiration (e.g., Cuo et al., 2009; Dunn and Mackay, 1995; Klöcking and Haberlandt, 2002; Lahmer et al., 2001) and altered surface roughness and soil properties, which modify the runoff concentration processes (Hundecha and Bárdossy, 2004).

In addition to anthropogenic land modifications, the vegetation itself responds to changes in climate with species movement or redistribution (Leuzinger, 2009; Schumacher and Bugmann, 2006; Theurillat and Guisan, 2001). In a mountainous environment, for example, increasing temperatures result in an upward movement of the tree line because the tree line is a climatically determined ecotone (Dullinger et al., 2004). Another climate-induced change in land cover is glacier retreat. Glaciers, however, constitute a special case of land cover since they produce runoff themselves from previously stored water.

The rapid and severe global glacier retreat due to the past increase in temperature is very well documented (see e.g., Arendt et al., 2002; Dyurgerov and Meier, 1997; Paul et al., 2004) and easy to comprehend. Concerning the increase in tree line it is often argued that trees are incapable of responding to changed environmental conditions within rather short time periods like, e.g. less than a century (Dullinger et al., 2004; Egli et al., 2008; Theurillat and Guisan, 2001). This is assumed because other environmental conditions than temperature, such as a low soil-moisture in shallow alpine soils, could prevent rapid upslope migration of trees (Henne et al., 2011). On the other hand, paleoecological records provide evidence for a rapid upslope (and downward) movement. Tinner and Theurillat (2003), for instance, who analysed pollen in lake sediment cores from study sites in southwest Switzerland, concluded that the tree line in this region fluctuated during the past 11 500 years, and Tinner and Lotter (2001) showed that these fluctuations can be attributed to climatic change, i.e. to increases and decreases in temperature. Moreover, Tinner and Kaltenrieder (2005) demonstrated that, during the Holocene, “[…] vegetation was in dynamic equilibrium with climate, [and] forecasted global warming may trigger rapid upslope movements of the tree line of up to 800 m within a few decades or centuries […].”

These observed and anticipated changes in forest cover in Switzerland are not only a result of climate change, but also a result of altered land use practices. Gehrig-Fasel et al. (2007), for example, found an increase in forest cover in the Swiss Alps for the very short period from 1985 to 1997. They attributed this increase to both the change in climate and in land use, the latter of which being most important for the observed increases in forest cover, however. They expect climate change to gain in importance for the 21st century, though.

In spite of this documented change in forest cover due to climate and land use change, most studies assessing the impacts of climate change on hydrological systems neglect the effects of accompanied changes in land cover (see e.g., Elsner et al., 2010; Gunawardhana and Kazama, 2012; Laghari et al., 2012). There is a growing consensus, however, that these land cover impacts have to be accounted for, to reliably assess future availability of water resources.
because of possible feedbacks between land cover and climate (e.g., Bronstert, 2004; Hejazi and Moglen, 2008; Viviroli et al., 2011).

Given that the forest and glacier area in Switzerland will change considerably, the question is, to what extent would this change alter the projected hydrological change? Or more specifically, how does the relative changes that are introduced by an altered glacier runoff and a changed forest cover compare to the relative impact of the climate signal itself? These questions are answered in this study by means of hydrological climate-impact modelling in 15 mesoscale catchments in Switzerland. A study with this focus is new so far and provides insight into the question whether or not it is necessary to account for land cover changes as part of climate change impacts on hydrological systems.

### III-2 Study area and data

We extended an earlier study by Köplin et al. (2012a) who modelled and analysed a comprehensive set of 186 mesoscale catchments in Switzerland with respect to hydrological change. They applied ten regional climate models (RCMs) as well as scenarios of glacier retreat that were derived from the projected climate change to determine climate-change sensitive regions in Switzerland. They ran the hydrological modelling system PREVAH (Viviroli et al. 2009a) with this input. Here, we use the same model set up with respect to the RCMs, the glacier retreat and the hydrological model but extend it by applying three different forest change scenarios (cf. Sect. III-2.3). Although climate scenario data for two periods (2025–2046 and 2074–2095) in the 21st century are available, we only assess the so called far-future period at the end of the century. This is to account for ecological time lags of a few decades (Harsch et al., 2009) that will likely prevent significant tree growth until the near-future period.

We will analyse the hydrological impacts of climate change together with its accompanying forest increase and glacier retreat in a sample of 15 case study catchments in Switzerland (Fig. 17). The catchments are representative of the different regions in Switzerland that are particularly sensitive to climate change as defined in Köplin et al. (2012a): each sensitive region (C2 to C6 in Fig. 17a) is represented by three case study catchments. Moreover, the case study catchments evenly cover an altitudinal range from 1000 to 2500 m a.s.l. (Fig. 17b). Catchments located within this range are specifically sensitive to changes in temperature, which was demonstrated by Köplin et al. (2012a). Since the land cover scenarios in this study solely depend on temperature change (cf. Sects. III-2.2 and III 2.3), the selected catchments constitute a suitable sample for our study.

The study catchments were parameterized through regionalization of calibrated parameter sets, for details see Köplin et al. (2010, 2012a) and Viviroli et al. (2009b, 2009c). A regionalization procedure was applied because most of the catchments in the high alpine area are used for hydropower production and can therefore not be calibrated on measured natural runoff data. That is, we study the natural runoff behaviour of the catchments under scenarios of climate and land cover change, which should be kept in mind when interpreting the results.
III-2.1 Climate scenarios

The climate scenarios are part of the Swiss climate change scenarios CH2011 (2011). They are provided for the meteorological variables temperature and precipitation and are based on the delta change approach. Bosshard et al. (2011) applied this downscaling procedure to ten RCMs from the ENSEMBLES-project (van der Linden and Mitchell, 2009), all of them driven by the A1B emission scenario. The novelty introduced to the downscaling procedure by Bosshard et al. (2011) is a spectral smoothing method to filter the annual cycle of daily deltas. This yielded continuous representations of the annual cycle of climate change signals. The annual cycles of temperature and precipitation were provided for all meteorological stations in Switzerland, i.e. 188 temperature and 565 precipitation stations (CH2011, 2011).

Because the climate scenarios are based on the delta change approach that assesses changes in the long-term mean annual cycle of the climate variables, all of the subsequent analyses of hydrological response variables are based on the mean annual cycle, too (i.e. mean monthly, seasonal and annual values, respectively).

The projected climate change for the case study catchments can be summarized as follows: the ensemble mean projects temperature increases during the whole year with the most pronounced increase in summer (4 K) and a smaller increase in spring (2.8 K). The winter precipitation increases by 10 % on average, whereas summer precipitation decreases by 20 % and spring as well as autumn precipitation do not show a distinct change signal.

III-2.2 Glacier retreat

The glacier scenarios are calculated as a function of the climate scenarios’ temperature deltas using a glacier retreat model (Linsbauer et al., 2012; Paul et al., 2007; Paul et al., 2011).
The model is based on alterations of the glaciers’ equilibrium line altitude (ELA). The ELA is the altitude at which the mass balance of a glacier equals zero or in other words, where accumulation equals ablation (Paul et al., 2007), and it rises with increasing temperature. In the model of glacier retreat, the equilibrium line is defined to rise 150 m per 1 K (Paul et al., 2011).

In the Swiss Alps, the glacier area above the ELA, the accumulation zone of a glacier, comprises 60% of the total glacier area, on average (MBB, 2005; Paul et al., 2007). An increase of the ELA entails adaptation of the glacier to the altered condition until the ELA divides the glacier at a ratio of 40 to 60% again. This adaptation occurs delayed over a longer time period whereas the ELA immediately reacts on altered temperatures. The delayed adaptation, i.e. the response time of a glacier, is specific for every glacier and is at 10–40 years for most glaciers in the Swiss Alps and 50–100 years for the thickest and largest ones (Paul et al., 2011). In the model applied here, a mean response time of 50 years is assumed, whereas the shift of the ELA is calculated with scenario-specific temperature changes.

The surface that is revealed when a glacier retreats is defined as rock because it is assumed that soil formation takes much longer than only 100 years, i.e. it is not completed in the time period from the control to the scenario period. The glacier change (GC), i.e. the retreat per catchment from the control to the scenario period is depicted in Fig. 18. It has to be stated that the glacier retreat assumed in this study is rather conservative because the model does not take into account enhanced input of dust or lake formation, for example, which would accelerate glacier retreat. Based on the latest observed temperature increase and considering positive feedbacks, the glacier retreat would be more severe than calculated with the model, here (Linsbauer et al., 2012). Nevertheless, these glacier scenarios constitute a unique data basis for our study since they comprehensively assess the glacier retreat for the entire Swiss Alps.

For the analysis of variance (Sect.III-3.2), we added an extreme glacier scenario to the setup, where we removed all glaciers from the catchments (GNO). This represents one possibility to assess the relative impact of glacier retreat on the projections if no scenarios were available. Moreover, we thereby cover the whole range of possible glacier extents, from the control period extent to a complete glacier-free state: as mentioned above, the scenarios of glacier retreat have to be considered being rather conservative, and most of the smaller glaciers in our study could possibly have disappeared at the end of the century.

III-2.3 Forest scenarios

In this study, vegetation change is defined as an increase of forest cover due to both the increase of the tree line and land abandonment. We narrowed down vegetation change to a change in forest cover, because the conversion of any vegetation into forest constitutes a drastic change in land cover and presumably causes the strongest hydrological signal.

Our forest change model comprises different rules that control tree growth: trees can only grow where the former land cover was bush, pasture, sub-alpine meadow, alpine meadow, alpine vegetation, rough pasture or bare soil vegetation, but they cannot grow on rock, urban areas, water and wetlands, for obvious reasons. Areas used for agriculture are excluded from
forest expansion, too, because these areas are protected by law in Switzerland since 1992 (Lüscher 2004). Furthermore, trees can only grow on areas with a slope of less than 40° because steeper slopes unlikely support higher vegetation (Theurillat and Guisan, 2001).

Temperature is the most important factor determining plant growth (Körner, 2007), since it controls, i.e. promotes and limits tree growth (Grace et al., 2002). This is why we calculated potential scenario tree lines based on mean annual temperature increases of the ten climate scenarios in use and without accounting for changes in precipitation. The increase in tree line was calculated according to the average temperature lapse rate of 0.56 K per 100 m (Körner, 1998; Theurillat and Guisan, 2001). The mean annual temperature deltas of the ten climate scenarios vary between 2.4 K and 4.2 K for the case study catchments. For a climate scenario with a rather low temperature increase, for example, the scenario tree line would be 465 m higher (2.6 K / 0.56 K * 100 m) than the actual catchment-specific control period’s tree line.

**Fig. 18.** Relative proportion of glacier, unproductive, productive, and coniferous and deciduous forest area per catchment, as well as proportional increase of the catchments’ mean soil depth. Unproductive area subsumes water bodies, urban area and rock; productive area comprises all vegetational land covers except for forest. The left column of each catchment-panel visualizes the control period’s proportional land covers (CTRL), the middle column those for both glacier retreat (GC) and tree line increase (FC1), the right column depicts additional land abandonment (FC2) and soil genesis (FC3), the latter shown on the lower right bar. The names of the catchments’ main channels are given in the legend, for the respective locations please see Fig. 17. The catchments marked with a red circle are analysed for changes of the water balance components (Sect. III-III-4); the catchments marked with a red asterisk are used in the ANOVA (Sect. III-III-4.3).
Based on the outlined forest scenario constraints, we define three different forest scenarios which we briefly describe in the following. Attention should be paid to the consecutive setup of the scenarios (see Table 6 for a summary): each scenario incorporates the changes of the previously introduced scenario, i.e. the second forest change (FC₂) integrates the changes of the first forest scenario (FC₁) whereas the third (FC₃) inherits the changes from both FC₁ and FC₂. All three forest scenarios, on the other hand, integrate glacier retreat (GC), and all four land cover scenarios are run with the climate scenario input (CC₁–CC₁₀), of course. We decided on this successive structure of the scenarios because this is a common increase of the degree of complexity observed in other impact studies. Thanks to this, the results are comparable to studies that do not account for land cover change at all, to studies that incorporate a glacier retreat and to studies that additionally assess changes in forest cover.

Table 6. Nomenclature of scenario combinations for the descriptive analysis (cf. also Fig. 20, upper half). CTRL always corresponds to the control period from 1984–2005, each scenario is valid for the scenario period from 2074–2095. Note the successive structure of the scenario combinations: per scenario just one member in the chain is changed.

<table>
<thead>
<tr>
<th>Name</th>
<th>Climate change</th>
<th>Glacier change</th>
<th>Forest change</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTRL</td>
<td>C_CTRL</td>
<td>G_CTRL</td>
<td>F_CTRL</td>
<td>Baseline scenario with control period climate, glacier and forest extent.</td>
</tr>
<tr>
<td>CC_EM</td>
<td>CC₁–CC₁₀</td>
<td>G_CTRL</td>
<td>F_CTRL</td>
<td>Climate change only. Note that for the descriptive analyses the ten simulations (due to ten CCs, i.e. RCMs) are averaged to the ensemble mean (EM).</td>
</tr>
<tr>
<td>GC_EM</td>
<td>CC₁–CC₁₀</td>
<td>GC</td>
<td>F_CTRL</td>
<td>Additional glacier retreat. Again, the ten resulting simulations (due to 10 CCs) are averaged to the EM.</td>
</tr>
<tr>
<td>FC₁_EM</td>
<td>CC₁–CC₁₀</td>
<td>GC</td>
<td>FC₁</td>
<td>Additional tree line increase, averaged to EM.</td>
</tr>
<tr>
<td>FC₂_EM</td>
<td>CC₁–CC₁₀</td>
<td>GC</td>
<td>FC₂</td>
<td>Additional land abandonment (i.e. in addition to tree line increase), averaged to EM.</td>
</tr>
<tr>
<td>FC₃_EM</td>
<td>CC₁–CC₁₀</td>
<td>GC</td>
<td>FC₃</td>
<td>Additional soil genesis, averaged to EM. Soil depth increases on all former and new forest areas.</td>
</tr>
</tbody>
</table>

The first forest scenario FC₁ represents tree line increase, where deciduous and coniferous forests are treated separately, here, because of their specific natural tree lines. First, the coniferous forest grows beyond its control period tree line on the allowed areas specified above and rises up to the scenario treeline, i.e. it is purely an upwards expansion. Then, the deciduous forest grows above its control period tree line and on the same allowed areas. Deciduous forest, however, can also replace coniferous forest. This first scenario of forest change thereby reflects findings from Leuzinger (2009) who assumes that the tree line in Switzerland will increase significantly and deciduous forest will replace the formerly dominating coniferous forest. It has to be stated, though, that some authors actually anticipate a shift of whole vegetation belts (e.g., Leuzinger, 2009; Theurillat and Guisan, 2001). For our forest scenario, however, existing trees
remain in the lower ranges, which we attribute to the Swiss forest law from 1991 (WaG, 2008). This law protects forested areas and aims at preserving the forest in Switzerland in its area and spatial distribution. Therefore, the formerly forested area is not changed, here.

The second forest change $FC_2$ is an additional land abandonment. Please note that only areas formerly used for alpine farming are abandoned in this scenario, e.g. sub-alpine meadows or pastures, not to be confused with the agricultural areas protected by law from abandonment (see above). Within the control period’s range of lower and upper tree line, first the coniferous forest grows on the allowed areas, then deciduous forest grows and again replaces coniferous within the deciduous forest’s tree line boundaries. That is, this scenario reflects a sideways forest expansion in addition to the previous upwards expansion. Both $FC_1$ and $FC_2$ are based on the results of Gehrig-Fasel et al. (2007) who found that climate change causes upward shifts of the tree line, whereas land abandonment results in forest ingrowth.

The last scenario of forest change ($FC_3$, soil genesis) is not a further increase in forested area but an additional increase in soil depth under forest cover. This increase in soil depth has to be distinguished from the slow soil formation on bare rocks mentioned in Sect. II-2.2. Here, it is an increase in depth of existing soils on forested areas because of the high input of organic matter through trees. It is based on results by Mavris et al. (2010) who found a distinct accumulation of soil organic matter within 150 years of exposure after glacier retreat and recolonization of higher plants at the Morteratsch glacier in eastern Switzerland. We mimic this in our scenarios with a general increase of soil depth by 10 cm in 100 years on forest covered areas, both new and existing forests.

The scenario tree lines of our study catchments for coniferous forest range from 1910 m a.s.l. where the control period’s tree line was low (1490 m a.s.l.), to 2870 m a.s.l. where the calculated shift in tree line due to the high temperature increase was maximal (780 m). The relative area of deciduous and coniferous forest per scenario, as well as the relative increase in soil depth per study catchment can be examined in Fig. 18.

III-2.4 Land cover in PREVAH

This section is based on the documentation of the hydrological modelling system PREVAH (Precipitation-Runoff-EVAporation-Hydrotope based model, Viviroli et al., 2007; Viviroli et al., 2009a). The land cover in PREVAH includes water bodies, glaciers, rock, bare soil, urban areas and natural as well as cultivated vegetation. Altogether, 22 land cover types are defined with the following land cover specific variables that are parameterized a priori on a monthly basis: surface roughness, which is represented by average vegetation height, root depth, minimal stomatal resistance, leaf area index (LAI), vegetation density, maximal interception storage and albedo. These vegetation-specific parameters are used, among others, to calculate potential evapotranspiration ($ETP$) after the Penman-Monteith equation (Monteith, 1975). The actual evapotranspiration ($ETA$) is then derived from $ETP$ using adjustment factors, dependent on the actual moisture and vegetation as well as soil conditions.
Vegetation therefore has a direct influence on interception ($SI$ and $EI$; see Fig. 19), depletes the soil moisture storage ($SSM$) via transpiration ($ESM$) and thereby alters $ETA$, which is a basic water balance component. Land cover, however, also modifies the maximum storage capacity of $SSM$: the storage's limit is defined vegetation-specific using plant-available soil-moisture capacity, root depth and soil depth. That is, in our scenarios $SSM$ is not only increased through the root depth of the increased forest cover but also through the increased soil depth under $FC_3$, of course. So, an increased forest cover increases $ETA$ and $SSM$, and thereby acts as a sink for runoff through withdrawal of water from the runoff generation modules ($SUZ$, $SLZ$). That is, the forest scenarios have the potential to indirectly reduce runoff, in particular the quick runoff.
component \((R_0)\). This indirect influence of vegetation on runoff reflects the commonly recognized effect of afforestation.

In contrast to vegetation, glaciers have a direct influence on runoff as they generate runoff themselves through melt of previously stored water which is added to different runoff components (see Fig. 19, lower left corner). Therefore, glaciers are a source for water in addition to liquid precipitation and snow melt and have to be considered a special case of land cover. The area that is released by the glacier is converted into rock (cf. Sect. III-2.2), which constitutes a drastic change: sublimation is reduced and, more important, the composition and amount of direct runoff \((R_D)\) is changed leading to an altered total runoff and a changed runoff behaviour.

As set out in this section, the hydrological modelling system PREVAH represents all important components that matter with respect to land cover change and its impact on hydrology, which is a prerequisite in this kind of impact study (Bronstert, 2004).

III-3 Methods

III-3.1 Descriptive analysis

We ran the hydrological model for all climate and land cover scenarios and then aggregated the hourly time series to the mean annual cycle of monthly values or seasonal and annual values, respectively. Because we study changes in water balance components, these aggregated values are more meaningful. For ETA and \(R_{tot}\) we computed the sum per month (season, year), and for SSM, being a state variable instead of a flux, we calculated the mean for the respective periods. The runoff coefficient \(RC\) was calculated as the ratio of direct runoff \((R_D)\) to the sum of liquid precipitation \((P_{liq})\) and snowmelt \((SME)\). \(R_D\) is the sum of surface runoff \((R_0)\) and interflow \((R_1)\) per time step, i.e. per month, season or year, minus the glacier melt \((GLAC)\). So \(RC\) is calculated as

\[
RC = \frac{(R_0+R_1)}{P_{liq}+SME}
\]  

(III–1)

We subtracted \(GLAC\) from \(RD\) because in the model structure of PREVAH the glacier melt is directly added to the surface runoff. To reduce the effect of glacier retreat on \(RC\) to its mere alteration of the land cover (conversion of ice to rock), we subtracted \(GLAC\) from \(RD\). Moreover, we do not so much aim at assessing the change in glacier runoff than at assessing its effect on the water balance components. The altered glacier runoff is implicitly incorporated analysing changes in the target variable \(R_{tot}\), of course. For all analyses in this study, we used the R version 2.14.1 (R Development Core Team, 2012).

Please note that, for the descriptive analysis and each target variable, we computed the ensemble mean of the climate scenarios per land cover scenario (see Fig. 20, upper half, right side). That is, we aggregated the spread in the target variables that is caused by the different climate models to the mean value, here, to oppose this single \(CC_{EM}\) value to the respective
values for GC_{EM} and FC_{1,EM}–FC_{3,EM} as well as to the CTRL. The spread that is caused by the climate scenarios will be analysed in the ANOVA (Sect. III-3.2).

**Scenario coupling descriptive analysis**

For the descriptive analyses, the ten climate model realisations for each combination of glacier and forest scenario are averaged computing the ensemble mean (right side, upper half) which results in six simulations to analyse (CTRL, CC_{EM}, GC_{EM}, FC_{1,EM}, FC_{2,EM}, FC_{3,EM}). Please note that the green lines between CC and GC symbolize the combination for all three forest changes (FC_{1}–FC_{3}). For the ANOVA, every possible combination of scenarios is used, resulting in 120 (10 CCs × 3 GCs × 4 FCs) simulations to analyse. The subscript CTRL indicates that the respective conditions during the control period (1984–2005) are considered.

**Comparison of water balance components**

First, we chose two very different catchments (5 and 9, cf. Fig. 18) to study the possible range of changes in the water balance components due to the climate and land cover change. Catchment 5 shows the strongest increase as well as the highest degree of forest cover under FC_{2} (CTRL: 32 %; FC_{2}: 87 %) and is not glaciated. On the other hand, catchment 9 shows the second lowest degree of forest cover under FC_{2} (34 %; CTRL: 14 %), the second highest relative glaciation (21.2 %) and the highest absolute glacier extent (117 km²) of all study catchments. The analyses are based on absolute values to ease the comparison between alterations of different water balance components; the results can be found in Sect III-4.1.

**Comparison of net changes between catchments**

Then, we analysed the net changes for the target variables actual evapotranspiration and total runoff both for the summer (ETA_{JJA}, R_{tot, JJA}) and the annual time scale (ETA_{a}, R_{tot, a}). The net change is defined as the change in a target variable that is caused by one particular scenario...
and that is calculated relative to its preceding scenario. That is, the net change of GC\textsubscript{EM} (cf. Table 6) is calculated relative to the simulation of CC\textsubscript{EM}, or the net change of FC\textsubscript{2, EM} is calculated relative to FC\textsubscript{1, EM}. This relative calculation is necessary because every scenario incorporates the changes of its preceding scenarios as explained in Sect. III-2.3.

We calculate the net changes per scenario and catchment to compare all 15 catchments and to analyse possible relations between the net change and the glacier retreat as well as the forest increase. For a strong forest increase, for example, one would expect a higher net change due to this forest change and compared to that of the climate and glacier changes. So, the net change allows to assess the relative importance one scenario has for the target variable and differs from the analysed absolute values mentioned in the previous section. The comparison of all catchments facilitates to distinguish systematic relationships between the relative importance and an associated degree of glaciation or forest cover, if at all measurable.

III-3.2 Analysis of variance (ANOVA)

To analyse the relative impact of the three types of scenarios (climate, glacier, forest) on the target variables, we furthermore conducted an analysis of variance (ANOVA; see e.g. Doncaster and Davie (2007) for a comprehensive overview, which this section is based on). In the following we explain how this analysis differs from the descriptive analysis above.

Through an ANOVA one can assess causal relationships between explanatory variables (the three types of scenarios) and a response variable (here one of ETA, SSM, \( R_{\text{tot}} \), RC). The explanatory variables can be of categorical scale, and in the ANOVA terminology they are referred to as factors, whereas their numbers of categories are called levels. For example, the climate scenarios constitute a factor with ten levels (i.e. ten different scenarios or categories). In contrast to the descriptive analysis above, which is more a qualitative comparison of the scenarios’ effects, the ANOVA facilitates to quantify the relative importance the scenarios have for the variation in the target variables. It assesses whether the target variables’ responses change for different levels of the factor. That is, an ANOVA decomposes the total variation of a target variable into variance fractions that can be ascribed to changes in the factor variables’ levels. The main advantage of this procedure is that the effects of various factors can be assessed simultaneously (and not separated as for the descriptive analysis), and, moreover, the effects of their interactions on the response can be accounted for, too. Interactions are defined as effects of a factor that depend on the effects of one or more other factors. Because of possible feedbacks between the scenarios (cf. Sect. III-1), these interactions are an important feature for our analysis.

To account for the interactions, the ANOVA design has to be a so called fully cross factored design, which means that all possible scenario combinations are assessed (see Fig. 20, lower half). The three-factor cross factored model in our study is then written as

\[ Y = C + G + F + I \]  \hspace{1cm} (III–2)
with \( Y \) being the total variation of the response, \( C \) being the variation explained through the climate scenarios, \( G \) that explained through glacier change and \( F \) that through forest change. The interaction term \( I \) is defined as

\[
I = C \times G + C \times F + G \times F + C \times G \times F \tag{III-3}
\]

Because the ANOVA assesses the impact of various categorical factor variables simultaneously and accounts for their interactions, too, it is an ideal tool for the analysis, here. This might also be the reason why it is increasingly used in hydrological climate-impact studies as a measure of uncertainty (see e.g., Bosshard et al., 2012; Finger et al., 2012; Rössler et al., 2012).

With the ANOVA, we analysed the annual cycles of monthly change signals of all target variables, separately. Because the additional glacier scenario (\( G_{\text{NO}} \), cf. Sect.III-2.2) required additional computationally demanding model simulations, we conducted the ANOVA on a subset of six catchments (see Fig. 18) that cover a certain gradient of glacier and forest extents.

### III-4 Results

#### III-4.1 Comparison of water balance components

In catchment number 5 (Fig. 21), the increased temperature in the scenario period leads to significantly increased liquid precipitation in winter (Nov–Feb) on the expense of solid precipitation and, therefore, on the expense of snow melt. The decreased snow storage in the scenario period also affects the snow melt in spring (Mar–May), which is considerably reduced at the end of the century, as is the summer precipitation. The increased temperature furthermore leads to increased evapotranspiration which interestingly is most pronounced in autumn, winter and spring instead of the summer. In July and August, even a slight decrease of actual evapotranspiration (\( \text{ETA} \)) is observed, whereas potential evapotranspiration slightly increases. This indicates a limiting effect of the reduced precipitation in this season. This assumption is supported by the projected changes in soil moisture storage SSM which is significantly depleted during the summer months of the scenario period. For the variables \( \text{ETA} \) and SSM, the resulting values for forest change are added to the plot. A slight effect of increasing forest cover can be observed for \( \text{ETA} \): the monthly values increase with every scenario of forest change (\( \text{FC}_{1,\text{EM}} \text{–FC}_{3,\text{EM}} \)), and these monthly changes add up over the year. For SSM, the soil genesis scenario (\( \text{FC}_{3,\text{EM}} \)) leads to a significantly increased soil moisture storage because the maximum storage capacity is, among others, defined via soil depth (cf. Sect. III-2.4). Summer \( \text{ETA} \), as a result, is significantly increased under this forest scenario, too. For the target variables \( R_{\text{tot}} \) and \( RC \), the annual cycle is clearly altered through the climate change signal, and the forest change scenarios follow this predefined annual cycle of the scenario period, in general. They lower the projected runoff and runoff coefficients slightly, though, which can be attributed to the increased \( \text{ETA} \) and SSM that constitute a withdrawal of water. In summary, there is an effect of the extreme change in forest cover in this catchment, especially with respect to changes in SSM.
For the other target variables and compared to the changes that can be attributed to the climate scenario alone, however, these changes are rather small.

![Diagram](image)

**Fig. 21.** Comparison of water balance components for the non-glaciated catchment 5 (for catchment characterization see Fig. 18). For every panel, the annual cycle of monthly values is displayed as well as the summer (JJA), winter (DJF) and annual (a) values (separated from the monthly cycle by a dash-dot line). In the top panel, stacked bars show the input into the simulated water balance (SME, P_liq and P_sol) for the control (CTRL, left bar per month, season, year) and the scenario climate (SCE, respective right bar per month, season, year). Superimposed, one can find the control (orange) and scenario (red) mean temperatures per time step. Below the input into the water balance the corresponding actual and potential evapotranspiration (ETA, ETP) is displayed for CTRL and CC_EM (left and right bar per time step). The resulting ETA values for the forest change scenarios (FC_1_EM–FC_3_EM) are added to the panel. The same applies to the other target variables soil moisture storage (SSM, second-upper panel), total runoff (R_tot, second-lower panel) and runoff coefficient (RC, lower panel).

Catchment number 9, on the contrary, has an entirely different hydrological regime because of the differing mean altitudes of the catchments. The high-alpine catchment 9 has a snow- and ice-fed regime with a typical peak in summer and a low flow season in winter (see Fig. 22). The increase in temperature causes an increase of liquid precipitation, similar to that of catchment 5,
but this effect is identifiable during the whole year, except for July and August. Snow melt occurs during the whole year, too, but it is markedly reduced in the summer of the scenario period. Due to the higher temperatures in the scenario period, the potential evapotranspiration is distinctly elevated. Actual evapotranspiration, however, does not change discernible, neither due to the climate scenario nor due to land cover change. Moreover, evapotranspiration as a water balance component has a minor relevance in this catchment compared to catchment 5. The same is true for the soil moisture storage SSM, which varies marginally over the year and for the scenarios, with the exception of FC₃, EM: the deeper soil causes slightly higher values for soil moisture in this scenario.

Fig. 22. Same as Fig. 21 but for catchment 9. Please note that this catchment is glaciated and has therefore an additional symbol per target variable (GC₃, EM, black squares).
For the target variables $R_{\text{tot}}$ and $RC$, the four symbols of land cover change are exactly superimposed. Because the forest scenarios are added to the glacier change (cf. Sect. III-2.3), this means forest change does not add a distinct signal to the projections and this change can be attributed to the glacier change, alone. The glacier retreat in turn has a pronounced effect on summer runoff through the reduced storage for ice melt. Not accounting for glacier retreat would therefore lead to a substantial overestimation of runoff in the melt season (Jun–Sep). This is particularly true if one considers that the glacier retreat might actually be more pronounced. The proportionately small forest extent and forest change in this catchment cannot further alter the projections that are strongly determined through climate and glacier change.

Overall, the analysis of these two very different catchments indicates distinct influences of the forest and glacier change on the water balance components in addition to the changes caused by the climate scenarios. This additional influence of forest and glaciers, however, highly depends on the considered target variable and is either substantial or negligible. To study the effects of the degree of forest and glacier cover in more detail, we compared all catchments for the two target variables $ETA$ and $R_{\text{tot}}$ in the next section.

### III-4.2 Comparison of net changes between catchments

As set out in the methods section, increasing net changes with increasing changes in forest cover would indicate a causal relationship between the degree of forest cover and its importance for the change in a target variable. Although there is no consistent pattern, this anticipated relationship can be observed for summer evapotranspiration ($ETA_{JJA}$; Fig. 23, left column): in the lower part of the column, the net changes due to the three forest scenarios are equally or even more important than the climate and glacier change. Remarkable are catchments 13 and 14, where the net change of $ETA$ due to the climate scenario is negative in summer, but it is converted into a positive signal under forest change. This effect was already observed in the previous section, where the climate signal alone yielded decreasing summer $ETA$, whereas it increased under forest change. This contrary signal was then attributed to the strong increase in soil moisture storage under forest change and therefore a higher amount of water available for evapotranspiration. Both catchments nevertheless show clear increases of annual $ETA$ due to the climate scenarios. We know from the previous analysis that $ETA$ increases during the whole year due to climate change except for the summer months, where decreasing precipitation limits actual evapotranspiration. In general, the annual $ETA$ shows a similar but less pronounced pattern of higher net changes with higher forest increase. The climate scenarios’ net changes are dominating the change in $ETA$, though. For the summer runoff as well as annual runoff ($R_{\text{tot, JJA}}$, $R_{\text{tot, a}}$, third and fourth column), the forest net change is negligible, which underlines the findings from the previous analyses.
Fig. 23. Comparison of relative net changes per scenario (CC\textsubscript{EM}, GC\textsubscript{EM}, FC\textsubscript{1,EM}, FC\textsubscript{2,EM}, FC\textsubscript{3,EM}) and catchment. The first column (left) displays results for summer evapotranspiration (\textit{ETA}_{JJA}), the second those for annual evapotranspiration (\textit{ETA}_a), the third column depicts summer total runoff (\textit{R}_{\text{tot},JJA}), the fourth (right) annual total runoff (\textit{R}_{\text{tot},a}). The scale is the same for each panel, ranging from -50–50 % (indicated for \textit{ETA}_{JJA}, catchment 3). The catchments are sorted from top to bottom according to increasing forest change between CTRL and FC\textsubscript{1} (light green bars) as well as FC\textsubscript{2} (dark green bars), see right panel of the figure. The relative glacier retreat in per cent catchment area is added to the right panel, too (light blue bars).
As opposed to the minor impact of forest change on the runoff, the glacier change has a noticeable effect on summer runoff. The net change of the glacier scenario slightly alters the annual runoff, too, but only for catchments where glacier retreat is substantial (e.g. 8, 9, 7, 12). However, the glacier net change never exceeds that of the climate scenario, with the exception of the summer runoff of catchments 9 and 7. Again, it has to be stated that the glacier effect might be more pronounced for extremer scenarios of glacier retreat.

To summarize, the comparison of all catchments shows a discernible effect of forest change on summer evapotranspiration for catchments with a strong forest increase of at least 35%. To a smaller degree, this additional effect of forest change can be observed for annual ETA, too. Furthermore, the glacier retreat clearly alters summer runoff in addition to the climate scenario. Overall, however, the climate scenario largely dominates the changes in the assessed target variables.

III-4.3 ANOVA

The ANOVA results for the sample of six catchments (Fig. 24, rows) and all four target variables (columns) can be studied per target variable from top to bottom or per catchment line by line. From top to bottom, the forest extents decrease, whereas the glacier extents increase. If there was a causal relationship between the land cover and the respective variation in the target variable, the variance fractions of the forest scenarios should decrease from top to bottom, whereas the variance fractions of the glacier scenarios should increase in the same direction. For all panels, the interaction term is rather small which indicates independence of the scenarios with respect to the considered target variables.

The abovementioned pattern, decreasing variance fraction for forest and increasing for glacier change from top to bottom, is particularly obvious for ETA: with decreasing forest area and increasing glacier extent, the variance fraction that is attributed to forest change decreases whereas glacier change gains in relative importance. For each catchment, a clear annual cycle of the variance distribution with respect to ETA is observed: the relative importance of forest change, for example, is largest in late summer, which can be attributed to the minor importance of the climate scenario in this season (cf. Sects. III-4.1 and III-4.2) rather than to the superior importance of the forest scenario. The increasing variance fraction of glacier change with respect to ETA might seem surprising, but evaporation from snow and ice comprises a non-neglectable amount of evaporation. Moreover, the relative importance of the forest scenarios is small in the highly glaciated catchments, which indirectly raises the variance fraction explained through glacier change. The major variance fraction in the less forested catchments arises from the climate scenarios, though.
Fig. 24. ANOVA for the annual cycles of monthly change values per target variable \( ETA \), \( SSM \), \( R_{tot} \) and \( RC \). Each column shows the ANOVA results for one target variable and each row of four panels represents the results per catchment. The catchment number is indicated in the upper right corner of the respective right panel. The catchments are sorted from top to bottom according to increasing glaciation as well as decreasing forest cover. The respective forest extents (from forest cover during control to forest cover in the scenarios) and glacier extents (from no glaciation to glaciation during control period) in per cent catchment area is given for every catchment (rightmost panel).

The forest change does not add a significant variance to the target variables \( R_{tot} \) and \( RC \) which confirms our findings from the descriptive analyses. The relative importance of glacier change for these two variables, in contrast, increases with glacier extent, which was also indicated by the previous results. As for \( ETA \), the climate scenarios account for the major part of the variance of \( R_{tot} \), too, and the contribution of glacier change is only distinct in summer during...
melt season. The catchment with the highest range of glaciation (catchment 8, lowest row in Fig. 24) shows a rather balanced variance fraction of around 30% during the whole year with a small peak during melt season. The relative importance of glacier change for the runoff coefficient $RC$ cannot be attributed to the altered direct runoff because we subtracted glacier melt from direct runoff to calculate $RC$ (cf. Sect. III-3.1). Glaciers and especially the snow on glaciers in PREVAH can store a certain amount of water, however. If the land cover glacier is converted to rock, this short-term storage is reduced and this in turn alters $RC$.

The interpretation of the soil moisture storage SSM is less straightforward. Not only does this target variable lack a clear pattern of glacier and forest change, but also is the interaction term quite large for two of the six catchments. One pattern that recurs in five of six catchments, though, is the significant peak of the climate scenario’s variance fraction in summer and the absence of the same during the rest of the year. This clear signal can be attributed to the pronounced temperature increase in summer and the associated depletion of SSM through evapotranspiration, but also to the decreasing summer precipitation and, therefore, a reduced input into the storage. An interesting feature can be observed comparing catchments 15 and 11: their relative forest cover does not vary substantially, but the composition of deciduous and coniferous forest does (cf. Fig. 18). For catchment 15, which has a higher proportion of coniferous forest, the variance fraction that is attributed to forest change is significantly higher, too. The same applies for these two catchments and their ANOVA results for $ETA$. Obviously, the different parameterizations of deciduous and coniferous forest effect the variance distribution. The seemingly wrong order of catchments 7, 12 and 9 with respect to the variance distribution for SSM cannot be explained.

The ANOVA results suggest that for catchments with a glaciation of 10% or more in the control period, glacier retreat contributes a considerable amount (40–90%) of variation to the hydrological projections in summer. Forest cover is always important as long the evapotranspiration is considered, and the variance fraction is proportional to the change in forested area. The variation of forest cover is negligible, however, with respect to total runoff or the monthly runoff coefficient.

### III-5 Discussion

We demonstrated a correlation between the degree of forested area and the variation in projected evapotranspiration. For extreme scenarios with forest increases on more than 35% of the catchment area, the net effect on $ETA$ caused by the forest change is larger than that caused by the climate scenarios, alone. Regarding total runoff or the monthly runoff coefficient, no effect of forest change was observed. These results are supported by previous studies (e.g., Fohrer et al., 2005; Hundecha and Bárdossy, 2004; Lahmer et al., 2001) who found only minor impacts of a changed land cover on hydrological systems. Those studies analysed catchments in similar mid-latitude climate regions, but only assessed land cover changes without examining climate change. Glacier retreat, in contrast to forest change, has a discernible influence on annual runoff and significantly alters the summer runoff even for catchments that are
moderately glaciated (10 %) during the control period. This is supported by a study from Cuo et al. (2009), who found that altered snow- and glacier-melt regimes dominate the hydrological response of a catchment to climate change. Climate change, in turn, proved to be the most important source of uncertainty in this study, by far, and dominates the changes in the target variables to a large extent. This result is supported by numerous studies, for example Arnell (2011), Jasper et al. (2004) and Kay et al. (2009) to name just a few.

In the following we discuss the validity of our results with respect to the forest scenarios. Our forest change scenarios represent a possible future forest extent under perfectly favourable growing conditions. The scenario tree lines in our study are therefore very likely too high, or, in other words, the increase in forest extent is too extreme. As Henne et al. (2011) argued it is unlikely that trees rapidly grow beyond historic tree lines, i.e. above 2550 m a.s.l., where soils are mostly undeveloped. Our maximum projected scenario tree line is at 2870 m a.s.l., though. Besides, several additional changes of environmental factors are expected to determine tree line, such as rising CO$_2$ concentrations, increasing deposition of nitrogen (Grace et al., 2002) and soil water availability (Henne et al., 2011). Moreover, we neglected natural hazards like avalanches or mudflows which actually play an important role for the distribution of forests in high alpine regions (Theurillat and Guisan 2001). These factors could be limiting rather than favourable for tree growth. Some authors (see e.g. Theurillat and Guisan, 2001) would furthermore anticipate an altitudinal shift of whole vegetation belts rather than an increase of the upper tree line, only. A shift, however, would lead to decreasing forest areas in the scenarios. For all those reasons, our forest change scenarios are extreme. Considering that, the runoff changes provoked by the forest scenarios are already at the maximum level but nevertheless insignificant.

One could argue, of course, that another hydrological model that is able to represent flexible feedbacks between the plant and the hydrology, i.e. a flexible growing season, for example, would yield different results regarding the impact of forest change. We showed, however, that the influence of forest change can be mainly attributed to its alteration of evapotranspiration. Evapotranspiration, on the other hand, is of minor importance in this region, which is the reason for the minor importance of forest change.

The successive structure of our scenarios (cf. Sect. III-2.3 and Table 6) should be critically discussed at this point, too. It is possible that the order of the scenarios (climate change – additional glacier change – additional forest changes) biases the results due to possible interactions of these different types of scenarios (cf. Sect. III-3.2). The ANOVA results, however, showed only very small interactions of the scenarios, almost without exception. Certainly, the glacier and forest scenarios depend on the climate scenarios, but their impact on the water balance components does not depend on each other. Therefore, we question the frequently proposed strong interactions of climate and land cover, at least for the studied climate region. Moreover, the small interaction terms thus indicate that the order in the successive setup does not affect the resulting projections.
III-6 Conclusion

There is a growing consensus that hydrological climate impact studies should integrate scenarios of associated land cover change to reliably assess future water availability. Bronstert (2004), for example, emphasized the necessity to apply coupled climate and land cover scenarios because of their strong interactions. Hejazi and Moglen (2008) concluded that these interactions “[…] can result in more significant hydrologic change than either driver alone”.

Therefore, we developed different scenarios of land cover change, i.e. changes in forest cover, that are based on the temperature increase of the climate scenarios used in this study. We applied those forest scenarios to extend an earlier climate impact study (Köplin et al., 2012a) that incorporated scenarios of glacier retreat, already. The relative influence of forest change on the hydrological projections was assessed and compared to the relative influence of glacier retreat and climate change. Through an ANOVA, the respective variance fractions of the three types of scenarios were analysed with respect to changes in actual evapotranspiration, soil moisture storage, total runoff and the runoff coefficient.

Our findings suggest that, at any rate, it is obligatory to apply an ensemble of climate scenarios because applying a single scenario could result in severely biased hydrological projections. If the runoff of a catchment with a significant glaciation (> 10 % in the control period) is analysed in the context of climate change, the accompanying glacier retreat has to be accounted for, too. If no such retreat scenario is available, the relative contribution of glacier melt to the total runoff has to be quantified, at least, for example by removing all glaciers from the catchment and evaluating the resulting changes in runoff. Thus, one can estimate the maximum error that is introduced to the projections by neglecting glacier retreat. The net impact of climate-induced changes in forest cover highly depends on the target variable considered. As long as total runoff or the runoff coefficient is concerned, the forest cover likely has a very minor impact on the projections and can be neglected. If the evapotranspiration or the soil moisture is of interest, the hydrological projections are altered significantly through forest change.

These findings, however, only apply to hydrological projections under mid-latitude, humid climate conditions and in a mountainous environment where precipitation exceeds evapotranspiration by far. Furthermore, they are only valid for the projections of mean flow conditions as analysed here. The net effect of land cover can be different if low or high flow conditions are concerned. This has to be kept in mind analyzing those variables while not accounting for land cover change.

An interesting extension of this study would be to apply the proposed setup but in another climate region, for example a more continental area or to assess the impact of the climate-induced land cover scenarios on the lower and higher quantiles of the projected hydrographs. This would complete the picture we established here.
The flood seasonality of catchments in Switzerland is likely to change under climate change due to alterations of precipitation as well as snow accumulation and melt. Information on the change is crucial for flood protection policies, for example, or regional flood frequency analysis. We analysed changes in the mean and maximum annual floods of 189 catchments in Switzerland for two scenario periods in the 21st century. The flood seasonality was analysed with directional statistics that allow assessing changes in the mean date a flood occurs as well as changes in the strength of the seasonality. We found that the change in flood seasonality is a function of the change in regime type. If snow accumulation and melt is important in a catchment during the control period, then the change in flood seasonality is most pronounced. Decreasing summer precipitation additionally affects the flood seasonality and leads to a decreasing seasonality in most cases. The magnitudes of mean annual floods and more clearly of maximum annual floods nevertheless increase in the future, due to changes in flood generating processes and scaled extreme precipitation. Southern alpine catchments show a different signal, though: the mean annual floods decrease in the far future, i.e. at the end of the 21st century.


Please note that this is the pre-peer reviewed version of an article submitted to Hydrological Processes in July 2012. For the final revised version consult the homepage of Hydrological Processes.
IV-1 Introduction

There is a general perception that the magnitude and frequency of floods will increase with climate change. Higher temperatures provoke higher water holding capacities of the atmosphere and therefore a higher probability of extreme precipitation events (Beniston, 2012; Boroneant et al., 2006). The increase in heavy precipitation results in an increased flood risk, consequently (Booij, 2005; Cunderlik and Simonovic, 2007; Pall et al., 2011; Tu et al., 2005). However, an increasing number of recent studies demonstrate that this relationship cannot be observed for measured discharge records of the 20th century where a substantial change in climate has already occurred (e.g. Hirsch and Ryberg, 2012). This is ascribed to the record length that is most often too short to allow for detection of trends in the time series, because extreme events are rare per definition (IPCC, 2012). Moreover, the strong natural variability of hydrological records additional hinders trend detection (Kundzewicz, 2012) because the change in a variable could have been also produced randomly by internal variability (Kundzewicz and Cramer 2012).

Although changes in climate extremes are likely (IPCC, 2012), their projections are highly uncertain, too (CH2011, 2011). Regarding precipitation, something that certainly changes, though, is the ratio of liquid to solid precipitation, which substantially alters the nature and processes of floods in a mountainous environment like Switzerland. The seasonal shift in precipitation (decrease in summer and increase in winter) is likely to alter the runoff behaviour and flood generation, additionally, so that the most obvious change in the distribution of floods will be a seasonal change (Blöschl et al., 2011; Sivapalan et al., 2005). Moreover, flood seasonality and its change is the key factor to understand the impact of climate change on floods (Blöschl et al., 2011).

The flood seasonality of a catchment can be interpreted as the likelihood of floods to occur during a certain period (Bayliss and Jones, 1993). This information is vitally important for water management, flood protection policy or regional flood frequency analysis, for example. In recent years, seasonality measures have increasingly been used to characterize flood generating processes or classify flood regions. Merz and Blöschl (2003), for example, used directional statistics to analyze flood process types in Austria at the regional scale. Parajka et al. (2010) used seasonality measures to study flood generating processes by comparing the seasonal statistics of extreme precipitation and floods across the Alpine-Carpathian range. Piock-Ellena et al. (2000) used seasonal analysis for regionalization of floods in Switzerland and Austria. Black and Werritty (1997) applied directional statistics to classify flood seasonality. Pfaundler and Wüthrich (2006) assessed the seasonality of Swiss catchments in general, and for case studies they tested different time periods in the 20th century for changes in seasonality. To our knowledge, so far no study used the seasonal analysis of floods in climate impact studies driven by state of the art climate scenarios.

We study the effect of climate change on the seasonality of floods in 189 mesoscale catchments in Switzerland that represent the range of different catchment types and hydrological processes (Köplin et al., 2012a). Earlier studies demonstrated the clear spatial pattern of flood
seasonality in Switzerland during control period conditions, i.e. the end of the 20th century (Pfaundler and Wüthrich, 2006; Piock-Ellena et al., 2000). How does this spatial pattern of flood seasonality change as a result of climate change? And can this change be attributed to changes in the flood generating processes?

We will analyse changes in flood magnitudes and examine the spatial distribution and variability of these changes to identify general tendencies and possible regional patterns that would indicate changes in the triggering processes. We will analyse the change in the type of floods, i.e. the spatially distributed seasonality of floods in Switzerland during control period conditions and for two scenario periods in the 21st century. For selected and representative case studies, the change in the causal processes is studied in more detail.

IV-2 Data and Methods

The hydrological model used in this study is the semi-distributed and conceptual, process-oriented model PREVAH (Precipitation-Runoff-EVApotranspiration-Hydrotope based model; Viviroli et al., 2009a). The calibration procedure applied here involves an iterative pairwise calibration of 12 tuneable model parameters (14 for glaciated catchments) that is evaluated with a linear and logarithmic Nash-Sutcliffe efficiency, a volumetric deviation measure as well as different peak flow sensitive scores (see Viviroli, 2007 and Viviroli et al., 2009b for a detailed documentation). This is to assure the good representation of both, the water balance as well as peak flows of a catchment, which was demonstrated in Köplin et al. (2010), Viviroli (2007) and Viviroli et al. (2009b).

The calibrated parameter sets were transferred to catchments without runoff data and those with discharge records that are influenced by hydropower production. We did this to assess the hydrological impact of climate change on a set of catchments that represents all different regime types and, therefore, runoff generation processes in Switzerland. Briefly speaking, the regionalization procedure is a combination of three different regionalization approaches and is described in Viviroli (2007) and Viviroli et al. (2009c), in detail. The regionalized parameter sets were extensively validated and evaluated for their use in assessing high flow conditions in the study domain (Köplin, 2012; Viviroli et al., 2007; 2009c; 2011). They proved good representation of peak flows as well as hydrological plausibility.

For 189 catchments (see Fig. 28 for their spatial location), model simulations in hourly resolution for the control period from 1984 to 2005 and two scenario periods (2025–2046, 2074–2095) were compiled. The required climate scenario data were provided by the CH2011 initiative (CH2011, 2011). Here, daily scenarios of ten different combinations of global climate models (GCMs) and regional climate models (RCMs) were used. The ten GCM-RCM model chains are post-processed through an extended delta change method (Bosshard et al., 2011) and are provided at 188 temperature and 565 precipitation stations. Due to the post-processing with the delta change method, the climate scenario data incorporate the wet- and dry-day frequency of the observations and represent the changes in the mean annual cycle of precipitation and
temperature. Future extreme precipitation is only as far considered as observed extremes are scaled. This is a limitation with respect to the analysis of floods, of course. We are well aware that we do not study the full possible range of changes in flood magnitudes. Therefore, we do not extrapolate the time series both because of the delta change scenarios and because of the rather short simulation period of 22 years. The annual distribution of precipitation as well as the proportion of liquid and solid precipitation is altered in the climate scenarios, though. We, therefore, assume that we analyse the underlying hydrological change signal, separated from changes in climate extremes.

Necessary scenarios of glacier retreat were provided within the project Climate Change and Hydrology in Switzerland (CCHydro; Volken, 2010; FOEN, 2012b) which this study is part of. They are based on an increase of the equilibrium line altitude (ELA) and a subsequent adaptation, i.e. retreat of the ablation zone (Paul et al., 2007). The increase in ELA is simulated according to the projected temperature increase of the climate scenarios (Linsbauer et al., 2012).

The analysis in this paper is based on annual maximum series (AMS). Frequently, a threshold value of 7 days between two peaks is applied to guarantee independence of two events (Maniak, 2005). The only possible situation where two peaks of an annual series are not independent is around the turn of the year, of course. We analysed the AMS and found that all 189 flood series are independent events. Deciding on the AMS to extract the high flows might lead to sampling of a peak that is not a flood, but the highest measured runoff of a particular year. Another frequently used sampling method, the peaks over threshold method (POT), would prevent sampling a discharge value that is no extreme value. For discharge series of > 20 years, however, AMS are preferred (Maniak, 2005) because they describe the high flow behaviour of a catchment evenly over time. Because the simulated discharge series in our study cover 22 years, we decided on the AMS to sample peak runoff. It has to be stated, though, that the peaks simulated represent the maximal hourly mean of a flood (as a result of the temporal modelling resolution) and not the highest measured peak value.

Three different high flow characteristic are derived from each AMS: the mean high flow (HQ\text{MEAN}), i.e. the mean value of all 22 peaks, the maximum or highest high flow of the series (HQ\text{MAX}) and the coefficient of variation (CV). This latter dimensionless ratio of standard deviation and HQ\text{MEAN} is used to compare the variation of peak flows in different catchments, particularly in catchments with varying size. To compare the discharge of differently sized catchments in another way, we compared their specific discharge rates (Hq\text{MEAN}, Hq\text{MAX}), defined as HQ\text{MEAN} or HQ\text{MAX} divided by catchment area. We evaluated the plausibility of simulated Hq\text{MEAN} and Hq\text{MAX} by comparing the simulated control period values to 54 catchments where natural discharge records in hourly resolution are available for the period 1984–2005. Those catchments cover roughly the same range of catchments sizes like the study catchments. Again, both the simulated and observed Hq values are based on hourly mean values.

Besides these measures that describe the quantitative aspects of floods, we studied the flood seasonality and its change. We calculated the seasonality following Bayliss and Jones (1993)
results and discussion

and Burn (1997): each annual peak $i$ of the AMS can be described with its day of occurrence given as Julian date and converted to an angular value in radians as

$$\theta_i = (\text{Julian date})_i \left(\frac{2\pi}{365}\right).$$  \hspace{1cm} (IV–1)

with Julian date 1 being January 1. The x- and y-coordinates of the mean date of flood, i.e. the centroid of all events (cf. Fig. 29) can be calculated as

$$\bar{x} = \frac{1}{n} \sum_{i=1}^{n} \cos \theta_i$$  \hspace{1cm} (IV–2a)

and

$$\bar{y} = \frac{1}{n} \sum_{i=1}^{n} \sin \theta_i.$$  \hspace{1cm} (IV–2b)

The mean date of the floods as an angular value, $\bar{\theta}$, is calculated as

$$\bar{\theta} = \tan^{-1} \left(\frac{\bar{y}}{\bar{x}}\right) \quad \text{for} \quad \bar{x} \geq 0$$  \hspace{1cm} (IV–3)

and

$$\bar{\theta} = \tan^{-1} \left(\frac{\bar{y}}{\bar{x}}\right) + \pi \quad \text{for} \quad \bar{x} < 0.$$  \hspace{1cm} (IV–4)

The angular value of the mean date of flood can be converted back to a Julian date $MDF$ (mean date of flood) as

$$MDF = \bar{\theta} \frac{365}{2\pi}$$  \hspace{1cm} (IV–5)

and the corresponding length of the seasonality vector $r$ is calculated as

$$r = \sqrt{\bar{x}^2 + \bar{y}^2}$$  \hspace{1cm} (IV–6)

with a value of 1 meaning all floods occur on the same date. We define $r$-values > 0.6 as a strong or clear seasonality, which means that there is a distinct season where most annual maxima occur. Smaller $r$-values indicate long or diverse flood seasons and thereby a weak seasonality, i.e. no concentration of annual maxima in a certain season. See the schematic in Fig. 29 for a visualization of $r$ and $MDF$. However, please notice that a small $r$ does not necessarily imply equally distributed floods throughout a year. This value could actually mask a bi- or multimodal distribution of floods. An extreme example would be: half of the floods occur on January 1, half of the floods on July 1, then the resulting $r$ would have a length of zero, but there is actually a strong bimodal flood seasonality. We analyze the changes in seasonality together with the causing processes, therefore (cf. Fig. 30), which will prevent misinterpretation of short seasonality vectors.

**IV-3 Results and Discussion**

We analysed the simulated $Hq_{\text{MEAN}}$ and $Hq_{\text{MAX}}$, first, to test the simulations for their physical plausibility (Fig. 25). We plotted the simulated values of the 189 study catchments
together with observed values of 54 similarly sized catchments: the simulated values for the control period are within the range of observed $H_{q_{\text{MEAN}}}$ and $H_{q_{\text{MAX}}}$. The specific discharges of catchments with an area less than 40 km$^2$ tend to be underestimated by the hydrological model, though. This effect was already observed in a study by Viviroli and Weingartner (2011), who assessed the use of the applied regionalization procedure for flood estimation in small to mesoscale catchments in Switzerland. They found that the model’s capability to adequately reproduce very fast runoff components that are important in small catchments is limited. Because only four catchments out of 189 in our study have an area of 40 km$^2$ or less, we assume that the model performance to simulate flood discharge is appropriate for our purpose. We also plotted the envelopes of instantaneous peak flows (Weingartner, 1999) to compare our results to these statistical relationships between catchment area and peak flow rate: if the simulated values are on or below the envelope, then the simulation is within the range of the observation. The two large catchments that lie above the northern envelope are no outliers: those are two catchments in the Ticino basin situated in the southern alpine region of Switzerland, where a different relationship between catchment size and $H_{q_{\text{MAX}}}$ is valid ("southern envelope", Fig. 25).

**Fig. 25.** Hourly means of specific discharge (left: $H_{q_{\text{MEAN}}}$, right: $H_{q_{\text{MAX}}}$) for 54 observed natural discharge records (OBS) and simulated control period discharge (CTRL). The dashed vertical lines indicate the catchment size below which the hydrological model performance in simulating high runoff is limited (< 40 km$^2$). The envelopes of instantaneous peaks for the northern and the southern alpine area are indicated for comparison (Weingartner, 1999).

We calculated the specific discharges for single GCM-RCMs (Fig. 26) to examine possible tendencies of the driving GCM to bias the projected mean (see Table 7 for an overview on the ten GCM-RCMs). For $H_{q_{\text{MEAN}}}$, no pattern regarding the driving GCM is observed; the spread due to single GCM-RCMs is negligible. For $H_{q_{\text{MAX}}}$, the highest values in the scenario result more often from model chains driven by the HadCM-GCM (red), but this pattern is not consistent for all catchments in the far future (bottom-right panel in Fig. 26). The climate model chains driven by this GCM project a strong increase in temperature throughout the year, i.e. both in winter and summer (CH 2011, 2011). This might lead to higher proportions of liquid precipitation, which, together with generally increased winter precipitation amounts, subsequently leads to increases in the $H_{q_{\text{MAX}}}$-values.
Table 7. Applied climate model chains from the ENSEMBLES project, post-processed and provided by the CH2011 initiative (CH2011, 2011).

<table>
<thead>
<tr>
<th>Institution</th>
<th>GCM</th>
<th>RCM</th>
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<tbody>
<tr>
<td>CNRM</td>
<td>ARPEGE</td>
<td>ALADIN</td>
</tr>
<tr>
<td>DMI</td>
<td>ECHAM5</td>
<td>HIRHAM</td>
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<tr>
<td>ETHZ</td>
<td>HadCM3Q0</td>
<td>CLM</td>
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<tr>
<td>HC</td>
<td>HadCM3Q0</td>
<td>HadRM3Q0</td>
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<tr>
<td>ICTP</td>
<td>ECHAM5</td>
<td>REGCM</td>
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<tr>
<td>KNMI</td>
<td>ECHAM5</td>
<td>RACMO</td>
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<td>MPI</td>
<td>ECHAM5</td>
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<td>SMHI</td>
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<td>SMHI</td>
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<tr>
<td>SMHI</td>
<td>HadCM3Q3</td>
<td>RCA</td>
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Fig. 26. GCM spread of $Hq_{\text{MEAN}}$ (left) and $Hq_{\text{MAX}}$ (right) for the near (top) and the far future (bottom). The one-to-one line is indicated for comparison.

A general pattern observed for $Hq_{\text{MAX}}$ is the large spread in projections due to single GCM-RCMs: in most catchments a range from slight decrease to strong increases of $Hq_{\text{MAX}}$ is projected. For $Hq_{\text{MAX}} > 1.5 \text{ m}^3/\text{s km}^2$ in the control period (x-axis), the GCM-RCMs reveal a clear pattern for the far future (bottom-right panel): the ARPEGE- and BCM-GCMs project...
slightly decreasing $Hq_{\text{MAX}}$ values, whereas the ECHAM-GCMs produce slightly increasing values and the HadCMs result in the strongest increase in $Hq_{\text{MAX}}$. This large spread from decrease to strong increase can be interpreted as a larger uncertainty in the projections for the far future period.

To visualize the change in specific discharge more clearly, we displayed the respective specific $Hq$ values of the catchments in boxplots and independently from catchment area (Fig. 27). The spread in projected specific discharge is larger for the far future period. The notches at the boxes can be used to compare the medians of two boxes: if the notches do not overlap (indicated for $Hq_{\text{MAX}}$, Fig. 27), the medians of the two samples differ significantly with an estimated 95% confidence interval (Chambers et al., 1983). All medians in Fig. 27 differ significantly, particularly those of specific $Hq_{\text{MAX}}$. Technically speaking, however, this assumption only holds for roughly equal sample sizes, which is not true for comparisons between the control and the scenario periods (the scenario samples have ten times the size of the control sample due to the ten GCM-RCMs). Still, the obvious differences between the medians indicate an increase of $Hq_{\text{MEAN}}$ and more pronounced of $Hq_{\text{MAX}}$ due to scaled extreme precipitation. Additionally, a change in the triggering processes might be observed here, for example an increase of rain-on-snow floods. This assumption will be addressed later in this section.

![Fig. 27. Boxplots of specific discharges (left: $Hq_{\text{MEAN}}$, right: $Hq_{\text{MAX}}$) of all 189 catchments for the control period (CTRL), the near future (SCE1) and far future period (SCE2).](image)

The spatial patterns of changes in absolute $HQ_{\text{MEAN}}$ and $CV$, given as ratios of scenario ensemble mean to control period (Fig. 28), explain the observed increase in specific $Hq_{\text{MEAN}}$. The absolute $HQ_{\text{MEAN}}$ increases uniformly but rather slightly (between 5 and 24%) in the near future period. This is a robust signal because in most catchments 9~10 (out of 10) GCM-RCMs agree in the sign of the change, with the exception of catchments in the central south (Ticino catchment) and the northeast (Thur catchment). In the far future, a strong increase


(25–49 % and higher in some catchments) in $\text{HQ}_{\text{MEAN}}$ is projected for the high alpine area and the western Prealps. Again, 9–10 GCM-RCMs agree in the sign of the change. A possible reason might be the increased proportion of liquid precipitation in these areas in the future. For the Ticino and the upstream part of the Thur catchment no change in the far future $\text{HQ}_{\text{MEAN}}$ is observed relative to the control period. The coefficient of variation as a measure of flood variability shows no obvious spatial pattern for the near future period: the change ranges from -25 % to an increase of > 50 %. The picture is somewhat clearer in the far future period. Catchments situated in the Jura mountain ranges (north-western Switzerland) show decreasing CVs. This might be ascribed to an increasing seasonality in those catchments, which will be explained in the following paragraph. Most catchments at higher elevations show robust and sharp gradients from control to scenario in the far future.

In the following the results for the flood seasonality are described. The flood seasonality of the study catchments, depicted by seasonality vectors in Fig. 29, shows a distinct spatial pattern for the control as well as the scenario periods. We subdivided the seasonality vector maps into five seasonality regions that correspond to the dominant hydrological regimes of the control period (Weingartner and Aschwanden, 1992) and that are summarized in the following. Interestingly, the spatial structure and grouping of the seasonality vectors does not change from the control to either one of the scenario periods, except for the pluvial zone that would actually stretch farther south in the western part in the far future (lower-right panel in Fig. 29). The
reason therefor is that flood seasonality is directly related to the hydrological regime (Pfaundler and Wüthrich, 2006). Changes in the regime due to climate change are translated to changes in flood seasonality, which are then similar for the different regime types.

Pluvial catchments in the north-western part of Switzerland have a pronounced winter to early spring flood seasonality, which marginally changes to earlier winter in the near and far future period and this with a stronger seasonality. Nivo-pluvial catchments, which are characterized by a mixture of snowmelt- and rain-fed runoff processes, have a less marked seasonality in the control period with a tendency towards summer floods. Their weak seasonality decreases further in the near future period and increases in the far future. In that scenario period, however, the catchments exhibit a tendency towards winter floods, which indicates a change in flood generating processes for nivo-pluvial catchments. The regime of nival alpine catchments is strongly determined through snow-melt processes and those catchments therefore show a clearer seasonality in the control period. This clear seasonality decreases successively from control to the near and far future period and changes from mid over late summer to early autumn floods in the far future. For glaciated catchments, the floods in the control period are in late summer and seasonality is strong in general, although it successively decreases here, too. The timing of floods does not change significantly, though. The last regime type, which is typical for the southern part of Switzerland, is characterized by early autumn floods with a very clear seasonality. In this region the seasonality hardly changes in the scenario periods, neither with respect to strength nor timing.

The results of the seasonal analysis for control period conditions reflect the results of Diezig and Kan (2010) for approximately 70 catchments with discharge measurement in the period 1971–2007. The subdivision into five main regions are in good agreement with the results from Pioc-Ellena et al. (2000), who analysed an extensive set of 793 discharge records in Switzerland and Austria and sought homogenous regions for the regionalisation of floods. Their classification of the Swiss part of the study region matches with our subdivision of catchments into the main regime types indicated in Fig. 29. The general pattern was also described by Pfaundler and Wüthrich (2006). The hydrological regime is basically a function of elevation. Therefore, our differentiation of flood seasonality and seasonality change is determined by elevation, to a large part. Parajka et al. (2009) came to the same conclusion, namely that “[…] altitude is one of the key factors that control the temporal stability and spatial variability of hydrological regime and flood seasonality […]” in a mountainous environment. Decreasing seasonality was also observed in a climate sensitivity study in the northern alpine Kander catchment (Wehren, 2010), which has a glaciation of 5.6 % in the control period. There, a clearly decreasing seasonality was simulated for increasing temperatures and more or less independently from the assumed precipitation changes, i.e. for both, increasing or decreasing precipitation. This sensitivity study suggests that the change in the strength of the seasonality in catchments where melt processes are important depends strongly on the temperature signal.

These results in changes of seasonality mirror a change in regime type, as mentioned earlier. Recent studies on hydrological impacts of climate change in Switzerland demonstrated a shift of the regime types to higher elevations in the future, e.g. snow-fed regime types will be
found at higher elevations in the future than today (e.g. FOEN, 2012b; Horton et al., 2006; Köplin et al., 2012a; Schädler and Weingartner, 2010). The shift of the hydrological regime implies a change in the dominant runoff generating processes, i.e. an increasing proportion of liquid precipitation leads to increased direct runoff, for example. The same applies to shifts in flood seasonality: the causing processes are altered through climate change which will be explained in the following with the example of five case study catchments that represent the range of regime types.

Fig. 29. Seasonality vectors for control (CTRL, top-right), near future (SCE\textsubscript{near}, middle-right) and far future period (SCE\textsubscript{far}, bottom-right). A vector’s origin is at the outlet of a catchment. In the top-left corner, a generalized visualization of the five main regime regions (Weingartner and Aschwanden, 1992) during the control period is depicted. The regime regions are indicated in the seasonality vector maps on the right side, too, to ease orientation and comparison. Below the regime overview on the left side, the scale for $r$ is given: a value of 1 means all floods occur on the same date, whereas small values indicate high seasonal variability. Below the scale, the schematic visualizes how to build and read a seasonality vector: the vector points to the average date of annual maxima ($\times$, centroid of all maxima) given in radians and starting at 0 rad in January moving clockwise. In the bottom-left corner the direction of seasonality vectors are summarized and grouped to the four seasons.
Fig. 30. Detailed analysis of five case study catchments; for their spatial locations see Fig. 28, the names of the main rivers are given in Table 8. On the left side of each row, the seasonality vectors for the control (solid line), the near future (dashed line) and the far future period (dotted line) are shown on polar plots. The seasonality vectors of the scenarios represent the ensemble mean. The grey-shaded sectors depict the range of ±1 standard deviation around the ensemble mean for SCE1 and SCE2 (see catchment 2 for the legend). The boxplots in the middle part of each row show event-based proportions of the input variables liquid precipitation (p_liquid) and snow and ice melt (accumulated to total melt), as well as event-based soil moisture deficits (ssm_deficit). Please note the different scales of the panels. To the right of the boxplots, the change in HQ_MEAN is shown for control (CTRL) and scenario ensemble mean values (SCE1 EM, SCE2 EM). At the right side of each row, the annual cycle of monthly precipitation for the control and the scenario ensemble means are visualized.
Although the change in flood seasonality and its causal processes is specific for every catchment, certain relationships are observed for greater regions as stated before. Each of the case study catchments (Fig. 30) represents one regime type with its associated changes in flood seasonality. The complex Fig. 30 will be described row by row in the following. For the pluvial catchment 1 (see Table 8 for additional information), the event-based amount of precipitation increases from the control to the scenario periods. Event-based is defined as the daily liquid precipitation, daily melt amounts or mean daily soil-moisture deficit, respectively, that were simulated on the dates the annual floods occurred. We analysed the three- and five-day sums, too (not shown here), and found that three-day sums explain the flood discharge better in some larger catchments. For the presented mesoscale case study catchments the one-day values were more meaningful, though.

The increase in event-based liquid precipitation in catchment 1 causes an increase of the winter seasonality; melt processes are only involved in some floods (outliers outside the whiskers) in this catchment. The median of soil moisture deficit is lower in the scenario periods, which indicates wetter conditions in the future before a flood occurs. The annual cycles of precipitation show increases in autumn and winter precipitation, which is why the winter flood season is intensified (larger $r$) and the $HQ_{\text{MEAN}}$ values increase. Compared to the other catchments, these absolute $HQ_{\text{MEAN}}$ values are very low in this small catchment (Table 8).

The nivo-pluvial catchment 2 shows no clear change in the event-based inputs for the near future period. Snow melt has an influence on events, here, but on a rather low level. The rain-fed summer floods in the control period are substituted by rain-fed winter floods in the far future which can be derived from the polar plot on the left side but also from the annual cycle of precipitation to the right: winter precipitation in the far future is higher than the decreased summer precipitation in this period. This change in the season might be a reason for the lower soil moisture deficit during an event, because the soil moisture cannot be significantly depleted through evaporation in winter. The variation in flood season due to single GCM-RCMs is high, however, depicted by the high standard deviation for both scenario periods. The projected increase in $HQ_{\text{MEAN}}$ is therefore not a very strong signal.

The range of ±1 standard deviation in catchment 3, the nival alpine example, is the largest of all observed catchments, indicating a rather unstable state of the hydrological regime and the associated dominant processes at the end of the 21st century. The precipitation regime is more balanced in the future, which is one reason for the unspecific seasonality in that period. Liquid precipitation increases in the far future period as well as event-based melt rates. This can be interpreted as an increase of rain-on-snow flood events, which should not be confused, however, with winter seasonality. It is more a diversification of flood types which is also indicated by the high standard deviation range.

The glacial catchment 4 shows increases in event-based liquid precipitation, whereas the melt component clearly decreases. The precipitation regime does not change significantly except for a clear decrease of the far future summer precipitation. The formerly pronounced summer seasonality decreases in the future, therefore. $HQ_{\text{MEAN}}$, however, increases clearly, which is explained by higher event-based precipitation amounts of the diversified floods.
The last case study, the southern alpine catchment 5, first shows a slight increase in event-based precipitation in the near future which then decreases below the control period level in the far future. This can be ascribed to the small increase of autumn precipitation in the near future and a subsequent clear decrease of spring to autumn precipitation in the far future. Because the catchments in the southern alpine region are characterized by a strong seasonality of late summer to autumn floods, this case study is the only one where a decrease of \( \text{HQ}_{\text{MEAN}} \) is projected for the far future. In the near future, however, \( \text{HQ}_{\text{MEAN}} \) increases. The results for all five case studies are summarized in Table 8.

### Table 8. Summary of catchment properties and changes in seasonality for the five case study catchments (cf. Fig. 30). A shift of the season in the scenario period to an earlier (←) or later date (→) is only indicated if the shift is more than a month. The up- and downward arrows (↑, ↓) symbolize an increase or decrease in \( r \), i.e. a change in the strength of the seasonality. The change of \( \text{HQ}_{\text{MEAN}} \) is summarized by up- and downward arrows, too.

<table>
<thead>
<tr>
<th>Name</th>
<th>Regime</th>
<th>Area [km²]</th>
<th>Mean altitude [m a.s.l.]</th>
<th>Month</th>
<th>( r ) for CTRL</th>
<th>Seasonal change SCE1</th>
<th>Seasonal change SCE2</th>
<th>( \text{HQ}_{\text{MEAN}} ) SCE1</th>
<th>( \text{HQ}_{\text{MEAN}} ) SCE2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Urtenen</td>
<td>pluvial</td>
<td>90</td>
<td>550</td>
<td>Jan</td>
<td>0.6</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
</tr>
<tr>
<td>2 Kleine Emme</td>
<td>nivo-pluvial</td>
<td>480</td>
<td>1060</td>
<td>Jul</td>
<td>0.3</td>
<td>→ ↓</td>
<td>→ ↓</td>
<td>↑</td>
<td>↑</td>
</tr>
<tr>
<td>3 Muota</td>
<td>nival alpine</td>
<td>220</td>
<td>1600</td>
<td>Jul</td>
<td>0.6</td>
<td>→ ↓</td>
<td>→ ↓</td>
<td>↑</td>
<td>↑</td>
</tr>
<tr>
<td>4 Chaers- telenb.</td>
<td>glacial</td>
<td>120</td>
<td>2190</td>
<td>Jul</td>
<td>0.8</td>
<td>↓</td>
<td>↓</td>
<td>↑</td>
<td>↑</td>
</tr>
<tr>
<td>5 Moesa</td>
<td>southern alpine</td>
<td>470</td>
<td>1660</td>
<td>Aug</td>
<td>0.7</td>
<td>↓</td>
<td>↓</td>
<td>↑</td>
<td>↓</td>
</tr>
</tbody>
</table>

### IV-4 Conclusions and outlook

We showed an analysis of projected changes in the spatial and seasonal distribution of floods in Switzerland. An extensive set of 189 study catchments that reflect the different hydrological regime types of a mountainous environment was calibrated and regionalized with emphasis on high flows and run for the control (1984–2005) and two scenario periods (2025–2046, 2074–2095). The whole set of study catchments was subdivided into five regions representing the main regime types pluvial, nivo-pluvial, nival alpine, glacial and southern alpine. Per region, one case study catchment was analysed in detail.

The specific \( \text{HQ}_{\text{MEAN}} \) and \( \text{HQ}_{\text{MAX}} \) discharge of the study catchments increases substantially from the control to both scenario periods, being more pronounced for the far future period. Considering that only changes in the mean annual cycle of temperature and precipitation are assessed and not changes in the frequency or intensity, this increase in \( \text{HQ}_{\text{MEAN}} \) and \( \text{HQ}_{\text{MAX}} \) might seem surprising, at first. The picture gets clearer by integrating a spatial component into the analysis: the clear increase in \( \text{HQ}_{\text{MEAN}} \) in the far future is mostly observed for the alpine
catchments that experience a strong shift from previously snow-melt dominated runoff processes to a more variable snow and rain fed regime type. The spatially distributed analysis of flood seasonality confirms this observation. To summarize the results for the flood seasonality (see also Table 8): the seasonality of pluvial catchments was strong in the control and gets stronger in the future because the dominant flood generating process – winter liquid precipitation – will be more pronounced in the future. Snow- and rain-fed (nivo-pluvial) catchments had a weak seasonality in the control that gets stronger in the future due to a shift to a solely pluvial regime. Therefore, the flood season of those catchments changes from summer to winter floods. Nival alpine catchments had a clear seasonality in the control that gets weaker as they change to both snow- and rain-fed catchments. They seem to be in an unstable state in the far future period indicated by the highest standard deviation of all catchments. The summer flood season of glacial catchments is not changed but the seasonality gets weaker because the summer precipitation – the dominant process during the control period – decreases in the future. Southern alpine catchments do not change markedly with respect to the seasonality but their HQ\text{MEAN} slightly decreases as a result of decreasing event-based precipitation amounts.

Our results of flood seasonality in the control period are in line with other studies in this study domain (Diezig and Kan, 2010; Pfaundler and Wüthrich, 2006; Piock-Ellena et al., 2000). The analysis was based on annual maximum series (AMS) as the only method to extract high flows from the simulated records. Some studies (e.g. Cunderlik et al., 2004) suggest, however, a peaks-over-threshold series (POT) might depict a clearer seasonality than the AMS. Although these findings are rather valid for shorter lengths of the discharge records, there might be an effect of the sampling method. Therefore, a possible extension of the analysis in this study would be to sample the high flow record with the POT, too, and compare the resulting seasonality plots with the ones based on AMS. Little differences between the seasonality resulting from the two sampling methods would substantiate the previous conclusions because the flood seasonality would be captured similarly by different sampling methods.

Weingartner et al. (2003) defined a threshold elevation of 2000 m a.s.l. above which flood risk is reduced due to short-term storage of precipitation as snow cover. Wehren et al. (2010) defined this threshold even a bit lower at 1800 m a.s.l. Our results suggest that the upper limit of the vulnerable zone that starts above 1000 m a.s.l. (Wehren et al., 2010; Weingartner et al., 2003) might rise substantially in the near and particularly in the far future, increasing the potential for more frequent, i.e. less seasonal stationary floods in the concerned areas.

It should be stated, again, that we studied the underlying or basic changes in high flow conditions due to the delta change scenarios that incorporate the precipitation frequency and intensity of the observations. Our results showed, however, that changes in the considered variables are already substantial. This can be attributed to the strong effect of temperature on the projected floods, because increasing temperature alters the ratio of liquid to solid precipitation and thereby the snow line altitude (Blöschl and Montanari, 2010). This is why changes in the seasonality of catchments that are associated with changes in snow line are considered clear signals (Blöschl et al., 2011). The next step would be to additionally assess the impact of frequency and intensity changes through different post-processing methods of the climate
scenario data, for example. This would allow estimating the relative contribution of both the changes in the mean annual cycle of the climate variables as well as the changes in their distributions.
In this section, the main findings from parts II to IV are revisited and put in another perspective. A general pattern was observed in all research papers regardless of the particular focus: the projected changes for the near future were rather indeterminate, and for the far future a clear hydrological change was observed. This pattern can be attributed to the same pattern in the climate change signals. What has not been covered so far is the relative importance of natural variability for the control and scenario periods’ simulations. Therefore, case studies of parts II to IV are revisited and their natural variability is assessed to shed a different light on the results. After that, the research questions are addressed and final conclusions are drawn.
1 Climate change sensitive catchments

In part II, the climate sensitivity of the study catchments was assessed and five sensitive regions were identified, each showing a specific annual cycle of hydrological change for the cluster mean. Catchments in north-western Switzerland showed a less clear response to climate change as opposed to snow- and ice-fed catchments, which were most sensitive. The identified five regions are represented by one case study each (Fig. 32) in this section. They were chosen due the small deviances of their runoff change signals from the respective cluster mean (C2–C6, Fig. 31, right side).

Fig. 31. Overview of case study catchments shown in the synthesis section. The good agreement of the case study catchments’ annual cycles of Delta $Q$ ($Q_{SCE}/Q_{CTRL}$) and the respective cluster mean is indicated for the catchments representing part II (sensitivity) of the thesis.

The spread of the control and scenario periods (Fig. 32) is an estimate of the year-to-year variability, i.e. it is the variation of monthly values given as interquartile range. The scenario envelopes include, however, also the variability in the data caused by the GCM-RCMs, meaning that not the spread of the ensemble mean is depicted but the spread of monthly runoff of all ten model chains. For the near future, the summer medians are projected to the lower boundary of the control period spread for all catchments except for the high alpine Lonza catchment. In this catchment, an increased spring runoff due to earlier snowmelt is projected. A tendency for increased winter runoff is projected for all catchments in the near future. In general, the spread of the control and near future periods’ monthly runoff is approximately similar. The minor changes of runoff in the near future found in part II are confirmed considering the year-to-year variability of the projections. Moreover, even if a slight change was observed, e.g. the decreasing summer runoff, the results in Fig. 32 demonstrate that the spread of monthly runoffs in the control and near future period does not differ substantially.
Fig. 32. Spread of monthly simulated control period runoff (bluish shading) and spread of monthly simulated runoff (purple shading) for the near (left) and far future period (right). The grey and purple lines show the control and scenario period medians, respectively. The spread depicts the interquartile range, i.e. the range from 25–75 %-quartil. The main river of a catchment is given at the upper-right corner of each panel as well as its area, mean altitude and corresponding cluster (C2 to C6, cf. Fig. 10, p. 31).
More interesting, of course, is the question if the clear signals for the far future found in part II also prove to be robust signals. A robust signal is assumed if the whole range of control and scenario period differs. In this case, the runoff behaviour changes substantially up to changes of the regime type. But also less strong yet clear signals can be determined: the projected median runoff of the Alp catchment, for example, is at the lower boundary of the control period in spring and summer and at the upper limit in winter. That is, monthly runoffs that were at the edges of the distribution during control period are most common in the far future. The spread of monthly summer runoff is below the control period spread for all other catchments, indicating a strong decrease. In winter the runoff is projected to increase either for the whole spread or for the median depending on the mean elevation of a catchment and the associated proportion of snow accumulation and snow melt. For the high-elevated Lonza and partly for the Medelser Rhine this increase extents to spring (Medelser Rhine) and also early summer (Lonza). The spread of monthly winter runoff increases in general in the far future due to more variable precipitation being a mixture of snow and rain. To conclude, the results presented in the research article in part II of the thesis (clear signals for the far future) are robust results, and natural variability does not confound them.

2 Additional impact of glaciers and forests

It is frequently posed that climate-induced changes in land cover might have an additional effect on the projected runoff changes. Only few impact studies account for these effects, though. We assessed those changes in runoff that can be attributed to glacier retreat and forest cover increase in addition to the projected changes in climate. We did this by applying different glacier and forest scenarios in part III of the thesis. The projected glacier effect was considered substantial regarding summer runoff. An increased forest extent, even though extreme, did not alter the projected runoff substantially in most cases. This could be ascribed to the forest affecting evapotranspiration mostly and therefore only indirectly affecting the projected runoff because evapotranspiration is of subordinate importance in the studied high alpine case studies.

The two case study catchments that were studied in detail in part III are analysed again, but with additionally accounting for the year-to-year variability as in the previous section. Here, only the far future is assessed and from the three different forest scenarios (cf. Sect. III-2.3) only the most extreme scenario (FC$_3$) is displayed. The results are confirmed for this analysis, too: the forest scenario does not alter the runoff in the high elevated Aare catchment (Fig. 33, right), i.e. the interquartile ranges and medians of GC (glacier change) and FC (forest change) do not discernibly differ. This can be attributed to the comparatively small increase in forest area and to the minor importance of evapotranspiration as a water balance component in this catchment. The envelopes of climate change (CC) and FC in the moderately elevated catchment (Fig. 33, left) show the same picture as observed in the paper: the monthly runoff is lowered by the forest increase throughout the year. In summer, the median monthly runoff for FC is at the 25 %-quartile of projected monthly runoff with climate change alone. That is, an influence of the forest cover can be observed for this extreme scenario. It should be stated, though, that such
an extreme forest increase on 54% of the catchment area, although theoretically possible, is most probably not realistic, especially with respect to the rather short time horizon.

**Fig. 33.** Spread of simulated control period runoff (CTRL), projected runoff for climate change signals only (CC), for additional glacier change (GC; the Jogne catchment is not glaciated) and additional forest change (FC). The forest and glacier extent is given in percent catchment area for the control period (F_{CTRL}, G_{CTRL}) and for the scenarios (FC, GC). Note that only the far future is displayed. The envelopes depict the interquartile range, i.e. the range from 25–75%-quartil. The main river of a catchment is given above of each panel as well as its area and mean altitude.

### 3 Future flood seasonality

We studied the future flood seasonality of all 189 study catchments because the seasonality will change most certainly with climate change (Blöschl et al., 2011; Sivapalan et al., 2005). We found that the flood seasonality changes with the change of a catchment’s regime type. For example, formerly snow-fed catchments with summer seasonality will be pluvial catchments with clear winter flood seasonality in the far future. High-elevated catchments will have the same summer seasonality as in the control period but it is less strong, meaning that the flood season is extended. Mean high flows (HQ{\text{MEAN}}) will increase in general and most pronounced in the alpine areas, with the exception of southern alpine catchments, where HQ{\text{MEAN}} decreases in the far future period. These exemplary results of the analysis in part IV refer to the projections for the ensemble mean. The spread that is caused by GCM-RCMs is evaluated in more detail in this section (Fig. 34); the cases A to K will be discussed in detail in the following.

Although the seasonality is quite clear in winter for the pluvial catchment (Urtenen, Fig. 34, A) and the spread due to individual GCM-RCMs is small (B), annual maximum floods (AMFs) are possible to occur in ten out of twelve months (C_{1}). The spread of the AMFs’ magnitudes is large (C_{2}), whereas the absolute flood discharges are small (HQ{\text{MEAN}} < 15 m^3/s, cf. Fig. 30) in this small catchment, which depicts the typical high variability of runoff in small-scale catchments. The nivo-pluvial catchment (Kleine Emme) shows a very weak seasonality for the near future period (D), which is the result of disagreeing GCM-RCMs (E) rather than equally distributed AMFs throughout the year, i.e. some GCM-RCMs project a summer and some a late autumn seasonality. For the whole ensemble, the AMFs are evenly distributed (F).
Fig. 34. Extended seasonality analysis in the five case study catchments of part IV (cf. Fig. 31). The left and middle columns show seasonality vectors for the ensemble mean (left) and single GCM-RCMs (right). Solid lines: control, dashed lines: near future, dotted lines: far future. The colour indicates the driving GCM. The right column is a similar visualization but for all annual maximum floods (AMFs) of the control (black filled circles), the near future (coloured circles) and the far future (coloured asterisks). The AMFs are normalized to the $HQ_{MEAN}$ of the control period; values $> 1$ indicate higher floods than the $HQ_{MEAN}$, values $< 1$ depict lower floods.
The higher elevated nival alpine catchment (Muota) keeps its late summer seasonality in the near future period and does not have a pronounced seasonality in the far future but a tendency to winter floods. Here, the same pattern of disagreement among the GCM-RCMs as for the Kleine Emme catchment is observed (G). Obviously, the transition from a clearly snow- to a more rain-dominated catchment is very sensitive to the climate change signal, i.e. the projected temperature change. Despite the comparatively small spread due to the climate models in a glaciated catchment (H, Chaerstelenbach) and the pronounced summer seasonality, rather high annual floods can occur in autumn, too (I). These projected high autumn floods might explain the stronger increase in HQ\textsubscript{MEAN} in the alpine area. The GCM-RCM spread for the southern alpine catchments (Moesa) is small, too (J). In contrast to the glacial catchment, however, the AMFs vary around the HQ\textsubscript{MEAN} (K), here. To conclude, the analysis of individual GCM-RCMs adds important information for the interpretation of the more generalized seasonality plots.

4 Research questions

After revisiting the most important results from the three research articles in parts II to IV and after examining their reliability, the research questions stated in the introduction are answered in detail in this section.

*Are there catchments that are particularly sensitive to changes in climate, and what are the dominant processes that cause a sensitive response?*

The hydrological response is specific for every catchment, but also regional similarities were observed. The elevation of a catchment, and therefore the temperature, determines hydrological change to a large extent in the majority of catchments. Catchments exhibit a particularly strong hydrological change if snow accumulation and snow and glacier melt processes are important in the control period. Or put another way: If the winter temperature is < 0 °C in the control but > 0 °C in the climate scenario, then the resulting effect on the hydrology is most pronounced. Precipitation change is the most important driver of hydrological change in catchments at lower elevations (below 1000 m a.s.l.). In those catchments a change in runoff is perceptible in the far future but the magnitude of the change, both absolute and relative, does not compare to the substantial changes in catchments at higher elevations that even provoke a change in regime type. Although the pattern of relative runoff change – increase in winter and decrease in summer – is observed for all study catchments, this relative change can amplify the original regime in one catchment and balance it in another. Hydrological changes that depend on temperature are robust signals because of the clear temperature signal. Where precipitation determines hydrological change to a large extent it is less certain. The detected hydrological change signals are even robust when additionally considering natural variability, and they are characteristic for mountainous environments. In mid-latitude, humid lowland areas, the temperature signal is likely to be of less significance and precipitation change might gain in importance for hydrological change.
Does a climate induced change in land cover, i.e. changes in forest and glacier extent, impact on the hydrology additionally, and how does this change compare to the hydrological change caused by the climate signal alone?

The glacier retreat has a pronounced effect on projected summer runoff if a catchment is > 10% glaciated during control period conditions. In this case glacier retreat has to be incorporated in the hydrological projections. Otherwise, the projected summer runoff would be substantially overestimated. In any case, one should account for glacier retreat in hydrological climate impact studies, though, because the relationship of increasing temperature and decreasing glacier extent is obvious and extensively documented. This is different for changes in the forest cover. Although the general relationship between increasing temperatures and increases in tree line altitude are proved for many regions in the Swiss Alps, it is much more uncertain, that forest grows extensively and rapidly with climate change, mostly because of land management. Still, we assessed different degrees of forest increase to study its impact on the hydrology, hypothetically. The effect of forest increase on the projected runoff is small compared to the absolute change due to the climate signal alone and especially when considering that the tested forest scenarios are extreme. Forest increase, however, can substantially alter the projected evapotranspiration: if forest increases on more than 35% of the catchment area, than its impact on evapotranspiration is more important than the climate signal. The climate change signal itself is most important for the hydrological projections, it determines the annual cycle of the runoff change signal. The land cover has an additional effect which is pronounced for glaciers (in moderately to strong glaciated catchments) and small to negligible for changes in forest extent. The results should, however, not be confused with the analysis of feedbacks between land cover and climate; we just analysed the one way impact of land cover on the hydrology in a mid-latitude, humid mountainous environment. The results of these top-down impacts still hold, if the natural variability is considered, additionally.

Does the flood runoff of catchments, and in particular their flood seasonality change due to changes in the mean annual cycle of precipitation and temperature?

The delta change method does not account for changes in the frequency and intensity of the climate variables and incorporates only the wet- and dry-day-frequency of the observations. Something that changes with delta change scenarios is the ratio of liquid to solid precipitation, and extreme precipitation is altered, too, because the observed extremes are scaled. The changes in flood magnitudes and flood seasonality that were detected are therefore still obvious, despite of the unchanged frequency and intensity. The mean and maximum annual flood values increase in both scenario periods, but more strongly in the far future. It has to be clearly stated, though, that this applies not to projections of the most extreme floods, because of the time series length (22 years) and because we applied only changes in the mean annual cycle of the climate variables. The flood seasonality of catchment with a snow-dominated regime type changes clearly because causal processes change with the changing regime. Most important is a change in short-term storage of precipitation as snow cover: in a warmer future, the precipitation is more often directly converted into runoff in autumn, winter and spring. Altitude, as a proxy for
temperature, is therefore a good indicator of the degree of change in high flows, too, as it was found for the climate sensitivity. Catchments with a distinct change from a snow to a more rain dominated runoff regime have the potential for more frequent, i.e. less seasonally stationary floods. To qualify these results it should be said, though, that the temperature increase projected by a single GCM-RCM is crucial for the projected change in flood seasonality. This strong dependence on the GCM-RCM can be interpreted as a high uncertainty. This statement is mostly valid for the far future because the climate models differ stronger there.

5 General conclusions and outlook

The changes in the mean annual cycles of precipitation and temperature induce pronounced and manifold changes in Switzerland’s hydrological systems which was demonstrated in this study. The dominant processes that proved to determine runoff change in Switzerland to a large extent are processes that involve the accumulation and ablation of snow. In snow-fed catchments the melt season starts earlier, which decreases summer runoff and subsequently leads to a shift of the annual maximum to an earlier time of the year. Winter runoff increases due to more liquid than solid precipitation. The temperature, therefore, has a strong impact on the projected runoff. These results were found in a number of other climate change impact studies in Switzerland, too, e.g. in Farinotti et al. (2011), Finger et al. (2012), Hänggi (2011), Horton et al. (2006) or Jasper et al. (2004), and they are not new: Bultot et al. (1994) found the same change pattern in general almost 20 years ago, although their climate scenarios were not as highly resolved as the scenarios applied here and in other recent studies.

In general, the stated change pattern applies to all types of snow-fed regimes, i.e. to nivo-pluvial as well as to nival, nival-alpine and glacio-nival catchments (Weingartner and Aschwanden, 1992). The strength of the snow signal, however, depends on the relative importance of snow in the control period. The results show that the snow line and thereby the altitude of a catchment is a strong indicator of hydrological change in a mountainous environment (Birsan et al., 2005). This change from snow- (and ice-)fed to more rain dominated regimes was already observed for the 20th century (Birsan et al., 2005; Schädler and Weingartner, 2010) and is projected to continue in the future and to affect more and higher elevated catchments in the 21st century. The precipitation change – increase in winter and decrease in summer – contributes additionally and alters the projected runoff in the same direction as the snow signal does. This is why snow-fed catchments show the most pronounced changes in runoff, in general. The higher or lower a catchment, the less important is the snow signal. Catchments at lower elevations are not characterized through snow accumulation and melt in the control period, which is the reason why precipitation change determines runoff change there (Horton et al., 2006). Catchments at very high elevations are still situated above the future snow line and the control periods’ regime is therefore altered only slightly (Nijssen et al., 2001): the regime of high alpine catchments will still be characterized through the seasonal redistribution, i.e. the storage of precipitation as snow and the subsequent melt, although the
melt season starts earlier there, too, and apart from increased glacier melt in the near future and decreased glacier melt due to glacier retreat in the far future (Huss et al., 2008).

To summarize the results, the change in the regime type is the key factor to understand hydrological change in a mountainous environment. It does not only determine changes in the water balance components but also substantially controls the flood seasonality of a catchment (Pfaundler and Wüthrich 2006). The regime and its change is therefore a comprehensive measure for hydrological change in general.

There are several points that were not covered in this study, all of them related to the issue of uncertainty in the climate impact modelling chain. A wide range of different uncertainty sources can be determined on the input-side. We did account for the climate model uncertainty by applying ten combinations of different GCMs and RCMs. Points that were not assessed are the effects of the driving emission scenario and the post-processing method, which can be substantial. The impact model, here a hydrological model, incorporates uncertainty in the model structure, too, and also in the calibrated parameters.

To account for model parameter uncertainty, several studies apply Monte Carlo simulations to calibrate the model and then apply the 10, 50 or 100 best parameter sets in further analysis, for instance to study climate change impact (e.g. Finger et al., 2012). The result is a spread of projections that can be interpreted as an uncertainty estimate of the model parameters. However, this does not assess the usability of the calibrated model parameters under future climate conditions, which is another issue related to impact model parameters. A method to test the validity of a model in simulating runoff under different climatic conditions is the differential split-sample test (Klemeš, 1986). The modelling period is split up into climatically different periods, and is then calibrated on, for example, a dry period and validated in a wet season (Ewen and Parkin, 1996). This approach is, for example, used to evaluate the model performance for flood estimation (Seibert, 2003), and it is probably the only way to test the parameters for their robustness under different climates. But it is not a proof that climatically robust parameter sets, which capture the observed natural variability, capture unknown future states, too, especially if the future state is outside the natural variability.

The uncertainty related to the hydrological model structure itself, i.e. the incorporated assumptions, process formulations and concepts, can be estimated by applying several hydrological models in one study. Two recent examples for this kind of study applied 10 (Huisman et al., 2009) and even 20 (Seiller et al., 2012) different hydrological models to assess their applicability under contrasted conditions. Both studies suggest that the ensemble mean of the models is the best predictor under changed conditions. Those extensive case studies provide priceless information on the reliability of hydrological models, but they are certainly out of scope, if a comprehensive set of catchments is to be analysed, like in the present study.

As stated above, we accounted for the GCM-RCM model-uncertainty and applied changes in the mean annual cycles of the climate variables because of the post-processing with the delta change method. It would be interesting, of course, how the hydrological projections evolve when additionally accounting for changes in the frequency and intensity of the climate
variables. That is, further post-processing methods, like e.g. quantile mapping, should be applied, at least in a representative sample of case study catchments.

The extensive quantitative information gathered within this project and within the other subprojects in CCHydro, however, shows a clear signal of hydrological change for the changes in the mean annual cycle of temperature and precipitation, already. So, the general direction of change is known by now. Hydrological projections are however in no case precise predictions of the hydrological future. Some limitations cannot be overcome: we cannot know, for example, if the calibrated model parameters are valid for the future (FOEN, 2012b) or if the bias correction that is derived from the deviance of model results and measurements still holds under a future climate (Teutschbein and Seibert, 2012). Nevertheless, for the study domain, a mountainous mid-latitude region, the general changes in climate and its main impacts on the hydrology are repeatedly and consistently stated in every new impact study. Moreover, they are already perceptible and easily comprehensible with common sense. Regardless of the knowledge on the exact magnitude of this change, the results are robust and should be translated into flexible and sustainable adaptation strategies.

This is, however, certainly not an easy task because adaptation has to act locally and specific, while climate change impacts are more perceptible on the regional scale and over longer periods. State-of-the-art adaptation strategies therefore focus on “low-regret” measures (IPCC, 2012), which means that the strategies should yield benefits regardless of the extent of climate change (Wilby and Keenan, 2012). Adaptation measures are, of course, not free of costs, which is why they should not be termed “no regret”, although this is what is sought (Wilby and Dessai, 2010). A number of recent studies deal with the question of how to best derive suitable adaptation strategies from climate scenarios, mostly with a focus on flood protection (e.g. Prudhomme et al., 2010; Wetterhall et al., 2011). The research on this topic has to be continued in the future.


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