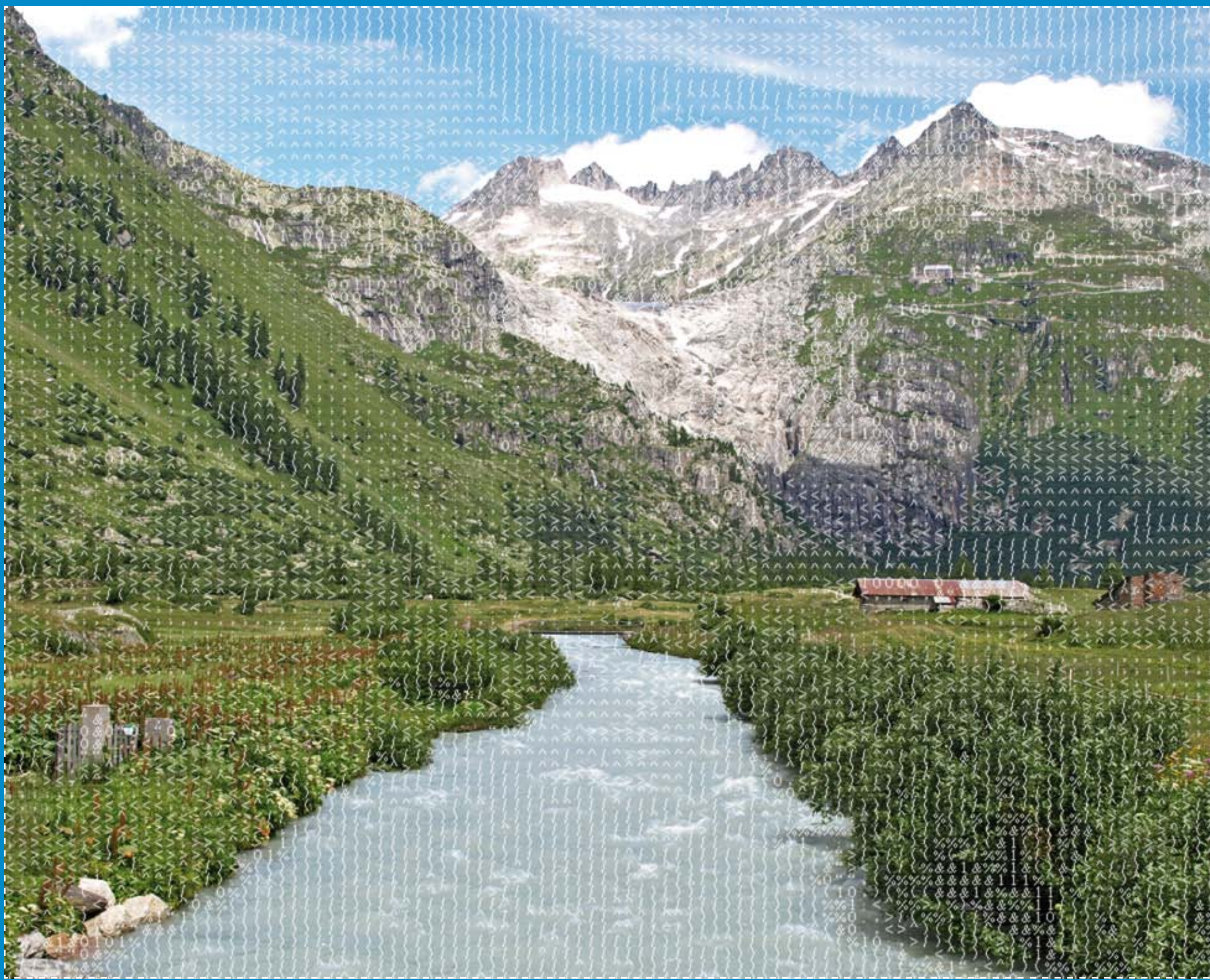
> Effects of Climate Change on Water Resources and Waters

Synthesis report on "Climate Change and Hydrology in Switzerland" (CCHydro) project



Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Confederation

Federal Office for the Environment FOEN

> Effects of Climate Change on Water Resources and Waters

Synthesis report on "Climate Change and Hydrology in Switzerland" (CCHydro) project

Published by the Federal Office for the Environment FOEN
Bern, 2012

Publisher
Federal Office for the Environment (FOEN)
The FOEN is an office in the Federal Department of the Environment, Transport, Energy and Communications (DETEC).

Project management
Dr. David Volken, FOEN, Hydrology Division

Senior project management
Dr. Adrian Jakob, FOEN, Hydrology Division
Dr. Willy Geiger, FOEN, Management board
Dr. Dominique Bérod, FOEN, Hydrology Division
Dr. Ronald Kozel, FOEN, Hydrology Division
Dr. Petra Schmocker-Fackel, FOEN, Hydrology Division
Dr. Hugo Aschwanden, FOEN, Water Division
Dr. Roland Hohmann, FOEN, Climate Division
Dr. Gian Reto Bezzola, FOEN, Hazard Prevention Division

Autors of final reports of CCHydro sub-projects
Institute for Atmosphere and Climate IAC at ETH Zurich:
Dr. Thomas Bosshard, Dr. Sven Kotlarski, Prof. Dr. Christoph Schär
Institute of Geography, University of Bern GIUB:
Nina Köplin, Raphael Meyer, Dr. Bruno Schädler, Prof. Dr. Rolf Weingartner
Department of Geography University of Zurich GIUZ:
Andreas Linsbauer, Dr. Frank Paul, Prof. Dr. Wilfried Haeberli
Swiss Federal Institute for Forest, Snow and Landscape Research WSL: Luzi Bernhard, Dr. Massimiliano Zappa
Laboratory of Hydraulics, Hydrology and Glaciology VAW ETH Zurich:
Dr. Daniel Farinotti, Dr. Andreas Bauder, Prof. Dr. Martin Funk
Laboratory of Environmental Fluid Mechanics and Hydrology, Ecole Polytechnique Fédérale de Lausanne:
Dr. Hendrik Huwald, Prof. Dr. Marc Parlange
HYBEST GmbH, Birmensdorf:
Dr. Felix Naef

Synthesis report authors
Dr. Bruno Schädler, Institute of Geography, University of Bern
Pascal Blanc, Institute of Geography, University of Bern
Dr. David Volken, FOEN, Hydrology Division

Citation
Federal Office for the Environment FOEN (publ.) 2012:
Effects of Climate Change on Water Resources and Waters.
Synthesis report on “Climate Change and Hydrology in Switzerland” (CCHydro) project. Federal Office for the Environment, Bern.
Umwelt-Wissen No 1217: 74 S.

Design
Ursula Nöthiger-Koch, 4813 Uerkheim

Cover picture
Gletsch with Rhone glacier, 2008, FOEN / E. Lehmann

Printed version and PDF download available from
BBL, Vertrieb Bundespublikationen, CH-3003 Bern
Tel. +41 (0)31 325 50 50, Fax +41 (0)31 325 50 58
verkauf.zivil@bbl.admin.ch
Order number: 810.300.127eng
www.bafu.admin.ch/uw-1217-e

This publication is also available in French and German.

> Table of contents

> Abstracts

In the project «Climate Change and Hydrology in Switzerland» (CCHydro) run by the Federal Office for the Environment (FOEN), the effects of climate change on the water balance in Switzerland by the year 2100 were studied. There will be little change in the amount of water available up to that date. However, as a result of the rise in the snow line associated with increasing air temperature, the volumes of snow and ice stored in the Alps will be greatly reduced. This will combine with a seasonal redistribution of the precipitation (drier in summer, wetter in winter) to cause a seasonal runoff redistribution. High and (particularly) low water flow events will probably occur more frequently – mainly in sensitive regions such as the Swiss Plateau, Valais and Ticino.

Keywords:
Climate change,
Hydrology,
Surface waters,
Water resources,
Snow,
Glaciers

Im Rahmen des Projekts «Klimaänderung und Hydrologie in der Schweiz» (CCHydro) des Bundesamts für Umwelt (FOEN) wurden die Auswirkungen des Klimawandels auf den Wasserhaushalt der Schweiz bis zum Jahr 2100 untersucht. Das Wasserdargebot wird sich bis dann nur wenig ändern. Als Folge des Anstiegs der Schneefallgrenze parallel zur Zunahme der Lufttemperatur werden die in den Alpen gespeicherten Schnee- und Eismassen jedoch stark vermindert. Zusammen mit einer saisonalen Umverteilung des Niederschlags (trockener im Sommer, feuchter im Winter) wird dies eine jahreszeitliche Umverteilung der Abflüsse hervorrufen. Hochwasser- und insbesondere Niedrigwasserereignisse werden wahrscheinlich vermehrt auftreten – vor allem in sensitiven Regionen wie dem Mittelland, dem Wallis oder dem Tessin.

Stichwörter:
Klimaänderung,
Hydrologie,
Gewässer,
Wasserressourcen,
Schnee,
Gletscher

Dans le cadre du projet «changement climatique et hydrologie» (CCHydro) de l'Office fédéral de l'environnement (OFEV), les conséquences du changement climatique sur les ressources en eau de la Suisse jusqu'à l'horizon 2100 ont été analysées en détail. Le total des ressources en eau disponible ne va que peu changer. Par contre, suite à l'élévation de la limite pluie-neige parallèlement à l'augmentation des températures, les masses de neige et de glace stockées dans les Alpes vont diminuer fortement. Combinées à une redistribution attendue des précipitations (plus sec en été, plus humide en hiver), ces modifications devraient entraîner une redistribution des débits au cours des saisons, conduisant à des situations de basses et hautes eaux plus fréquentes, particulièrement dans certaines régions sensibles comme le Plateau, le Valais ou le Tessin.

Mots-clés:
Changement climatique,
Hydrologie,
Eaux,
Ressources en eau,
Neige,
Glaciers

Nel quadro del progetto «Cambiamenti climatici e idrologia in Svizzera» (CCHydro) dell'Ufficio federale dell'ambiente (UFAM) sono stati analizzati gli effetti dei cambiamenti climatici sul regime idrico della Svizzera fino al 2100. Di fatto, le risorse idriche subiranno solo lievi modifiche. L'innalzamento del limite delle nevicate e il parallelo aumento della temperatura dell'aria provocheranno tuttavia una forte diminuzione delle masse di neve e ghiaccio accumulate nelle Alpi. Questo effetto, associato a una ridistribuzione delle precipitazioni (più secco in estate e più umido in inverno), dovrebbe causare una diversa distribuzione delle portate nel corso delle stagioni. Gli eventi di piena e soprattutto quelli di magra saranno più frequenti, in particolare in regioni sensibili quali l'Altopiano, il Vallese o il Ticino.

Parole chiave:
Cambiamenti climatici,
Idrologia,
Acque,
Risorse idriche,
Neve,
Ghiacciai

> Foreword

First drought, then flooding; first too hot, then too cold; 2011 and the winter which followed give an indication of how the climate in Switzerland may develop in coming years. There is increasing evidence that human behaviour is resulting in a change in the climate. But it is not clear whether or not we will be able to reverse this trend in the medium term. We therefore need to develop new strategies which make it possible for society to adapt to the new climatic conditions.

The Federal Office for the Environment FOEN is heading the work on drawing up a national strategy on adapting to climate change. In future it will be ever more important to protect the resource water, to prevent conflicts over its use and to alleviate the effects of an increase in flood events.

All strategies are based on knowledge – on knowledge about natural and human processes and potential scenarios. The FOEN's task is to encourage, support and lead studies and so ensure that the necessary bases for strategic thinking and decision-making are available. The CCHydro project is a perfect example of the role the FOEN plays: in conjunction with highly qualified partners, a knowledge base could be created which enables us to predict the effects of different climate scenarios on individual elements in the hydrological cycle. At the same time, cooperation with other studies could be established. These include a research project into the consequences of climate change for hydroelectric power, the results of which were published in 2011, and the 'Sustainable Water Management' National Research Project 61, which runs from 2010 to 2013.

The CCHydro research project has contributed greatly to adaptation strategies relating to water systems and has shown that in Switzerland our knowledge in this area can be improved. We must continue to conduct scientific research and carry out monitoring long term, as this is the key to sustainable, balanced and adaptable policy.

Dr. Willy Geiger
Vice Director
Federal Office for the Environment FOEN

> Summary

The CCHydro project

In 2009 the Federal Office for the Environment FOEN, under the project “Climate Change and Hydrology in Switzerland” (CCHydro), commissioned various research institutes to investigate how the water balance in Switzerland, the frequency of floods and low water as well as the water temperature might change by the end of this century. These studies were carried out on the basis of national climate scenarios developed at the same time. This report details the main results of the project.

Stream flow scenarios

In the near term (until 2035), annual available water resources in Switzerland will change very little, apart from temporary increases in the stream flows in heavily glaciated regions. In the long term (by 2085) the available water resources will fall slightly, particularly in the Lake Maggiore basin (Rivers Ticino and Toce, minus 10%). However, the seasonal distribution of runoff (runoff regime) will shift almost everywhere in Switzerland. By the end of the century, glacial and nival based catchments will only be found in isolated areas. Small catchments will increasingly be dominated by regimes characteristic of the Swiss Plateau and southern Switzerland. The Swiss Plateau will see the development of a new type of regime called *pluvial de transition*, which will be characterised by a distinct minimum runoff in August and two seasonal peaks in January and March. In many regions, runoff is expected to be much higher in winter but lower in summer – except in the regions where glaciation remains. In most of the Swiss Plateau, therefore, the period of potential flooding will move from early summer to the winter season and will sometimes last longer. The frequency of average flood events (in the Alpine foothills and the Alps) or high (in the Swiss Plateau and Jura) is also likely to increase in many regions. The major rivers, which are fed by numerous smaller catchments, will change accordingly. On the Rhine for example, a second seasonal maximum will develop over time in winter in addition to the one in early summer. In the watercourses of the Alpine foothills and the Alps, low water events will shift from winter to late summer and will be less pronounced. In the Swiss Plateau regions discharge during low water events will decrease considerably and these periods will be longer. For instance, water levels in the Aare in late summer will gradually fall below those currently experienced in winter.

Effects of climate change on water reservoirs

The regime changes and the increased frequency of high and low water events which are already being observed can be explained by the changes in climatic conditions. Over the past 100 years, the average annual temperature in Switzerland has risen by more than 1.5° C. By the year 2085, temperatures are expected to increase by 3° C ± 1° C compared with the 1980 to 2009 period. This is bound to have an impact on seasonal hydrological reserves in Switzerland: The increase in temperature will be accompanied by a rise in the snow line. The average area covered by snow is being continually reduced, as is the depth and duration of the snow cover. Finally, the reserves of snow available for melting are decreasing. Some 40% of runoff out of Switzerland during the 1980–2009 consisted of snow melt. This proportion will fall to about 25% by 2085. This will lead to an increasing proportion of rainfall being free to drain away immediately, particularly in winter. Less than 2% of annual runoff is currently derived from the summer glacier ice melt, but in summer the proportion is much greater in watercourses in the vicinity of glaciers.

Because glaciers – which react only slowly to environmental changes – are already too large for current and future climatic conditions, they will continue to melt rapidly. This will lead to more runoff in the Alpine catchments, if only for a relatively short time: up to about 2040 for the glaciers with greater volume, whilst smaller glaciers are already demonstrating decreasing runoff levels. By 2100 it is likely that only 30% of the current volume of ice will remain, mainly in the Rhone basin.

Expected precipitation changes

Total precipitation in Switzerland rose slightly during the 20th century. The annual precipitation trend observed will continue during the 21st century: Precipitation will increase slightly in the north but will fall slightly in the south. A significant redistribution over the course of the year will take place on both sides of the Alps, however: summer precipitation will decrease markedly (by 20%), but it will increase over the rest of the year (except in spring in the south). This redistribution of seasonal precipitation will intensify the effects of temperature-related changes in reserves (snow and ice) on runoff: More precipitation in liquid form in winter, much lower precipitation and reduced meltwater volumes in summer. By the end of the century every second summer will be at least as warm as the summer of 2003. Droughts are likely to occur more often and last longer.

Uncertainty

Reliable statements on extreme high precipitation events cannot be given at present. The uncertainties in the emission and climate scenarios are also considerable. The uncertainty about temperature changes makes it difficult to quantify the rate at which the changes in snow and ice reserves will occur and it is still uncertain how marked the seasonal redistribution of precipitation volumes will actually turn out to be. These uncertainties have been allowed for in the hydrological modelling, making it possible to obtain an idea of the changes in the Swiss water balance as a result of future climate developments.

Water management and ecological consequences

The effect of climate change on runoff described above will have consequences for water management. Existing flood protection measures must be reviewed in the Swiss Plateau and Jura. An increased risk of water shortages in the summer may lead to a potential for conflict among the different users. As runoff regimes and in some cases water temperatures will change significantly, the statutory regulations in various fields (introduction of cooling water, waste water, lake control regulations, residual water) must be reviewed. The need for additional (multipurpose) reservoirs must be clarified. More frequent and serious low water events and higher winter discharge could increasingly affect navigation on the Rhine.

Finally, river ecosystems will be doubly affected by climate change due to the higher air temperature and the seasonal redistribution of runoff. Higher air temperatures and associated higher water temperatures and lower levels in summer are likely to put pressure on river ecology and therefore on water use (agriculture, heat input from industrial cooling) and fishing.

Outlook

It has not yet been possible to answer all questions definitively. Further research is required in relation to uncertainties in regional climate modelling, the change in intensity and frequency of high-precipitation events and their associated rare flood events, future low water discharge in the Alpine foothills and Alps and changing water temperatures. The “Climate Change and Hydrology in Switzerland” (CCHydro) research project has provided important hydrological foundations for strategic considerations and decisions. The results of the CCHydro project allow us for the first time to estimate comprehensively the future effects of climate change on the individual components of the hydrological cycle for the whole of Switzerland.

> Zusammenfassung

Das Projekt CCHydro
Im Rahmen des Projekts «Klimaänderung und Hydrologie in der Schweiz» (CCHydro) hat das Bundesamt für Umwelt BAFU ab 2009 verschiedene Forschungsinstitute beauftragt, zu untersuchen, wie sich der Wasserhaushalt in der Schweiz, die Häufigkeit von Hoch- und Niedrigwasser sowie die Wassertemperatur bis zum Ende des laufenden Jahrhunderts verändern könnten. Diese Untersuchungen wurden auf der Grundlage von zugleich erarbeiteten nationalen Klimaszenarien durchgeführt. Der vorliegende Bericht legt die wichtigsten Ergebnisse des Projekts dar.

Abflussszenarien
Bis in die nahe Zukunft (2035) wird sich das jährliche Wasserdargebot der Schweiz mit Ausnahme vorübergehender Zunahmen der Abflüsse in stark vergletscherten Gebieten nur wenig verändern. Langfristig (bis 2085) werden die verfügbaren Wasserressourcen leicht abnehmen, vor allem im Einzugsgebiet des Lago Maggiore (Flüsse Ticino und Toce, minus 10 %). Die jahreszeitlichen Verteilungen der Abflüsse (Abflussregimes) hingegen werden sich beinahe in der ganzen Schweiz verschieben. Glazial und nival geprägte Einzugsgebiete werden gegen Ende dieses Jahrhunderts nur noch vereinzelt zu finden sein. Die kleinen Einzugsgebiete werden zunehmend mittelländisch bzw. meridional geprägt sein. Im Mittelland wird ein neuer Regime-Typ auftreten, *pluvial de transition,* welcher sich durch ein ausgeprägtes Abflussminimum im August und zwei Maxima im Januar und im März auszeichnen wird. Im Winter wird in vielen Gebieten deutlich mehr Abfluss, im Sommer jedoch weniger – ausser in den noch vergletscherten Gebieten – erwartet. Deshalb wird sich im grössten Teil des Mittellandes die potenzielle Hochwasserzeit vom Frühsommer in das Winterhalbjahr verschieben und teilweise auch verlängern. Die Häufigkeit von mittleren (in den Voralpen und Alpen) bzw. grossen (im Mittelland und Jura) Hochwasserereignissen dürfte zudem in vielen Gebieten steigen. Auch die grossen Flüsse, welche aus zahlreichen kleineren Einzugsgebieten gespeist werden, werden sich entsprechend verändern. Im Rhein wird sich beispielsweise im Lauf der Zeit zusätzlich zum Frühsommer ein zweites saisonales Maximum im Winter bilden. Niedrigwasserereignisse werden sich in den Fliessgewässern der Voralpen und der Alpen vom Winter in den Spätsommer verschieben und dann weniger ausgeprägt sein. In den Gebieten des Mittellandes werden die Niedrigwasserabflüsse deutlich abnehmen und die Niedrigwasserperioden länger werden. So werden beispielsweise die Niedrigwasserabflüsse der Aare im Spätsommer allmählich Werte annehmen, welche tiefer sein werden als heutzutage im Winter.

Auswirkungen der Klimaänderung auf die Wasserspeicher
Die Regimeänderungen und die erhöhte Disposition für Hoch- und Niedrigwasser, welche bereits heute zu beobachten sind, lassen sich durch die veränderten klimatischen Bedingungen erklären. In den letzten 100 Jahren hat die mittlere Jahrestemperatur in der Schweiz um mehr als 1,5 °C zugenommen. Im Vergleich zu 1980 bis 2009 wird die erwartete Temperaturzunahme von heute bis zum Jahr 2085 3 °C ± 1 °C betragen. Dies wird nicht ohne Auswirkungen auf die saisonalen hydrologischen Speicher in der Schweiz bleiben: Parallel zur Temperaturerhöhung findet ein Anstieg der Schneefallgrenze statt. Die im Mittel von Schnee bedeckte Fläche nimmt stetig ab, gleichzeitig vermindern sich die Mächtigkeit und die Dauer der Schneedecke. Schliesslich sind weniger Schneereserven vorhanden, welche geschmolzen werden können. Rund 40 % des Abflusses aus der Schweiz in der Periode 1980–2009 bestand aus Schneeschmelze. Dieser Anteil wird bis 2085 auf etwa 25 % sinken. Damit wird ein immer grösserer Teil des Niederschlags, insbesondere im Winter, sofort abfliessen können. Nur weniger als 2 % des Jahresabflusses entstammen heute der sommerlichen Gletscherschmelze. In gletschernahen Fliessgewässern bildet sie jedoch im Sommer einen bedeutenden Anteil.

Da die Gletscher, welche nur träge auf Umweltveränderungen reagieren, zu gross sind im Vergleich zu den heutigen und zu den erwarteten zukünftigen Klimabedingungen, werden sie weiterhin stark schmelzen. Dies

wird zu zusätzlichen Abflüssen in den alpinen Einzugsgebieten führen, allerdings nur für eine relativ kurze Zeit: Für die volumenmässig grösseren Gletscher bis etwa 2040, bei kleineren Gletschern nehmen die Abflüsse bereits jetzt wieder ab. Bis 2100 werden voraussichtlich nur noch 30 % der heutigen Eisvolumen übrig bleiben, hauptsächlich im Einzugsgebiet der Rhone.

Erwartete Änderungen des Niederschlags

Während des 20. Jahrhunderts haben die Niederschläge insgesamt für die Schweiz leicht zugenommen. Die beobachtete Tendenz der Jahresniederschläge wird sich im Laufe des 21. Jahrhunderts fortsetzen: Die Niederschläge werden im Norden leicht zunehmen, im Süden aber leicht zurückgehen. Eine deutliche Umverteilung im Jahresverlauf wird jedoch beidseits der Alpen stattfinden: Im Sommer werden die Niederschläge sehr stark zurückgehen (um 20 %), in den übrigen Jahreszeiten jedoch zunehmen (ausser im Frühling im Süden). Diese Umverteilung der saisonalen Niederschläge wird die Auswirkungen der temperaturbedingten Speicheränderungen (Schnee, Eis) auf den Abfluss verstärken: Im Winter mehr Niederschlag in flüssiger Form, im Sommer deutlich weniger Niederschlag und reduzierte Schmelzwassermengen. Bis Ende des Jahrhunderts wird jeder zweite Sommer mindestens so warm sein wie derjenige von 2003. Trockenperioden dürften damit häufiger auftreten und länger anhalten.

Unsicherheiten

Verlässliche Aussagen betreffend extreme Starkniederschlagsereignisse können zurzeit keine gemacht werden. Ausserdem bleiben die Unsicherheiten in den Emissions- und in den Klimaszenarien gross. Die Unsicherheiten bezüglich der Temperaturzunahme lässt die Geschwindigkeit der Änderungen der Schnee- und Eisspeicher nicht genau beziffern, zudem bleibt noch unsicher, wie stark die jahreszeitliche Umverteilung der Niederschlagsmengen tatsächlich ausfallen wird. Diese Unsicherheiten wurden in den hydrologischen Modellierungen berücksichtigt, sodass es möglich ist, sich ein Bild der Änderungen im Schweizer Wasserhaushalt je nach künftiger Klimaentwicklung zu machen.

Wasserwirtschaftliche und ökologische Folgen

Die beschriebenen Auswirkungen der Klimaänderung auf die Abflüsse werden wasserwirtschaftliche Folgen haben. Die bestehenden Hochwasserschutzmassnahmen müssen im Mittelland und Jura überprüft werden. Zudem bergen grössere Risiken für Wasserknappheit im Sommer ein Konfliktpotenzial unter den verschiedenen Nutzern. Da sich die Abflussregimes und z. T. die Wassertemperaturen markant verändern, müssen die rechtlichen Regelungen in verschiedenen Bereichen (Einleitung von Kühlwasser, Abwasser, Regulierreglemente der Seen, Restwasser) überprüft werden. Der Bedarf an zusätzlichen (Mehrzweck-)Speichern muss abgeklärt werden. Häufiger und stärker vorkommende Niedrigwasserereignisse sowie höhere Winterabflüsse könnten die Rheinschifffahrt vermehrt beeinträchtigen.

Schliesslich werden die Ökosysteme der Fliessgewässer doppelt vom Klimawandel betroffen sein: Durch die erhöhte Lufttemperatur und durch die jahreszeitliche Umverteilung der Abflüsse. Erhöhte Lufttemperatur und damit erhöhte Wassertemperatur sowie tiefere Pegelstände im Sommer dürften die Ökologie der Fliessgewässer und damit die Wassernutzung (Landwirtschaft, industrielle Wärmezufuhr) und die Fischerei vermehrt unter Druck setzen.

Ausblick

Es konnten noch nicht alle Fragen abschliessend beantwortet werden. Weiterer Forschungsbedarf wurde in den Bereichen der Unsicherheiten der regionalen Klimamodellierung, der Veränderung der Stärke und Häufigkeit von Starkniederschlägen und der damit verbundenen seltenen Hochwasser, der zukünftigen Niedrigwasserabflüsse in den Voralpen und Alpen sowie der Veränderung der Wassertemperaturen identifiziert. Mit dem Forschungsprojekt «Klimaänderung und Hydrologie in der Schweiz» (CCHydro) konnten wichtige hydrologische Grundlagen für strategische Überlegungen und Entscheidungen bereitgestellt werden. Die Resultate des Projekts CCHydro erlauben es, erstmals flächendeckend für die ganze Schweiz die zukünftigen Auswirkungen der Klimaänderung auf die einzelnen Komponenten des hydrologischen Kreislaufs abzuschätzen.

> Résumé

Le projet CCHydro
Dans le cadre du projet «Changement climatique et hydrologie en Suisse» (CCHydro), l'Office fédéral de l'environnement (OFEV) a depuis 2009 chargé différentes institutions spécialisées d'étudier les changements qui pourraient survenir en Suisse d'ici à la fin du siècle dans les domaines suivants: régime des eaux, fréquence des crues et des étiages et température des eaux. Ces études reposent sur des scénarios climatiques nationaux élaborés en parallèle au projet. Les principaux résultats obtenus sont présentés dans ce rapport.

Scénarios de débits
A court terme (soit d'ici à 2035), le niveau annuel des ressources en eau dans notre pays ne va pratiquement pas changer, à l'exception d'une augmentation temporaire des débits dans les zones fortement englacées. A long terme (soit d'ici à 2085), les ressources en eau disponibles baisseront légèrement, surtout dans le bassin versant du Lac Majeur (moins 10 % pour le fleuve Tessin et pour le Toce). La distribution saisonnière des débits (régime d'écoulement) va quant à elle changer dans presque toute la Suisse. Vers la fin du siècle, pratiquement tous les bassins versants à régime glacio-nival auront disparu. Les régimes des petits bassins versants acquerront un caractère de type méditerranéen respectivement méridional toujours plus accentué. Sur le Plateau, un nouveau type de régime, appelé *pluvial de transition,* fera son apparition. Il se distingue par un débit minimal marqué en août et par deux maxima en janvier et en mars. Les débits seront nettement plus importants dans de nombreuses régions en hiver et moindres en été, excepté dans les zones encore englacées. C'est pourquoi, dans la majeure partie des régions du Plateau, la période de crue potentielle du début de l'été va se reporter au semestre d'hiver et parfois se prolonger. La fréquence des crues moyennes (dans les Préalpes et les Alpes) et importantes (sur le Plateau et dans le Jura) devrait également augmenter dans de nombreuses régions.

Les grandes rivières, qui sont alimentées par de nombreux petits bassins versants, subiront également une évolution. Avec le temps, le Rhin verra par exemple apparaître un deuxième maximum saisonnier, en hiver, en sus de celui que le fleuve connaît aujourd'hui au début de l'été. Les étiages des cours d'eau préalpins et alpins ne se produiront plus en hiver mais à la fin de l'été, et seront moins marqués. Sur le Plateau, les débits vont nettement baisser et les périodes d'étiage s'allonger. Ainsi, le débit de l'Aar à la fin de l'été va graduellement s'abaisser en dessous de celui mesuré actuellement en hiver.

Impact des changements climatiques sur les réservoirs
Les modifications du régime des eaux et la plus grande probabilité de crues et d'étiages que l'on observe déjà aujourd'hui sont dues aux changements climatiques. En effet, au cours des 100 dernières années, la température annuelle en Suisse a augmenté de 1,5 °C. Par rapport à l'évolution constatée entre 1980 et 2009, la hausse prévue entre 2012 et 2085 est de 3 °C ± 1 °C, ce qui ne manquera pas d'affecter les niveaux saisonniers des réservoirs hydrologiques en Suisse. En parallèle à cette hausse de la température, on constatera une élévation de la limite des chutes de neige. La superficie enneigée décroît régulièrement, tout comme l'épaisseur et la persistance du manteau neigeux. Les réserves d'eau de fonte sont en fin de compte moins abondantes: alors que près de 40 % des débits mesurés en Suisse entre 1980 et 2009 étaient alimentés par la fonte des neige, ce pourcentage va baisser à environ 25 % d'ici à 2085. Ainsi, une part toujours plus importante des précipitations pourra s'écouler immédiatement, surtout en hiver. Aujourd'hui, un peu moins de 2 % des débits annuels sont liés à la fonte estivale des glaciers. Dans les cours d'eau à proximité des glaciers, ce pourcentage est toutefois nettement plus conséquent en été.

Les glaciers, qui répondent avec un temps de retard aux changements climatiques, ont une taille disproportionnée par rapport aux conditions climatiques actuelles et à venir; ils continueront donc à fondre. Ce phénomène va induire des écoulements supplémentaires dans les bassins versants des Alpes, mais sur une période relativement limitée. Pour les glaciers de grande taille, cette

période va durer jusqu'en 2040, alors que les écoulements dus aux glaciers de moindre importance ont déjà recommencé à baisser. D'ici à 2100, il ne restera que 30 % du volume de glace actuel, principalement dans le bassin versant du Rhône.

Modification prévisible des précipitations

Dans l'ensemble, les précipitations en Suisse ont légèrement augmenté au cours du 20e siècle. Cette tendance va se confirmer durant le 21e siècle: les précipitations seront à peine plus fréquentes au nord, mais se feront en revanche quelque peu plus rares au sud de notre pays. Toutefois, les deux versants des Alpes verront s'opérer une nette redistribution dans les années à venir. Les précipitations diminueront fortement en été (de 20 %) et augmenteront le reste de l'année (sauf au printemps dans le sud). Cette redistribution des précipitations saisonnières renforcera l'impact sur les débits des changements observés dans les réservoirs (neige, glace) suite à la hausse de la température. En hiver, il y aura plus de précipitations liquides, et en été, nettement moins de pluies et d'eaux de fonte. D'ici à la fin du siècle, un été sur deux sera au moins aussi chaud que celui de 2003. Les sécheresses seront donc plus fréquentes et dureront plus longtemps.

Incertitudes

Actuellement, toute prévision fiable concernant les épisodes de fortes précipitations est impossible. De plus, les scénarios liés aux émissions et au climat présentent de grandes incertitudes, notamment en ce qui concerne la hausse de la température. Dans ces conditions, il n'est pas possible de déterminer exactement à quelle vitesse les réservoirs de neige et de glace vont diminuer. En outre, la redistribution saisonnière des précipitations ne peut pas encore être définie clairement. Ces incertitudes ont été prises en compte dans les modélisations hydrologiques et il est donc possible de se faire une idée des modifications du régime des eaux en Suisse en fonction des changements climatiques à venir.

Les changements climatiques auront un impact sur les débits et par conséquent sur la gestion des eaux. Les mesures de protection contre les crues existantes sur le Plateau et dans le Jura doivent être révisées. Etant donné le risque aggravé de pénurie d'eau en été, le potentiel de conflits entre les différents utilisateurs prend également de nouvelles dimensions. Etant donné que le régime des eaux et notamment la température des eaux vont subir de nets changements, il s'agira d'examiner les règlementations légales relatives aux différents domaines concernés (déversement d'eaux de refroidissement, eaux usées, règlements de régulation des lacs, débits résiduels). Le besoin supplémentaire en réservoirs (à usage multiple) doit également être éclairci. De plus, la navigation sur le Rhin pourrait être entravée plus fréquemment en raison de la fréquence et de l'intensité accrues des périodes d'étiage et des débits hivernaux plus importants.

Conséquences pour la gestion des eaux et l'écologie

Enfin, les écosystèmes des cours d'eau seront doublement touchés par les changements climatiques: ils souffriront de la hausse de la température de l'air et de la redistribution des débits. Le réchauffement des eaux qui résultera de la hausse de la température atmosphérique, associé à la baisse des niveaux en été, accroîtra la pression sur ces écosystèmes, ce qui se répercutera sur les utilisateurs d'eau (agriculture, rejets de chaleur industrielle) et sur les pêcheurs.

Perspectives

Il n'est pas encore été possible de répondre de manière exhaustive à toutes les questions posées. Des recherches supplémentaires doivent être menées dans les domaines suivants: modélisations climatiques régionales, évolution de l'intensité et de la fréquence des fortes précipitations et des crues rares qui en résultent, niveau des débits (étiages) dans les Préalpes et les Alpes et modification de la température des eaux. Le projet CCHydro a permis de mettre en place des bases hydrologiques essentielles aux réflexions et décisions stratégiques en la matière. Grâce aux résultats obtenus, il est pour la première fois possible d'évaluer à l'échelle de la Suisse l'impact des changements climatiques sur les différents éléments du cycle hydrologique.

> Riassunto

Il progetto CCHydro
Nel quadro del progetto «Cambiamenti climatici e idrologia in Svizzera» (CCHydro), dal 2009 l'Ufficio federale dell'ambiente (UFAM) ha incaricato diversi istituti di ricerca di analizzare i cambiamenti che potrebbero intervenire sino alla fine del secolo in corso nel regime idrico della Svizzera, nella frequenza degli eventi di piena e di magra e nella temperatura delle acque. Le analisi sono state effettuate in base a scenari climatici nazionali elaborati in contemporanea. Il presente rapporto riporta i principali risultati del progetto.

Scenari di deflusso
A breve termine (fino al 2035) le risorse idriche annue della Svizzera subiranno pochi cambiamenti, tranne un aumento temporaneo delle portate nelle zone in cui sono presenti molti ghiacciai. A più lungo termine (fino al 2085) le riserve idriche disponibili diminuiranno leggermente, soprattutto nel bacino imbrifero del lago Maggiore (fiumi Ticino e Toce, –10 %). Per contro, le distribuzioni stagionali delle portate (regime di deflusso) subiranno modifiche in quasi tutta la Svizzera. Verso la fine del secolo, i bacini imbriferi di origine glaciale o nivale saranno molto rari. I bacini imbriferi piccoli assumeranno un carattere sempre più mediterraneo o meridionale. Nell'Altopiano apparirà un nuovo tipo di regime *(pluviale di transizione)* caratterizzato da una portata minima ad agosto e due punte massime a gennaio e marzo. In numerose regioni si prevedono portate sensibilmente superiori in inverno e inferiori in estate, tranne nelle zone in cui si trovano ancora dei ghiacciai. Il periodo di piena nella maggior parte dell'Altopiano potrebbe quindi spostarsi dall'inizio dell'estate al semestre invernale e risultare in parte anche più lungo. Inoltre, si prevede che gli eventi di piena di media (nelle Prealpi e nelle Alpi) o grande entità (nell'Altopiano e nel Giura) diventino più frequenti in molte regioni. I principali fiumi, alimentati da numerosi bacini imbriferi di più piccole dimensioni, subiranno cambiamenti analoghi. Nel Reno si formerà ad esempio nel corso degli anni un secondo massimo stagionale in inverno in aggiunta a quello di inizio estate. Gli eventi di magra nei corsi d'acqua delle Prealpi e delle Alpi si sposteranno dall'inverno alla tarda estate e saranno meno accentuati. Nelle zone dell'Altopiano le portate di magra si accentueranno e i periodi di magra si prolungheranno. Le portate di magra dell'Aar scenderanno gradualmente al di sotto dei valori registrati attualmente in inverno.

Effetti dei cambiamenti climatici sulla capacità di immagazzinamento idrico
Le modifiche del regime e la maggiore predisposizione a piene e magre, già osservabile ai nostri giorni, è riconducibile ai cambiamenti climatici. Negli ultimi cento anni, la temperatura media annua in Svizzera è aumentata di oltre 1,5 gradi. Rispetto all'evoluzione constatata fra il 1980 e il 2009, l'aumento di temperatura atteso fino al 2085 è pari a 3 gradi (con una tolleranza di ± 1 °C). Ciò si ripercuoterà sulla capacità d'immagazzinamento idrico regionale, in quanto l'aumento della temperatura causerà un innalzamento del limite delle nevicate. Le zone centrali coperte da neve diminuiranno sempre più e, al contempo, si ridurrà lo spessore e la durata della copertura nevosa. Infine saranno disponibili sempre meno riserve di neve che possono sciogliersi. Nel periodo 1980–2009 in Svizzera il 40 per cento circa delle portate era costituito da neve sciolta. Tale quota scenderà fino a circa il 25 per cento entro il 2085. Una parte sempre più consistente delle precipitazioni, soprattutto in inverno, potrà quindi defluire immediatamente. Solo meno del 2 per cento delle portate annue deriva attualmente dallo scioglimento estivo dei ghiacciai. In estate, tuttavia, nei corsi d'acqua situati nelle vicinanze dei ghiacciai, l'acqua di scioglimento costituisce una quota importante.

I ghiacciai, che reagiscono lentamente agli effetti dei cambiamenti climatici, sono troppo grandi in rapporto alle condizioni ambientali attuali. Essi continueranno a sciogliersi in modo massiccio. Ciò comporterà portate supplementari nei bacini imbriferi alpini. Il fenomeno sarà comunque di durata relativamente breve: per i ghiacciai più grandi in termini di volume fino circa al 2040, mentre per quelli più piccoli si registra già attualmente una diminuzione delle portate. Nel 2100 rimarrà presumibilmente solo il 30 per cento del volume attuale dei ghiacciai, principalmente nel bacino imbrifero del Rodano.

Cambiamenti previsti nelle precipitazioni
Durante il XX secolo le precipitazioni hanno registrato un leggero aumento su tutto il territorio nazionale. La tendenza osservata nelle precipitazioni annue proseguirà nel corso del XXI secolo: esse aumenteranno leggermente nella parte settentrionale del Paese, mentre si ridurranno in misura attenuata in quella meridionale. Una ridistribuzione significativa nel corso dell'anno avverrà comunque su entrambi i versanti alpini: le precipitazioni diminuiranno fortemente (di circa il 20 %) in estate, mentre aumenteranno nelle altre stagioni (tranne in primavera sul versante meridionale). Questa ridistribuzione delle precipitazioni stagionali accentuerà le ripercussioni sulle portate dovute ai cambiamenti della capacità di immagazzinamento (di neve e ghiaccio), che dipende dalle temperature, e inciderà maggiormente sulle portate: in inverno si registreranno più precipitazioni in forma liquida, mentre in estate vi saranno molto meno precipitazioni e un apporto inferiore di acqua di scioglimento. Sino alla fine del secolo, ogni due anni si registreranno estati calde almeno quanto quella del 2003. I periodi di siccità saranno più frequenti e di più lunga durata.

Incertezze
Per il momento non è possibile fare previsioni attendibili su eventi estremi di forti precipitazioni. Permangono inoltre notevoli incertezze in merito agli scenari relativi alle emissioni e al clima. L'incertezza sull'aumento delle temperature non consente di valutare esattamente la rapidità dei cambiamenti nella capacità di accumulazione di neve e ghiaccio. Infine, rimangono incertezze sull'entità effettiva della ridistribuzione stagionale del volume delle precipitazioni. I modelli idrologici tengono conto di tutte queste incertezze ed è quindi possibile farsi un'idea dei cambiamenti che interverranno nel regime idrico svizzero in base alla futura evoluzione climatica.

Conseguenze nella gestione delle acque e nell'ecologia dei corsi d'acqua
Gli effetti dei cambiamenti climatici sulle portate illustrati nella presente pubblicazione avranno conseguenze a livello di gestione delle acque. Le misure di protezione contro le piene adottate finora nell'Altopiano e nel Giura dovranno essere riesaminate. Inoltre, i rischi di penuria d'acqua nel periodo estivo costituiscono una potenziale fonte di conflitto fra i diversi utenti. A causa delle importanti variazioni del regime delle portate e in parte della temperatura dell'acqua, occorrerà rivedere le norme giuridiche di differenti campi (emissione delle acque di raffreddamento, acque di scarico, regolazione dei laghi, acque residuali). Va chiarita inoltre la necessità di creare bacini di accumulazione supplementari (multiuso). Eventi di magra più frequenti e intensi e portate maggiori durante l'inverno potrebbero perturbare più sovente la navigazione sul Reno.

Infine, gli ecosistemi dei corsi d'acqua subiranno doppiamente gli effetti dei cambiamenti climatici: da un lato, in seguito all'aumento della temperatura dell'aria e, dall'altro, alla ridistribuzione stagionale delle portate. L'aumento della temperatura dell'aria e quindi dell'acqua e livelli d'acqua più bassi in estate potrebbero mettere ancor più a dura prova l'ecologia dei corsi d'acqua e dunque l'utilizzazione delle acque (per l'agricoltura, l'erogazione di calore industriale) e la pesca.

Prospettive
Finora, non è stato possibile rispondere in modo esaustivo a tutte le domande. Ulteriori ricerche saranno necessarie sia laddove sussistono incertezze legate ai modelli climatici a livello regionale, sia per quanto attiene alla variazione della frequenza e dell'intensità delle forti precipitazioni e, dunque, della rarità degli eventi di piena, alle future portate di magra nelle Alpi e nelle Prealpi e alla modifica della temperatura delle acque che ne conseguono. Il progetto «Cambiamenti climatici e idrologia in Svizzera» (CCHydro) ha consentito di creare basi idrologiche solide per le riflessioni e le decisioni di ordine strategico. Grazie ai risultati di questo progetto è per la prima volta possibile valutare a livello nazionale gli effetti futuri dei cambiamenti climatici sui singoli elementi del ciclo idrologico.

1 > Introduction

Adaptation to climate change: federal strategy

In August 2009 the Federal Council gave the federal departments and offices responsible the task of drawing up a strategy for adapting to climate change. In the first part of this strategy, general objectives and principles for adaptation were formulated, action areas and objectives for new sectors described and the greatest, cross-sector challenges identified (FOEN 2012). Fourteen areas of action with varying degrees of urgency were described for the water management sector. Increasing levels of summer drought and the growing likelihood of flooding were identified as two of the cross-sector challenges. The second part of the strategy will present an action plan setting out how the challenges in the different areas can be addressed.

With a view to providing scientific hydrological data for this adaptation strategy, the Federal Office for the Environment FOEN decided back in 2008 to launch a large-scale research project entitled 'Climate Change and Hydrology in Switzerland' (CCHydro).

CCHydro: Objectives and sub-projects

The aim of this project was to present scenarios with enhanced spatial and temporal resolution for the hydrological cycle and runoff in the different climate regions and altitudes in Switzerland for the periods around 2035 and 2085, based on the latest climatic data. This would provide a basis for analysing changes in extreme discharge values (high and low water), water temperature, and water resources and their annual distribution (regimes) (Volken 2010).

The CCHydro project comprises seven modules drawn up by various scientific institutes between 2009 and 2011:

1. Climate scenarios for Switzerland up to 2100, Institute for Atmosphere and Climate IAC, ETH Zurich
2. Natural water regime in Switzerland and its major catchments, Swiss Federal Institute for Forest, Snow and Landscape Research WSL in cooperation with the Department of Geography, University of Zurich GIUZ
3. Climate change and water regime in sensitive balance regions, Institute of Geography, University of Bern GIUB
4. Climate change and low water, Institute of Geography, University of Bern GIUB
5. Discharge modelling of Swiss glaciers, Laboratory of Hydraulics, Hydrology and Glaciology VAW, ETH Zurich
6. Climate change and flooding, HYBEST GmbH
7. Climate change and water temperature (pilot study), Laboratory of Environmental Fluid Mechanics Hydrology, EPF Lausanne

Quantitative aspects of surface hydrology were looked at within the scope of these modules. Questions regarding water quality (with the exception of the pilot project on water temperature) and specific questions regarding lakes and groundwater were not dealt with.

A sub-project report was submitted on each module in the CCHydro project. These are listed in the bibliography and can be accessed on the FOEN website. Several scientific publications have also appeared.

Related projects

Further fundamental aspects of hydrology and water management in general have been looked at in a range of other national and international projects and programmes. CCHydro worked symbiotically with all these projects. In particular, joint climate scenarios were used and basic data and results exchanged. These partner projects are as follows:

- Effects of climate change on flood protection in Switzerland (Auswirkungen der Klimaänderung auf den Hochwasserschutz in der Schweiz) (Flood Protection Commission KOHS 2007)
- “RheinBlick2050”, a project by the International Commission for the Hydrology of the Rhine Basin (CHR), investigating the impact of climate change on discharge in the Rhine River basin (CHR 2010)
- Water Management in a Changing Environment – Strategies against Water Scarcity in the Alps (AlpWaterScarce 2011)
- Adaptation to Climate Change in the Alpine Space – Work Package Water Regime (WP4) (Adaptalp 2011)
- Effects of climate change on hydropower use (Auswirkungen der Klimaänderung auf die Wasserkraftnutzung) (Swiss Society for Hydrology SGHL and Swiss Hydrological Commission CHy 2011)
- Projects by the Climate and Groundwater working group at the Swiss Society for Hydrology (Schürch 2011)
- National Research Programme 61 “Sustainable Water Use”, including eight projects in each of the areas hydrology and water management (Swiss National Science Foundation 2010). The results of this programme are expected in 2013/14.

2 > Methods

Objective

The main objective of the CCHydro project was to create scenarios with enhanced spatial and temporal resolution for the hydrological cycle and runoff for the periods around 2035 and 2085. As it was not possible to achieve this objective by applying one single large model, it was necessary to divide the scientific work into different modules, these being: changes in glacier surface area, volume and runoff, and snow melt volumes; detailed modelling of the hydrological cycle and runoff for small and large river catchments; analysis of low water and flood discharge.

The common basis for all hydrological and glaciological models was provided by recently developed climate scenarios for Switzerland (Bosshard et al. 2011a). This ensured that the results of all modules were comparable in terms of the time period and climate scenarios.

In order to be able to take account of the impact of glaciers on the hydrological modelling, the results of glacier modelling for the whole of Switzerland were considered uniformly (Linsbauer et al. 2012).

2.1 Time periods

Control period

The years 1980–2010 were taken as a common time basis, providing a control period for all projects. For some projects, slightly different (shorter) control periods had to be set, as determined by the available data. All details regarding changes in the climate or hydrological cycle scenarios relate to these control periods.

Scenario period

The periods 2021–2050 and 2070–2099 were taken for the scenarios. In this report, these two time periods are referred to as the Period 2035 or 'near future' and Period 2085 or 'long-term future' respectively. Further time periods were set for the investigations into glaciers.

In this document the results of individual days, months and years will not be compared and analysed, but rather the average values for these time periods or other statistical evaluations over the whole of the time periods, as is usual in climate studies. These restrictions are necessary to ensure that the results of climate modelling are meaningful (CH2011, 2011).

2.2 Area studied

Catchments

The area studied covers the whole of Switzerland plus the bordering areas which are drained by the large Rhine, Rhone, Ticino and Inn rivers. The whole area was divided up into 25 sub-catchments, which were individually modelled (Zappa et al. 2012). A further 189 areas were established to study sensitive medium-sized catchments (cf fig.

23 and fig. 27; Köplin et al. 2011). The low-water analysis was carried out in 29 catchments in the Swiss Plateau (cf. fig. 35; Meyer et al. 2011a). Questions on flooding were studied by Naef (2011) in 94 mainly very small catchments.

Glaciers studied

Detailed studies were carried out on the seven glaciers Aletsch, Rhone, Trift, Gries, Findelen, Silvretta and Morteratsch (VAW 2011). Linsbauer et al. (2012) looked at all glaciers in Switzerland in order to determine the degree of glacial retreat.

2.3 Models

Climate scenarios

The delta change method was used to calculate climate scenarios. Results from ten model chains selected from the European ENSEMBLES project provided the basis for this. Each chain resulted from the combination of a global climate model (GCM) and a regional climate model (RCM). The A1B greenhouse gas emissions scenario (IPCC 2008) formed the common basis for all models. The ENSEMBLES results were interpolated for 189 temperature and 565 precipitation stations and the delta change factors then determined. This was achieved by means of a harmonic analysis of the annual variations in temperature in precipitation, from which the average delta change factors for each day of the year were determined (Bosshard et al. 2011a, b, c; CH2011, 2011). All of these climate scenarios can be viewed at *www.ch2011.ch*.

Emissions scenario A1B

Water regime and discharge modelling

The well known PREVAH hydrological model (Viviroli et al. 2009) was used to model the water regime and runoff in three different variations:

> The original PREVAH model was used to study the sensitivity of medium-sized areas, whereby the model parameters were regionalised (Köplin et al. 2010, 2011, 2012).
> In order to model low water flow, the PREVAH model was extended by a module which made it possible to calibrate the base flow. This made it possible to calibrate on a multi-criterion basis, thereby improving the accuracy of low-water modelling in the future scenarios (Meyer et al. 2011b, 2012a, b).
> A variant of the PREVAH model was used to model the large catchments; this makes calculations on the basis of a grid of evenly sized squares rather than areas with comparable hydrological characteristics (hydrotopes) (Bernhard et al. 2011, Zappa et al. 2012).

Flood potential

The analysis of the catchments in terms of their flow characteristics and flood potential was carried out using a well proven method which allows us to predict runoff characteristics of surfaces during heavy rainfall. A differentiated presentation of the runoff characteristics in catchments can therefore be made (Naef et al. 2007, Naef 2011).

Detailed modelling of a selection of large glaciers is based on the glacier evolution and runoff model GERM. Using this model it is possible to simulate accumulation, ablation, glacier evolution, evapotranspiration and runoff formation in enhanced spatial and temporal resolution (Huss et al. 2008, Farinotti et al. 2011).

Modelling of all glaciers

Swiss modelling of all glaciers was carried out using the ‘equilibrium line shift’ model for applications in the PREVAH hydrological model. The model assumes that the equilibrium line rises as temperatures rise, and that the accumulation area becomes correspondingly smaller. Knowing the relationship between the accumulation area and ablation area of a glacier system which is in equilibrium with the climate allows us to determine the new total size of the glacier (Paul et al. 2007). Additional model approaches, the thinning model and GlabTop model, have been developed and tested for modelling throughout Switzerland (Linsbauer et al. 2012, Paul und Linsbauer 2012).

2.4 Data

The models used in the CCHydro project require extensive amounts of data from a wide range of areas. The main sources of data were:

> Swiss Federal Statistical Office FSO: land use, land cover, height model
> Swisstopo: digital height model, digital official maps, information on geology and land use
> MeteoSwiss: climate data time series, interpolated precipitation maps
> Federal Office for the Environment FOEN: hydrological data time series

2.5 Uncertainties

Uncertainties can be found in all components of the model chain used. They spread from one component to the next, becoming either stronger or weaker:

> One of the greatest uncertainties, in particular for the long-term future, lies in the emissions scenarios employed, as this involves making assumptions about population growth, economic development, trade, resource extraction and the impact of policies on greenhouse gas emissions reductions.
> Although climate modelling has made huge advances, the local climatic conditions in the Alpine area cannot be reconstructed. For example, the spatial resolution of the climate model does not allow us to establish clear values for Valais or the Engadine (CH2011, 2011).
> Current hydrological models are of a very high quality. It is however difficult to predict what future uncertainties in modelling will entail, as calibration applies to current environmental conditions and the parameters may change. There is still considerable uncertainty in the modelling of extreme values.
> There have also been huge advances in glacier modelling. However, it is still very difficult to determine reliably the rate at which glaciers of different sizes and lengths are retreating.

Ten climate scenarios

Uncertainties in climate modelling were taken account of by developing ten different climate scenarios to cover the potential range of future climatic conditions. These ten scenarios were therefore included in all hydrological and glaciological modelling, so that the climate-related uncertainties are considered in the runoff scenario uncertainties. This makes it is possible to form a picture of the changes in the Swiss water regime according to different developments in the climate.

3 > Climate change

Over the last 100 years the temperature in Switzerland has risen by more than 1.5° C. In the north a slight increase in annual precipitation has been recorded, and in the south there has been a slight decrease (both insignificant). These tendencies will continue and their intensity will depend on the way greenhouse gas emissions develop. The most dramatic changes are expected throughout Switzerland in summer: Based on the rather optimistic A1B emissions scenario, by the end of the century we can expect summer temperatures to be 4° C warmer and summer precipitation levels to be up to 20% less than in the period 1980–2009. Heat waves will become more frequent and will last longer. No reliable statements can yet be made about the intensity and frequency of future extreme precipitation events.

3.1 Previous observations

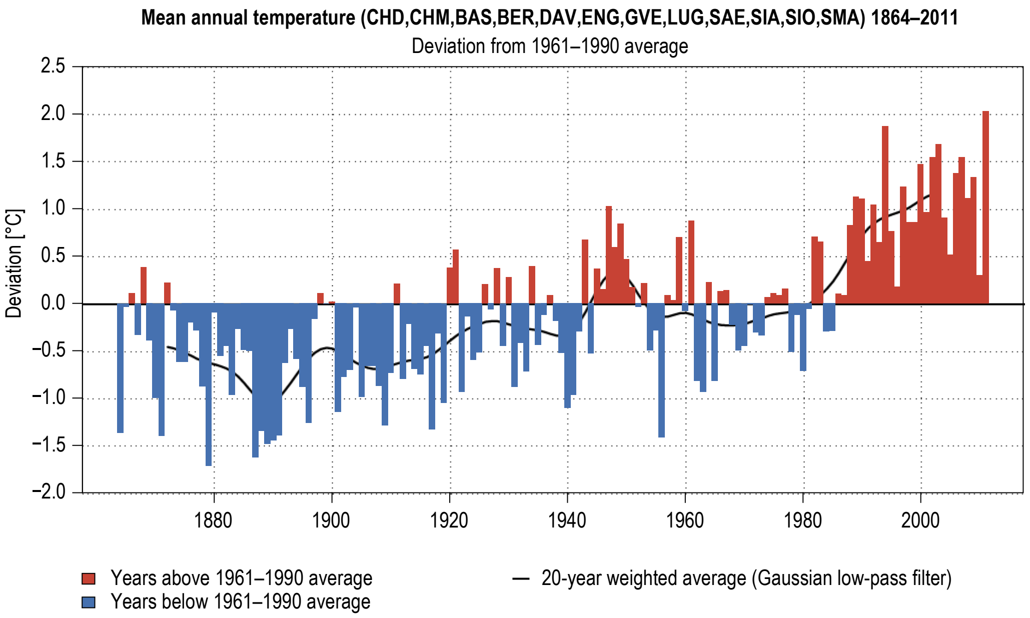
Temperature

In the last 100 years the average annual temperature in Switzerland has risen by more than 1.5° C (fig. 1). Over the past 30 years (1982–2011), the atmosphere has been warming up at an ever increasing rate, by as much as 0.5° C each decade. This value is the result of particularly marked increases in spring and summer at lower altitudes. Warming in Switzerland appears to be about twice that of the global average, which may be explained in part by the differences in physical characteristics of land and sea surfaces. Furthermore, large areas in the northern hemisphere, including the Alps, are covered in ice and snow. These areas are getting smaller, meaning there is a larger dark surface area and so lower albedo (ratio of reflected radiation to incident radiation) and an increase in the energy balance (snow-albedo and ice-albedo feedback).

Precipitation

Considerable natural variability makes it very difficult to make clear statements about changes in precipitation over the past century (fig. 2). The trends observed depend on the particular time period and differ according to season and geographical area: whereas between 1971 and 2000 precipitation amounts rose by up to 25%, particularly in the eastern foothills of the Alps, between 1982 and 2011 they fell by about 15%, in particular in western and southern Switzerland (fig. 3).

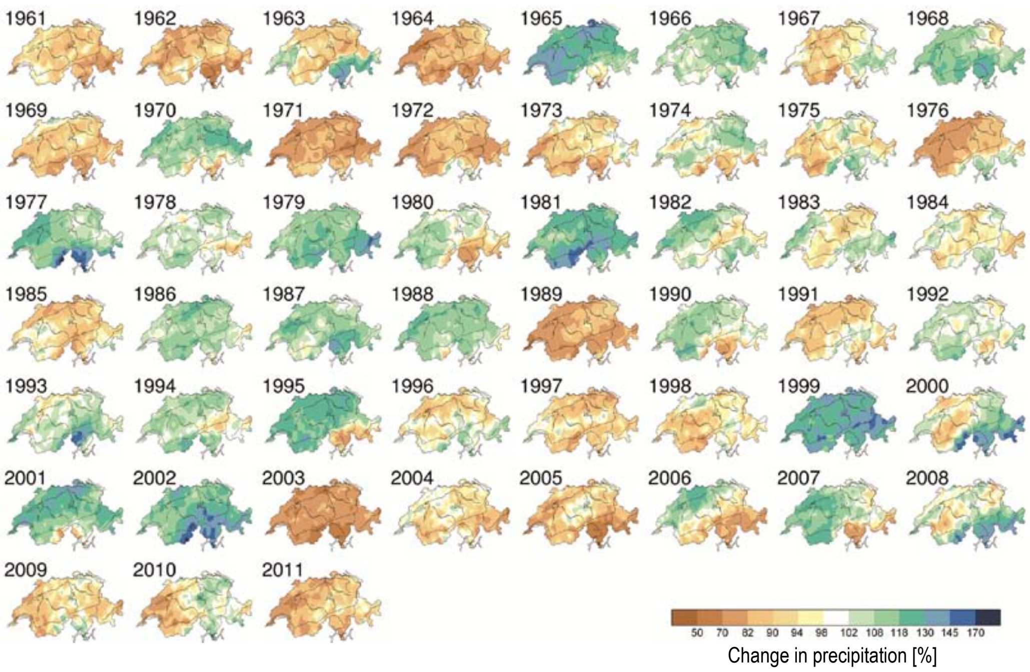
Fig. 1 > Deviation in average annual temperature from the average for 1961 to 1990 in Switzerland



MeteoSwiss 2012a

Fig. 2 > Spatial patterns of deviations in annual precipitation amounts over the past 50 years compared with the period 1961–1990

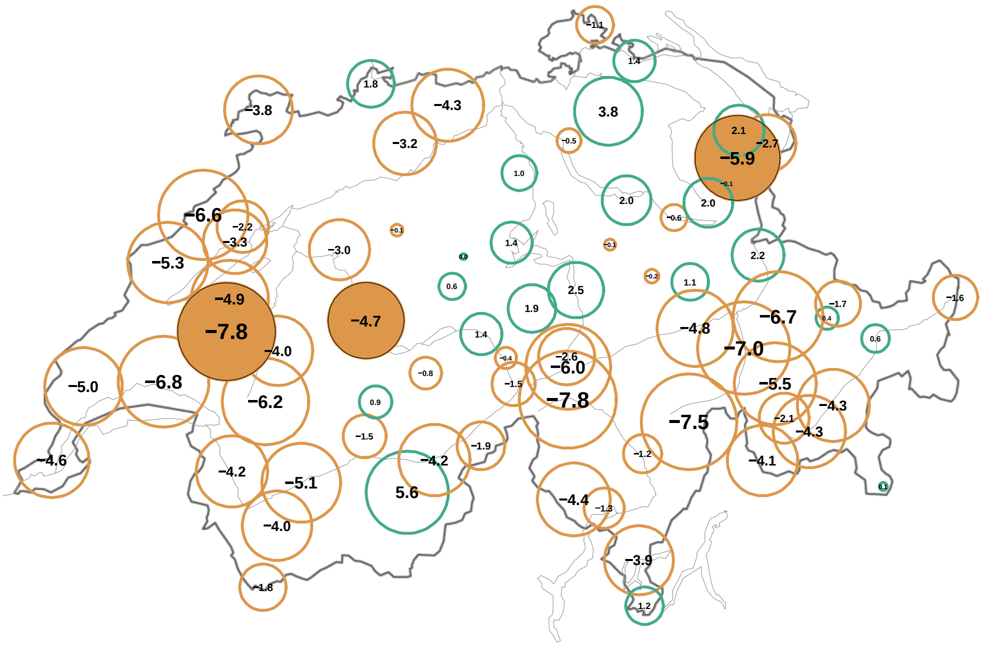
Wetter and drier phases can be distinguished, and there are years with marked regional differences. These changes can be ascribed to the variability in atmospheric circulation.



MeteoSwiss

Fig. 3 > Spatial pattern of annual changes in precipitation from 1982 to 2011 in Switzerland

Whereas there are clear temperature trends in all regions and at all altitudes, there are marked regional differences in precipitation levels. The size of the circles indicates the extent of the change per decade as a percentage. Green indicates an increasing trend, brown a decreasing trend. Filled circles indicate a significant downward trend with 95% confidence.



MeteoSwiss 2012b

3.2 Most recent climate scenarios

A1B emissions scenario as basis

The global and regional climate models used to create the most up-to-date climate scenarios are based on what are known as emissions scenarios. These were drawn up by the Intergovernmental Panel on Climate Change (IPCC 2008) and predict possible future developments in greenhouse gas emissions. They take account of demographic, socioeconomic and technological factors and energy policy measures. However, it is not possible to provide an accurate projection of trends in world population growth and the global economy’s dependence on fossil fuels. For this reason, future levels of greenhouse gas emissions can only be forecast with great uncertainty. Emissions trends will influence the way in which annual temperatures and summer precipitation change over the next century (fig. 4). The A1B scenario, upon which this study is based, assumes that by 2050 emissions will have increased twofold compared to 1990 levels, and will become stable thereafter. Under this scenario, the world economy will continue to grow rapidly, as will the global population. Fifty percent of our energy needs will be met by renewables and the other fifty by fossil fuels.

Fig. 4 > Global greenhouse gas emissions

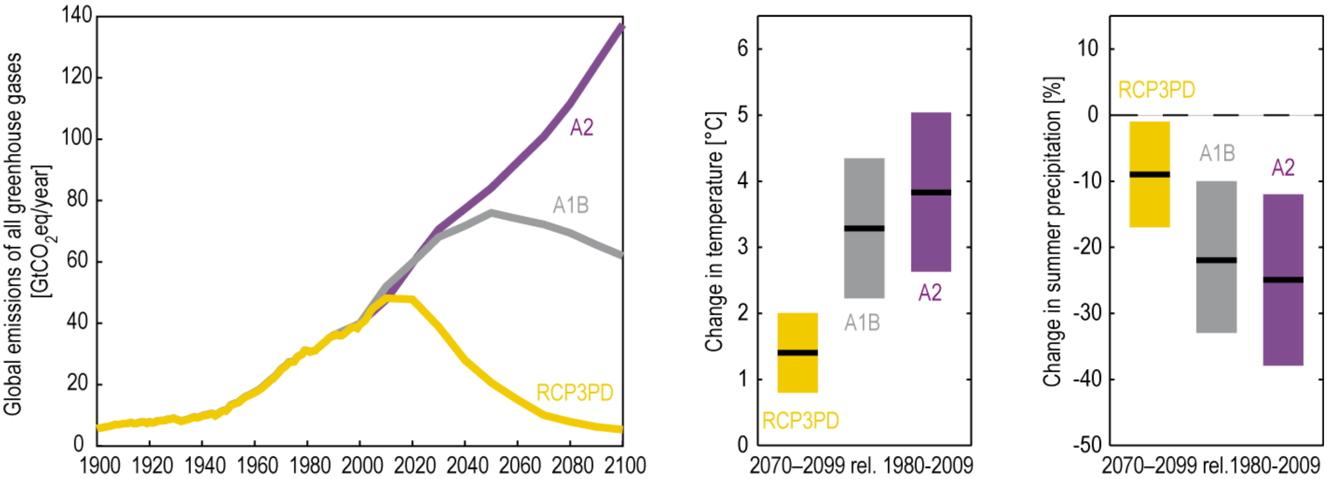
Past and three possible future developments in global greenhouse gas emissions in CO_2 equivalents. The RCP3PD scenario envisages a reduction in greenhouse gas emissions necessary to reach the 2° C target (limiting global warming to 2° C compared to the pre-industrial period).

Change in temperature

Medium-range temperature changes (changes in° C) for Switzerland up to the 2070–2099 scenario period compared with the 1980–1999 reference period, based on the three emissions scenarios. The black lines indicate average values; the coloured bars indicate the extent of model uncertainties.

Change in precipitation

Similar development scenarios as for the middle graph, but for summer precipitation levels (changes in%).



CH2011, 2011

Climate scenarios drawn up for CCHydro

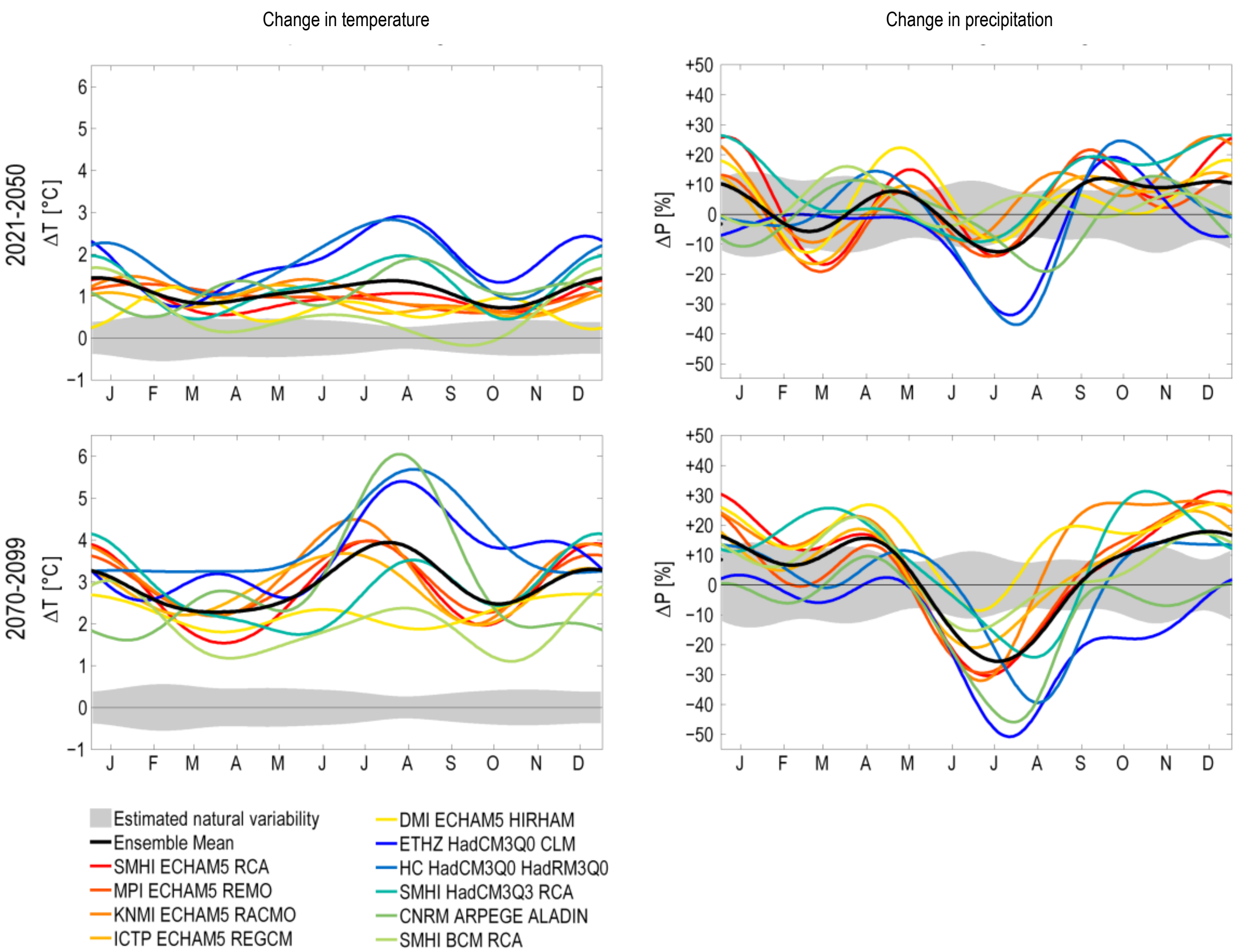
Regional climate scenarios were developed for Switzerland using a range of methods (CH2011, 2011). These are based on the results of the European ENSEMBLES project. Probabilistic seasonal scenarios were calculated for the three major regions (northern, western and southern Switzerland), based on three emissions scenarios. The scenarios used in the CCHydro project are based on ten model chains and one single emissions scenario, but provide information at daily and local resolution (Bosshard et al. 2011a). Taking the A1B emissions scenario as a basis, each model chain simulates possible climatic development for the whole of Europe up until the year 2100. In each model chain a global climate model with low spatial resolution was used, the results of which were refined by a regional climate model with greater spatial resolution (25 x 25 km). It is hoped that this will provide a better description of the regional variability in the climate parameters, in particular in the topographically complex Alpine area. However, despite the relatively high spatial resolution of the regional climate models, local climatic conditions (e.g. inner-Alpine valleys or individual mountain peaks) cannot be depicted.

Delta change method

It was necessary to process the data in order to be able to use them in further small-scale hydrological investigations. The results of the regional climate models were interpolated applying inverse distance weighting to the four nearest grid points at individual sites (189 temperature and 565 precipitation sites). This smoothed the results spatially. The actual climate signal also had to be isolated from natural variability. This was done by applying a spectral filter over the annual cycles and then using it in the delta change method (Bosshard et al. 2011b). A climate change signal for temperature and precipitation was calculated for each station and each day of the year, (an example is shown in fig. 5). The data observed at the stations were altered with the climate change signal. Two limitations to this delta change method should be mentioned: it is unsuitable for estimating changes in extreme precipitation events, and it does not record the impact of changes in the frequency of certain weather conditions on temperature and precipitation variability.

Fig. 5 > Annual cycles of climate change signals for temperature and precipitation for the Bern/Zollikofen station and both scenario periods 2021–2050 (above) and 2070–2099 (below)

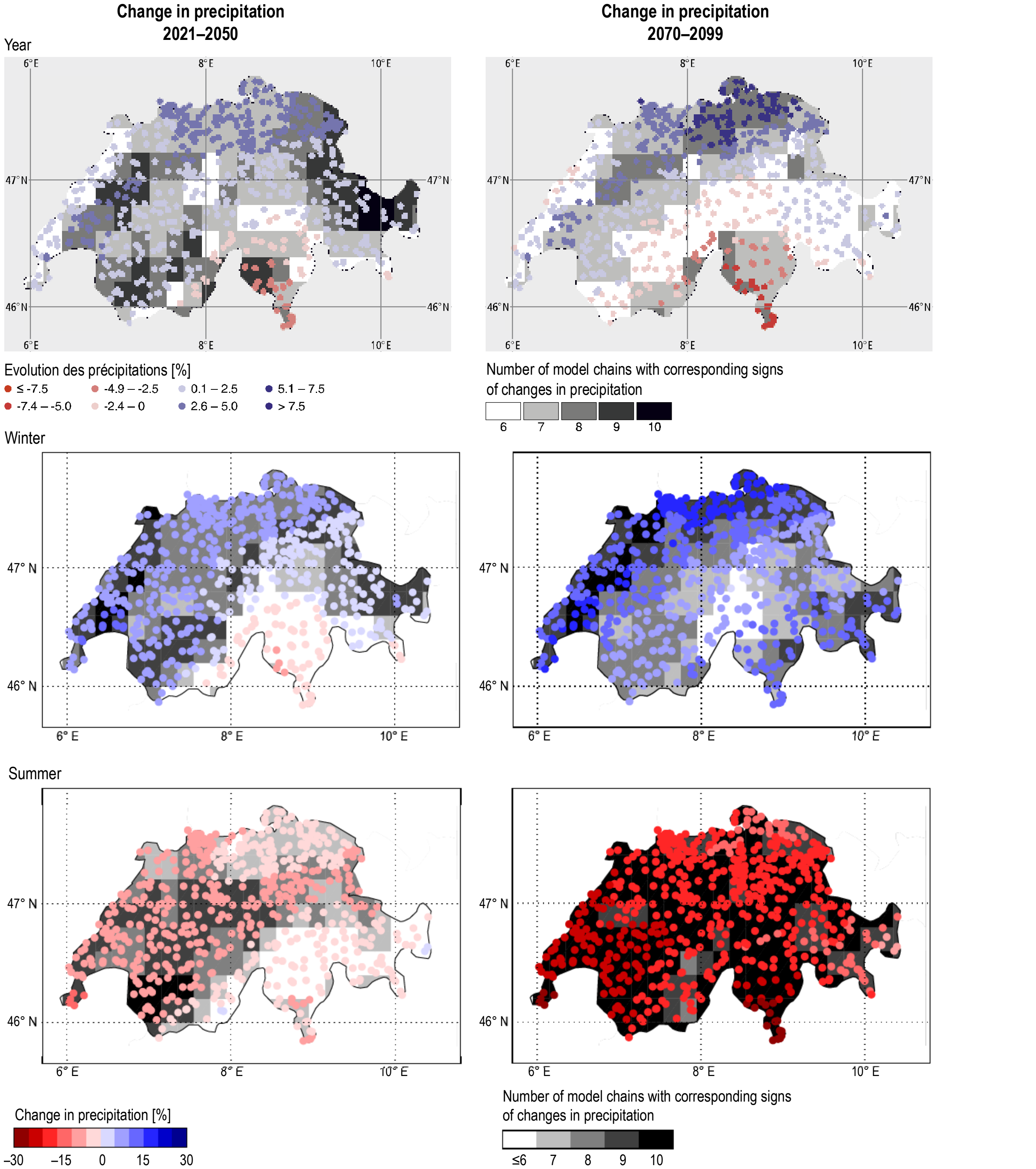
The black line represents the average of the 10 model chains used (coloured lines). The grey area shows the standard deviation in natural variability.



Bosshard et al. 2011a

Fig. 6 > Spatial pattern of changes in precipitation for the periods 2021–2050 and 2070–2099 compared with 1980–2009

The top images show changes in the annual totals; in the middle are changes in winter precipitation amounts and at the bottom, changes in summer precipitation amounts. The grey shading shows the number of climate model chains with similar indications of changes in precipitation. The darker the area, the better the correspondence between the model chain and the trend.



Bosshard et al. 2011a

Changes in temperature and precipitation

All model chains predict an increase in temperature in all periods of the year over the next few decades. For the period 2021–2050 warming is already expected to be consistently above the margin of uncertainty of natural variability, and this trend will continue up until 2070–2099 (fig. 5). The greatest changes in temperature are expected to occur in summer on both sides of the Alps. Seasonal and regional differences in precipitation will become greater over time (fig. 6). There is predicted to be a clear decrease in summer both north and south of the Alps (of 18 to 28% by 2070–2099). In the south, a marked increase in precipitation is expected in winter. In the north, there is likely to be less precipitation in summer only, and more at other times of the year. A clear summary of the results is presented in fig. 7. Over the course of the year, a north-south pattern can be discerned: In the north slightly more humid conditions are expected, while in the south conditions will be slightly drier (fig. 6).

Fig. 7 > Climate change in Switzerland for the two periods 2021–2050 and 2070–2099 under the A1B emissions scenario

The figure shows temperature (Ensemble average), uncertainties in temperature (standard deviation) and precipitation trends (provided at least 7 of the 10 model chains agree on the direction of change. Red arrows indicate dry conditions, blue arrows indicate wetter conditions. N stands for Switzerland north of the Alps. S (south) indicates Ticino, south-eastern Valais, the Engadine and the southern valleys of Graubünden.

	2021–2050		2070–2099	
	Temperature	Precipitation	Temperature	Precipitation
Year	+1.2°C ± 0.5°C	N S	+3°C ± 1°C	N S
Spring	+1°C ± 0.5°C		+2.5°C ± 1°C	N S
Summer	+1.5°C ± 0.5°C	N	+4°C ± 1°C	N/S
Autumn	+1°C ± 0.5°C	N	+2°C ± 1°C	N
Winter	+1°C ± 0.5°C	N	+3°C ± 1°C	N/S

slight (< 10%) heavy (10 - 20%) very heavy (> 20%)

Bosshard et al. 2011

3.3
Extreme events

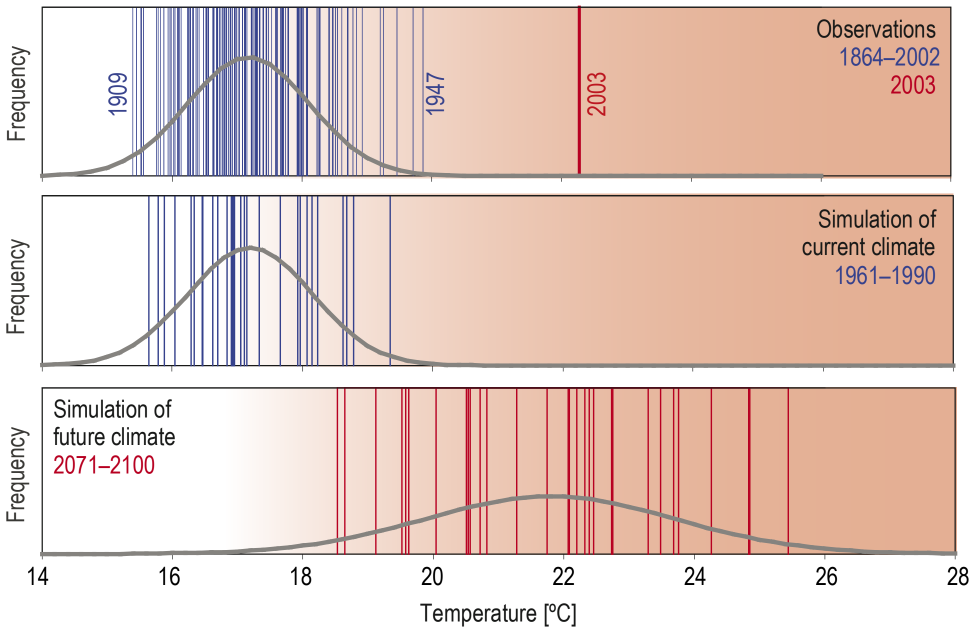
Heat waves

Climate change will have an impact on average values and the distribution of climatic parameters and therefore on the frequency of extreme events (fig. 8). In summer there will be more frequent heat waves, as suggested by the most recent CH2011 calculations (CH2011, 2011). Extreme summers such as 2003 could become the norm towards the end of the century (Schär et al. 2004), with every second summer being at least as hot as that of 2003. Greater inter-annual variability in summer temperatures is also expected. Most models agree that dry periods in summer will become longer, but there is still considerable uncertainty about this (values range between –10 und + 70% [CH2011, 2011]). At the moment it is not possible to make quantitative statements about the future frequency and intensity of summer thunderstorms. There is a considerable spread in results regarding intensity of extreme precipitation events across the different model chains (CH2011, 2011). The ENSEMBLE average value does not indicate any clear trend. With the current state of knowledge, it is not possible to predict whether there will be an increase or decrease. An earlier study predicted an increase in the frequency of extreme precipitation events by up to 50% in spring (Frei et al. 2006).

Heavy precipitation

Fig. 8 > Expected changes in the distribution of summer temperatures compared with 1961–1990

The form and position of the distributions (average, span) relate to the frequency and intensity of extreme events.



OcCC 2008, nach Schär et al. 2004

3.4 Uncertainties in the climate scenarios

The regional climate models are linked to global models and both types of model therefore contribute towards uncertainty in the scenarios. Besides processes for which parameters need to be defined in climate models due to their low spatial resolution, there are others which have not yet been sufficiently researched. There are thus still considerable uncertainties regarding cloud cover and its effects on albedo, and regarding changes in the carbon dioxide cycle (in particular the absorption and release of CO_2 by plants and the oceans). Furthermore, changes in atmospheric circulation or seasonal phenomena can often only be simulated unsatisfactorily (ProClim, OcCC 2011). Studies using global models for temperature and precipitation in Europe have shown that the greatest uncertainties (50 to 85%) are of intrinsic origin (Prein et al. 2011), that is to say, arise from uncertainties in the modelling. Ten to twenty percent result from the natural variability in the chaotic system. The impact of the emissions scenarios on the overall temperature uncertainty is almost negligible up to 2050. Thereafter, the scenarios are the source of growing uncertainty (up to 35%). The overall uncertainty in the precipitation results is considerably greater and less influenced by the development in emissions than temperature (fig. 4). This can be explained by the fact that precipitation shows significant natural variability (fig. 5) and due to the complexity of the model processes a wide range of parameters is involved.

4 > Glaciers

Since the end of the Little Ice Age (circa 1850), the volume of the glaciers in Switzerland has declined by at least half. Were current climate conditions to remain stable, the glaciers would lose half of their current volume over the next few decades before achieving a new state of balance. However, if temperatures increase as expected, glacial retreat will accelerate. Models predict that by 2100 20–30% of the current glacier volume will remain, largely in the Rhone basin.

4.1 Basic processes

As glacial ice is formed from restructured, compacted snow, glaciers are only found where snow falls over many years. Snow collects in suitable topographical areas (high altitude, not too steep) and, over the decades, turns into ice under the pressure of the layers of snow above. Under the force of gravity this then flows valleywards into areas at higher temperatures, and melts. The flowing ice transports mass from the area where ice accumulate to the zone in which they ablate, and if climatic conditions are constant, a glacier forms in which accumulation and ablation are in balance. The equilibrium line divides the accumulation and ablation zones. For there to be mass balance, the accumulation zone (corresponding roughly to the area still covered by snow at the end of the summer) should on average be about 60% of the total area (e.g. WGMS 2009). If it is smaller as a result of a change in the climate (e.g. higher temperatures), the amount of ice that melts is usually greater than the amount of snow added to the glacier, and there is a total net loss in mass.

Glacier mass balance – Glaciers will continue to retreat

Besides annual changes in the mass balance which are the direct result of the weather experienced during the year (temperature, precipitation, irradiation etc.), over the long term the extent of a glacier can also clearly be seen to be reacting to changes in the climate. A glacier can be envisaged as a kind of conveyor belt of ice, which gets shorter more as the ice melts at a faster rate than it forms (and vice versa). The rate at which the ice flows determines how much ice is delivered, and is a determining factor in the growth or retreat of the glacier. The flow rate gradually decreases as less snow falls to feed the glacier: less ice flows into the valley, the glacier becomes thinner and shorter, thereby reducing the ablation area. However, this all takes some time, and meanwhile the climate has probably changed again. A change in glacier size is the result of continuous and long-term adaptation to a climatic signal in the past. The current glacier extent is much too great for current temperature levels; if temperatures were to remain stable over the next few decades, glacial mass would nonetheless continue to decrease. This is particularly true of large glaciers, which take a long time to adapt. Over time, about half of the current volume of ice in Switzerland would disappear, until a new equilibrium was established.

4.2 Changes in glaciers since the Little Ice Age

Maximum extent around 1850

In the so-called Little Ice Age (1600–1850), summers in the Alpine area were frequently cool and the snow line was generally low. These climatic conditions were favourable to glacier growth and led to maximum glacier extent in about 1850 (fig. 9). The fluctuations in glacier extent in the Alps during the Little Ice Age are well documented in numerous pictures and written documents (Zumbühl et al. 2008). After 1850 there was a rise in temperature and in summer the glaciers frequently lost more mass due to melting than they gained during the year due to snowfall (negative mass balance). As a result, the glaciers began to retreat over the long term, although this trend was broken for a few years in the 1890s, 1910s and 1970s, when mainly smaller glaciers experienced a modest gain in size (fig. 10). Cool summers and a generally lower snowline were characteristic of these interim phases. Large glaciers such as the Great Aletsch adapt only very slowly to a changed climate and do not react to short-term climatic fluctuations (fig. 10).

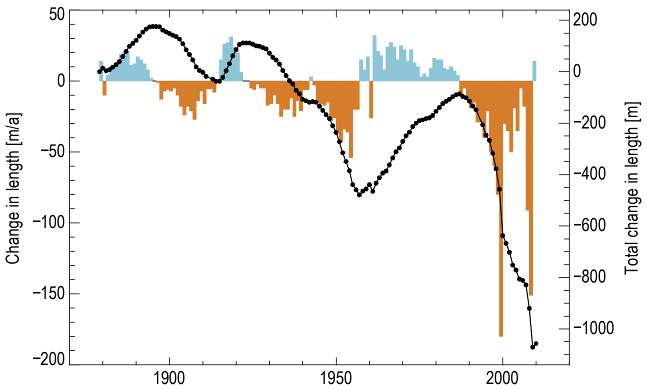
Fig. 9 > The Great Aletsch glacier in 1880 and 2010, photographed from Hotel Belalp

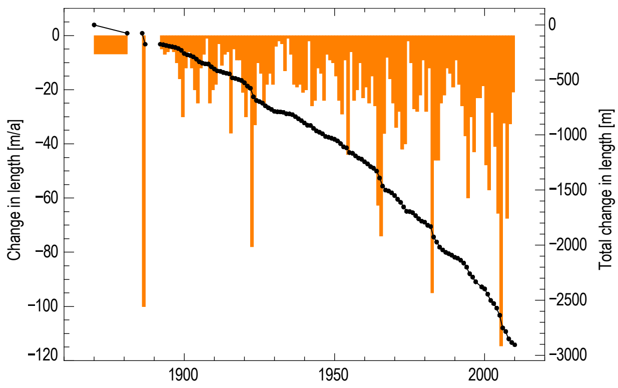
Photos: www.myswissalps.ch/507, H. Holzhauser (left); R. Schmid (right)

Glacier volumes – thinning of one metre per year

Between 1960 and 1980 summer temperatures remained fairly constant, but have risen by about one degree Celsius since; most summers have been markedly warmer than the average for 1961–1990, although snow accumulation on glaciers has barely changed. This has resulted in considerable thinning of the glaciers in Switzerland, which is currently occurring at a rate of about one metre per year. The amount of ice lost annually differs depending on the characteristics of the glaciers and their surroundings (elevation, topography etc.). For the existing total glacier area of around 1000 km² this corresponds to an annual loss in the volume of ice of about 1 km³, with approximately 55 km³ ± 15 km³ still remaining. The resulting volume of meltwater averages a total of 25 m³ per second over the year; the majority of this flows off the glaciers between the months of June and September, at a much greater rate.

Fig. 10 > Change in length of the Trient glacier and the Great Aletsch glacier





Glacier reports 1881–2011

4.3 Glacier retreat scenarios

Initial model calculations for the expected retreat of the glaciers throughout the Alpine area (Haeberli & Hoelzle 1995, Zemp et al. 2006) are largely confirmed here by more recent and more detailed model calculations. The use of digital elevation models (DEMs) and glacier limits allows us to model the basic physical connections and extrapolate them for given future climate scenarios. The input data required for the calculations may vary depending on the model. An initial model, based on a mass-balance approach, was applied to individual glaciers and their hydrological catchments; besides the glacier evolution it also calculated development in runoff (VAW 2011). A second model, based on an equilibrium line approach (Paul et al. 2007), showed the future development of total glacier area in Switzerland in order to predict future total runoff using a hydrological model (Chapter 6).

4.3.1 Modelling for individual glaciers

Modelling of large glaciers

The modelling in VAW (2011) is based on a combined hydro-glaciological model (Glacier Evolution Runoff Model, GERM, Huss et al. 2008) to predict the future evolution of ice masses and runoff in nine glaciated catchments. The strongly glaciated areas looked at in this study, Gorner and Mattmark (SGHL and CHy 2011) and Aletsch, Rhone, Trift, Gries, Findelen, Silvretta and Morteratsch (VAW 2011), contain about 40% of the current ice mass in Switzerland. Additional studies are also being conducted under the National Research Programme NRP 61. The modelling is based on daily data for temperature and precipitation and also takes into account irradiation conditions (shadow zones). Homogenised historical data were provided by MeteoSwiss. Projected values were generated taking account of changes in climate signals (Bosshard et al. 2011a). In order to consider variability in temperature and precipitation, for each of the ten model chains considered, ten different future time series were generated displaying the variability observed in the past. This created a series of 100 possible developments in temperature and precipitation for the period 2010–2100 with which to feed the GERM model. Glacier measurements (contours and elevation of ice surface from topographical maps and aerial photographs from the 1960s onwards), and data on the depth of the glacier bed (radar profile) and mass balances were used to calibrate the model.

4.3.2 Glacier modelling throughout Switzerlnad

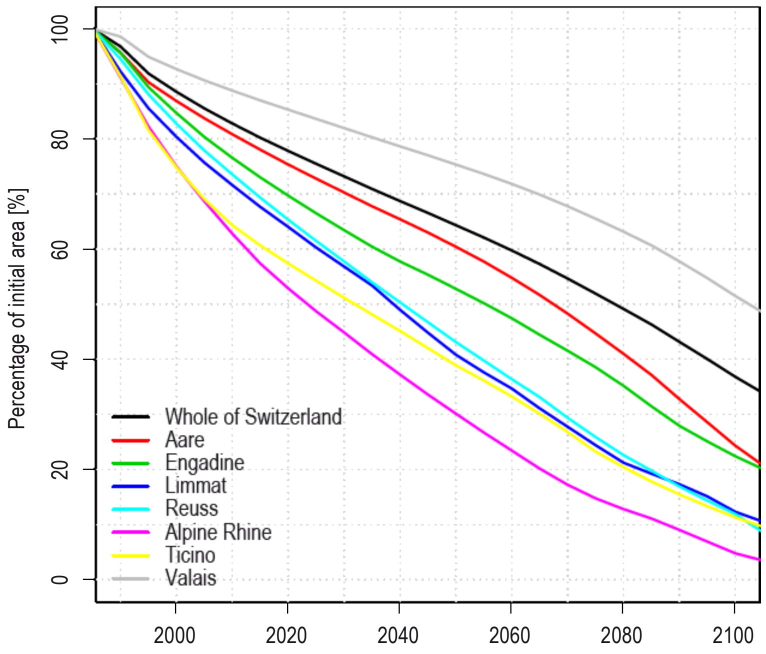
All glaciers in Switzerland – a lot of ice in Valais

In order to model the future evolution in water runoff for the whole of Switzerland (cf. Chapter 6), it was necessary to create scenarios for the future extent of all glaciers. To do this the model by Paul et al. (2007) was used, which determines new glacier surfaces on the basis of a terrain model and digital glacier profiles for a given rise in temperature. For this study, the results of temperature evolution by Bosshard et al. (2011a) were combined into three scenarios and linked to the model applying a shift in the equilibrium line caused by a change in temperature. This results in a new area for all glaciers in Switzerland, with 100-metre spatial resolution and in five-year time increments. In order to implement time dependency in the model, it was assumed that glaciers take 25 years to adapt to new climatic conditions. This is a mean value for most glaciers, which admittedly overestimates the rate at which the surface area of large glaciers declines and underestimates the rate at which small or very steep glaciers retreat. A further model was used to determine the evolution in surface area and volume of all Swiss glaciers. Firstly the spatial ice thickness distribution for all glaciers was determined and then the glacier thinning observed in the period 1985–2000 was extrapolated linearly into the future (Linsbauer et al. 2012).

4.3.3 Findings

By the end of the century, depending on the model and climate scenario, we can expect to see a loss of between 60 and 80% of the current glacier cover in Switzerland. The greatest absolute losses will be experienced in the Rhone and Aare basins, as this is where there is most ice. However, due to the thickness of the ice in these regions, the relative losses in surface area will occur only slowly (fig. 11). Four-fifths of the current total volume of ice in Switzerland is found in Valais, and so this is where the greatest amounts of ice will remain in 2100 (still about 30%) of the current ice masses. Other regions are expected to have 10% at most remaining. There are considerable differences between the studied areas in terms of size, altitude and extent of glaciation. No general conclusions can be drawn from the findings in individual catchments, therefore.

Fig. 11 > Relative changes in area between 1985 and 2100 for each large catchment separately and for the whole of Switzerland according to thinning model in nationwide modelling

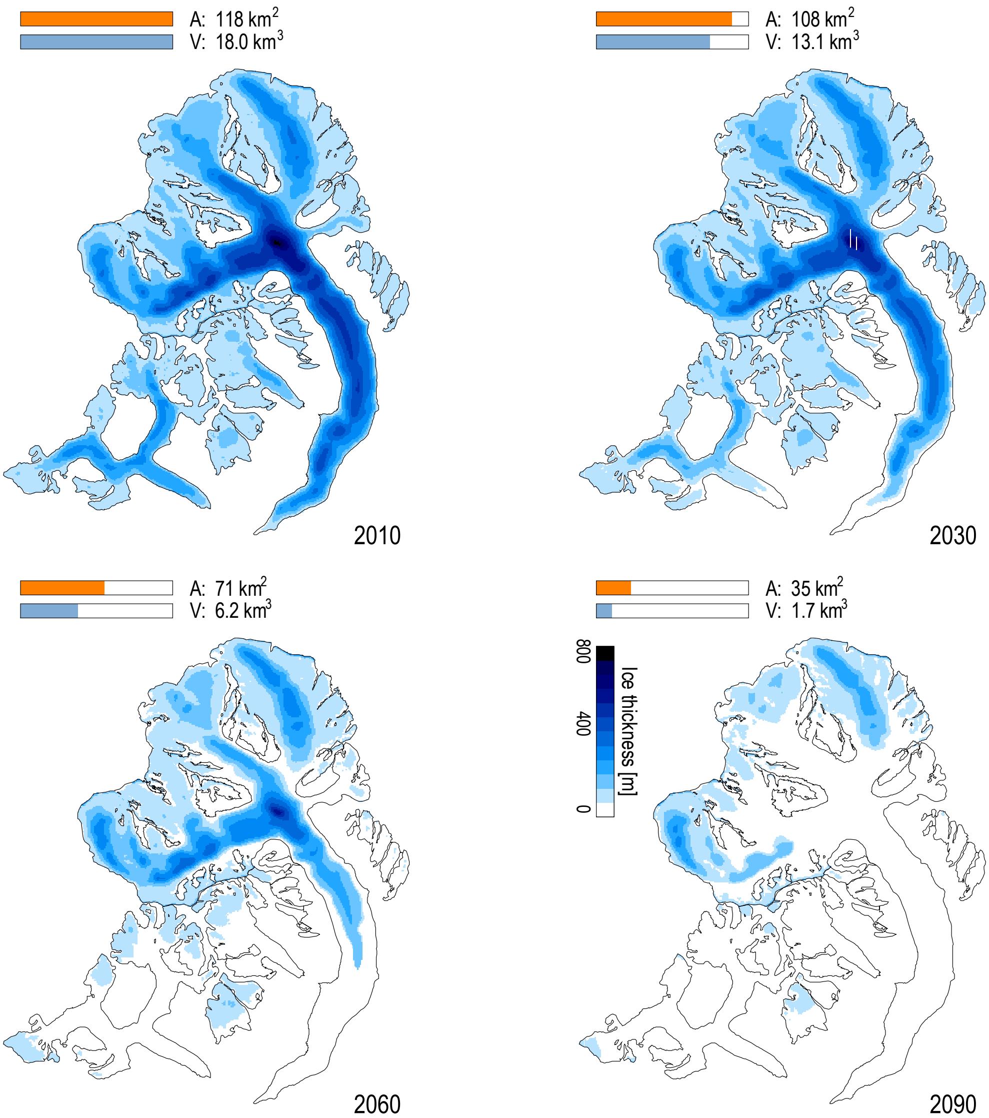


Linsbauer et al. 2012

As examples from the models for individual glaciers, Figures 12 and 14 show glacier evolution in two catchments with differing characteristics. Despite its thickness (up to 900 m of ice at Konkordiaplatz), the Aletsch glacier will have largely lost its snout by 2100 (fig. 12). The principal reason for this is the low-lying glacier bed, which means the glacier cannot retreat to higher (and therefore cooler) altitudes. Instead, the ice becomes thinner and the glacier surface drops to lower and therefore warmer altitudes. This is a self-reinforcing process which accelerates melting and is also expected to occur in, for instance, the Unteraar glacier, as modelling for the whole of Switzerland with the thinning model shows (fig. 13). Glaciers at higher altitudes such as the Silvretta glacier (fig. 14) will react later, but more rapidly. The comparatively flat accumulation area will then be completely snow-free and become ablation area. Under these circumstances, the whole glacier will disappear very quickly. This process has already begun in the similarly flat Plaine-Morte glacier.

Fig. 12 > Development of glaciers in Aletsch region to 2090

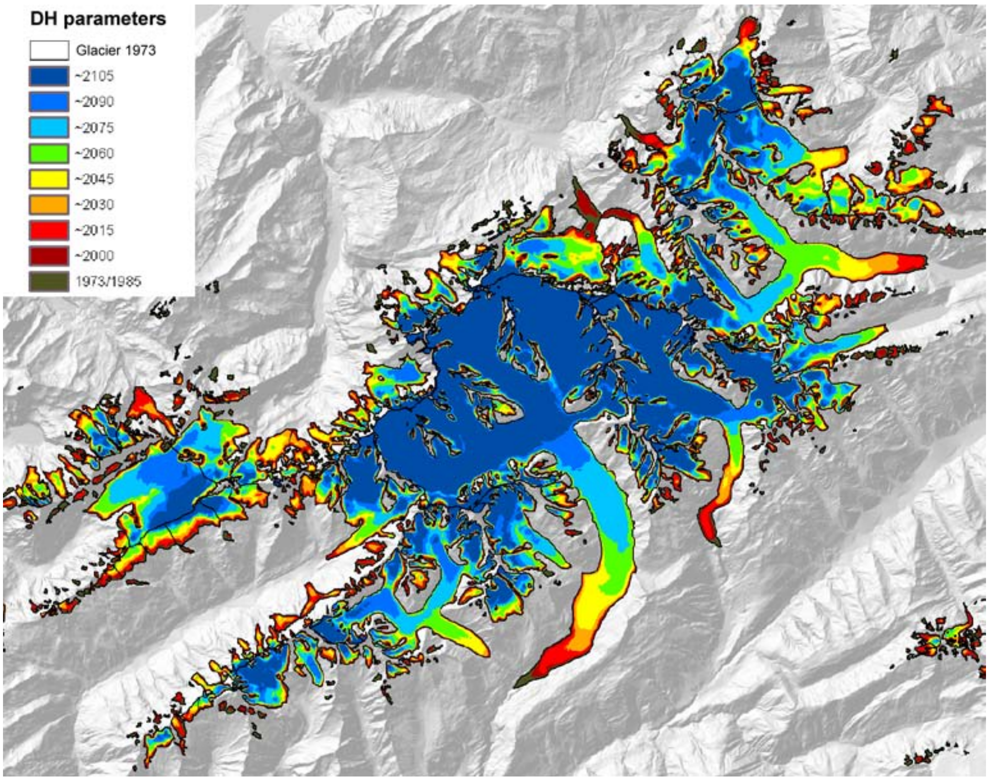
The glacier profiles show the situation in 1999. The blue areas show average ice thickness. Areas which are predicted to be ice free in more than half of all possible scenarios are shown in white.



VAW 2011

Fig. 13 > Extract from the nationwide modelling for the Aletsch region with thinning model

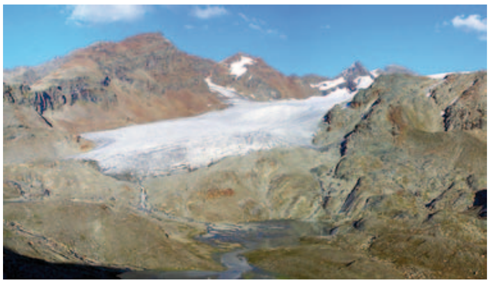
Despite differences in the methodology, the findings are similar to those presented in fig. 12.

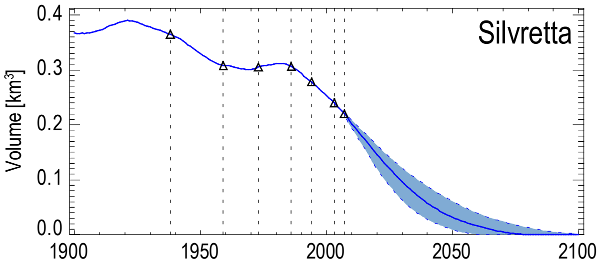


Linsbauer et al. 2012

Fig. 14 > Silvretta glacier

The small Silvretta glacier will have disappeared by the end of the century (see ice volume in glacier area, right).





VAW 2011; Photo: http://glaciology.ethz.ch/swiss-glaciers/glaciers/silvretta.html, M. Huss

New lakes

When the glaciers melt, areas of overdeepening in the bedrock will be exposed in which new lakes may form (Linsbauer et al. 2012). This process has been observed in numerous large valley glaciers (z. B. Trift, Gauli, Rhone) in recent years and is also a problem in other countries. The lakes may increase the risk of local natural hazards occurring (rockfalls into the lakes causing flood waves), but they also present opportunities for hydropower (SGHL & CHy 2011) and tourism (NELAK 2012).

4.3.4 Uncertainties

Ice melts more rapidly

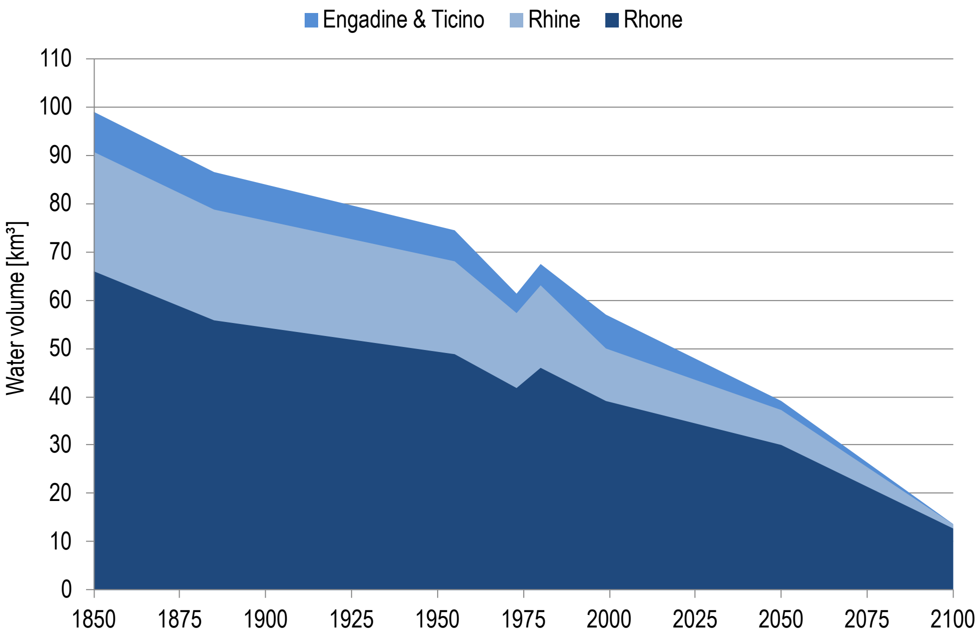
The models used to gauge future glacier evolution are not perfect, and the current volume of ice in Switzerland can only be determined to within 20 to 30% accuracy, as the models used to determine the distribution of ice thickness can only provide an approximation of the complex reality (Farinotti et al. 2009, Linsbauer et al. 2009, 2012). Furthermore, the uncertainties in the climate scenarios create uncertainty in the glacier scenarios. In all models used to determine glacier evolution, a range of processes were not taken account of. These include the decline in albedo values observed over recent years (dust makes the surface darker, causing the ice to melt at a much faster rate), and this is expected to continue in future and increase the rate of melting even more (Oerlemans et al. 2009). The formation of lakes at the glacier snout may also lead to more rapid melting. On the other hand, additional material deposits from destabilised rock faces and moraines caused by the lack of pressure from ice (now melted) and thawing permafrost above the glaciers may slow down the rate at which the ice melts.

4.4 Conclusion

Figure 15 shows a overview of the development in ice masses for the three large catchments in Switzerland from the end of the Little Ice Age up to 2100. It is based on extrapolated estimations and past glacier inventories and modelled findings from this study. Apart from a short period of recovery in the 1970s, there is a clear downwards trend. There will no doubt still be ice in Switzerland in 2100, but there will no longer be the typical glaciers that we are familiar with today. If, by the end of the 21st century, temperatures rise much more dramatically than in the middle scenario selected here, the glaciers will disappear at a much faster rate. The consequences for runoff in the glaciated catchments are discussed in Chapter 6.

Fig. 15 > Development in volume of water stored in Swiss glaciers (Rhone and Rhine basins, Engadine and Ticino) since the end of the Little Ice Age

Estimated since the end of the Little Ice Age (degree of uncertainty 20–30%) and simulated up to 2100.



Schädler 1985; Farinotti et al. 2009; Linsbauer et al. 2012

5 > Snow

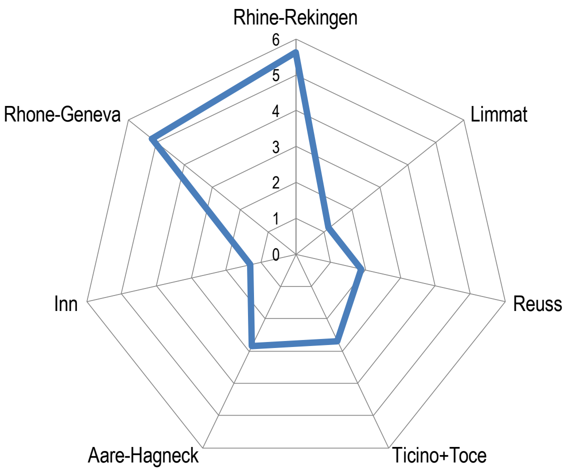
Each year, snowmelt contributes about 22 km³ of water to runoff in Switzerland. That is about 40% of the total runoff and is considerably more than the amount contributed by glacier melt (1 km³).
As temperatures continue to rise, so will the snowline, and regions up to about 3500 m above sea level will be increasingly snow-free in summer. By the end of the century, snow cover at altitudes below 3500 m will last about one month less. Furthermore, the maximum depth of the snow will decline by more than half. This will mean a reduction of about 40% in the water reserves contained in snow cover.

Snow cover provides the greatest amounts of meltwater

Whereas water is stored in glaciers over several decades, it remains in the form of snow for only a few months. Snow cover increases during winter and the amount of stored water gradually reaches its maximum, until temperatures rise again and the snow begins to melt. About 22 km³ of snow melts in Switzerland annually (Zappa et al. 2012). This large amount is the annual average volume of water from snow cover which can be expected as runoff from the catchments in Switzerland (fig. 16). Up until now, little attention has been paid to the role of snow cover in the hydrology of Switzerland. As climate change progresses, this situation is sure to change.

Fig. 16 > Annual volume of meltwater from snow in large catchments in Switzerland (average values 1980–2009, in km³)

The greatest snow reserves are in the Rhone and Rhine basins.

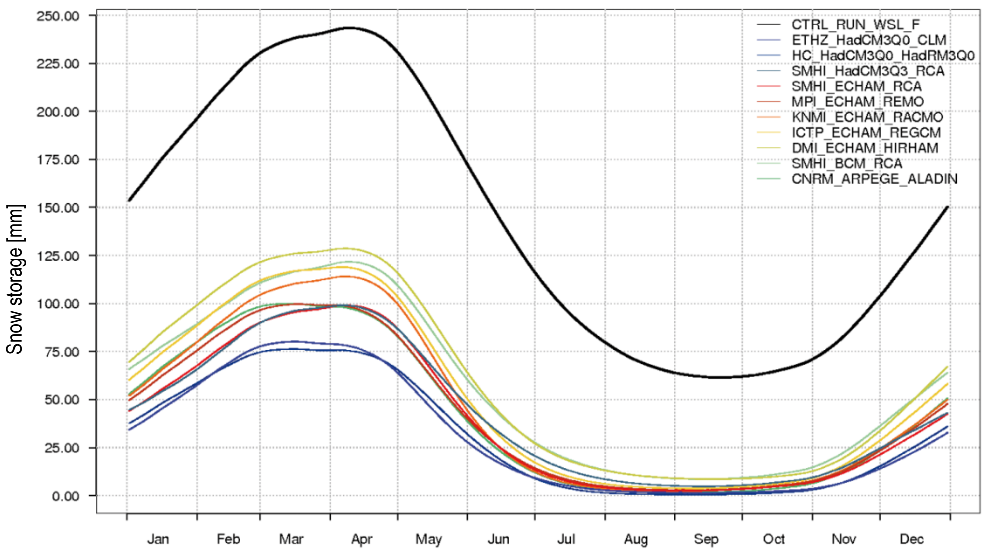


Zappa et al. 2012

Changes in snow cover

It is assumed that the maximum water equivalents in snow cover will decrease dramatically in future, except for at very high altitudes. Zappa et al. (2012) estimate that in Switzerland the maximum amount of water stored as snow will decrease by 20 to 50% by 2035 and even by 50 to 60% by 2085 (fig. 17). The depth of snow will increase more slowly in winter in the long-term future, and the maximum will be reached about two weeks earlier than now. Furthermore, there will be less natural annual fluctuation in the volume of water stored as snow, as there will be fewer winters with a lot of snow. The average time the snow lasts will also decrease: by 2035 this can already be expected to be 25 days fewer than now above about 1200 m (Hänggi et al. 2011). However, there are considerable uncertainties in the model predictions.

Fig. 17 > Yearly cycle of snow cover water equivalent (coloured line, in mm) in Switzerland for the scenario period 2070–2099 compared with control cycle 1980–2009 (black), based on a range of climate model chains

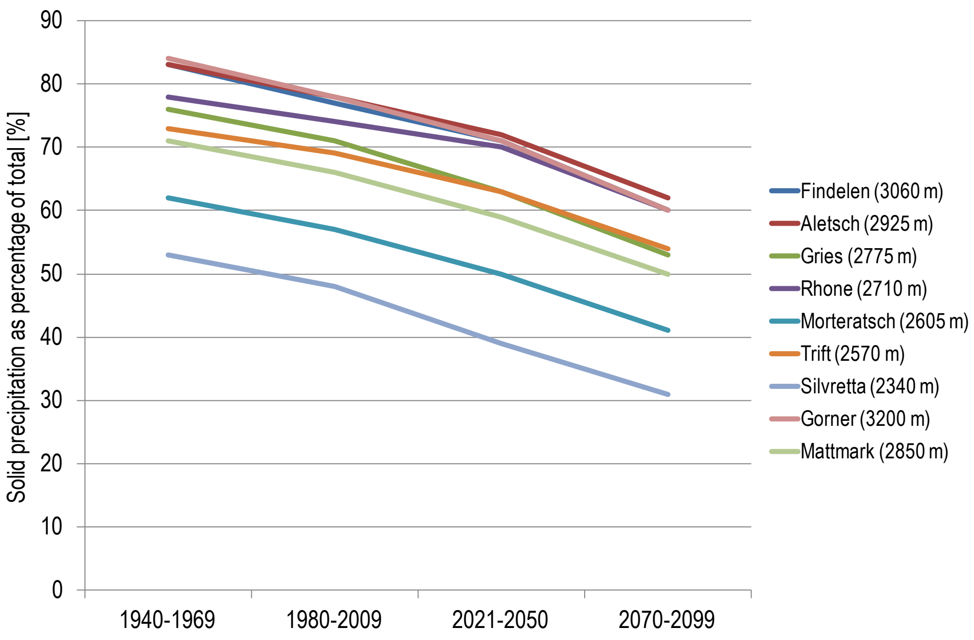


Zappa et al. 2012

Days with snowfall

In the last 30 years it has been observed that the ratio with days of snowfall to the total number of days with precipitation has declined drastically. This development was particularly marked between 1985 and 1995 in low-lying areas, as here fewer snow days in absolute figures are recorded overall. Between 1978 and 2009, the number of snow days below an altitude of 500 m declined by over 40% (Laternser et al. 2003, Serquet et al. 2011). It is predicted that the number of snow days as a proportion of total days with precipitation will decrease at higher altitudes in particular. By 2100, the number of days with solid precipitation in high glaciated areas will have declined markedly and have assumed values that were usual in areas 500 m lower down in 1950 (cf. Findelen and Morteratsch regions in fig. 18).

Fig. 18 > Solid precipitation as a percentage of total precipitation in different strongly glaciated catchments, showing average altitude above sea level



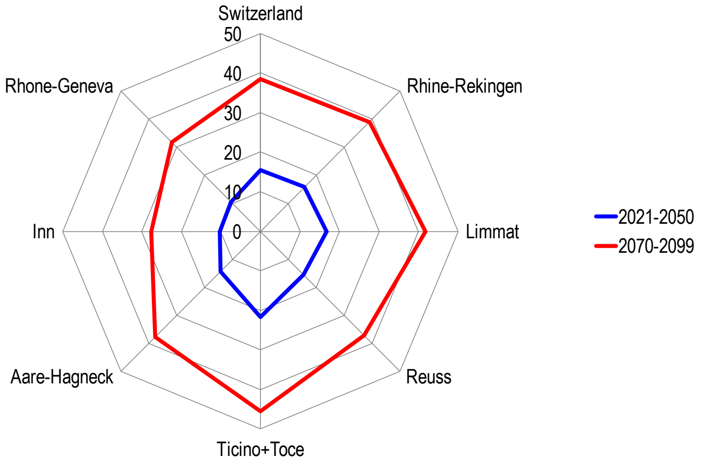
VAW 2011

Snow storage

Climate change will have manifold effects on snow storage in Switzerland. An increase in winter temperatures of about 3° C by 2070–2099 (fig. 7) will raise the snowline by around 500 metres. As precipitation levels in winter may be expected to rise over the course of the century, it is possible that greater amounts of snow will fall at very high altitudes, as was observed in the winters around the year 2000. The total area covered by snow in winter will however become less, as will the depth of snow cover in both lower and higher regions, and as a result there will be fewer water equivalents available to melt (fig. 19). This will have a direct impact on runoff and its distribution over the course of the year (see Chapter 6).

Fig. 19 > Decrease in meltwater from snow shown as a percentage of total (see fig. 16) for all large catchments in Switzerland and both scenario periods

Ticino will be particularly affected.



Zappa et al. 2012

6 > Runoff

Runoff in Switzerland will change little in the near future (2035), with temporary increases in strongly glaciated areas. There will be a slight decline in runoff in the long-term future (2085), with the exception of the Ticino and Toce rivers, where runoff will decrease by about 10%.
In the Alpine area, higher temperatures will have the greatest impact on the seasonal distribution of runoff: The snowline is rising and winter snow reserves, glacier volume and glacier surface area are declining.
The seasonal distribution of runoff (runoff regime) is changing in almost all parts of Switzerland. There is considerably more runoff in many areas in winter, but less in summer. Large rivers are also changing accordingly.
This is leading to a shift and/or extension in the potential flooding period in many parts of the Swiss Plateau. For example, the Rhine will experience a second seasonal runoff maximum in winter. Serious flood events will become more frequent in many areas.
On the Swiss Plateau, low-water events will become more severe and last longer (summer).
This will also be the case in the large rivers. In the Alps, the period of low water shift partly from winter to late summer.
The impact of these changes on water management could be:
> Existing flood prevention measures on the Swiss Plateau and in the Jura must be re-examined.
> More extreme low-water coupled with a greater demand for water during warmer and drier summers may lead to conflicts between the different users. Statutory regulations in a range of areas (water abstraction, introduction of cooling water, lake control regulations etc.) must be re-examined.
> It must be determined if there is a need for additional (multi-purpose) reservoirs.

6.1 Water cycle and water balance

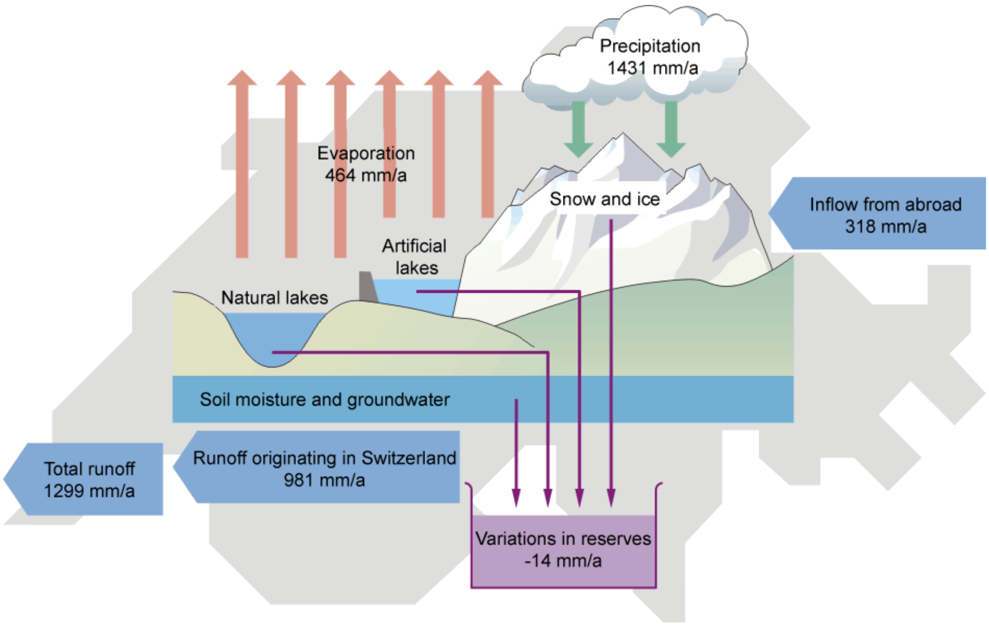
The water flowing in streams and rivers are the renewable water sources available in a given region. This runoff is the result of the regional water balance, which takes account of precipitation, evaporation and changes in storage:

runoff = precipitation – evaporation – changes in storage

The water balance in Switzerland is well documented thanks to measurements taken over many years by MeteoSwiss, the Hydrology Section at the Federal Office for the Environment and the Cryospheric Commission (CC) of the Swiss Academy of Sciences (SCNAT). In the 20th century, average annual precipitation was 1431 mm in Switzerland, a third of which evaporated and two thirds of which flowed out of the country via the large rivers (fig. 20). Annual fluctuations in precipitation and runoff are considerable, and during the 20th century precipitation levels have increased slightly, whilst runoff has remained constant as evaporation levels have increased to a similar degree (Hubacher & Schädler 2010).

Fig. 20 > Average water balance in Switzerland in the years 1901–2000

One mm over the whole of Switzerland corresponds to 41.3 million cubic metres of water.



Hubacher & Schädler 2010

Precipitation

Weather conditions and topography have a considerable influence on the behaviour and intensity of precipitation. The way in which precipitation and temperature are changing in Switzerland is described in Chapter 3. The temperature determines the altitude of the snowline, that is to say, the height below which precipitation falls as rain rather than snow.

> *Results of climate change:* The snowline moves up about 150 m per one degree Celsius rise in temperature. This means that the area of land covered in snow becomes smaller and smaller over time and there are fewer snow reserves at the end of winter. It also means that most precipitation falls in liquid form, and runs off immediately or helps to replenish soil moisture and groundwater levels. Changes in the ratio of solid and liquid precipitation in high-lying areas are presented in fig. 18 in Chapter 5. These have a significant influence on the seasonal distribution of runoff, the runoff regimes, in these areas.

Evaporation

The rate of evaporation is dependent on the available energy or temperature and on the amount of moisture available in the soil. Higher temperatures lead to an increase in the greatest possible rate of evaporation (potential evapotranspiration). For actual evaporation to increase in summer, sufficient water must be present in the soil.

> *Results of climate change:* Dry and hot summers such as that experienced in 2003 are likely to occur more frequently in future (Meyer 2012, Schär et al. 2004). This means that actual evaporation will decrease in many regions of Switzerland in the summer months, as the soil is more likely to be dry. At other times of year it will increase slightly, so that changes in evaporation seen over the whole year will not be particularly significant, especially when compared with the entirety of the available water resources.

Changes in storage

Water storage media include natural and artificial lakes, glaciers, snow cover, soil moisture and groundwater. In Switzerland, some of these storage media are of considerable size (tab. 1), but are unlikely to change much long-term, with the exception of the glaciers. The volume of glaciers, by contrast, is undergoing considerable change (fig. 15, Chapter 4). Changes in water storage media are mainly seasonal: reserves of snow cover, groundwater and soil moisture increase in winter, whilst reserves in all storage media decline in summer, apart from artificial reservoirs and to some extent natural lakes. These changes in reserves influence our water resources, or runoff. In smaller, strongly glaciated areas with large snow reserves the seasonal impact is particularly great. Changes in reserves have the greatest effect on the runoff regime, that is to say, the seasonal fluctuation in runoff at medium and high altitudes (fig. 21). The higher the catchments lie, the more marked the seasonal fluctuations.

Tab. 1 > Water storage media in Switzerland

Storage medium	[km³]	[mm]
Lakes (area in Switzerland)	130	3147
Glaciers in 1850	100	2421
Glaciers in 2008	57	1380
Reservoirs	4	97
Groundwater	150	3630
Maximum snow reserves (c. April) (incl. parts abroad)	13	240
Soil moisture available to plants (incl. parts abroad)	9	170

Schädler 1985, Zappa et al. 2012, Farinotti et al. 2009, FOEN

> *Results of climate change:* Future changes in the climate will have a marked impact on storage capacity: snow cover will decline in terms of both surface area covered – with the exception of very high lying areas – and of depth and duration. This means that less snow is available to melt in spring and summer, and so there is less runoff. Conversely, the glaciers, which formed significant water reserves a long time ago, are melting at a greater rate, thus releasing more water into the hydrological cycle and increasing the amount of summer runoff in strongly glaciated catchments. However, as the glaciated area becomes smaller over the years, the amount of meltwater contributed to the regime by the glaciers will continue to decrease and will eventually cease completely. The overall contribution made by snow cover to meltwater will be considerably greater (see Chapters 5 and 6.4).

6.2 Seasonal distribution of runoff and changes in the future

Runoff regime

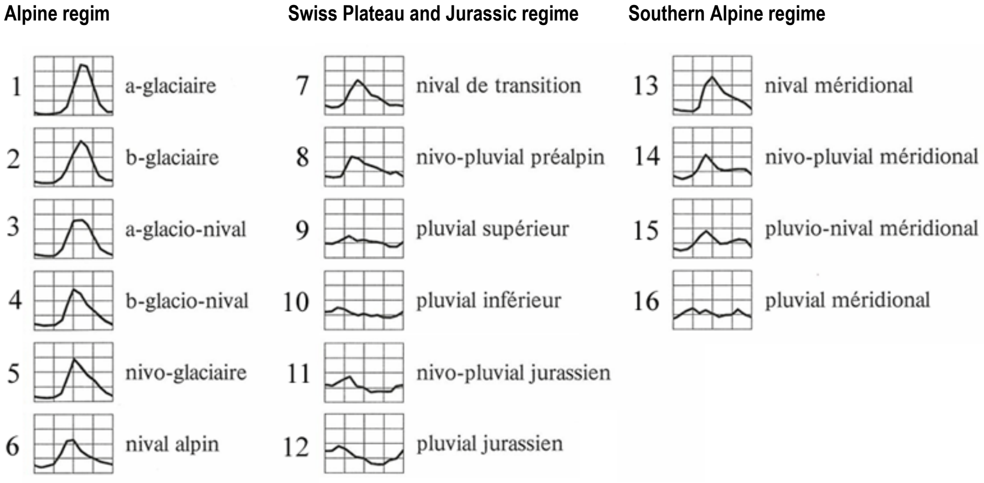
Aschwanden & Weingartner (1985) and Weingartner & Aschwanden (1992) described 16 typical regimes depicting the seasonal distribution of runoff of all waters in Switzerland (fig. 21). Using detailed hydrological modelling and the PREVAH hydrological model (Viviroli et al. 2009), and based on the climate scenarios described in Chapter 3, Köplin et al. (2012) carried out hydrological modelling of 189 mesoscale catchments. This made it possible to determine the regime types for the control period (CTRL), the near future (period around 2035) and the long-term future (period around 2085). The following data is based on the average values calculated by Köplin et al. (2012) for the ten model calculations per time period.

With the exception of a few catchments, there are some very significant shifts in the regimes. One example is provided by the Simme (fig. 22), which changes from a *nival de transition* regime with peak runoff in May and minimum runoff in winter to a new regime type in which maximum runoff still occurs in May but minimal runoff is now expected in late summer (similar to today’s Jurassic nivo-pluvial type).

Pardé coefficients

Pardé coefficients allow us to compare the seasonal development of runoff in different catchments. They show the ratio of average monthly runoff to average annual runoff.

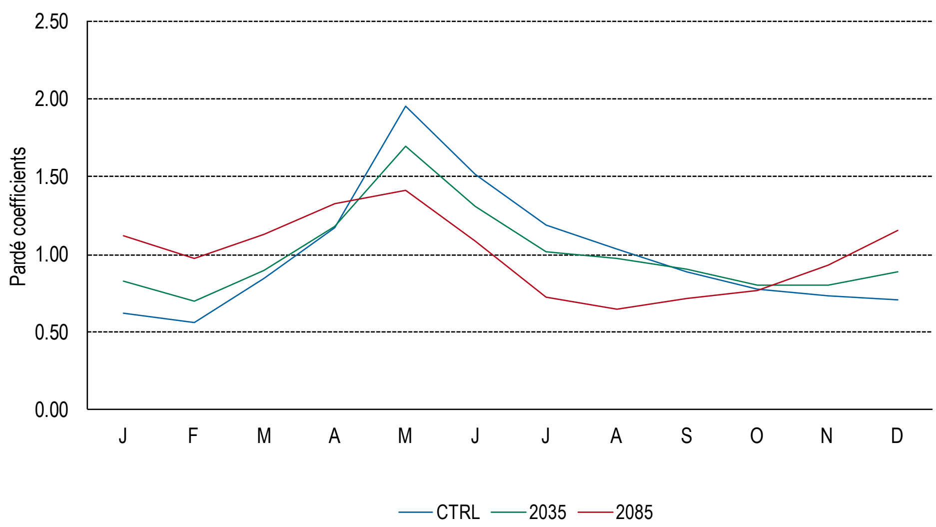
Fig. 21 > Monthly runoff (Pardé coefficients) for 16 Swiss regime types



Weingartner & Aschwanden (1992)

Fig. 22 > Change in the runoff regime in the Simme catchment as far as the Kander confluence from *nival de transition* (CTRL, 2035) to a new type (2085) resembling the Jurassic nivo-pluvial regime

Area 596 km², average altitude 1600 m above sea level, glaciation in control period 2%.

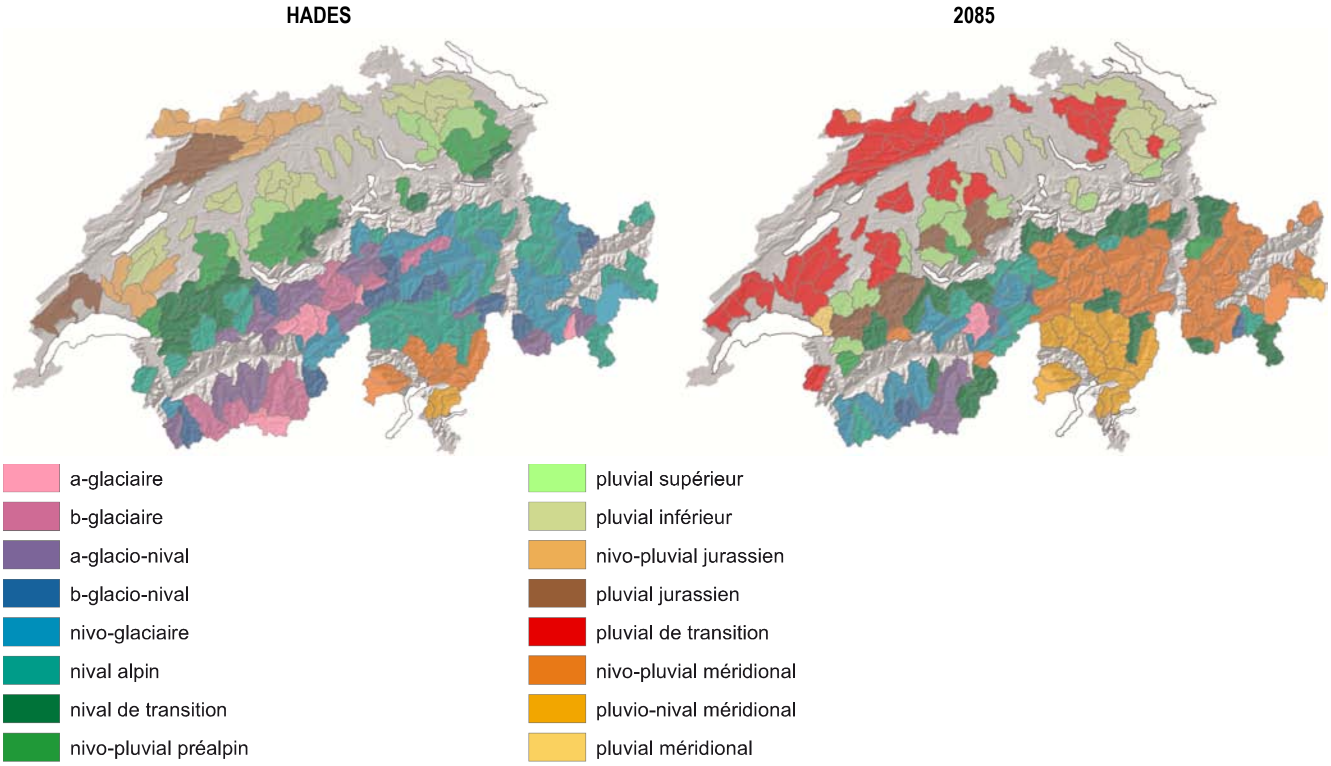


Shift in runoff regime

An overview of the distribution of the regimes and the changes they experience from the middle of the 20th century to the end of the 21st century is provided by two maps showing all the studied regions, which cover 63% of the area of Switzerland (fig. 23). The glacial regimes, which originally spread across large swathes of the high Alpine region, will completely disappear in the long-term future, with the exception of the River Massa basin, which contains the largest Alpine glacier, the Great Aletsch. As temperatures rise, many other Alpine regime types are being transformed into regime types which are currently common in areas of lower altitude. However, this is not the case in areas in the central, southern and eastern mountainous areas of Switzerland (including the Engadine): here the regimes are becoming similar to southern Alpine regimes. On the Swiss Plateau and in the Jura, many areas are changing into a regime type currently unknown in Switzerland, here called *pluvial de transition*, with maximum runoff in winter and a marked minimum level in August (cf. fig. 24). These new catchments, which are mainly fed by rainwater, are likely to be particularly sensitive to periods of drought in summer. As their runoff minimum occurs at the height of summer – when there is the greatest probability of heat waves occurring – the impact of dry periods will be very serious. Extreme low-water events will result (Meyer et al. 2011a, Meyer 2012).

Fig. 23 > Runoff regimes in 189 mesoscale catchments in Switzerland

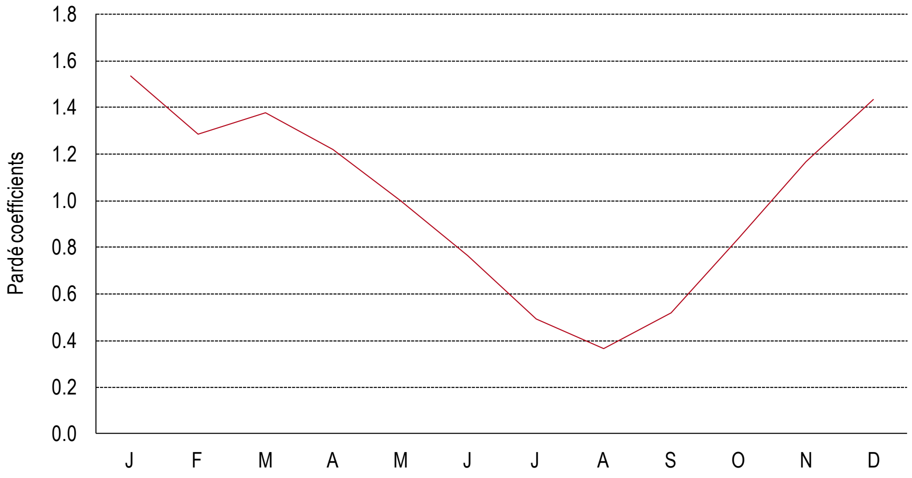
Left, the classification from the Hydrological Atlas of Switzerland (HADES) for the period 1950–1980 (Weingartner & Aschwanden 1992) and right, for the long-term future circa 2085.



Data from Köplin et al. 2011

Fig. 24 > Pardé coefficients for the new *pluvial de transition* regime type

Characteristic of this regime type is a marked minimum in August and a maximum in January, plus a secondary maximum in March.

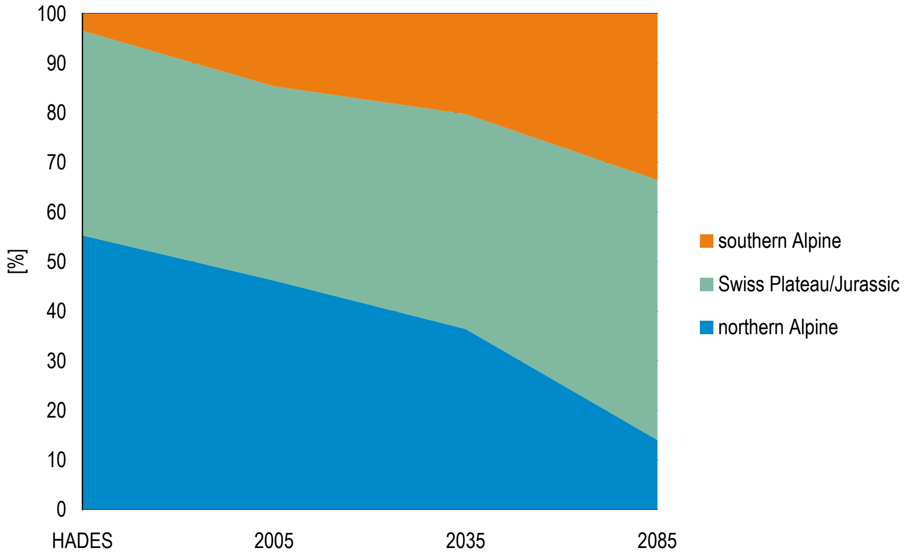


New distribution in runoff regime

fig. 25 gives a summarised overview of the dramatic changes expected in the distribution of the runoff regime up until 2085: In future, we can expect a dramatic increase in the number of southern Alpine runoff types, of which there are only a few today. Formerly northern Alpine regimes, with a characteristic pattern of maximum in summer and minimum in winter, will disappear, and in the *nivo-pluvial meridional* regime type will occur in about 20% of areas. This may lead to an increase in the average runoff in summer with a growing number of low-water events in late summer. The number of Swiss Plateau and Jurassic regimes remains about the same, but their geographical position will shift noticeably (fig. 23). They will be increasingly dominated by the *pluvial de transition* regime type, which is associated with the Swiss Plateau. The Jurassic runoff regimes will disappear almost completely, occurring only in isolated cases in the Alpine foothills.

Fig. 25 > Change in frequency of runoff regimes in Switzerland for the main groups of regimes shown in fig. 21

In the period c. 1950–1980 (indicated by HADES) over 50% of the catchments were designated as being of the northern Alpine regime type and only 5% southern Alpine. Changes can already be seen up to the control period (indicated by 2005), and by the end of the 21st century these will result in just 20% of the areas being of the northern Alpine type, about 30% current southern Alpine type and over 50% Swiss Plateau/Jurassic type.



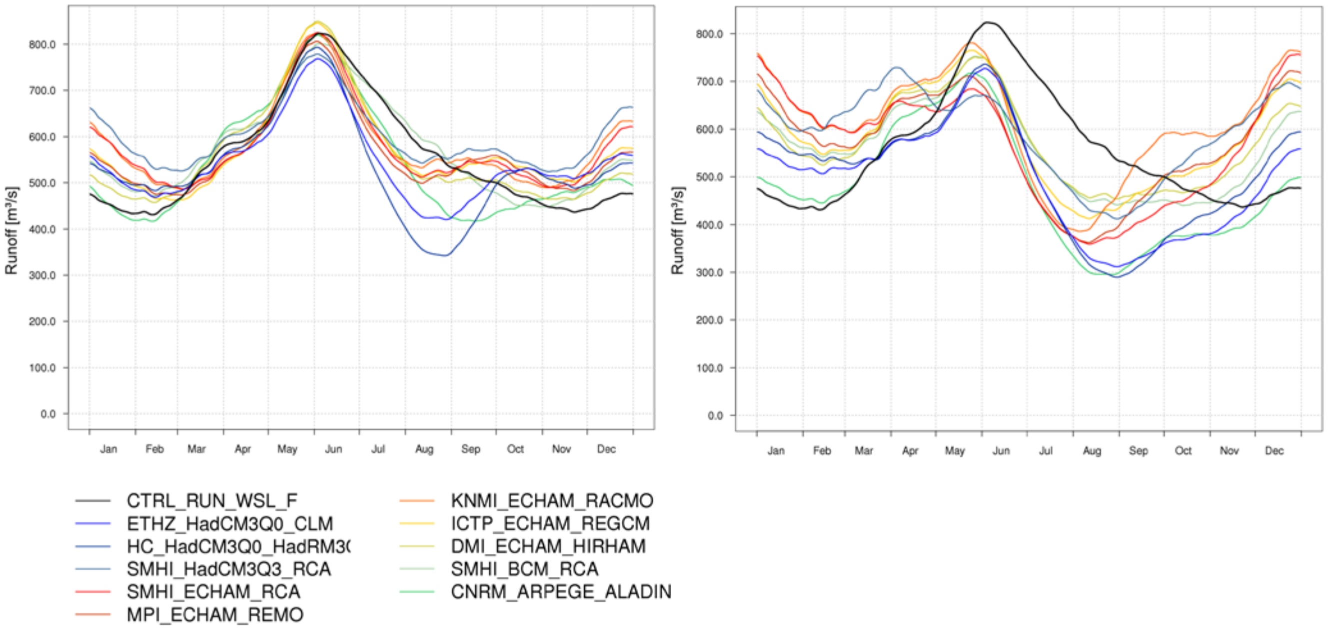
Changes in large catchments

What impact do regime changes in the mesoscale catchments studied have on the runoff regimes of the larger rivers? In their investigations, Zappa et al. (2012) projected discharge in all larger river catchments in Switzerland. Fig. 26 shows an example of the impact of regime changes in the different catchments on discharge in the River Aare. In the near future discharge is more even for a time, and slightly increased in autumn and winter. In the long-term future, however, considerable changes can be observed: there are two peaks, one in early summer, and another in December, which is quite new and somewhat greater. The discharge minimum is now in late summer, at a rate which is 300 to 450 m^3/s less than the winter minimum in the past.

In larger catchments formerly with marked Alpine characteristics, such as the Rhone basin in Valais, clear shifts can also be observed. Peaks in summer will become higher for a while, becoming lower towards the end of the century and occurring earlier in the year compared with today. In summer considerably less water will flow and there will be another minimum in August, in addition to the winter one. Discharge will then be about as low as the current winter minimum. The discharge volume in the months of June to August will drop markedly below today's levels. A new second maximum will occur as autumn turns to winter.

Fig. 26 > Discharge projections in River Aare at confluence with Rhine

The black line indicates the control period, coloured lines the ten climate scenarios; left shows the near future c.2035, right the long-term future c.2085.



Zappa et al. 2012

6.3 Which catchments react sensitively to climate change?

The question now arises as to which catchments will display a particularly sensitive reaction to climate change and for what reasons. By carrying out a cluster analysis, Köplin et al. (2012) established which catchments behave similarly in terms of changes in temperature, precipitation and runoff and what the characteristic features of these areas are. These analyses were carried out for both time periods 2035 and 2085. The catchments could be divided as follows into seven sensitivity types C1 to C7 (cf. fig. 27). They cover from 31 to 41 areas, with the exception of sensitivity types 3 and 7 (only 9 and 5 areas) and have the following characteristics (Köplin et al. 2012):

Sensitivity types

> **Sensitivity type 1:** Swiss Plateau and Jura; slight increase in precipitation, little change in runoff, snow reserves will decline.
> **Sensitivity type 2:** Swiss Plateau/Alpine foothills and southern Ticino; slight decrease in precipitation, slightly lower average annual runoff, but more in winter, significant decline in snow reserves.
> **Sensitivity type 3:** Only a few areas in western Alpine foothills; little change in precipitation and average annual runoff, increasing amounts of runoff in winter, significant decline in snow reserves especially in long-term future.
> **Sensitivity type 4:** High-lying areas in Valais and Central Graubünden with medium glaciation; little change in precipitation, marked increase in average annual

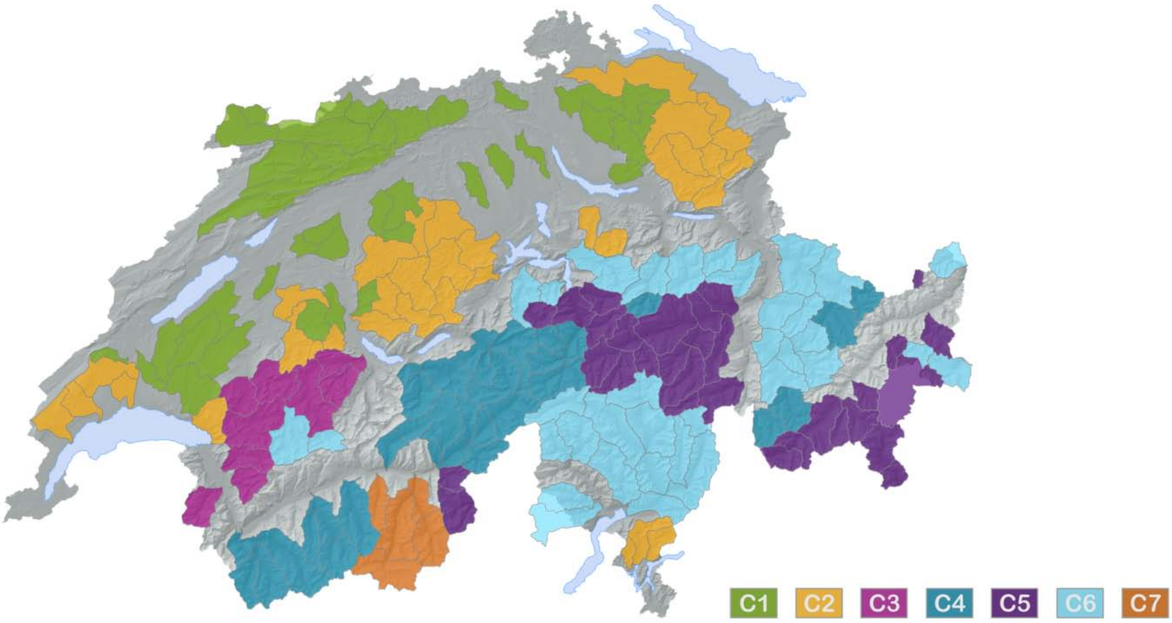
runoff mainly due to increased runoff in winter; fewer snow reserves; decreasing glacier melt as the result of reduced glacier area.

> **Sensitivity type 5:** High-lying areas in Central Switzerland, Central Graubünden and the Engadine with little glaciation; little change in precipitation, less average annual runoff, especially in the long-term future, although much greater in winter; significantly fewer snow reserves, decreasing glacier melt in the long-term future.
> **Sensitivity type 6:** Only a few high-lying areas in whole of Alpine area with little glaciation; less precipitation in the long-term future, less average annual runoff, especially in the long-term future, much greater in winter; significantly fewer snow reserves.
> **Sensitivity type 7:** Only a few areas in central southern Valais, very high, heavily glaciated areas, runoff first increasing, in the long-term future markedly less, slightly higher in winter; significantly fewer snow reserves; rapid increase in glacier melt initially, followed by marked decrease.
> Evaporation rate in all areas initially increases moderately, then more rapidly.

If we compare the spatial distribution of the sensitivity types with the spatial distribution of the changed regime types in the long-term future (fig. 23), clear similarities can be seen. Each sensitivity type displays a characteristic annual cycle of the changes in individual water regime components. There are sensitivity types whose future seasonal runoff distribution is to a large extent determined by temporal changes in snow accumulation and melting processes. The altitude of the catchment has a considerable influence on changes in runoff, also because the degree of glaciation is mainly dependent on height above sea level. Because of the temperature rise, the degree of glaciation clearly plays a decisive role in sensitivity in terms of seasonal and annual runoff. It is therefore clear that in any hydrological modelling conducted over a long time period there must also be explicit modelling of glacier surface area.

Fig. 27 > Regions divided into seven sensitivity types C1 to C7 according to similar sensitivity in terms of changes in temperature, precipitation and runoff

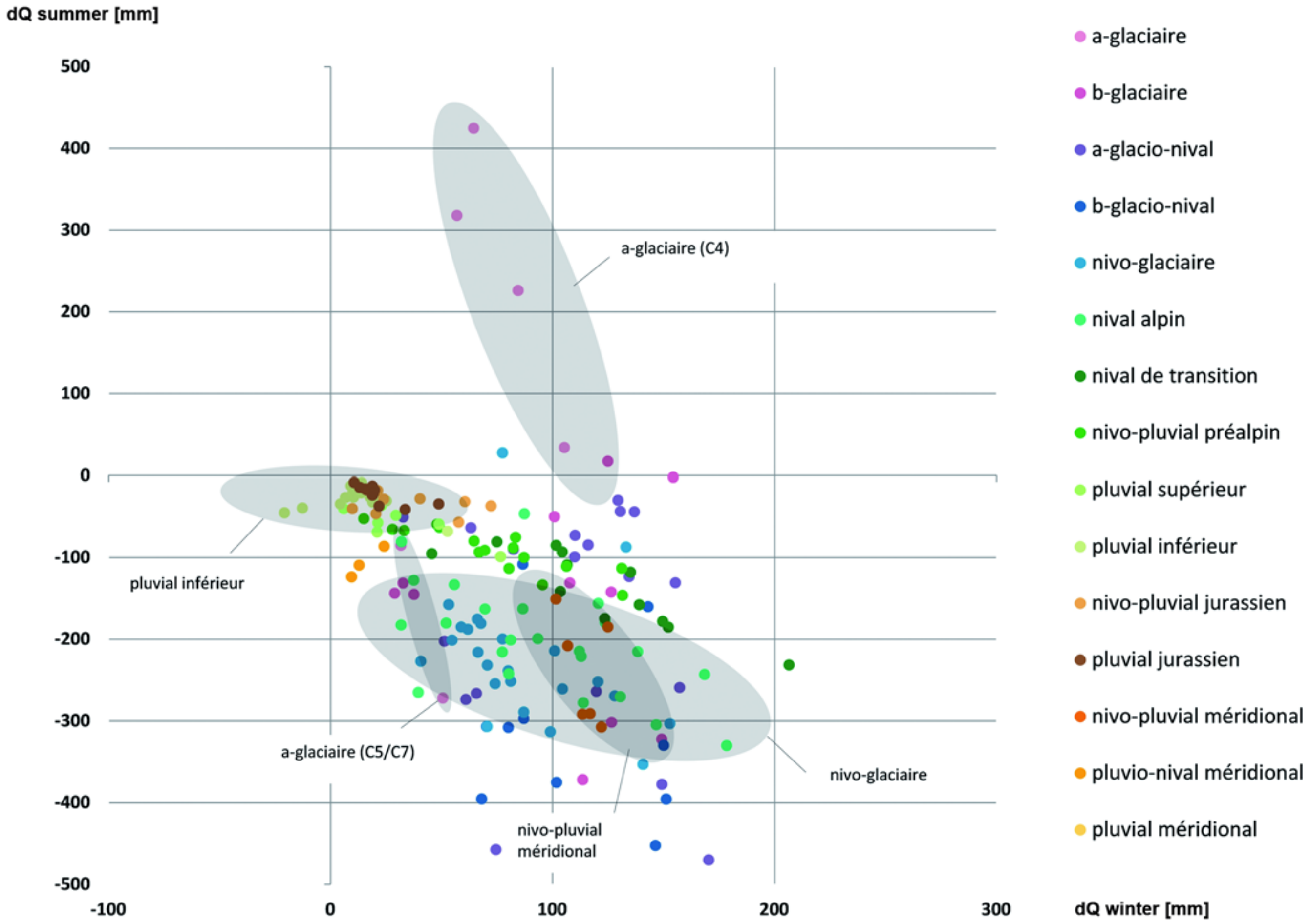
The analysis takes account of changes in both the near and long-term future.



Köplin et al. 2012

Fig. 28 > Change in average winter runoff (dQ winter: December to February) compared to change in average summer runoff (dQ summer: June to August) for all 189 catchments studied, indicating original regimes in the period c. 1950–1980

The areas marked in grey show areas with originally similar regimes.



Köplin et al. 2011

In general, it can be predicted that runoff will increase markedly in almost all areas due to both the higher snowline and the general increase in precipitation in the winter months December to February. In the summer months June to August, however, there will be a sharp decrease in runoff, with few exceptions (fig. 28). This reflects the regime changes as demonstrated by fig. 22 to fig. 25. All changes in the water regime components will be looked at in the following chapter.

6.4 Water resources and water regime

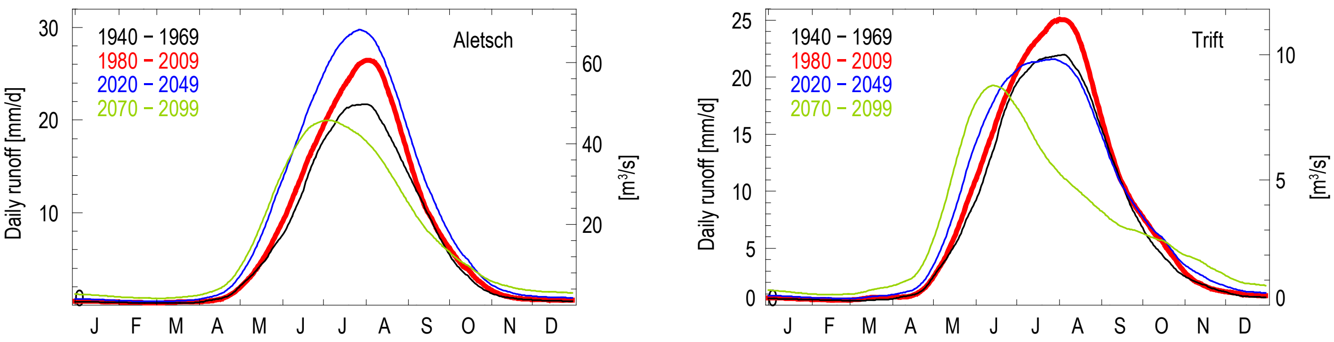
Strongly glaciated catchments react sensitively

High-lying, strongly glaciated catchments react particularly sensitively to rises in temperature. The glaciers do not only melt very rapidly in summer, they also begin to melt earlier in the year, in late spring, and stop melting later in autumn. Over time the glacier surface area is reduced, so that the amount of meltwater as a proportion of total runoff decreases.

Large glaciers

fig. 29 shows changes in seasonal runoff in the small catchment of the Trift glacier in the Berner Oberland and that of the larger, higher-lying Aletsch glaciers (Large, Middle and Upper Aletsch) in Valais. Since the 1940s, summer runoff in the Aletsch region has increased and continues to do so. Maximum runoff in summer now occurs slightly sooner, in July rather than early August. In the long-term future dramatic changes are expected: the maximum seasonal runoff will drop below 1940–1969 levels because the glacier surface area will decrease markedly, from today's 123 km² to a mere 39 km². In addition, the seasonal maximum will shift to June. Meltwater from the glaciers and snow (cf. fig. 30) will still form a large part of the total runoff, and so this will still be an essentially glacial regime. In lower-lying areas of the Trift glacier runoff has already passed its peak volume. Lower summer runoff levels are expected in the near future; this can be seen clearly in the months of July to September.

Fig. 29 > Development over period of thirty years of seasonal runoff in the Aletsch glacier catchment (glacier surface area 123 km², average altitude of catchment 2925 m) and of the Trift glacier (18 km², 2570 m)



VAW 2011

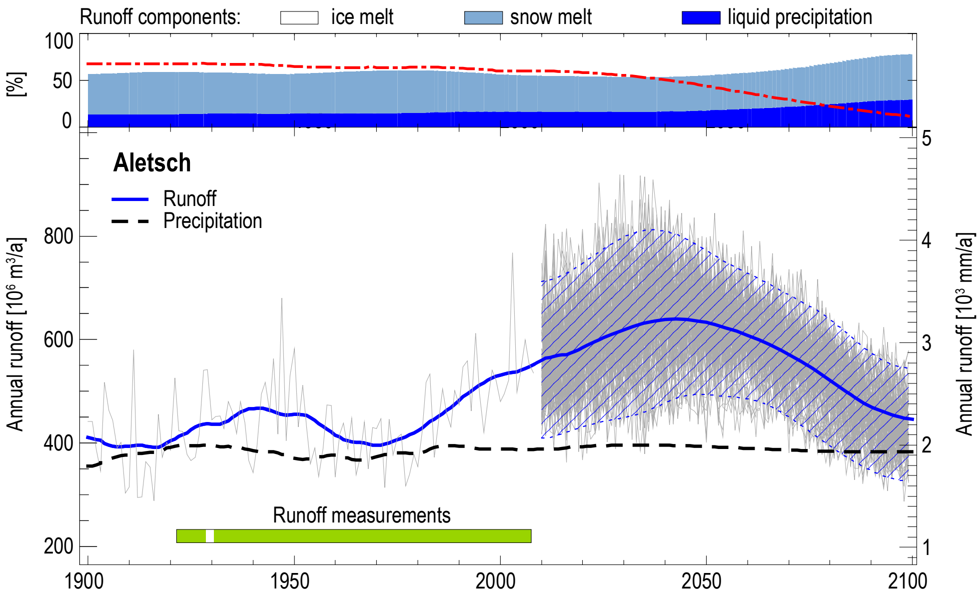
As can been seen in the Aletsch glacier, the volume of runoff has been increasing since the 1970s (fig. 30). This will reach a peak around 2050, dropping off towards the end of the 21st century but nonetheless remaining at a higher level than in 1900. However, it should be noted that annual runoff will not decline to below 1900-levels, provided the amount of precipitation does not fall drastically, and also because there will be little change in evaporation rates at this altitude, both in absolute terms and compared with precipitation levels (c. 2000 mm/a).

Small glaciers

For a time, the annual runoff will reach a maximum in strongly glaciated areas at different times of the year, depending on the size and type of glacier (fig. 31). The smaller glaciers, Gries, Trift and Silvretta, have already reached their maximum levels, whereas the larger glaciers will not experience maximum runoff levels until around 2050. It is notable that in the catchments of the Morteratsch glacier and in particular of the Gries glacier, runoff around 2100 will be considerably less than levels around 1900 (Farinotti et al. 2011). In the case of the Gries glacier, lower annual precipitation levels (Chapter 3) are a factor in this.

Fig. 30 > Annual runoff at the FOEN Massa measurement station near Blatten (Naters), which has measured runoff in the Aletsch glacier catchment since 1922

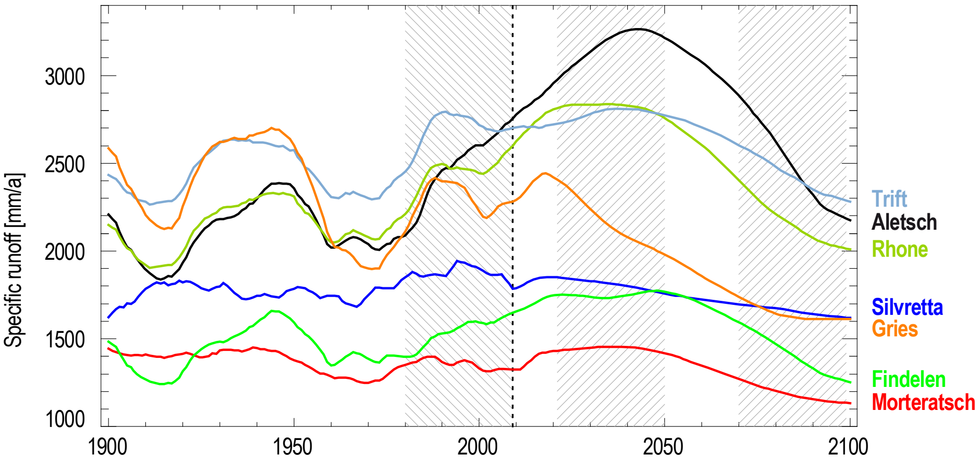
The upper part of the graph shows the proportions in runoff of snow melt (light blue), ice melt (white) and directly from rainfall (dark blue). The red line shows the degree of glaciation in the catchment. In coming years, runoff levels will increase due to greater amounts of ice melt, to be dominated at a later period by snow melt. The hatched area represents the area of uncertainty arising from the climate scenarios.



VAW 2011

Fig. 31 > Development of specific runoff in the glaciated catchments studied

In the period 2009–2100 the average for the uncertainty range (cf. fig. 30) is shown for each catchment. The hatched areas indicate the reference period and the two scenario periods.



VAW 2011

Changes in runoff in mesoscale and large catchments

Runoff constitutes a considerable part of the useable water resources in a region or country. In the 189 mesoscale (medium-sized) catchments studied in Switzerland, long-term changes in the average annual runoff are generally slight. In the near future, an increase (average + 52 mm) in runoff is expected in about half of the areas, whilst in the other half a decrease is predicted (- 33 mm), resulting in an overall average increase of 12 mm. However, a decrease of 75 mm is expected long term in 80% of the areas compared with today. This will be mainly due to slightly lower precipitation levels and a slightly higher evaporation rate. In the other 20% of the areas (mainly at high altitudes), there will be an increase in runoff of 205 mm compared with today. This figure, however, must be treated with caution, as the uncertainties arising from model assumptions are considerable.

Zappa et al. (2012) investigated the effect of changes in the individual sub-catchments on large river basins and for the whole of Switzerland. In general, we can say that the changes set out above are largely confirmed.

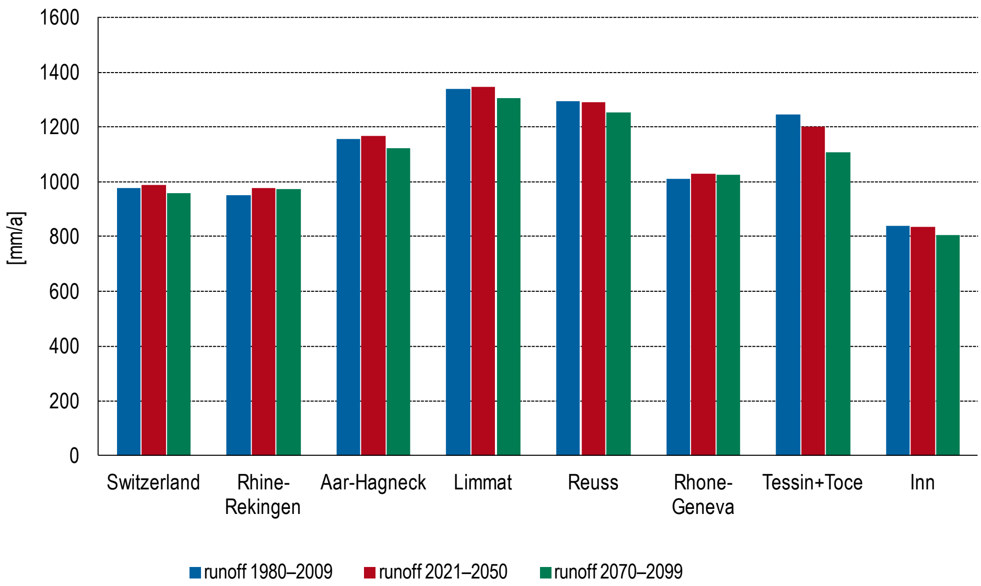
Tab. 2 and fig. 32 show how renewable water resources (average runoff) change in the individual large catchments. The changes identified are mainly slight and lie both within the range of model uncertainties and also firmly within the considerable natural fluctuations which occur from one year to the next. The only marked change can be seen on the southern side of the Alps, where resources may decrease into the long-term future as a result of lower precipitation levels. However, the Lago Maggiore catchment (Ticino and Toce rivers) experiences above-average precipitation levels.

Tab. 2 > Change in average runoff in large catchments in Switzerland, including inflow from abroad

	Runoff [mm/a]	Runoff [m³/s]	Change [%]	
	1980–2009	1980–2009	2021–2050	2070–2099
Switzerland	977	1658	1.1	-2.0
Rhine-Rekingen	950	443	2.8	2.7
Aare-Hagneck	1155	187	1.0	-2.9
Limmat	1340	102	0.6	-2.7
Reuss	1294	141	-0.2	-3.2
Rhone-Genf	1011	270	1.8	1.5
Ticino + Toce	1245	265	-3.5	-11.0
Inn	839	61	-0.5	-4.2

Zappa et al. 2012

Fig. 32 > Development in water resources in large catchments in Switzerland



Zappa et al. 2012

6.5 Extreme runoff

The method employed to form climate scenarios, the delta change method, does not make it possible to change the frequency distribution of dry periods or extreme precipitation events in the future. Meyer et al. (2011a, 2012b) therefore only identified very slight changes in the length of droughts (number of days with precipitation < 1 mm/d) in the climate scenarios. However, as the occurrence of periods of low water or potential flood situations depends not only on precipitation distribution but also – to a greater extent – on seasonal and daily complex hydrological interactions e.g. in the soil moisture regime or the formation and decline of snow cover, we can nonetheless make statements about possible changes in low-water and flood occurrence. The changes in the runoff regime, as described in the previous chapters, suggest that there is a new disposition for extreme events to occur. This potential can be seen in the rarer quantile values (10% and 90% quantiles) for the runoff scenarios (fig. 33, fig. 34).

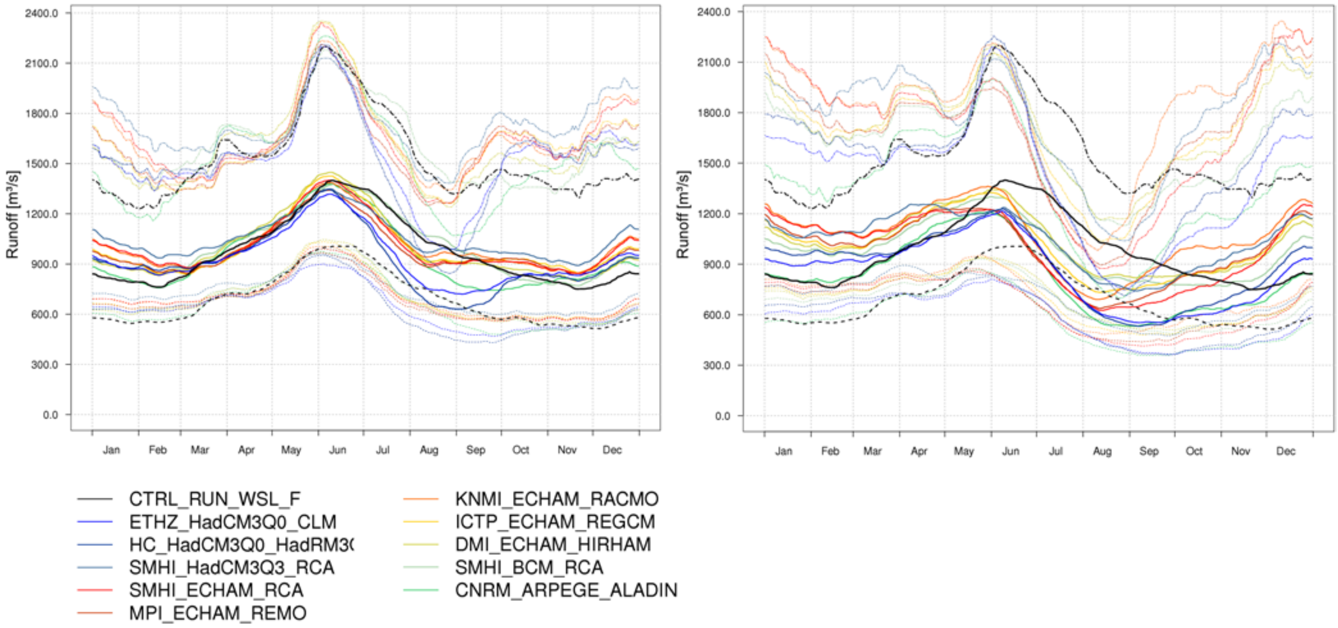
Rhine in Basel

fig. 33 shows that there is a disposition for low water in the Rhine at Basel not only in winter as hitherto, but also in late summer, whereby in particular in the long-term future the 10% quantile (in autumn) could be much lower. The disposition for high runoff levels also changes fundamentally towards the end of the 21st century: Until now, flooding has tended to occur in summer, but henceforth it must be expected also to occur in winter. This will have an impact on the middle and lower reaches of the Rhine in particular, where most flooding is already experienced in winter.

In high-lying glaciated catchments the situation looks somewhat different (fig. 34). In these areas, which currently experience marked low water levels in winter, low water occurrences may become less extreme, even if there is generally less runoff in late summer. Neither is a considerable change in flood events to be expected, as the drier summers are unlikely to increase the disposition for heavy precipitation and the subsurface in the catchments will most probably be drier.

Fig. 33 > Runoff in the Rhine at Basel

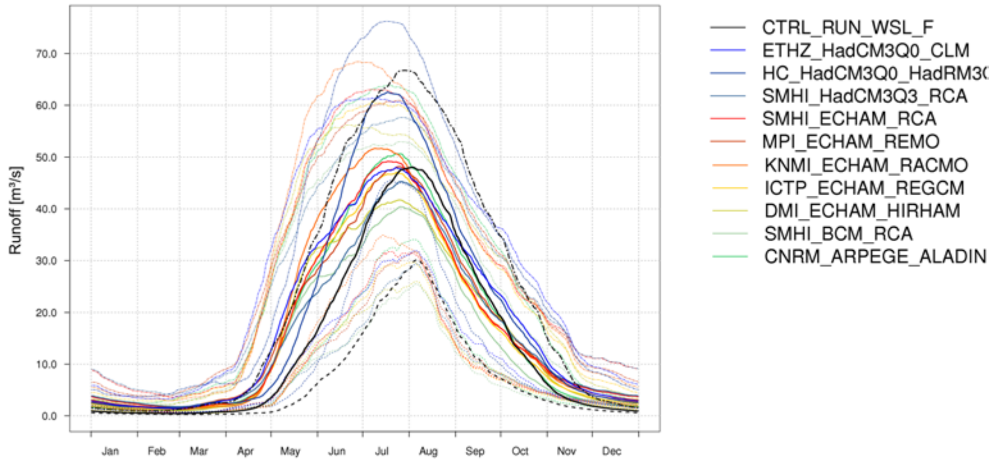
The graphs show the 10%, 50% and 90% quantiles for the control period (black line) and all 10 climate scenarios (coloured lines), on the left for the near future around 2035, on the right for the long-term future around 2085.



Zappa et al. 2012

Fig. 34 > Runoff in the Massa at Blatten (Naters)

The graph shows the 10%, 50% and 90% quantiles for the control period (black line) and all climate scenarios (coloured lines) for the long-term future around 2085.



Zappa et al. 2012

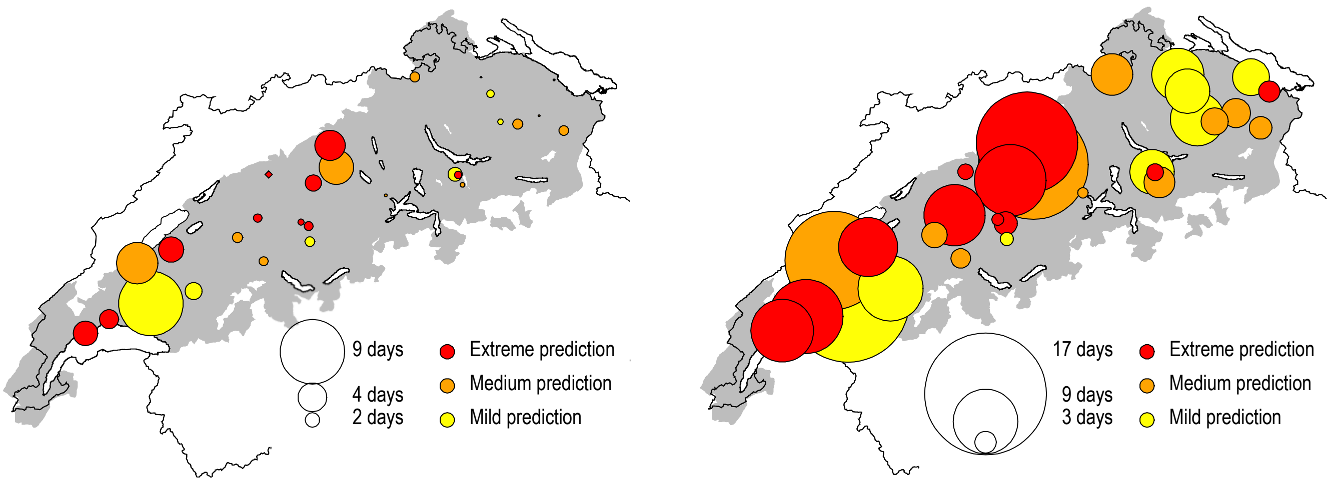
6.5.1 Low water

Changes in low water in 29 catchments on the Swiss Plateau were investigated using a model approach which was specifically designed for low water modelling and ensured that base flow was correctly modelled (Meyer 2012a, b).

More days with low water

Water levels below current 95% quantile (Q_{347}):
The duration during which discharge fall below a threshold value is of particular interest in waters use and to assess the effects of low water on the ecosystem. The threshold value depends on the specific issue at hand and greatly affects the results. In Switzerland the 95%-quantile (Q_{347}) is the statutory basis for determining residual flow. The Q_{347} is equivalent to the average discharge reached or exceeded on 347 days in the year. In other words, the average time that this level is not reached is 18 days a year. It is highly likely that this number will rise in the central Swiss Plateau in future (fig. 35); increases of up to 17 additional days have been calculated for the period to the end of the 21st century. In the west of the Plateau there may be an additional 17 days, but up to nine additional days is more likely. In the east of the Plateau an additional nine days are possible, but three more probable. This means that in future the Q_{347} discharge will be significantly less in some areas. It cannot be said definitely that low flow rates will lead to waters running dry, as this depends to a large extent on the local morphological characteristics of the riverbed. Lower flow rates may affect water quality (conditions for waste water disposal, warming from e.g. thermal power plants). There is also a danger that smaller waters in the Swiss Plateau will no longer provide a reliable source of water for withdrawal.

Fig. 35 > Comparison of average length of period below 95% quantile in control period with comparable length in both scenario periods, left for the near future around 2035, right for the long-term future around 2085



Meyer et al. 2012b

Lowest arithmetical average of seven consecutive daily discharge averages (AM7):
This figure shows the low-water flow rate during a continuous dry period – in this case, in summer. Meyer et al. (2012b) showed in their analysis that in all areas of the Swiss Plateau studied, the average values over the whole period (MAM7) decline in both scenario periods. This decrease is particularly marked for the near future in central and western areas of the Plateau. In the long-term future, the values decline most markedly in the eastern and western areas of the Swiss Plateau. In many catchments it must be expected that the MAM7 value will decrease in the near future by around 20%, and by about 40% in the long-term future, although the degree of fluctuation between the areas and in particular in individual years may be relatively large.

6.5.2 High water

An analysis of the high-water conditions shows a tendency towards higher flow peaks, in particular in the long-term future. In the Vorder Rhine area, for example, it was observed that a ten-year event in the control period corresponds to a flow rate of about 550 m³/s, and in the long-term future this will rise to about 700 m³/s (Köplin et al. 2011). This result is confirmed by modelling conducted by Zappa et al. (2012), with increases compared to the control period of 10 to 50% (depending on the scenario).

Flood potential

Flood flow with a short recurrence interval could also be predicted for large catchments. For example, flow peaks in twenty-year flood events HQ20 for the River Aare in Hagneck change depending on the scenario by –8 to + 12% in the long-term future. Lower-lying catchments appear to display a more marked increase in flood peaks occurring at regular intervals.

Naef (2011) indicates that regions with extensive surfaces with a delayed reaction to precipitation are particularly liable to extreme flooding resulting from very heavy, prolonged rain. Such areas may not yet have experienced extreme flooding, but could suddenly demonstrate non-linear flow behaviour and experience unwonted flooding in future as a result of heavy and prolonged rain. Unfortunately it is not currently possible to make any clear statements about changes in extreme and very rare precipitation events in the Alpine area (CH2011, 2011).

6.6 Conclusion

Into the near future (2035) the amount of water available annually in Switzerland will change little, with the exception of temporary increases in runoff in the more glaciated areas. In the long term (to 2085), the available and renewable water resources will decline slightly, especially in Ticino (by about 10%). The runoff regimes, that is to say the seasonal distribution of runoff, will shift throughout most of Switzerland. In many areas, considerably more runoff is expected in winter and less in summer, apart from in areas which are still glaciated. This means that in the greater part of the Swiss Plateau the potential flood period will shift from early summer to the winter months, and may last longer. The disposition for medium-sized flood events (in the Alpine foothills and Alps) and large flood events (on the Swiss Plateau and in the Jura) may become more acute in many areas. For low-water events, two different region-dependent tendencies were diagnosed: in watercourses in the Alpine foothills and Alps low water levels may rise and shift from winter to late summer. In most areas in the Swiss Plateau, low water flow is expected to decline markedly and last for longer periods. The described impact of climate change on runoff will have consequences for water management, with greater likelihood of water shortages in summer leading to potential conflicting interests between the various users. The statutory regulations in various fields (water use, introduction of cooling water, lake control regulations etc.) must be reviewed. The need for additional (multi-purpose) storage facilities must be investigated. Furthermore, more frequent and more extreme low-water events and higher levels of dicharge in winter could have negative effects for shipping on the Rhine.

7 > Water temperature

Air temperature has the greatest impact on water temperature. The temperature of watercourses will be affected twofold by climate change, due to increases in air temperature and to a seasonal redistribution in runoff. Water use and the ecology of watercourses will come under increasing pressure due to increased air temperatures and lower water levels in summer. Further investigations into water temperature modelling are required and should take account of any changes in runoff regimes.

7.1 Air temperature is the greatest impact factor on water temperature

Water temperature is a key indicator of the quality of a watercourse. It is influenced by a wide range of factors. The thermal balance of a watercourse is affected by the temperature of its source water and tributaries, the introduction of glacier melt and snowmelt, heat exchange with the subsurface and – to a much more significant extent – with the atmosphere. Factors here are irradiation, precipitation, evaporation and condensation. Air temperature provides a good indication of radiation balance and the exchange of sensitive and latent heat, and is therefore a good predictor of water temperature. Other processes, which are more difficult to assess, also play an important role, such as turbulence in water flow, shaded areas, infiltration of groundwater, exfiltration to the subsurface etc. Apart from in steep Alpine streams, friction has a negligible impact.

Temperature at the source of a watercourse remains fairly constant throughout the year; it corresponds to the local annual average air temperature and thus depends on the altitude (with the exception of thermal sources). During the flow process, water flows through a number of different environments and is subject to repeated fluctuations in air temperature and other influences. As the water moves further away from its source, water temperature gradually rises and approaches the equilibrium temperature, around which the temperature usually then oscillates. The equilibrium temperature is the temperature the water would reach if it were to be in thermal equilibrium with its environment at a specific point in time. However, this equilibrium is rarely reached, as water has a higher heat capacity than air and reacts slowly to changes in the environment. Furthermore, in mountainous Switzerland water flows through considerable changes in altitude, with the ambient air temperature inevitably increasing.

Lakes encountered by the watercourse act as a buffer, in particular for short-term changes in water temperature, and have the capacity to store heat. On average, water flowing out of a lake will be up to 5° C warmer than the water flowing into it (e.g. Lake Lucerne), with the highest differences observable in summer (Pfammatter 2004). This temperature difference depends on the time the water spends in the lake, and this correlates closely with the lake's total water volume.

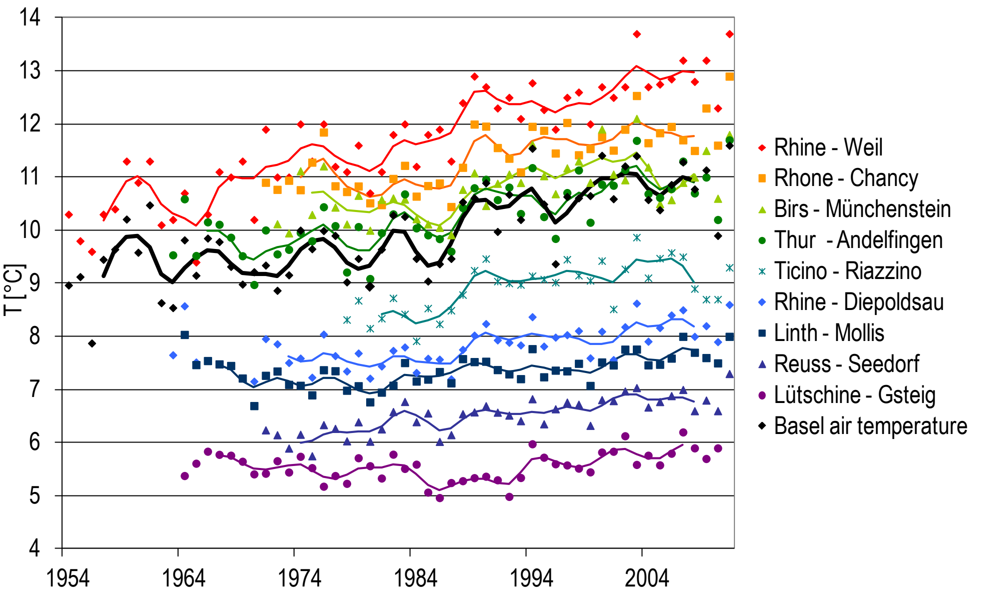
7.2 Water temperature in watercourses: a review

Increase in water temperature

In recent decades, the water temperature of watercourses in Switzerland has increased significantly. Average water temperature has increased in line with average air temperature. This relationship, however, has less of an impact on watercourses than on lakes, in which other factors such as the runoff regime also play a role. The majority of the Federal Office for the Environment's stations in a network measuring water temperature across Switzerland's watercourses (particularly since 2004, with 70 stations), have shown warming of between 0.1 and 1.2° C over 40 years (1970–2010). There was an remarkably high increase (up to + 1° C) recorded at all stations between 1987 and 1988, the result of an increase in air temperature (fig. 36): since 1988 all annual average temperatures were above the average for the period 1961–1990 (fig. 1, Chapter 3). In strongly glaciated catchments the increase in water temperature was less marked (Jakob 2010).

Fig. 36 > Developments in water temperature over recent decades in nine selected stations and in Basel (air temperature)

For stations with low average water temperatures (e.g. Lütschine-Gsteig), there is a less striking increase between 1987 and 1988. There is also less marked inter-annual variability in their water temperature. Both show the balancing effect of the glaciers.



FOEN 2012

Impact of meltwater on water temperature

A qualitative description of the relationship between monthly air and water temperatures in three typical regions with different runoff regimes (data from studies by Pfammatter 2004) is given here in fig. 37. Although this depicts the system in a highly simplified way, it provides an informative prediction of future effects of climate change on water temperature. Rivers in the Swiss Plateau (e.g. Broye, Birs) are mainly fed by springs and groundwater. In this kind of watercourse there is generally a linear relationship between air temperature and water temperature. This means that the warming and cooling mechanisms in the catchment balance each other out. In the area around the source of an Alpine river (e.g. Lütschine in Gsteig, Rhone in Sion) with an Alpine runoff regime, the degree of glaciation and the extent and thickness of snow cover plays a significant role. Up to about 0° C the relationship between air and water temperature can be said to be linear. Furthermore, in addition to source and groundwater, meltwater from snow and glaciers also plays a role, thus weakening the relationship. Where a measuring station is installed below a lake (e.g. the Aare in Bern), hysteresis arises due to the heat storage function of the lake: in April and October, for example, air temperatures are similar, whereas the average water temperature varies between the two months by several degrees, being warmer in October.

7.3 Future water temperatures

New research projects

In the future, the average air temperature at all times of the year will continue to rise. This will necessarily result in an increase in water temperatures. No quantitative data are available, but research on this topic is being carried out. The EPFL (Laboratory of Environmental Fluid Mechanics Hydrology) has been commissioned by the Federal Office for the Environment (FOEN) to construct a standardised data basis for water temperature modelling in Switzerland. Under the National Research Programme NRP 61 the project entitled “Integriertes der Wasserqualität in Fliessgewässern” (Integrated Management of Water Quality in Watercourses) is also investigating future aspects of water temperature (Swiss National Science Foundation 2010). Similar projects are underway in Germany and the Netherlands. Statistical and deterministic processes may be considered for modelling water temperature (Pfammatter 2004, Huwald et al. 2010). Previous studies have shown, however, that regression models based on air temperature are inadequate, in particular when short-term changes in water temperature occur. However, such models are useful in determining the impact of rising air temperatures on water temperature, as the interest is not in individual daily values and the method is relatively easy to implement, provided enough data is available.

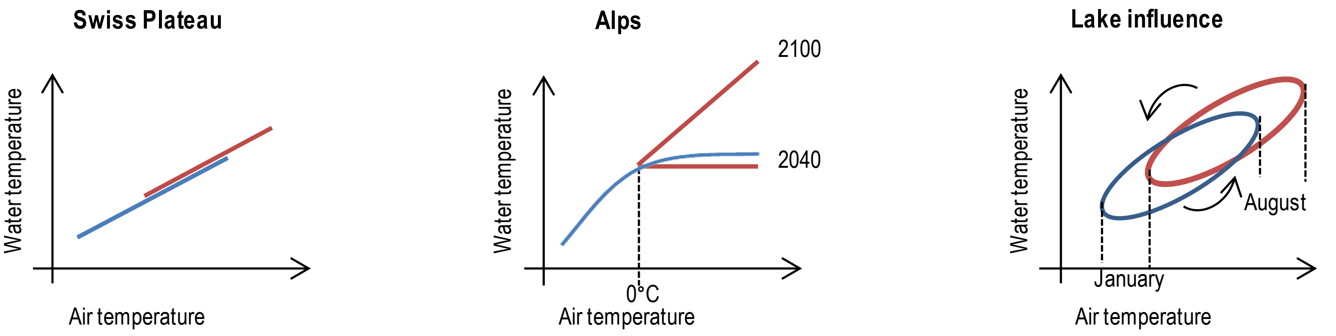
Hypotheses for the future

Hypotheses can be formed based on the three selected river types (fig. 37). It is clear that the temperature of watercourses will be affected by climate change twofold, that is to say, by higher air temperatures and the seasonal distribution of runoff. In the Swiss Plateau it can be assumed that the linear relationship will continue, even when the climate is warmer. But low water levels and wide river channels serve to increase temperatures (SAEFL, FOWG, MeteoSwiss 2004). Low-water events will become more frequent in future (Meyer et al. 2011a) and water temperatures can therefore be expected to react more severely to rising air temperatures. By contrast, in strongly glaciated catchments greater volumes of glacier meltwater are expected (until c. 2040), which could reduce sensitivity to air temperature and even lead to lower temperatures.

As the glaciers disappear in the second half of this century, the amount of runoff in summer will decrease dramatically and this will mean a significant rise in water temperature. Stations which are influenced by lakes will probably experience a shift in hysteresis, and the form this takes could be changed by a marked decrease in summer runoff. Larger volumes of runoff in winter and spring could lead to higher water temperatures. These effects of climate change will greatly impact water use (heat input from industry) and fishing, in particular in summer. As a result of warming, trout are now found at altitudes 100–200 metres higher than previously (Hari et al. 2006). Reduced and warmer discharge reduces the concentration of oxygen considerably and encourages the spread of fish diseases (e.g. proliferative kidney disease, PKD), thus increasing fish mortality.

Fig. 37 > Relationship between monthly air and water temperatures

Depending on the runoff regime of the watercourse, the relationship between monthly air and water temperatures behaves differently (blue). The regime must therefore be taken into account when quantifying the effects of future climatic warming (red). Hybrid forms are, however, possible. It is assumed that the schematic Alpine catchment will no longer be glaciated by 2100. The arrows for the lake influence type show the direction in which the water temperature changes within the hysteresis.



8 > Conclusion

Thanks to the concerted efforts of the CCHydro project, it has been possible for first time to make scientifically reliable, quantitative predictions about possible future changes in the hydrological cycle for the whole of Switzerland. New climate scenarios for Switzerland drawn up with the support of CCHydro provided a broad basis for achieving comparable and coherent results in the different project modules. This comparability is thus also assured in cooperation with other national and international projects (cf. Chapter 1).

8.1 Adaptation measures

Even though the uncertainties in the climate scenarios in the Swiss Alpine area are still considerable, especially in terms of precipitation, new and clear predictions regarding the development of the hydrological regime in Switzerland can be made. The water resources in Switzerland will change only slightly in the future. Switzerland will remain 'Europe's reservoir'. However, local and regional bottlenecks may occur due to a considerable shift in the seasonal distribution of runoff, and adaptive measures in water measurement will be required. In this respect, see the Walter postulate 'Water and agriculture. Future challenges', which calls on the Federal Council to draw up a report on sustainable water strategy from the point of view of the various user groups. The strategy should contain both proposals for action and solutions for dealing with short-term events such as localised, temporary water shortages, and consider the long-term perspective, e.g. how the Federal Council proposes to deal with reduced water supplies as the result of climate change. At the time of publication of this synthesis report, work on the report on the Walter postulate is in progress. It contains proposals for cross-sector and sector-internal measures. The permanent monitoring and early recognition of changes in waters will also play an important role in this in the future.

As part of the efforts to adapt to climate change, in Spring 2012 the Federal Council approved the first part of its strategy entitled 'Adaptation to Climate Change in Switzerland', which formulates objectives, describes challenges and defines areas of action for all sectors (FOEN 2012). In the water management sector fourteen areas of action of varying degrees of urgency were identified. The CCHydro project provides an important scientific, hydrological basis for formulating in greater detail the objectives and options set out in the adaptation strategy in an action plan.

8.2 Outlook

The CCHydro research project has identified the following issues which require further, more detailed research:

- How great are the uncertainties in regional climate modelling, and how reliable are the emissions scenarios?
- How will extreme precipitation and the associated rare flood events change (size, place, time)?
- How will dry periods (precipitation-free periods) and the resulting extreme low water discharge change?
- What changes will there be in variables which are significant for hydrological modelling, such as irradiation, cloud cover, air humidity and wind speed?
- What changes will there be in low water flow in the Alpine foothills and the Alps, where low water has so far always occurred in winter?
- How will water temperatures change and what changes will there be as the result of regime changes and changes in low water flow?

In addition to these hydrological issues, there are obvious gaps in the data both in the bases for modelling and for assessing the results:

- Hydrologically relevant soil characteristics are not available throughout
- Measurement data on current soil moisture levels and evaporation are not available
- There are considerable uncertainties associated with information on reserves in the form of snow (water equivalent of snow cover), in particular at high altitudes and during the melting season.

The methods for modelling the water cycle are constantly being developed. It is still unclear how model parameters which have been established by adjusting model results to measured data can be applied in a future time period with changed climatic and hydrological conditions.

8.3 Acknowledgements

The “Climate Change and Hydrology in Switzerland” (CCHydro) research project provides important hydrological bases for strategic considerations and decisions. Thanks to our highly qualified partners, a solid knowledge base could be developed which allows us to predict the future effects of climate change on the individual elements of the hydrological cycle for the whole of Switzerland. Networking and coordination with other ongoing studies, such as the research project into the impact of climate change on hydropower use and the National Research Programme 61 ‘Sustainable Water Management’, was excellent at all times. In future it is vital that scientific research be continued and this multi-disciplinary approach in the scientific field maintained.

> Bibliography

Sub-project reports

Bosshard T., Kotlarski S., Ewen T., Arnold J., Pall P., Schär C. 2011a: Klimaszenarien für hydrologische Impaktstudien in der Schweiz. 14 pages.

Huwald H., Tomasic N., Parlange M.B. 2010: Stream temperature evolution in Switzerland under clilmate change scenarios – Feasibility study. Laboratory of Environmental Fluid Mechanics and Hydrology. EPFL: 24 pages.

Köplin N., Schädler B., Viviroli D., Weingartner R. 2011: Klimaänderung und Wasserhaushalt in sensitiven Bilanzierungsgebieten. 43 pages.

Linsbauer A., Paul F., Haeberli W. 2012: Grossräumige Modellierung von Schwundszenarien für alle Schweizer Gletscher. Modellvergleich, Unsicherheiten und eine Analyse bezogen auf Grosseinzugsgebiete. Schlussbericht CCHydro, Ergebnisse vom Teilprojekt CCGlinCH. 18 pages.

Meyer R., Schädler B., Viviroli D., Weingartner R. 2011a: Auswirkungen der Klimaänderung auf die Niedrigwasserverhältnisse im Schweizer Mittelland für 2021–2050 und 2070–2099. 42 pages.

Naef F. 2011: Untersuchung über die Auswirkungen der Zunahme der Hochwasserhäufigkeiten in neuerer Zeit und in Zukunft. 50 pages.

VAW 2011: Gletscher- und Abflussveränderungen im Zeitraum 1900–2100 in sieben Einzugsgebieten der Schweiz. 77 pages.

Zappa M. et al. 2012: Klimaänderung und natürlicher Wasserhaushalt der Grosseinzugsgebiete der Schweiz (in preparation).

Other literature

AdaptAlp 2011: Adaptation to Climate Change in the Alpine Space – Work Package Water Regime (WP4). Summary Report. 24 pages.

AlpWaterScarce 2011: Water Management in a Changing Environment – Strategies against Water Scarcity in the Alps – Project Outcomes and Recommendations. 76 p.

Aschwanden H., Weingartner R. 1985: Abflussregimes in der Schweiz. Pub. "Gewässerkunde" No 65. Institute of Geography, University of Bern: 238 pages.

FOEN 2012: Adaptation to Climate Change in Switzerland – goals, challenges and areas of action. Part 1 of the Federal Council's strategy of 2 March 2012. Bern: 81 pages.

Bernhard L., Zappa M., Bosshard T. 2011: Klimaänderung und natürlicher Wasserhaushalt der Grosseinzugsgebiete Alpenrhein und Engadin – Technical Report. Eidg. Forschungsanstalt für Wald, Schnee und Landschaft WSL, Birmensdorf.

Bosshard T., Kotlarski S., Ewen T., Schär C. 2011b: Spectral representation of the annual cycle in the climate change signal. Hydrol. Earth Syst. Sci. 15: 2777–2788.

Bosshard T. 2011c: Hydrological climate-impact modeling in the Rhine catchment down to Cologne. Diss. ETH 19 861.

SAEFL, FOWG, MeteoSwiss 2004. Auswirkungen des Hitzesommers 2003 auf die Gewässer. Publication "Unwelt" No 369. Swiss Agency for the Environment, Forests and Landscape, Bern: 174 pages.

CHR 2010: Assessment of Climate Change Impacts on Discharge in the Rhine River Basin – Results of the RheinBlick 2050 Project. Report No I-23 of the CHR: 212 p.

CH2011, 2011: Swiss Climate Change Scenarios CH2011, published by C2SM, MeteoSwiss, ETH, NCCR Climate, and OcCC. Zurich: 88 pages. ISBN 978-3-033-03065-7.

Farinotti D., Huss M., Bauder A., Funk M. 2009: An estimate of the glacier ice volume in the Swiss Alps. Global and Planetary Change 68: 225–231.

Farinotti D., Usselmann S., Huss M., Bauder A., Funk M. 2011: Runoff evolution in the Swiss Alps: projections for selected high-alpine catchments based on ENSEMBLES scenarios. Hydrological Processes, doi:10.1002/hyp.8276.

Frei C., Schöll R., Fukutome S., Schmidli J., Vidale P.L. 2006: Future change of precipitation extremes in Europe: Intercomparison of scenarios from regional climate models. Journal of Geophysical Research 111.

Glacier reports (1881–2011): Die Gletscher der Schweizer Alpen. Annals of the Cryospheric Commission monitoring networks of the Swiss Academy of Sciences (SCNAT) 1–128. Published since 1964 by the Laboratory of Hydraulics, Hydrology and Glaciology (VAW) at the ETH Zurich. www.glaciology.ethz.ch/swiss-glaciers/.

Haeberli W., Hoelzle M. 1995: Application of inventory data for estimating characteristics of and regional climate-change effects on mountain glaciers: a pilot study with the European Alps. Annals of Glaciology 21: 206–212.

Hänggi P., Bosshard T., Weingartner R. 2011: Swiss discharge regimes in a changing climate. In: Hänggi P.: Auswirkungen der hydroklimatischen Variabilität auf die Wasserkraftnutzung in der Schweiz, Dissertation University of Bern: 77–100.

Hari R.E., Livingstone D.M., Siber R., Burkhardt-Holm P., Güttinger H. 2006: Consequences of climatic change for water temperature and brown trout populations in Alpine rivers and streams. Global Change Biology 12: 10–26.

Hubacher R., Schädler B. 2010: Wasserhaushalt grosser Einzugsgebiete im 20. Jahrhundert. Tafel 6.6. In: Weingartner R., Spreafico M. (Hrsg.): Hydrologischer Atlas der Schweiz (HADES). Federal Office for the Environment, Bern.

Huss M., Farinotti D., Bauder A., Funk M. 2008: Modelling runoff from highly glacierized alpine drainage basins in a changing climate. Hydrological Processes 22(19), 3888–3902, doi:10.1002/hyp.7055.

IPCC 2008: Climate Change 2007. Synthesis report. Berlin.

Jakob A. 2010: Temperaturen in Schweizer Fliessgewässern – Langzeitbeobachtung. GWA 3/2010. S. 221–231.

KOHS 2007: Auswirkungen der Klimaänderung auf den Hochwasserschutz in der Schweiz. Ein Standortpapier der Kommission Hochwasserschutz im Schweizerischen Wasserwirtschaftsverband (KOHS), Wasser Energie Luft 99: S. 55–57.

Köplin N., Schädler B., Viviroli D., Weingartner R. 2010: How does climate change affect mesoscale catchments in Switzerland? – A framework for a comprehensive assessment. Advances in Geosciences 27: 111–119.

Köplin N., Schädler B., Viviroli D., Weingartner R. 2012: Reducing hydrological climate-impact studies to their most important components: Assessment of a comprehensive set of mesoscale catchments in Switzerland. Hydrol. Earth Syst. Sci. Discuss. (submitted).

Laternser M., Schneebeli M. 2003: Long-term snow climate trends of the Swiss Alps 1931–1999. International Journal of Climatology 23: 733–750.

Linsbauer A., Paul F., Hoelzle M., Frey H., Haeberli W. 2009: The Swiss Alps without glaciers – a GIS-based modelling approach for reconstruction of glacier beds. Proceedings of Geomorphometry 2009. Zurich: 243–247.

Meyer R., Viviroli D., Schädler B., Weingartner R. 2011b: Die Rolle des Basisabflusses bei der Modellierung von Niedrigwasserprozessen. In: Klimaimpaktstudien Hydrologie und Wasserbewirtschaftung 55(5): 244–257.

Meyer R., Viviroli D., Schädler B., Weingartner R. 2012a: Multi-variable calibration for a sound modeling of low flow under future climates. Hydrol. Proc. (submitted).

Meyer R., Schädler B., Viviroli D., Weingartner R. 2012b: Implications of projected climate change on summer low flow in the Swiss Plateau. Hydrol. Sci. J. (submitted).

Meyer 2012: Die Auswirkungen der projizierten Klimaänderung auf Sommerniedrigwasser im Schweizer Mittelland basierend auf einer multi-variablen Kalibrierung des hydrologischen Modellsystems PREVAH. Inauguraldissertation of the Philosophisch-naturwissenschaftlichen Fakultät, University of Bern.

MeteoSchweiz 2012a: Klima heute – Trends Schweiz. www.meteoschweiz.admin.ch/web/de/klima/klima_heute/trends_schweiz.html (März 2012).

MeteoSchweiz 2012b: Klima heute – Trends an Stationen. www.meteoschweiz.admin.ch/web/de/klima/klima_heute/trends_an_stationen.html (März 2012).

Naef F., Margreth M., Schmocker-Fackel P., Scherrer S. 2007: Automatisch hergeleitete Abflussprozesskarten – ein neues Werkzeug zur Abschätzung von Hochwasserabflüssen. Wasser, Energie, Luft.

NELAK 2012: Neue Seen als Folge der Entgletscherung im Hochgebirge: Klimaabhängige Bildung und Herausforderung für eine nachhaltige Nutzung (NRP 61 NELAK project, Physicale Geography, University of Zurich, being printed).

OcCC 2008: Das Klima ändert – was nun? Der neue UN-Klimabericht (IPCC 2007) und die wichtigsten Ergebnisse aus Sicht der Schweiz. OcCC – Organe consultatif sur les changements climatiques. Bern: 47 pages.

Oerlemans J., Giesen R.H., van den Broeke M.R. 2009: Retreating alpine glaciers: increased melt rates due to accumulation of dust (Vadret da Morteratsch, Switzerland). Journal of Glaciology 55.

Paul F., Maisch M., Rothenbuehler C., Hoelzle M., Haeberli W. 2007: Calculation and visualisation of future glacier extent in the Swiss Alps by means of hypsographic modelling. Global Planet Change 55(4): 343–357.

Paul F., Linsbauer A. 2012: Modeling of glacier bed topography from glacier outlines, central branch lines and a DEM. International Journal of Geographical Information Science.

Pfammatter F. 2004: Untersuchungen zur Wassertemperatur in schweizerischen Fliessgewässern. Dissertation.

Prein A.F., Gobiet F., Truhetz H. 2011: Analysis of uncertainty in large scale climate change projections over Europe. Meteorologische Zeitschrift 20: 383–395.

ProClim, OcCC (Hrsg.) 2011: Wie gut sind Klimamodelle? Climate Press. Hintergründe der Klima- und Global Change Forschung Nr. 30.

Schädler B. 1985. Der Wasserhaushalt der Schweiz. Mitteilung der Landeshydrologie.

Schär C., Vidale P.L., Lüthi D., Frei C., Häberli C., Liniger M.A., Appenzeller C. 2004: The role of increasing temperature variability in European summer heatwaves. Nature 427: 332–336.

Schürch M. 2011: Arbeitsgruppe “Grundwasser und Klima”. Auswirkungen des Klimawandels auf das Grundwasser. GWA 3/2011: 177–182.

Swiss National Science Foundation 2010: Sustainable Water Management. Portrait of the National Research Programme NFP 61. Bern: 54 pages.

Serquet G., Marty C., Dulex J.-P., Rebetez M. 2011: Seasonal trends and temperature dependence of the snowfall/precipitation-day ratio in Switzerland. Geophysical research letters 38.

SGHL, CHy (Publ.) 2011: Auswirkungen der Klimaänderung auf die Wasserkraftnutzung – Synthesebericht. Beiträge zur Hydrologie der Schweiz No 38. Bern: 28 pages.

Viviroli D., Gurtz J., Zappa M., Weingartner R. 2009: An introduction to the hydrological modelling system PREVAH and its pre- and post-processing tools. Environmental Modelling & Software 24: 1209–1222.

Volken D. 2010: Projektbericht. CCHydro – Auswirkungen der Klimaänderung auf die Wasserressourcen und die Gewässer in der Schweiz. Hydrologie und Wasserbewirtschaftung Bd. 54: 143–146.

Weingartner R., Aschwanden H. 1992: Abflussregimes als Grundlage zur Abschätzung von Mittelwerten des Abflusses. In: Hydrologischer Atlas der Schweiz, Tafel 5.2, Federal Office for the Environment FOEN, Bern.

WGMS, Haeberli W., Gärtner-Roer I., Hoelzle M., Paul F., Zemp M. 2009: Glacier Mass Balance Bulletin No. 9 (2006–2007), CSU (FAGS) / IUGG (IACS) / UNEP / UNESCO / WMO, World Glacier Monitoring Service, Zurich.

Zemp M., Haeberli W., Hoelzle M., Paul F. 2006: Alpine glaciers to disappear within decades? Geophysical Research Letters 33.

Zumbühl H.J., Steiner D., Nussbaumer S.U. 2008: 19th century glacier representations and fluctuations in the central and western European Alps: an interdisciplinary approach. Global and Planetary Change 60: 42–57.

> Abbreviations, figures and tables

Figures

Tables